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Characterization of Ground Nozzles for Pesticide Applications

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CHARACTERIZATION OF GROUND NOZZLES FOR PESTICIDE APPLICATIONS

by

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CHARACTERIZATION OF GROUND NOZZLES FOR PESTICIDE APPLICATIONS

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Pesticide applications are a common component of crop production systems in the United States (US). For row crop systems (e.g. corn, soybean, or wheat), pesticides are applied by ground, aerial, or chemigation methods. The exact method of pesticide delivery is not universally regulated/ prescribed in the US, and the equipment and application technique are largely defined by the individual applicator. A wide variety of choices and decisions must be made by applicators to result in a successful pesticide application. Examples of these choices include proper active ingredient(s), carrier volume and equipment (e.g. nozzle type, spacing, and operating pressure) selection while also considering environmental influences such as wind speed and temperature. However, applicators are often limited in guidance on making successful applications, and this can result in off-target movement of the pesticide(s) causing unintentional injury to vegetation, environmental contamination, and/or human exposure. This has prompted several state and federal agencies to monitor pesticide applications and development strategies or programs to reduce off-target movements of pesticides.

The objectives of the current research were to 1) incorporate and expand upon the US Environmental Protection Agency (EPA) drift reduction technology (DRT) guidelines using a wind tunnel laboratory, 2) characterize the droplet size, velocity, pattern uniformity, and drift potential of commonly used application nozzles for ground systems

in the US, and 3) bridge laboratory and field studies in pesticide application technology using established and new methodologies.

The data from this research aided in the development of a robust application technology program within the University of Nebraska and advanced the EPA DRT guidelines for wind tunnel testing of pesticides. Furthermore, the data demonstrated the impacts of ground nozzle selection upon the drift potential of new and existing herbicides in the US. The methods and equipment utilized in this research will be beneficial to researchers in application technology and can serve as a foundation for future experiments.

For my wife and best friend, Lauren.

I love you more and more with each passing day.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

LITERATURE REVIEW

Agricultural producers in the US rely on the application of pesticides to control pests and protect yields and profits. Nearly twenty percent of on-farm expenditures can be tied to pesticide applications, including purchase price, equipment purchase or lease, and fuel usage (NASS, 2012). In addition to direct costs, pesticide applications have been associated with detrimental costs to both human and environmental health. Human health effects include acute poisonings, chronic/cancer-related concerns, and residues left on fruits, vegetables, tree nuts and other food products. Environmental health effects include ground and surface water contamination, destruction of sensitive plant species and beneficial insects, and poisoning of farm and house animals (Pimentel 2005). Selection pressures associated with pesticide usage on pests have also aided the development of pesticide resistance in weed, insect, and fungal species (Hoy et al. 1998; Powles and Yu 2010). While the evolution of resistance is complex, direct links of resistance to poor application strategies have been documented, e.g. using reduced rates to minimize costs, in pests like grass weeds (Neve and Powles 2005) or insects (Gressel 2011). In addition to these issues, the development of novel pesticide modes of action has stalled in recent years (Duke 2012), necessitating research to continually improve the application process.

Programs to Reduce Drift

Applicators have been encouraged to reduce pesticide drift by incorporating drift reduction technologies (DRTs) and choosing sound application strategies. The

Environmental Protection Agency (EPA) estimates that one to ten percent of pesticides applied in the US are lost to particle drift, which equates to roughly 70 million pounds of active ingredient. The growing public awareness of the risks of pesticide exposure, such as the potential for reproductive harm (Shirangi et al. 2011) have accelerated the need for DRTs in recent years. The EPA DRT program is currently voluntary and intended to encourage DRT manufacturers and pesticide registrants to develop and test DRT technologies (EPA 2015). The intended goal is to increase applicator awareness of these DRTs and provide incentives for their use such as reduced buffer zones. Examples of DRTs include nozzle type, sprayer modifications (e.g. hooded sprayers or shielded nozzles), or spray modifiers (e.g. drift reduction adjuvants). At current, the EPA DRT program is in under development and several items still need addressed, such as the development of robust test and quality assurance plans at each testing laboratory, the incorporation of spray modifiers with nozzle types into testing, and field testing methods of potential DRTs.

In addition to the EPA DRT program, applicators can voluntarily participate in private programs to mitigate pesticide drift. For example, BASF Crop Protection offers a stewardship program called the "On Target Application Academy" to growers focused on ground applications, while aerial applicators can participate in "Operation Self-Regulating Application and Flight Efficiency" from the National Agricultural Aviation Association. Applicators can also register for communications hosted by the "FieldWatch" network to check for nearby drift-sensitive vegetation or bee apiaries.

Nozzle Type Effects on Droplet Size

Nozzles utilized for pesticide applications include conventional hydraulic (CH), air-inclusion (AI), and straight or solid stream (SS). Specialized nozzle types are available to applicators, such as electrostatic nozzles (Edward Law 2001) or rotary atomizers (Teske et al. 2005). The choice of nozzle type is often made by the applicator, although restrictions to nozzle type can be made by the pesticide label.

Most conventional hydraulic nozzles operate as a pressurized liquid exits through a discharge orifice. This causes the liquid to atomize and produce a droplet size distribution (DSD) following the breakup of a liquid sheet. Air-inclusion nozzles behave in a similar manner, except the liquid typically enters an expansion chamber, with AI ports, prior to exiting the nozzles. For a given orifice size and pressure, the DSD produced by CH nozzles is finer than an AI nozzle (Arnold 1983; Butler-Ellis et al. 2002; Creech et al. 2015). The DSD for pesticide applications is typically 100 to 2,000 µm (Etheridge et al. 1999; Guler et al. 2007), although smaller and larger droplet diameters can be present based on nozzle type. Straight stream nozzles force the liquid through a relatively larger and more circular orifice than CH or AI nozzles, and this liquid stream can be secondarily atomized by wind shear in aerial application conditions (Hoffmann et al. 2008). The DSD for SS nozzles is heavily dependent upon this secondary atomization process.

The DSD of a pesticide application is important because it influences final efficacy and drift potential. Control of diamondback moth larvae with the insecticide permethrin decreased with DSD (Omar et al. 1991), while control of larval tobacco budworm in cotton increased with a smaller DSD (Reed and Smith 2001). Similar relationships between DSD and efficacious control have been studied in weed (Knoche 1994; Ramsdale and Messersmith 2001; Rogers 1989) and fungal (Frick 1970; Wolf and Daggupati 2009) species. Physical drift of pesticide droplets is heavily dependent upon the DSD of the application (Al Heidary et al. 2014b; Nuyttens et al. 2009). Using computer simulations, Zhu et al. (1994) predicted that water droplets can drift from 57 to 0.03 meters downwind of the application zone for droplets ranging from 50 to 1,000 µm, respectively. The drift potential of any droplet is also influenced by boom height above canopy, operating pressure, and wind speed (Nordby and Skuterud 1974; Nuyttens, David et al. 2007). While any droplet has the potential to move off-target, the definition of a “driftable droplet” is not well defined. Some researchers have declared droplets 200 µm (Etheridge et al. 1999) or 150 µm (Yates et al. 1985) in diameter or below to be “driftable”. A droplet diameter of 141 µm or below has been proposed to be the proxy for drift potential determinations for current and future DRTs (Hoffmann et al. 2012).

The DSD of a pesticide application can be measured using laser diffraction (LD) techniques. Laser diffraction is a spatial sampling method, meaning that droplets are measured based on their position within the measurement zone. A signal is received by the LD device, which is then converted to population of droplets of a certain volume, based on the droplet diameter, of a spray measured in a user-defined timeframe (Dodge et al. 1987). This measurement technique in pesticide droplet sizing experiments allows for testing the complete fan angle of the spray, while using lower spray volumes than temporal sampling techniques, like phase doppler particle size analyzer (PDPA). This technique simultaneously measures the droplet diameter and velocity (Chapple et al. 1995) in a relatively smaller proportion of the spray volume than LD. For these reasons, LD techniques are more convenient than PDPA to measure the DSD of a pesticide application (Hewitt 1994), and LD will be the method utilized in the current research.

Spray Pattern Uniformity

Pattern uniformity can affect the final efficacy of a pesticide application, because it influences the placement of the active ingredient(s) on the target pest. Prior research has demonstrated that as little as one to three percent of the total spray volume impacts the target species, the rest being captured by the crop, lost as runoff from the target, or merely impacting the ground (Ebert et al. 1999). Nozzle type (Etheridge et al. 1999; Womac et al. 2001) and equipment setup and operation (Jeon et al. 2004; Langenakens et al. 1999) can affect the pattern uniformity under the boom. Etheridge et al. (1999) measured the pattern uniformity of four AI nozzles and one CH nozzle, and found that the coefficient of variation (CV) ranged from 12.1 to 22.6 % for the CH and AI nozzles, respectively. Using CV as a measure of variability is commonly used to describe the evenness of the spray pattern underneath a boom. Increasing sprayer speeds from 6.4 to 19.3 km h-1 did not affect the CV of coverage on water-sensitive cards for an AI and CH nozzle, even though the mean droplet diameter was close to five times larger with the AI nozzle (Womac et al. 2001). Operating parameters that can affect pattern uniformity include lateral boom rolling (Mawer and Miller 1989) and the pitch of the fan behind air-blast nozzles (Muhammad and Landers 2004). Increasing boom height above a canopy, and reducing tire pressure and application speed improved pattern uniformity by minimizing the vertical motions of the boom (Langenakens et al. 1999; Langenakens et al. 1995).

Pattern uniformity can be measured by both static and dynamic methods. Static methods typically employ a patternator table with graduated cylinders to catch and measure the spray across the boom width (Etheridge et al. 1999; Womac et al. 2001), although more technically advanced static systems (Herbst and Wolf 2001) and computer simulations (Chapple et al. 1993; Langenakens et al. 1995; Mawer and Miller 1989) have been used. Dynamic methods involve the movement of a spray boom over a measurement zone. Water sensitive cards are commonly used for ground applications (Jeon et al. 2004; Womac et al. 2001), while aerial applications commonly use petri dishes (Hofman et al. 1985) or string collectors (Whitney and Roth 1985) across the flight line.

Drift Measurement Techniques

Drift measurements in a wind tunnel typically focus on measuring the DSD of the spray or measuring downwind deposition and/ or airborne flux of the spray particles. The DSD can be measured using laser diffraction or image analysis devices (Arnold 1990). The DSD data can then be assigned drift reduction ratings when compared to a reference spray, such as the scheme utilized by the British Crop Protection Council (Nuyttens, D. et al. 2007) or the US EPA DRT program (ASABE 2009b). In addition, the DSD data can be input into computer simulation models, such as AGDISP (Bilanin et al. 1989), AgDRIFT (Teske et al. 2002), or BREAM (Kennedy et al. 2012). Both AGDISP and AgDRIFT focus on modelling the trajectories of spray droplets as they move out of the application zone, taking into account aircraft wake, surface characteristics, and environmental effects (Teske et al. 2002). Utilizing these programs has been encouraged for assessing potential DRTs in the US EPA DRT program (EPA 2015). BREAM was developed to model bystander exposure and inhalation risks from pesticides based on parameters including nozzle type, characteristics of the bystander (e.g. height, breathing rate, etc.), and environmental conditions (Kennedy et al. 2012). Deposition and/or flux measurements involve capturing and collecting any spray material downwind of the nozzle. Taylor et al. (2004) used monofilament lines to obtain flux and deposition measurements and found both measurements increased as spray quality decreased, as expected. Collection tubes coupled with load cells were used to calculate drift ratios of several nozzle by wind speed combinations, and over 90 % of the spray volume was captured within 9 meters downwind of the nozzle (Al Heidary et al. 2014a).

Measuring spray drift in a field setting focusses on downwind deposition and/or airborne flux of spray particles. These studies are typically setup where the drive or flight line is perpendicular to the prevailing winds and the downwind measurement site (ASABE 2009). Collection media such as monofilament lines (Fritz et al. 2011), plastic drinking straws (Longley et al. 1997), or active air samplers (Arvidsson et al. 2011) have previously been used. Donkersley and Nuyttens (2011) examined the measurement techniques of ten field drift studies and found most differences between the collection media were between zero and five meters downwind. Lastly, simulated field drift studies entail applying fractional pesticide active ingredient rates over-the-top of a sensitive plant species. For example, injury to cotton from 2,4-D and dicamba was evaluated using rates of 1/200 and 1/400 of the normal use rate of 561 grams ae ha-1(Marple et al. 2008). However, for an actual pesticide drift scenario, the droplet size, pesticide active ingredient concentration contained within these droplets, and deposition potential of the droplets impacting the sensitive species are unlikely to be similar to these over-the-top applications.

Objectives

The most dominate factor influencing droplet size in agrochemical applications is the nozzle. Agriculturalists in the US have a wide range of nozzle choices for ground application of pesticides which leads to significant confusion when making operational decisions. Proper nozzle selection setup and operation is critical as the resulting droplet size and swath uniformity play a key role in determining the efficacy and drift potential for a given application scenario. Therefore, the overall objective of this research was to characterize the operational performance characteristics of a selection of the most commonly used ground nozzles in the US under typical application conditions and for typical tank mixes to provide applicators with scientifically based guidance that can be used to optimize the spray application process to maximize product efficacy while mitigating off-target losses.

To meet the overall objective, several sub-objectives were addressed. The first was to characterize a collection of the most typical ground nozzles with respect to their droplet size distribution (DSD), velocity profile, and pattern uniformity. The second was to understand how these parameters, especially DSD and pattern uniformity, impact herbicide efficacy and drift potential using wind tunnel, greenhouse, and field experiment methods. Thirdly to determine the influence formulated products and real-world tank-mixtures have with respect to the outcomes of the first two sub-objectives. Fourthly, to explore the role measurement bias plays in the results from droplet sizing and to expand existing techniques to more fully characterize the effect , nozzle droplet size and spray pattern play on full-boom swath uniformity The results presented will directly benefit pesticide applicators in the US through sound guidance, and lay further groundwork for continued research in this area.

CHAPTER 2

THE INFLUENCE OF NOZZLE TYPE, OPERATING PRESSURE, AND TANK-MIXTURE COMPONENTS ON DROPLET CHARACTERISTICS AND THE EPA'S DRIFT REDUCTION RATING

Abstract

The introduction of the Drift Reduction Technology (DRT) guidelines by the United States Environmental Protection Agency has established testing protocols for nozzles, agrochemicals, application parameters, and combinations thereof, for applying agrochemicals in by certified individuals in the U.S. The Pesticide Application and Technology Laboratory in North Platte, Nebraska, USA sought to develop a large database of droplet spectrum data in regards to agrochemical applications by ground systems. The results of this study indicated that nozzle type had the greatest impact on the droplet spectra measured. DRT star ratings ranged from zero to four, depending upon nozzle selection and adjuvant inclusion. The results of this study indicated that factors that affect a droplet spectrum, which include nozzle type, tank-mixture components, and operating pressure should be tested together when submitting data to the EPA.

Introduction

Synthetic pesticide use for agriculture has been a key component of cropping systems in the U.S. for several decades. Currently in the U.S., growers apply a variety of pesticides per year including fungicides, insecticides, and herbicides, and this represents approximately 20% of the total farm input costs (USDA NASS, 2012). The reliance on pesticides has contributed to large gains in yield and productivity per acre across the

U.S., but it can also be attributed to inadvertent human exposure and damage to susceptible crops from drift or misapplication. To combat these negative effects of pesticide use, the Environmental Protection Agency (EPA) established guidelines for a voluntary program that provides incentives for the testing, and ultimate use of, drift reduction technologies (DRTs) (EPA 2006).

A key component of the EPA's DRT program is the analysis of the droplet spectrum produced during the application of a pesticide. Research involving the analysis of droplet spectra from sprays has been well documented. Mohamed et al. (1981) utilized laser diffraction to determine particle size distributions from nebulizer aerosol samples and found the approach to be a more convenient method droplet size analysis than flame or fluorescence spectroscopy. Further research examined potential limitations of laser diffraction for particle size analysis (Dan Hirleman 1988; Gülder 1990; Kokhanovsky and Weichert 2001; Wild and Swithenbank 1986), yet this methodology is widely accepted when studying pesticide sprays including those for agricultural purposes (Hewitt and Valcore 1995).

Droplet size is an important factor in the efficacy and drift potential of pesticides. Omar et al. (1991) found that efficacy of permethrin on diamondback moth larvae decreased with droplet size, regardless of carrier volume, presumably due to a lessened concentration of lethal insecticide concentrations in the small droplets. Smaller droplets (<150 µm) increased control of grass species than did larger droplets (>150 µm) when using foliar-applied herbicides, although these effects where influenced by herbicide mode of action, carrier volume, and leaf morphology (Knoche 1994). Physical drift of pesticides is heavily influenced by droplet size, wherein smaller droplets have the greatest potential to move off target and cause damage to susceptible vegetation, expose humans to pesticide, or contaminate waterways. While there is no specific droplet size that defines a driftable droplet, some researchers have proposed using a droplet diameter of 141 µm as the proxy for determination of drift potential (Hoffmann et al. 2012). An accurate analysis of droplet size is also a key component in computer models designed to estimate pesticide drift (e.g. AGDISP or AgDRIFT).

Spray droplet velocity is also an important component to the overall efficacy of a pesticide application (Miller and Butler Ellis 2000). For example, adhesion of spray droplets to pea leaves was inversely related to droplet size and velocity (Stevens et al. 1993). The droplet velocity can be influenced by a variety of factors, including nozzle type (Nuyttens, D. et al. 2007) and composition of the spray mixture (Butler Ellis and Tuck 1999; Holloway et al. 2000) and pressure (Fritz, Bradley K et al. 2014). Measurement of droplet velocity from the nozzle has been an important factor in developing computer models for predicting deposition and drift (Teske et al. 2011). Furthermore, when measuring droplet sizes using spatial techniques (e.g. laser diffraction) it is important to consider both the droplet velocity and coaxial airstream velocity to minimize measurement error (Dodge 1987; Force 1997; Frost and Lake 1981). Characterization of droplet velocities produced from sprays in ground application should be an important consideration for laboratories involved in droplet size analysis as well as current and upcoming testing standards being revised or developed (Astm 2011).

The objectives of this study were to characterize the droplet size spectrum and velocity profile of several ground nozzles as influenced by nozzle type, application pressure, and components of the tank-mixture and then to utilize the new EPA DRT guidelines for assigning a drift potential rating. The EPA DRT program builds upon the classification schemes of nozzles evaluated in Europe (Nuyttens, D. et al. 2007) and Japan (Bai et al. 2013); however; the nozzles used in this study will be representative of common ground nozzles used in U.S. production systems.

Materials and Methods

Three spray nozzle types (XR, AIXR, and TTI) were assessed in this study to represent the most common types used in the U.S. Each nozzle was tested at 207 and 414 kPa. Prior to droplet size and velocity analysis, the nozzles were tested with water to ensure a proper flow rate at a given pressure, based on the manufacturer-supplied information. A range of formulation types (soluble liquid concentrates, emulsifiable concentrates, and water dispersible granules) for both the pesticide and adjuvant types (microemulsions, high surfactant oil concentrates, and crop oil concentrates) of the spray solution were used (Table 2.1). These formulations were chosen to represent those commonly used in the U.S., and previous research has indicated a need to consider both nozzle and spray solution when evaluating pesticide performance and drift potential (Hilz and Vermeer 2013).

Droplet size measurements were made using a Sympatec HELOS/KR (Sympatec, INC. Pennington, NJ, USA) laser diffraction instrument. The manufacture denoted R7 lens was used which is capable of measuring droplet sizes in the range of 18 to 3,500 µm.

The entire spray plume was traversed vertically through the measurement zone by means of a linear actuator. At least three complete traverses (replications) for each treatment were made for statistical analysis. Testing took place in a low-speed wind tunnel (PAT Lab, North Platte, NE, USA) with a laminar wind speed velocity of 6.7 m/s (Fritz, Bradley K. et al. 2014).

Droplet velocity measurements were made using a LaVision SprayMaster (LaVision Inc., Ypsilanti, MI). This system utilized a double pulsed laser and camera to take two sequential images of the spray droplets eight nanoseconds apart. The images were taken directly under the nozzle orifice at a distance of 30 cm (Fritz et al. 2009). The LaVision software was used for processing the raw data by which the velocity profile of the spray was determined.

Data generated in this experiment was analyzed using SAS Enterprise Guide (SAS, Cary, NC, USA). A modified PROC MIXED code was used with replication set as a random factor in analysis. A Tukey's means separation procedure was used to determine statistical significance with $\alpha=0.05$. The spray characteristic analyzed was the percent of the spray volume less than 141 µm (Pct<141µm), and the droplet velocity (m/s), but only Pct<141µm was analyzed using ANOVA. The spray category classification values are based on data generated using the guidelines established in ASAE S572.1 "Spray Nozzle Classification by Droplet Spectra" (Table 2.3).

Results and Discussion

Nozzle type had the largest effect on droplet size in this study (Table 2.2) and accounted for 71 % of the variability in the data, followed by solution type (6 %) and operating pressure (4 %). This was consistent with previous research which indicated that the nozzle effect was the most determinate of droplet spectrum; however, most of these studies were performed using water or limited component tank-mixtures (Bai et al. 2013; Butler Ellis et al. 1997; Nuyttens, D. et al. 2007). The TTI nozzle produced the largest droplet spectrum of the nozzles tested, regardless of pressure or formulation (Table 2.6). The XR nozzle produced the smallest droplet spectrum in this study, with "medium" being the highest droplet classification observed (Table 2.4).

Formulation of the tank-mixture can influence the final droplet spectrum by altering the physical properties of the spray solution and/or the interaction between the formulation and the nozzle type (Hewitt 2008; Hilz and Vermeer 2013). Typical impacts on the spray solution properties include altering the surface tension, viscosity or by including inhomogeneities in the spray solution. Nearly all tank-mixtures with adjuvants decreased the Pct<141 µm relative to no adjuvants in the tank-mixture for the XR nozzle, and the ME typically had the lowest Pct<141 of the adjuvants tested (Table 2.4). In most cases, the droplet classification assigned to each herbicide by adjuvant combination were not different, and at 414 kPa there was no difference between any of the tank-mixtures.

The impact of formulation of the tank-mixtures was less apparent for the air-inclusion nozzles indicating the larger the droplet size produced by the nozzle the less effect tank-mixture will have on the spray droplet size spectrum. While ANOVA tests captured differences in the Pct<141 µm, the magnitude of the differences were much less than the XR nozzle. The spread of Pct<141 µm for the AIXR nozzle ranged between zero and two percent within a given pressure by tank-mixture (Table 2.5), and for the TTI nozzle the spread was typically only a few tenths of a percent (Table 2.6). The statistical differences observed can be explained by the extremely low rep-to-rep variability in the droplet spectrum measured using laser diffraction. This leads to large F-values in ANOVA leading to significant statistical differences between treatments with very small numerical differences, many likely not observable in the field. On the basis of spray category classification, only a few differences existed within a herbicide by adjuvant combination for both air-inclusion nozzles. The notable exception to this was the tank-mixtures involving the WDG herbicide with the TTI nozzle. Inclusion of an adjuvant generally decreased the spray category classification by one level for the adjuvants tested (Table 2.6).

The velocity profiles for the XR, AIXR and TTI nozzles were measured at 414 kPA using four tank-mixtures. In general, inclusion of an adjuvant with the SL herbicide reduced the velocity of similar sized droplets (Figures 2.1, 2.2 and 2.3). The highest droplet velocities observed were approximately 12 m/s for droplets between 400 and 500 µm, 10 m/s for droplets between 600 and 700 µm, and 8 m/s for droplets between 900 and 1,000 µm for the XR, AIXR, and TTI nozzles, respectively. For a given droplet size below 400 µm, the velocity was higher for the hydraulic XR nozzle as compared to the air-inclusion nozzles, likely as a result of the air-inclusion pre-orifice structures which effectively reduce the pressure on the fluid as it passes through the exit orifice. This supports previous research using water and additional nozzle types and orifices not used in the current study (Dorr et al. 2013; Nuyttens, Schampheleire, et al. 2009). The velocity of droplets less than 200 µm was between 0.5 and 2 m/s (Figure 2.3). At 30 cm below the nozzle, these small, slow moving droplets are immediately susceptible to entrainment and movement with ambient wind conditions leading to off-target movement. This may explain the detection of off-target particles several meters downwind of the application site with this nozzle and comparable tank-mixtures in previous studies (Henry, Ryan S. et al. 2014). Knowledge of droplet velocity profiles and how they may be influenced by various application parameters can also be beneficial to understanding droplet and target interactions (bounce, shatter, interception, etc.) (Dorr et al. 2008) as well as updating ground-based drift prediction models (personal communication, Dr. Andrew Hewitt).

Assigning a star rating to proposed DRTs will be a key component of the US EPA's drift reduction testing and verification program (Epa 2015). These ratings are on a one to four scale, based on the reduction of percent of the spray volume less than 141 µm, relative to a the XR11003 at 300 kPa. A reduction in the Pct<141 micrometers (as compared to the ASABE FM reference nozzle) of 0 to 24, 25 to 49, 50 to 74, 75 to 89, and 90 to 100 % will correspond to a zero, one, two, three, and four star rating, respectively. DRT star ratings for the XR nozzle ranged from zero to two stars at 207 kPa, with the two star ratings including the ME adjuvant (Table 2.4). At the 414 kPa all droplet categories were "fine", and no star ratings were assigned for this nozzle. This indicated that pressure has a greater influence on droplet than tank-mixture in this data set. Air-inclusion nozzles ranged in droplet classifications from "coarse to extremely coarse" (AIXR) and "extremely coarse to ultra coarse" (TTI) (Tables 2.5 and 2.6). At these droplet classifications, star ratings ranged from two to four. The combination of lower pressure (207 kPA) and a tested adjuvant in the tank-mixture typically resulted in a four star rating for the AIXR nozzle (Table 5). At 414 kPa, no four star rating was observed for this nozzle. Combination of pressure and tank-mixture tested with the TTI nozzle resulted in a four star rating (Table 2.6). These studies have borne out the need to test individual nozzle, solution, and pressure combinations, as each combination generates a specific rating that cannot always be interpolated from other data sets.

Conclusions

The results of this study indicated that nozzle selection has the largest impact on the droplet classifications, velocity profile, and drift reduction star rating. While statistical differences were observed amongst and between treatments, this was largely attributed to the low variation in treatment replications. Based on the results of this study, it is evident that droplet size testing of a candidate DRT for submission to the EPA should couple all factors that drive atomization, including nozzle type, active ingredient or adjuvant, and operating pressure.

Table 2.1. List of nozzles, operating pressures, and pesticide and adjuvant formulation types used in the study. Each nozzle by pressure by formulation type was characterized for droplet size and droplet velocity.

Nozzle Type[a]	Operating Pressure (kPa)	Pesticide Formulation Type[b]	Adjuvant Formulation Type[c]
Extended Range (XR) Air Induction Extended Range (AIXR) TurboTeeJet Induction (TTI)	207, 414	SL, EC, WDG	ME, HSOC, COC

[a]The listed nozzle types were all orifice size "03" with a manufacturer rated spray plume angle of 110°

[b]SL=Soluble concentrate, Roundup PowerMax® (540 g ae/L)

EC=Emulsifiable concentrate, Cobra® (240 g ai/L)

WDG=Water dispersible granules, Classic® (0.25 g ai/g)

[c]ME=Microemulsion, Interlock® (2.5% v/v)

HSOC=High surfactant oil concentrate, Destiny HC®(1% v/v)

COC=Crop oil concentrate, R.O.C.® (5% v/v)

Table 2.2. ANOVA results for the percent of the spray volume less than 141 µm from the experimental dataset.

Source	df[a]	SS[b]	MSE[c]	F value	Pr>F	η^{2}[d]
Solution	11	2466.6	224.2	772.2	<.0001	0.06
Nozzle	2	27168.2	13584.1	46782.0	<.0001	0.71
Pressure	3	1636.5	545.5	1878.7	<.0001	0.04
Solution*Nozzle	22	2847.4	129.4	445.7	<.0001	0.07
Pressure*Solution	33	175.3	5.3	18.3	<.0001	0.00
Pressure*Nozzle	6	1156.3	192.7	663.7	<.0001	0.03
Pressure*Solution*Nozzle	65	302.8	4.7	16.0	<.0001	0.01
Rep	8	1.1	0.1	0.5	0.9	0.00

[a] df=degrees of freedom

[b] SS=Sum of Squares

[c] MSE= Mean squared error

[d] η2= Total variation accounted for by main effect or interaction term

Table 2.3. Droplet size spectra for reference nozzle kit used at the PAT Lab, North Platte, NE. The measurements were taken in accordance with ASASBE S572.1 guidelines.

Nozzle	Pressure	Dv10	Dv50	Dv90	Pct<105	Pct<141	Pct<150	Pct<210	Pct<730	Category
	kPa	µm								
11001	450	62	139	239	31.16	51.21	56.17	82.64	100.00	Fine
11003	300	112	245	400	8.41	17.00	19.30	38.21	100.00	Medium
11006	200	154	340	556	3.91	8.17	9.33	19.76	99.80	Coarse
8008	250	187	419	698	2.44	5.21	5.97	12.84	92.69	Very Coarse
6510	200	224	500	818	1.53	3.36	3.86	8.56	82.46	Extremely Coarse
6515	150	305	645	1009	0.41	1.26	1.50	3.88	61.28	Ultra Coarse

Table 2.4. Droplet classification, percent of the spray volume less than 141 µm, and the DRT rating for various tank mixtures using the XR11003 nozzle at 207 and 414 kPA. Data were separated by pressure, and means in the same column followed by the same letter are not different (α=0.05).

Pressure	Herbicide	Adjuvant	Classification	Vol<141		DRT rating
kPA				%		
207	EC	none	Medium	8.7	F	*
		COC	Medium	8.8	F	*
		HSOC	Medium	8.7	F	*
		ME	Medium	8.4	F	**
	SL	none	Fine	20.5	A	-
		COC	Fine	17.9	B	-
		HSOC	Fine	20.2	A	-
		ME	Fine	11.6	E	*
	WDG	none	Fine	15.3	C	-
		COC	Medium	11.8	E	*
		HSOC	Medium	12.9	D	-
		ME	Medium	7.3	G	**
414	EC	none	Fine	18.0	FG	-
		COC	Fine	18.1	F	-
		HSOC	Fine	17.4	G	-
		ME	Fine	17.5	FG	-
	SL	none	Fine	35.2	A	-
		COC	Fine	30.8	B	-
		HSOC	Fine	31.4	B	-
		ME	Fine	22.9	DE	-
	WDG	none	Fine	29.2	C	-
		COC	Fine	22.4	E	-
		HSOC	Fine	23.5	D	-
		ME	Fine	16.2	H	-

Table 2.5. Droplet classification, percent of the spray volume less than 141 µm, and the DRT rating for various tank mixtures using the AIXR11003 nozzle at 207 and 414 kPA. Data were separated by pressure, and means in the same column followed by the same letter are not different (α=0.05).

Pressure	Herbicide	Adjuvant	Classification	Vol<141		DRT rating
kPA				%		
207	EC	none	Very Coarse	1.4	BC	****
		COC	Very Coarse	1.4	BC	****
		HSOC	Very Coarse	1.3	C	****
		ME	Very Coarse	1.3	C	****
	SL	none	Very Coarse	2.7	A	***
		COC	Very Coarse	2.5	A	***
		HSOC	Very Coarse	2.6	A	***
		ME	Very Coarse	1.1	C	****
	WDG	none	Extremely Coarse	2.1	AB	***
		COC	Extremely Coarse	1.2	C	****
		HSOC	Extremely Coarse	1.4	BC	****
		ME	Extremely Coarse	1.1	C	****
414	EC	none	Coarse	3.6	CD	***
		COC	Coarse	4.1	C	***
		HSOC	Coarse	3.4	DE	***
		ME	Coarse	3.5	CDE	***
	SL	none	Coarse	5.6	B	**
		COC	Coarse	5.8	B	**
		HSOC	Fine	18.7	A	-
		ME	Coarse	3.6	CD	***
	WDG	none	Coarse	5.4	B	**
		COC	Coarse	3.5	CDE	***
		HSOC	Coarse	3.9	CD	***
		ME	Coarse	2.9	E	***

Table 2.6. Droplet classification, percent of the spray volume less than 141 µm, and the DRT rating for various tank mixtures using the TTI11003 nozzle at 207 and 414 kPA. Data were separated by pressure, and means in the same column followed by the same letter are not different (α=0.05).

Pressure	Herbicide	Adjuvant	Classification	Vol<141		DRT rating
kPA				%		
207	EC	none	Ultra Coarse	0.4	A	****
		COC	Ultra Coarse	0.4	A	****
		HSOC	Ultra Coarse	0.3	A	****
		ME	Ultra Coarse	0.3	A	****
	SL	none	Ultra Coarse	0.3	A	****
		COC	Ultra Coarse	0.2	A	****
		HSOC	Ultra Coarse	0.3	A	****
		ME	Ultra Coarse	0.3	A	****
	WDG	none	Ultra Coarse	0.1	A	****
		COC	Extremely Coarse	0.4	A	****
		HSOC	Ultra Coarse	0.1	A	****
		ME	Ultra Coarse	0.3	A	****
414	EC	none	Extremely Coarse	1.2	A	****
		COC	Extremely Coarse	1.2	A	****
		HSOC	Extremely Coarse	1.1	A	****
		ME	Extremely Coarse	1.3	A	****
	SL	none	Extremely Coarse	1.0	A	****
		COC	Extremely Coarse	0.9	A	****
		HSOC	Extremely Coarse	0.9	A	****
		ME	Extremely Coarse	1.0	A	****
	WDG	none	Ultra Coarse	0.8	A	****
		COC	Extremely Coarse	1.1	A	****
		HSOC	Extremely Coarse	0.9	A	****
		ME	Extremely Coarse	0.9	A	****

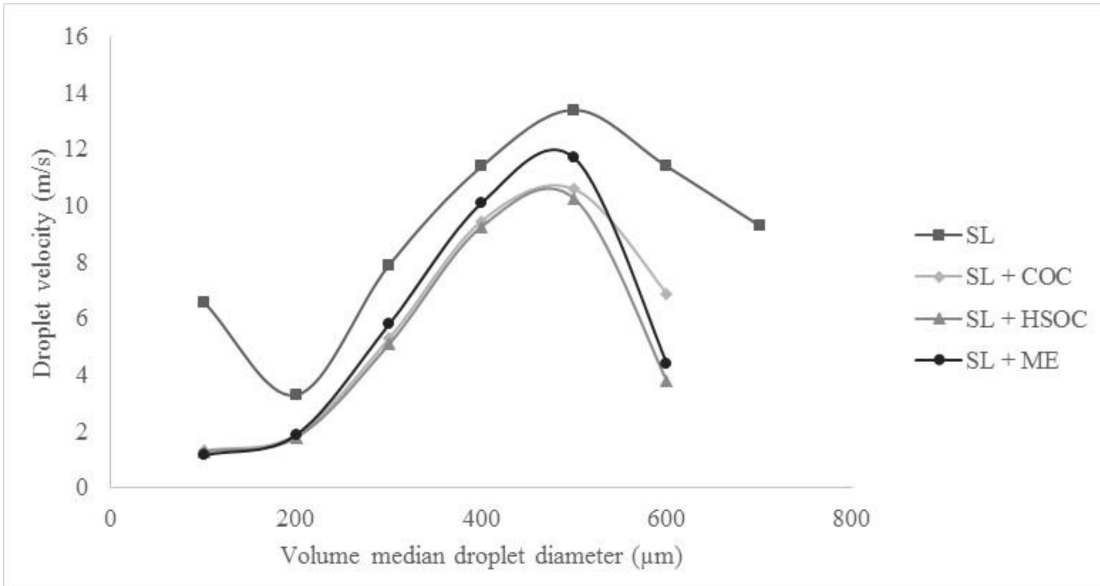

Figure 2.1, Velocity (m/s) by droplet diameter (microns) for the XR11003 at 414 kPA using various tank-mixtures.

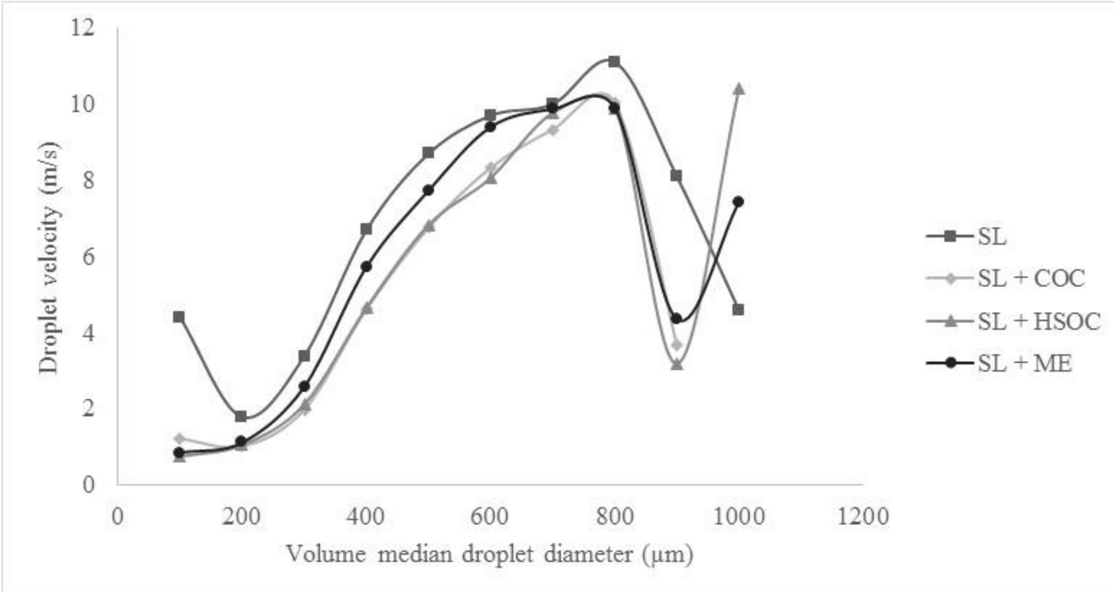

Figure 2.2, Velocity (m/s) by droplet diameter (microns) for the AIXR11003 at 414 kPA using various tank-mixtures.

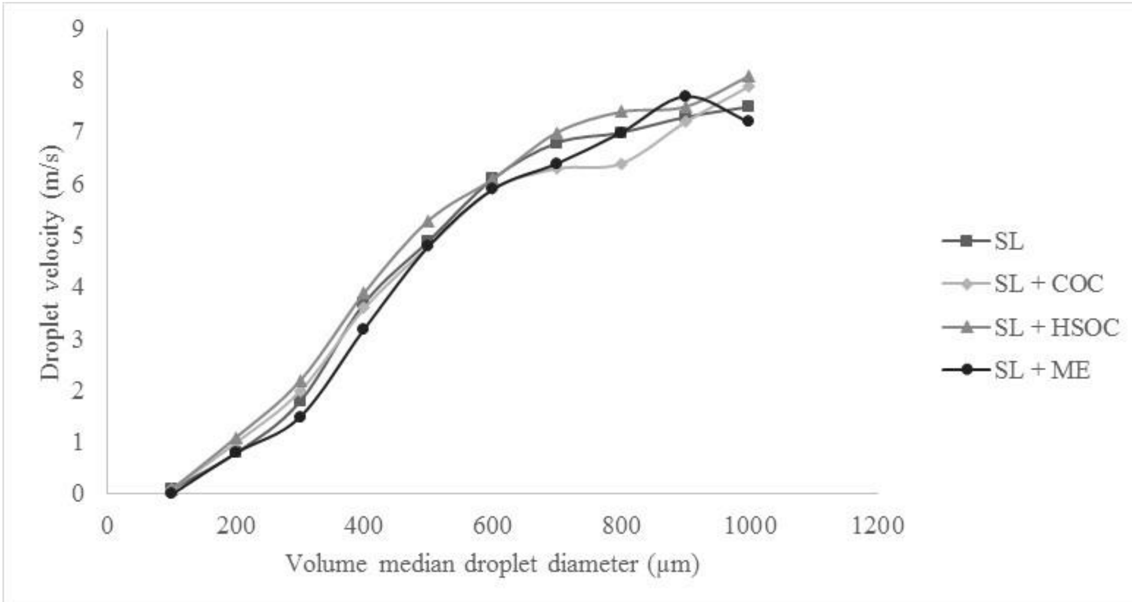

Figure 2.3. Velocity (m/s) by droplet diameter (microns) for the TTI11003 at 414 kPA using various tank-mixtures.

CHAPTER 3

IMPACT OF SPRAY CLASSIFICATION CATEGORIES ON SPRAY PATTERN UNIFORMITY AND PERFORMANCE OF PPO INHIBITING HERBICIDES

Abstract

Spray pattern uniformity is an important component of the pesticide application process. Poor pattern uniformity can result in delivering a sub lethal dosage of active ingredient to the target pest. It can also result in over and/or under applications of the pesticide(s) in the field, resulting in off-label applications or poor control. The objective of the current study was to evaluate several nozzle types representing a broad range of droplet size categories to optimize spray pattern uniformity. A laboratory experiment using a customized spray patternator demonstrated that air-inclusion/venturi type nozzles and hydraulic flat fan nozzles had similar pattern uniformity levels. Coefficient of variation (CV) values ranged from 5 to 18%, depending on nozzle and pressure combination. When increasing pressure and reducing nozzle spacing, the CV value for the TDXL-D nozzle was less than half than the lower operating pressure and nozzle spacing tested. Field scale evaluations of pattern uniformity using similar treatments resulted in similar trends. Lastly, a greenhouse study was conducted to evaluate the performance of several PPO-inhibiting herbicides using droplet size categories ranging from Fine to Ultra Coarse. For grain amaranth (*Amaranthus hypochondriacus* L.) and velvetleaf (*Abutilon theophrasti* Medic.), no differences in control were observed between the droplet size categories. In common waterhemp (*Amaranthus rudis* Sauer AMATA) and common lambsquarter (*Chenopodium album L.*), Very Coarse and Ultra

Coarse, applications reduced control versus the Fine spray categories in a minority of observations. Overall, this study indicated that growers can achieve uniform applications and control of broadleaf weeds with contact based herbicides with Coarse or coarser spray categories.

Introduction

Optimal spray uniformity and coverage is an important component of the pesticide application process. Previous research has demonstrated that as little as one to three percent of the total spray volume impacts the target species, whereas the remainder is either captured by the crop, lost as runoff from the target, or impacts the ground (Hall, 1985). Application efficiency can be improved by a variety of methods, including changing nozzle spacing and speed of application for a given spray release height, along with a recommended adjuvant , or adjusting the liquid physical properties to achieve the optimum droplet size spectrum (Holloway et al. 2000; Wolf et al. 2000; Hewitt 2008). The imminent need to reduce application costs and rising presence of herbicide-resistant weed species have increased the emphasis on making successful herbicide applications. Although a wide variety of spray systems, nozzle types/configurations, and chemistries are commercially available, there is limited information on the proper combinations to achieve high spray pattern uniformity in a given ground application of agrochemicals.

Spray pattern uniformity can be affected by a variety of application conditions. For example, increasing the boom roll angle decreases spray pattern uniformity of an 18 m boom in computer models (Mawer and Miller 1989). In an orchard setting, it was found that properly pitching the angle of air-blast nozzles around the fan increased uniformity of deposition by nearly 20% (Muhammad and Landers 2004). Moreover, adjuvants may improve pattern uniformity by decreasing the spray angle and subsequent pattern uniformity (Chapple et al. (1993). The manipulation of factors such as boom height, application speed and tire pressure also impact pattern uniformity. Langenakens et al. (1999).found that increasing the boom height above canopy from 0.4 to 0.5 meters decreases the CV by approximately 6%, due to reductions in the vertical motions of the boom, and that that reducing tire pressure and application speed improved pattern uniformity for similar reasons.

Applications with high spray pattern uniformity under the boom lead to greater coverage and delivery of the pesticide's active ingredient(s) to the target species. An additional benefit is the avoidance of over/under application of pesticides, which could lead to environmental concerns and poor pest control (Langenakens et al. 1995) It has long been accepted that a uniform delivery of the active ingredient to the leaf surface is necessary to achieve high efficacy for protoporphyrinogen oxidase (PPO)-inhibiting herbicides. These herbicides are contact based (non-systemic) and interrupt the photosynthetic pathway of the leaf tissue, leading to cell destruction. Recommendations for PPO herbicides often require uniform application on the leaf surface with a particular droplet size distribution, and the vast majority of these herbicide labels require Fine to Coarse sprays. These requirements are based on a variety of studies that link droplet size to pesticide performance (Hewitt et al. 1994; Knoche 1994; Reed and Smith 2001; Stainier et al. 2006).

A key driver of the droplet size distribution is nozzle type (Nuyttens et al. 2007). Nozzle design has continued to advance over the years, such that a range of pre-orifice flat-fan, hollow cone, air inclusion/venturi, and dual orifice nozzles are now available to applicators. The design and features of these nozzles can have an effect on their performance and spray characteristics (Nuyttens et al. 2007; Wolf 2000), especially when considering the physical properties of the spray solution (Butler Ellis et al. 1997; Miller and Butler Ellis 2000). To date, there is scarce information on how spray pattern uniformity is affected by nozzle type or influences the performance of PPO herbicides. Therefore, the objectives of this research were to determine the spray pattern uniformity of several common ground nozzles used in the U.S. in a laboratory and field setting, and assess the performance of several nozzle types when applying a PPO herbicide. This information will assist applicators to make better management decision in a given application scenario.

Materials and Methods

Spray pattern uniformity study under laboratory conditions. The droplet size data (DSD) for each treatment were measured at the Pesticide Application Technology Laboratory at the West Central Research and Extension Center in North Platte, NE. A low-speed wind tunnel was utilized for data collection. The setup and steps of collection regarding the use of this wind tunnel were performed as described by Creech et al. (2015) and Henry et al. (2014). Data were subjected to ANOVA using PROC Mixed in SAS 9.4 (Littell et al. 2006). Means were compared using Tukey's HSD test at a 5% level of significance.

Spray uniformity testing was completed at the Sprayer Research Laboratory in Lincoln, NE, USA. A spray patternator (Figure 3.1) was utilized for the uniformity measurements. The tested nozzles were XR11004, AIXR11004, TTI11004 (Teejet Technologies, Spraying Systems Co., Springfield, IL, USA), and TDXL-D11004 (Greenleaf Technologies, Covington, LA, USA). The nozzles XR11004 and AIXR11004 were tested at 276 kPa and TTI11004 and TDXL-D11004 were tested at 276 and 483 kPa to accommodate the wide range of operating pressures which are commonly operated at higher pressures (G. Kruger, personal communication, 2015). The spraying solution was prepared with water and non-ionic surfactant (NIS) (Table 3.1) at a rate of 0.25 % v/v was used in this study. No active ingredients were used due to laboratory restrictions, however previous research on droplet sizing and/or application technology has utilized water in addition to adjuvants to simulate field application of pesticides (Combellack et al. 1996; De Ruiter et al. 1990; Etheridge et al. 1999; Hewitt et al. 1994; Wolf and Daggupati 2009). Four nozzles of the same type were spaced at 76 cm and supported by a dry boom 76 cm above the ground. Nozzles were flow rated using water prior to analysis and then compared against the flow rate at 276 kPA listed by the nozzle manufacturer with a tolerance of +/- 2.5 % of the listed flow rate. The volumetric collection tubes were coupled with liquid sensors to record collection start and stop times. The collected data were sent to a custom LabVIEW software, where the variation in time to fill each tube was recorded, and the coefficient of variation (CV) across the platform was calculated. A complete description of the setup and operation is available in Luck et al. (2015).

The test procedures were to (1) set the operating pressure, (2) initiate spray application, (3) stop application after volumetric tubes were filled, (4) repeat process to achieve six treatment replications. Coefficient of variation (CV) data were subjected to ANOVA using SAS v9.4 (SAS, Cary, NC, USA). Means were compared using Tukey's HSD test at the 5% level of significance.

Field spray uniformity testing was completed at the Dryland Research Farm in North Platte, NE, USA. The field site was a wheat stubble field with an elevation grade of approximately one percent in the testing area. The sprayer utilized was a John Deere 2955 coupled with an 18.3 m boom. This sprayer was equipped with a TeeJet 844-E sprayer control system (TeeJet Technologies, Spraying Systems Co., Springfield, IL, USA). Boom pressure was set at the control system, and nozzle flowrate was measured using graduated cylinders on each boom section prior to the start of testing. The nozzles tested were the XR11004, AIXR11004, and TTI11004 (TeeJet Technologies, Spraying Systems Co., Springfield, IL, USA). The operating pressure was set at 276 kPa. Nozzles were spaced at 76 cm and the application height was 76 cm above the collection strings. The collection cotton strings were approximately one mm in diameter. The strings were pulled tightly just above the wheat stubble and on either side of the tractor. The strings were placed in the center of the application area, and each string was nine meters in length. After each pass, the strings were spooled up and stored. There were at least six replications per treatment. Carrier volumes of 97 L ha^{-1} and 187 L ha^{-1} were applied by regulating ground speed at 10 and 20 KPH, respectively, to maintain a consistent droplet distribution for each application while acknowledging different speeds induce varying sprayer/boom movement (Langenakens et al. 1995), although such movements were not measured in this study. Rhodamine dye (Cole Parmer, Vernon Hills, IL, USA) was added to the tank mixture at a rate of 0.25% v/v to allow for fluorimetric analysis.

The collection strings were analyzed for pattern uniformity using a custom built analysis system (USDA-ARS, College Station, TX, USA). This system was capable of running the strings through a fluorimeter that measures the emission levels of the rhodamine dye as the string passed through the sensor. The data were stored in a text file for future processing. Coefficient of variation (CV) data were subjected to ANOVA using SAS v9.4 (SAS, Cary, NC, USA). Means were compared using Tukey's HSD test at 5% level of significance.

Testing of nozzle type by PPO-inhibiting herbicides was performed in a greenhouse at the Pesticide Application Technology Laboratory located at the West Central Research and Extension Center in North Platte, NE. Common waterhemp (*Amaranthus rudis* Sauer AMATA), grain amaranth (*Amaranthus hypochondriacus* (L.)), velvetleaf (*Abutilon theophrasti* Medic.), and common lambsquarter (*Chenopodium album L.*) were grown in 10 cm cone-tainers (Stuewe and Sons Inc., Corvallis, OR, USA) using standard potting mixture (Ball Horticulture Company, West Chicago, IL, USA). The pots were watered as needed and fertilized with a standard fertilizer mix (Scotts Miracle-Gro® All Purpose, The Scotts Company, Marysville, OH, USA) at least once per week. The greenhouse was maintained at 28°C during the day and at 18°C night with a photoperiod 16 hours daylength. Supplemental lighting was provided by LED lighting (NeoSolTM DS 300W, Illumitex, Austin, TX, USA). The study had at least 12 replications per plant species evaluated and two experimental runs separated by two weeks. Each spray solution consisted of a PPO-inhibiting herbicide and an appropriate adjuvant as recommended by the label. The rate of the herbicides were 0.05, 0.22, and 0.19 L ha^{-1} for carfentrazone-methyl, flumiclorac, and lactofen, respectively, which was 0.5x the labelled rate as a manner to increase the ability to determine treatment differences among the nozzle types. The rate of the COC was a label designated standard rate of 1.0 % v/v. The XR110025, AIXR110025, and TTI110025 nozzles (Teejet Technologies, Spraying Systems Co., Springfield, IL, USA) were all operated at 276 kPa to achieve a carrier volume of 187 L ha^{-1}. These nozzles were flow rated as described previously. A single nozzle track sprayer (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN, USA) was used to apply the treatments. Treatments were applied to the plants when they reached approximately 10 to 15 cm in height. Six plants were randomly assigned to a rack and placed width wise into the spray chamber 50 cm below the spray tip. After the plants were sprayed, they were removed and placed back into the greenhouse. Visual estimations of injury were recorded at 7, 14, and 28 days after treatment (DAT).

Data from each treatment were analyzed separately in SAS v9.4. A generalized linear mixed model (PROC GLIMMIX) was chosen for analysis of the injury ratings. Data from the two experimental runs were combined as they did not differ. Treatment means of injury ratings at 7, 14, and 28 DAT were compared using Tukey’s HSD at a 5% level of significance.

Results and Discussion

The droplet size data (DSD) results are summarized in Table 3.2. For the laboratory and field pattern uniformity treatments, the spray classifications ranged from Fine to Ultra Coarse (Table 3.2). In general, treatments that operated at 276 kPa had lower $D_{v0.1}$ and VMD values and higher %vol<105 than 483 kPa. Increasing the operating pressure for both the TDXL-D and TTI11004 nozzles resulted in a 23 and 20 % decreases in $D_{v0.1}$ and VMD values, respectively. The spray classifications shifted from Ultra Coarse to Extremely Coarse for both nozzles with the increased operating pressure. Overall, the AIXR, TDXL-D, and TTI11004 nozzles all had a coarser DSD than the hydraulic nozzle (XR) for the tested tank-mixture at 276 kPa. These results are consistent with previous research (Creech et al. 2015, Nuyttens et al. 2007).

The DSD results for the spray chamber study are presented in Table 3.3. For tank-mixtures, the finest DSD resulted from using the XR11004, and the coarsest DSD resulted from using the TTI11004. Spray classifications ranged from Fine to Ultra Coarse for each tank-mixture. The largest VMD value was observed when using the TTI11004 with the carfentrazone-ethyl plus NIS tank-mixture. Treatments containing the TTI11004 had less than 1 % of the spray volume less than 105 µm. These results are consistent with the DSD data from the pattern uniformity treatments. Analysis of treatment variance accountancy (η^2) found that the nozzle effect accounted for approximately 65% of variability in both DSD datasets (data not shown).

Spray pattern uniformity data for the different nozzles at 276 and 483 kPa are presented in Table 3.4. Under 276 kPa, the TDXL-D11004 had the highest CV (least uniformity) across the 1.5 m measurement section, which was statistically different than the other treatments (Table 3.4). Increasing the operating pressure of this nozzle to 483 kPa increased pattern uniformity by7%. Overall, the TTI11004 had the highest spray pattern uniformity in addition to the coarsest DSD. Increasing the operating pressure of TTI11004 did not change its CV value, unlike with the TDXL-D11004. This indicated that proprietary features of a given nozzle may influence the uniformity of air-inclusion nozzles differently. This finding is supported by previous literature, which has reported that application parameters such as DSD and/or velocity profiles often differ for air-inclusion nozzles (Bai et al. 2013).

It was observed that at 76 cm nozzle spacing for the TDXL-D11004, several of the volumetric tubes were filling at rates close to one-half of the others (Figure 3.2). This indicated gaps in the spray pattern, leading to high CV values, particularly at 276 kPa. Reducing nozzle spacing to 51 cm resulted in a 7% reduction in CV value at 483 kPa (data not shown) (Figure 3.3), following a similar pattern to the other treatments. In summary, TDXL-D11004 produced acceptable CV values when operated at a higher pressure and narrower nozzle spacing.

Overall, the CV values obtained when testing XR, AIXR and TTI nozzles at 93 and 187 L ha^{-1} resulted in little variation (Table 3.5). Despite this similarity, XR11004 at 187 L ha^{-1} had the highest CV (2.3 %), whereas the TTI11004 at 93 L ha^{-1} had the greatest uniformity. The uniformity data ranged from 1.1 to 2.3% for the field testing in this dataset (Table 3.5). Increasing carrier volume by reducing ground speed in half did not alter spray pattern uniformity within a given nozzle type. The recorded weather data indicated a range of wind speeds of 2.2-3.1 m s^{-1} passing behind the sprayer at time of application, which commonly occurs during the cropping season at the testing site and likely did not influence the experimental results.

Herbicide efficacy ratings for grain amaranth (*A. hypochondriacus*) and velvetleaf (*A. theophrasti*) for the different PPO-inhibiting tank-mixtures was not impacted by the nozzle types tested in this study (P>0.05). Reduced herbicide efficacy was observed in common lambsquarter (*C. album*) (Table 3.6) and common waterhemp (*A. rudis*) (Table 3.7) when using a VC (AIXR) or UC (TTI) nozzle. This was observed at 7 DAT and 14 DAT or only at 7 DAT depending on the weed species by PPO tank mixture combination. Visual estimates of injury ranged from 32 to 100 % among the nozzles tested for these two weed species when using the lactofen + COC tank mixture.

Overall, the trends of the spray pattern uniformity data were similar between the laboratory and field-testing experiments. The spray patternator used in this study was constructed to enhance the ASTM standard E641-01, Standard Methods for Testing Hydraulic Spray Nozzles Used in Agriculture. This equipment has also been used for static spray pattern uniformity using either ball patternator tables, water sensitive (Guler et al. 2007) or Kromekote® paper (Roten et al. 2015) and has advantages and disadvantages. Testing on the spray patternator led to repeatable data from at the replicate level due to the digital volumetric tubes. In addition, the LabView is a user-friendly software that allows modifications according to the intended objective. Lastly, boom or nozzle alterations (e.g. plugged nozzles, nozzle angle or pitch) can be performed to examine its influence on the CV. However, this system requires a large quantity (~250 liters) of the tank-mixture to generate the data. The field uniformity testing was completed using similar treatments as in the laboratory, though with different testing equipment. Cotton strings for pattern testing of aerial applications has been used for many decades (Whitney and Roth 1985). The equipment and methods used in this study is an adaptation of these aerial methods towards ground-based methods. No effect of groundspeed by carrier volume was observed in a given nozzle type in this study. Womac et al. (2001) tested several nozzles by groundspeed combinations in the field and found several differences between coverages or spot densities on water sensitive paper between the treatments. The effects of end boom acceleration, vertical movement, and topography indicated maximum coverage and minimum variation among replicates for tractor setups using relatively slower speeds, lower boom heights, and smaller droplets (Jeon et al. 2004). The equipment used in the current study could be used for pattern uniformity under various boom bounce conditions. Although a limited treatment list was tested, this method has the advantage of accommodating large factorial studies with relative ease.

The similar pattern uniformity between the nozzle types/DSD in the laboratory and field testing served as a basis for conducting the nozzle by PPO-inhibiting herbicide study. Seven out of the 108 treatments (herbicide by nozzle by rating date) resulted in less control than the hydraulic nozzle, indicating that Coarse and coarser sprays may be capable of controlling broadleaf weeds while lessening the drift potential of the application. It is noteworthy that efficient and timely weed management is crucial for crop competiveness and reducing selection pressure for herbicide resistance. On the basis of this dataset, a grower might choose not to use, for example, carfentrazone-methyl plus NIS tank-mixture with a TTI nozzle (Ultra Coarse spray quality) if common lambsquarter (*C. album*) is a problematic weed in the field. Frequent application of sub-lethal dose of a given active ingredient may favor the development of herbicide resistance (Neve and Powles 2005; Norsworthy et al. 2012). While the amount of active ingredient on the weed species was not measured, it is reasonable to assume that greater uniformity in the pesticide application will enhance the delivery of the active ingredient to the target. Although laboratory and field studies resulted in similar spray pattern uniformity levels, the control of the weed species evaluated was occasionally reduced at VC and UC spray qualities for the herbicides in question. This could be due to the droplet size (i.e. a coarser DSD is not as effective as a finer DSD with these applications) (Knoche 1994; Ramsdale and Messersmith 2001) or shatter, bounce, and roll off of larger droplets to the various leaf surfaces (Dorr et al. 2008; Reichard 1988).

The use of a single nozzle spray chamber for studying pattern uniformity in different weed species is not optimal due to the absence of spray overlap between adjacent nozzles, which may lead to sub-lethal doses if not checked carefully. Our findings indicated low efficacy ratings in some treatments may be correlated with the low herbicide rate applied in the study. Thus, the combination of many replicates and random assortment across the spray chamber’s width helped reduce treatment variance. Overall, the spray chamber data indicated that growers might be able to use VC and UC spray qualities with some PPO-inhibiting herbicides. Future studies are needed to examine additional combinations of nozzle/spray quality and herbicide with a multiple nozzle boom. This data will strengthen the knowledge in this testing method, and provide growers with impactful knowledge to enhance pesticide applications with PPO-inhibiting herbicides and weed control.

Acknowledgments

The authors would like to thank the researchers and graduate students in Drs. Luck and Krugers' programs. Their hard work was very much appreciated. All authors especially thank Shawn Forney's help and guidance in the laboratory pattern testing and Gary Mahnken's help with the field pattern testing.

Table 3.1. Source of materials used in this study.

Common name	Trade name	Treatment rate	Manufacturer
Carfentrazone-ethyl	AIM EC®	0.05 L ha^{-1}	FMC Corporation, Philadelphia, PA US
Crop oil concentrate	R.O.C. ®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA US
Flumiclorac	Resource ®	0.22 L ha^{-1}	Valent USA Corporation, Walnut Creek, CA USA
Lactofen	Cobra®	0.19 L ha^{-1}	Valent USA Corporation, Walnut Creek, CA USA
Non-ionic surfactant	R-11®	0.25% v/v	Wilbur-Ellis Company, Fresno, CA, 94596

Table 3.2. Droplet size distribution for a water plus non-ionic surfactant tank-mixture for pressure by nozzle combination used in the laboratory and field testing of spray pattern uniformity. Dv0.1 is the percent of the spray volume of which 10 % of the droplets are of the given diameter and below. VMD is the volume median diameter of the spray. Vol<105 is the percent of the spray solution that contains droplets 105 µm in diameter or less. The spray classifications is based on guidelines established in the ASAE S572.1 standard.

Pressure	Nozzle[a]	Dv0.1		VMD		vol<105		Spray classification[b]
kPA		µm				%		
276	XR	106	F	232	F	3.5	A	F
	AIXR	224	E	453	E	0.3	B	VC
	TDXL	358	B	690	B	0.0	C	UC
	TTI	402	A	790	A	0.1	C	UC
483	TDXL	279	D	563	D	0.2	BC	EC
	TTI	302	C	629	C	0.5	BC	EC

[a]All nozzles tested were designated 11004

[b]F=Fine, VC=Very Coarse, EC=Extremely Coarse, UC=Ultra Coarse

Table 3.3. Droplet size distributions for each tank-mixture by nozzle combination used in the spray chamber. Dv0.1 is the percent of the spray volume of which 10 % of the droplets are of the given diameter and below. VMD is the volume median diameter of the spray. Vol<105 is the percent of the spray solution that contains droplets 105 µm in diameter or less. The spray classifications is based on guidelines established in the ASAE S572.1 standard.

Tank-mixture[a]	Nozzle[b]	Dv0.1		VMD		vol<105		Spray classification[c]
				µm		%		
Carfentrazone-ethyl + NIS	XR	96	C	206	C	12.8	A	F
	AIXR	259	B	514	B	0.5	B	VC
	TTI	433	A	822	A	0.0	C	UC
Lactofen + COC	XR	122	C	234	C	6.4	A	F
	AIXR	264	B	494	B	0.3	B	VC
	TTI	395	A	740	A	0.0	B	UC
Flumiclorac + COC	XR	115	C	225	C	7.6	A	F
	AIXR	298	B	515	B	0.2	B	VC
	TTI	416	A	772	A	0.0	B	UC

[a]NIS=non-ionic surfactant, COC= crop oil concentrate. The rates of all products are listed in Table 3.1.

[b]All nozzles tested were designated 110025 and operated at 276 kPa at 15 KPH airspeed.

[c]F=Fine, VC=Very Coarse, UC=Ultra Coarse

Table 3.4. Spray pattern uniformity data using four nozzles, two operating pressures, and a water + NIS tank-mixture on a spray patternator.

Pressure	Nozzle[a]	CV[b]	
kPa		%	
276	XR	8.9	BC
	AIXR	7.8	BC
	TDXL-D	18.1	A
	TTI	7.1	CD
483	TDXL-D	11.0	B
	TTI	5.0	D

[a]All nozzles tested were designated 11004

[b]CV=Coefficient of variation

Table 3.5. Spray pattern uniformity data using three nozzles, two carrier volumes, and a water + NIS tank-mixture in a field environment. All treatments were operated at 276 kPa.

Carrier Volume	Nozzle[a]	CV[b]	
L ha^{-1}		%	
93	XR	2.2	AB
187		2.3	A
93	AIXR	1.3	BC
187		2.1	AB
93	TTI	1.7	ABC
187		1.1	C

[a]All nozzles tested were designated 11004 at 276 kPa at 10 or 20 KPH for 93 or 187 L ha^{-1} carrier volume, respectively.

[b]CV=Coefficient of variation

Table 3.6. Injury ratings of common lambsquarters (*Chenopodium album* L.) from three different PPO-inhibiting herbicides applied with three nozzle types in a spray chamber.

		7		14		28	
Tank-mixture[a]	Nozzle[b]	DAT[c]					
Carfentrazone-ethyl + NIS	XR	32	A	47	A	52	A
	AIXR	31	A	45	A	55	A
	TTI	10	B	34	B	47	A
Flumiclorac + COC	XR	46	A	50	A	51	A
	AIXR	45	A	58	A	55	A
	TTI	39	A	56	A	56	A
Lactofen + COC	XR	38	A	61	A	69	A
	AIXR	32	A	54	A	65	A
	TTI	33	A	60	A	67	A

[a]NIS=non-ionic surfactant, COC= crop oil concentrate. The rates of all products are listed in Table 3.1.

[b]All nozzles tested were designated 110025 and operated at 276 kPa at 5 KPH.

[c]DAT=Days after treatment

Table 3.7. Injury ratings of common waterhemp (*Amaranthus rudis*) from three different PPO-inhibiting herbicides applied with three nozzle types in a spray chamber.

		7		14		28	
Tank-mixture[a]	Nozzle[b]	DAT[c]					
Carfentrazone-ethyl + NIS	XR	41	A	46	A	45	A
	AIXR	32	A	29	B	42	A
	TTI	13	B	21	B	40	A
Flumiclorac + COC	XR	45	A	33	A	41	A
	AIXR	19	B	30	A	46	A
	TTI	27	B	40	A	426	A
Lactofen + COC	XR	98	A	98	A	100	A
	AIXR	99	A	99	A	99	A
	TTI	97	A	98	A	97	A

[a]NIS=non-ionic surfactant, COC= crop oil concentrate. The rates of all products are listed in Table 3.1.

[b]All nozzles tested were designated 110025 and operated at 276 kPa at 5 KPH

[c]DAT=Days after treatment

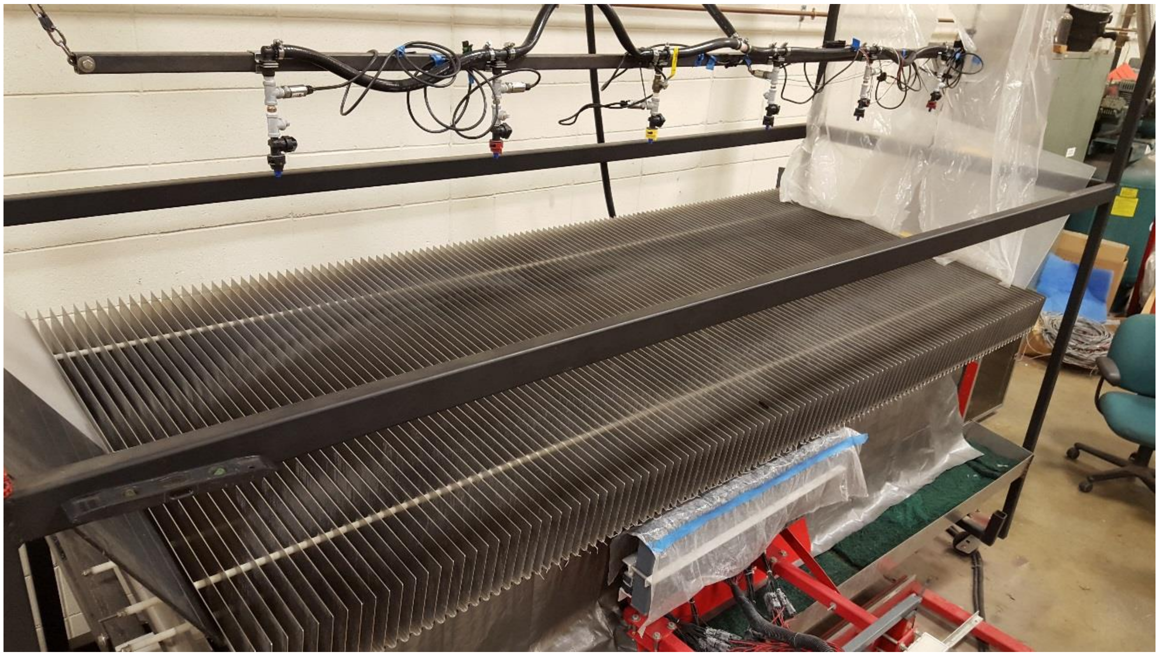

Figure 3.3. Spray patternator at the Sprayer Research Laboratory in Lincoln, NE, USA. The table is 3 meters in length and segregated by 25 cm grooves. The liquid level sensors are pictured at the bottom and can be moved laterally across the length of the table. They are covered to prevent debris entry between tests. Note the nozzles above the table are not the nozzles used in the current study.

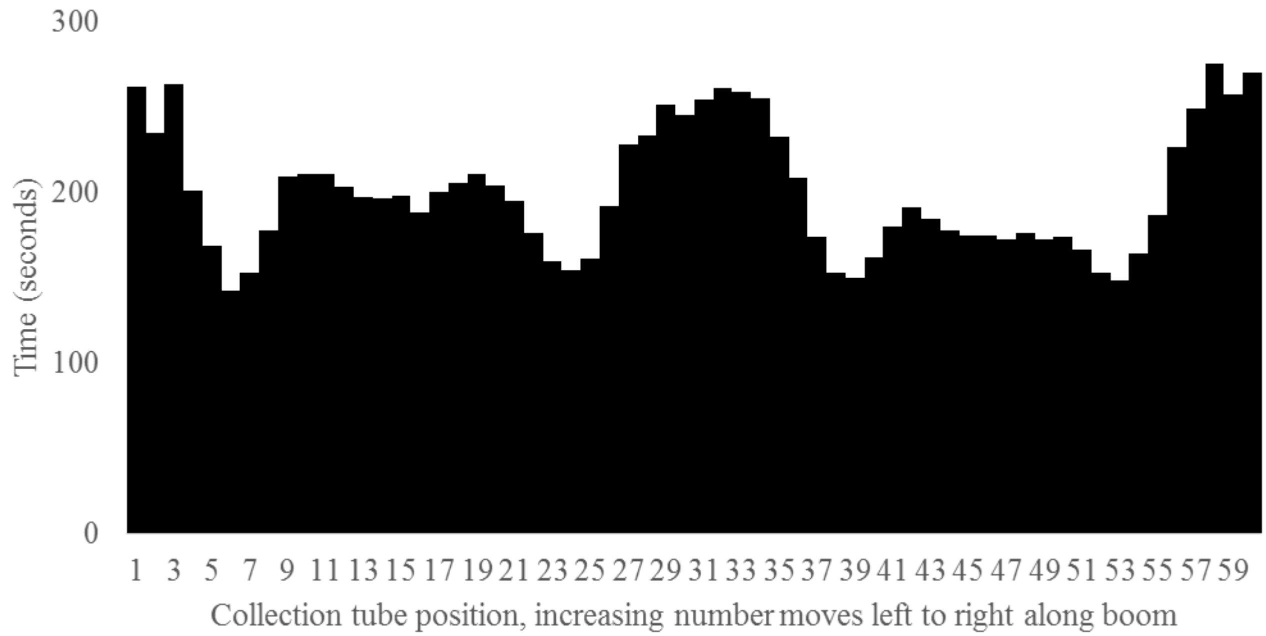

Figure 3.4. Visual representation of spray pattern uniformity results of the TDXL-D11004 at boom height and nozzle spacing of 76 cm and operated at 276 kPa using a water + NIS tank-mixture. The center nozzle is located above collection tube 30.

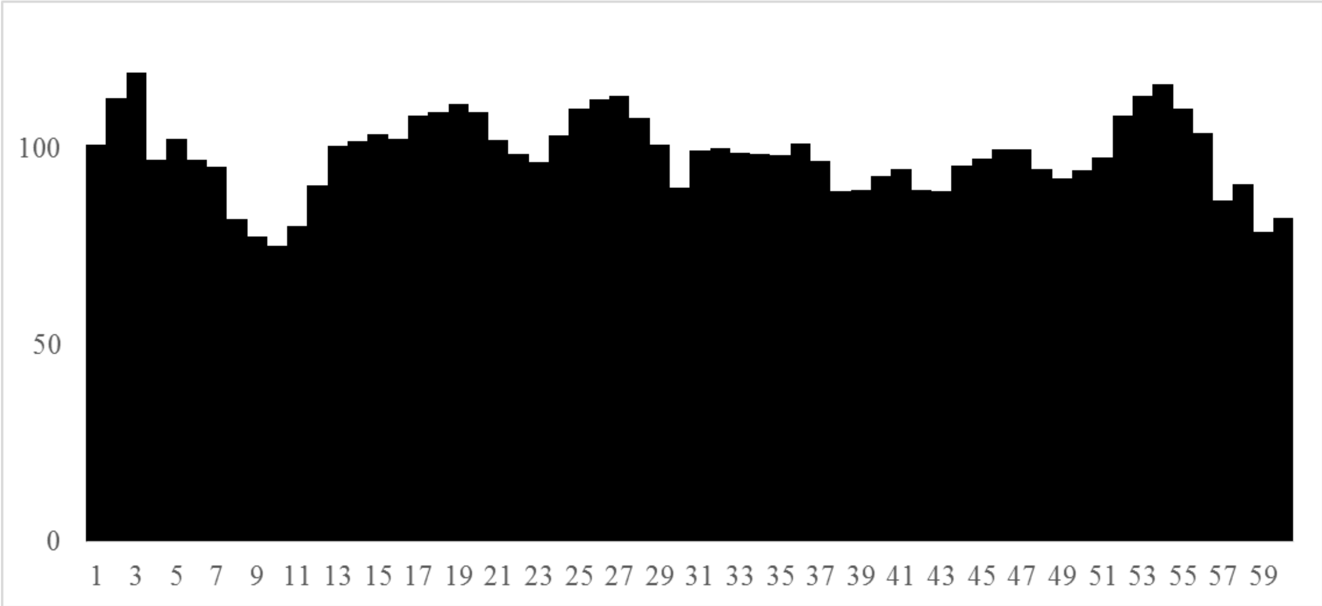

Figure 3.3. Visual representation of spray pattern uniformity results of the TDXL-D11004 at boom height and nozzle spacing of 50 cm and operated at 483 kPa using a water + NIS tank-mixture. The center nozzle is located above collection tube 30.

CHAPTER 4

LOW SPEED WIND TUNNEL AND FIELD DRIFT EVALUATIONS OF THE HERBICIDE ENLIST DUO®

Abstract

The herbicide Enlist Duo® was evaluated for drift potential in a low-speed wind tunnel and in a field setting. The purpose of the study was to test this new herbicide with three nozzle types and collect data on drift accumulation and damage to a sensitive species at various downwind distances. The results showed that downwind drift can be reduced, both in a low-speed wind tunnel and field setting, by applying Enlist Duo® with a very coarse and extremely coarse spray quality nozzle. The use of very coarse and larger spray qualities was shown to result in minimal off-target deposition past 16m in a field setting, which would be anticipated to cause little or no visual damage to plants. On the basis of this dataset, applications of Enlist Duo® should be made with very coarse or above spray qualities to minimize spray drift potential.

Introduction

Application of pesticides to crops, orchards, and rangeland in the US is a common practice in non-organic production systems. It is a complex process that demands proper selection of agrochemicals and operational parameters, wherein the end goal is total biological efficacy. Unfortunately, drift of pesticides does occur, often by reasons beyond the operator's control (e.g. climatic conditions). Unintended exposure of humans or animals, contamination of aquatic systems, or deposition onto sensitive plant species are typically listed as negative consequences of pesticide drift (EPA 1999). The EPA has been developing a voluntary program to mitigate the potential of pesticide drift (EPA 2015) , which is largely based on the multi-year findings of the Spray Drift Task Force (Hewitt 2000). At present, validation of technologies or practices that may reduce pesticide drift can be performed in low-speed wind tunnels (LSWT), high-speed wind tunnels, or field drift experiments (EPA 2015).

Numerous researchers have performed field drift experiments over the past several decades. These experiments have largely focused on quantification of drift at various downwind distances in a variety of climatic conditions (De Snoo and De Wit 1998; Fehringer and Cavaletto 1990; Fritz et al. 2011; Longley et al. 1997; Wolters et al. 2008). Data generated from these type of experiments have aided in the generation of several mathematical based models to predict drift from aerial (Teske et al. 2002) and ground (Baetens et al. 2009; Kennedy et al. 2012; Tsay et al. 2002) application scenarios. An advantage of these models is the rapid generation of drift potential without the need for an expensive field experiment; however, these predictions of physical drift do not elucidate biological damage to sensitive species.

Several factors contribute to spray particle drift from ground applications, including boom height, topography, and canopy characteristics. Previous research on the effects of drift onto sensitive species has predominately involved application of reduced rates of a herbicide to the specie(s) in a small-plot setting (Ellis and Griffin (2002). This approach is often labeled as “simulated drift”. The advantages of this approach is that it allows for total control of the application rate and thereby, convenient and cost-effective data generation. The main disadvantage of this approach is the exclusion of environmental conditions, particularly wind, which is an important and significant factor to consider (Donkersley and Nuyttens 2011). The spray applications in "simulated drift" studies are generally made over the top of the canopy. For an actual pesticide drift scenario, the droplet size, pesticide active ingredient concentration contained within these droplets, and deposition potential of the droplets impacting the non-target species are unlikely to be similar to these over-the-top applications.

The future release of dicamba and 2,4-D-resistant cotton, corn, and soybean will lead to increased use of these growth regulator herbicides in the US. It will be critical to determine potential biological damage associated with drift from these herbicides to minimize damage to susceptible field crops, orchards, vineyards, vegetables, and ornamentals during their application. Field drift experiments generally use collection stations (e.g. petri dishes, mylar strings, air samplers) to monitor and quantify drift at various downward distances (Fritz et al. 2011); however, it will be advantageous to growers and applicators to link pesticide drift with plant damage. Therefore, the objective of our study is to measure pesticide drift with damage to sensitive plant species while using stewardship guidelines established by Dow AgroSciences LLC for the Enlist Duo® herbicide technology. These include using an air-inclusion type nozzle in wind speeds of less than 6.7 m s^{-1} when spraying Enlist Duo®. The experiments were first performed in a low-speed wind tunnel (LSWT) to ascertain preliminary findings that would further guide the implementation of a field-scale drift experiment. The findings from both studies will be discussed separately, as the U.S. EPA recognizes wind tunnel droplet sizing experiments and field drift experiments as suitable, but different, approaches for drift prediction in the Drift Reduction Technology (DRT) program (EPA

2015). The data of these experiments will help guide best management practices for applicators applying Enlist Duo®.

Materials and Methods

Droplet size measurements were made using a laser diffraction (LD) particle size analyzer in a LSWT at the Pesticide Application Technology Laboratory (PAT Lab) in North Platte, NE. The instrument used was a Sympatec HELOS/KR with the manufacturer denoted R7 lens installed, which provided for a dynamic measurement size range of 18 to 3500 µm. The measurements were conducted at 6.7 m s^{-1} laminar airflow. The distance from the nozzle tip to the measurement zone was fixed at 30.5 cm. Droplet size data for each treatment were evaluated with a minimum of three replicates. Each replicate consisted of the entire width of the spray plume being traversed vertically through the LD measurement zone by means of a linear actuator. The herbicide was applied using three air-inclusion nozzles at 276 kPa. No adjuvants were included with the herbicide, and the complete treatment list for the droplet size measurements, LSWT, and field trials are listed in Table 4.1. Upon completion of the measurements, $D_{V0.1}$ and $D_{V0.5}$ data were recorded for further analysis. These values corresponding to the droplet size diameter for which 10 and 50 percent of the total spray volume is comprised of that size or smaller, respectively. $D_{V0.5}$ is also referred to as the volume median diameter, or VMD. Additionally, the percent of the spray volume contained in droplets of 141 µm and smaller (%Vol<141µm) was also recorded (Table 4.1). To match the treatments used in the LSWT and field experiments, rhodamine dye (Rhodamine WP, Cole Parmer, Vernon Hills, IL) was included in the tank mixtures at 0.25 % v/v. The rates of Enlist Duo® herbicide used in the LSWT and field experiments were 2.8 and 5.95 %v/v, respectively. This was done to minimize the amount of active ingredient in the laboratory, and to utilize the maximum use rate for this herbicide in the field experiment. Spray category classifications are based on data generated at the PAT Lab using the guidelines established in ASABE S572.1 “Spray Nozzle Classification by Droplet Spectra” (ASABE 2009b)

The LSWT drift experiment was conducted at the PAT Lab in North Platte, Nebraska, US. Eight sections with dimensions of 1.2 m x 1.2 m x 2.4 m (WxHxL) were situated between a 5.6 kW axial fan for wind generation and a 7.5 kW scrubber system to comprise the LSWT. The nozzle was placed 0.6 meters away from the generating fan outlet, with the nozzle plume orientated perpendicular to the airflow. The nozzle height was set at 1.06 m above the collection stations. The collection stations were comprised of single tomato (*Solanum lycopersicum)* plant approximately 15 cm in height and a mylar (Grafix Platics, Cleveland, OH) card placed on an adjacent metal plate, held in place by a paper clip on the upwind side of the mylar card. The height of the mylar card was in line with the soil layer of the tomato plant. The tomato plants were cultivated in a greenhouse facility using 10 cm cone-tainers (Stuewe and Sons Inc., Corvallis, OR U.S.) filled with a potting mixture (Ball Horticulture Company, West Chicago, IL U.S.). The plants were watered as needed and fed with supplemental nutrition (Scotts Miracle-Gro® All Purpose, The Scotts Company, Marysville, OH U.S.) approximately once per week. The greenhouse was maintained at 25 degrees Celsius day and night, and supplemental lighting was provided using LED fixtures (NeoSol™ DS 300W, Illumitex, Austin, TX U.S.).

When testing was ready to begin, collection stations were placed downwind of the nozzle at distances of 1.5, 3.0, 6.1, 9.1, and 12.2 m. The wind speed was set at 4.5 m s^{-1}, and the duration of each spray application was five seconds. After waiting 30 seconds for all of the spray material to travel downwind, the collection stations were removed from the LSWT. The mylar cards were placed into pre-labeled plastic storage bags and stored in a dark storage bin to minimize photodegradation potential. The tomato plants were placed into a greenhouse. A minimum of two minutes was observed before new collection stations were placed into the LSWT. The tunnel was also scrubbed with water and bleach twice per day during each day of testing. After testing was complete, a tank sample was collected and stored with the mylar cards. Visual injury ratings were assessed at 14, 21, and 28 days after treatment (DAT) for the treated plants and compared to an untreated, control group.

The field scale drift experiment was conducted north of Advance, Indiana U.S. (39°59′48″N 086°37′09″W) in a fallow field. A CASE IH (Racine, WI US) Patriot® 4440 self-propelled sprayer was utilized for this study. This sprayer was equipped with a 27.4 meter boom, and the nozzles were spaced 76.2 cm apart. The treatments used in the field study were similar to those used in the LSWT. The boom height was set 76.2 cm from the canopy, which consisted of small (<3 cm) annual weeds. The speed of the sprayer was maintained at 13 km h^{-1}, and the nozzles were operated at 276 kPa, for a calculated carrier volume of 147 L ha^{-1}. Prior to the start of the trial, a tank sample was collected after the water, Enlist Duo® herbicide, and rhodamine dye were thoroughly mixed in the sprayer.

A 150 m driveline was established in the center of the field with a heading of due south by south west (195º), perpendicular to the prevailing winds. A sampling line was set up perpendicular to this driveline at distances of 3, 8, 16, 31, 38, 46, 61, 77, and 90 m. These distances were based on the last nozzle tip on the boom of the sprayer. Mylar cards (10 cm x 10 cm) were placed on metal plates at each sampling location along the line.

Prior to the start of each replicate, the collection stations were set up and the wind speed and direction was checked to ensure it was perpendicular to the driveline. After the treatment replicate was finished, a period of three minutes was observed to allow any droplets to reach the furthest distance and deposit. Samples were then collected and placed into pre-labeled plastic storage bags and placed in a dark storage bin. The nozzles on the sprayer were then changed, and the process was repeated until trial completion. Finally, a tank sample was collected from the sprayer and stored with the sample bags.

The mylar cards from the LSWT and field study were processed at the PAT Lab. Forty mL of distilled water was pipetted into each bag, which was then shaken by hand for approximately 15 s. A 3 mL sub-sample was pipetted into a sterile cuvette and placed into a fluorometer (Trilogy Laboratory Fluorometer, Turner Designs, San Jose, CA) with manufacturer designated green module installed. This module had a minimum detection limit of 0.01 ppb of the rhodamine analyte.

A 1:10 serial dilution was made using the tank samples collected in the LSWT and the field. These dilutions were processed in the fluorometer to establish a PPM by fluorescence curve. The curve was analyzed in Microsoft Excel® to determine the best fit line. The equation of these curves was used to convert the LSWT and field raw fluorescence data in PPM. These data were further defined as PPM per area by dividing the data by the area of the mylar cards. Finally, data were adjusted for recovery rate of the dye by wash procedure. This was done by spiking a 3 mL sample from the respective tank samples onto six mylar cards. These cards were washed as described above, and the results were compared to a separate 3 mL sample. The recovery rates for the LSWT mylar cards and field mylar cards were 72 and 74 %, respectively.

Statistical analysis for the dataset was conducted using SAS v9.4 (SAS, Cary, NC). Data from the droplet size testing were analyzed using PROC MIXED. Concentration of Enlist Duo® was treated as a fixed effect in the model, and data were separated by nozzle type. Means were compared using Tukey's test and were tested at a five percent significance level (α=0.05). Deposition and tomato injury data were analyzed using PROC MIXED with nozzle type, distance, and nozzle type by distance interaction considered fixed effects and replicate and run considered as random effects. Means were compared as before.

Results and Discussion

The droplet size distribution data for the two herbicide concentrations utilized in the LSWT and field setting are presented in Table 4.1. Nozzle type was significant ($P \leq 0.05$) so the data were not pooled across nozzle types. Spray classification categories ranged from very coarse (AIXR) to extremely coarse (TDXL and ULD). Increasing the Enlist Duo® rate from 2.8 to 5.95 %v/v for the LSWT and field experiments, respectively, increased the $Dv_{0.5}$ within each nozzle type. All treatments contained less than 2.5% of the volume of droplets less than 141 μm in diameter. This metric, combined with the $D_{v0.1}$ and $D_{v0.5}$ data points, indicated the drift potentials within a nozzle type were similar for the LSWT and field experiments. Across nozzle types, the drift potential of the AIXR nozzle was greater than the TDXL and ULD nozzles due to its smaller droplet size distribution. This is because droplet size data is a determining factor in predicting drift potential for a given application (Teske et al. 2002).

The highest deposition of rhodamine dye was observed at the closest downwind distances in the LSWT (Table 4.2). For the nozzle types tested, ANOVA indicated the nozzle by distance interaction was significant ($P \leq 0.05$). Therefore, data were analyzed together. Deposition was higher using the AIXR nozzle than the TDXL and ULD nozzles at 1.5 m downwind. Beyond 1.5 m, no treatment differences were observed across the nozzle types at a given downwind distance. Deposition of the rhodamine dye was 0.02 PPM for all treatments at the three furthest downwind distances. Visual injury ratings of the tomato plants taken at 28 DAT ranged from 77 to 98 percent from 12 to 1.5 m downwind distances, respectively, across all three nozzles (Table 4.3). Injury decreased as downwind distance increased within a nozzle type. Visual injury ratings were not different across nozzle types at 1.5, 3.0, and 6.1 meters downwind. Injury was higher when using the AIXR nozzle compared to the TDXL and ULD nozzles at 9.1 and 12.2 meters downwind. Overall, visual injury to the tomato plants was extensive across treatments, even though deposition of the rhodamine dye ranged from 0.04 to 0.02 PPM (Figure 4.1).

Simulated pesticide drift experiments in a LSWT are not intended to be representative of real-world pesticide applications for several reasons. The pesticide droplets were confined in the tunnel and not permitted to behave by typical dispersion principles, e.g. Langrangian (Bilanin et al. 1989; Teske et al. 2011). In addition, pesticide drift can be influenced by the number of nozzles used and their relative position to the prevailing winds (Al Heidary et al. 2014b). Applying pesticides laterally (wind parallel to the main spray axis) as opposed to frontally (wind perpendicular to the main spray axis) can reduce pesticide deposition in a wind tunnel, especially when air-inclusion nozzles are utilized (Al Heidary et al. 2014a). Furthermore, no canopies were utilized in the LSWT, and canopies can contribute to pesticide drift reduction by serving as natural barriers (Schou et al. 2012; Wolters et al. 2008). Parkin and Wheeler (1996) developed a vortex flow model to test vertical displacement of droplets in a wind tunnel. Their findings indicated the vertical displacement of a 50 µm droplet was influenced by wind tunnel width, cross sectional area, and wind speed, and as each property increased, the vertical displacement of the droplet decreased. Droplets with diameters larger than 75 µm are less prone to vertical displacement, especially at wind speeds above 2 m s^{-1} (Parkin and Wheeler 1996). The LSWT used in the current study has dimensions of 1.2 m by 1.2 m and the wind speed was set at 4.5 m s^{-1}. Furthermore, none of the nozzle types produced droplets of 50 µm or below as measured by LD (data not shown). Therefore, the LSWT used was suitable for testing simulated pesticide drift. Even still, the deposition of the rhodamine dye and tomato injury results were likely due to the constant, sustained wind speed and the lack of canopy. A similar application in a field environment would likely result in less deposition and plant injury at similar downwind distances and environmental conditions. However, the operational control on the drift testing in the LSWT allowed for the relative testing of differences between nozzle types on deposition and plant injury. Overall, the LSWT drift study results showed no differences between the nozzles types on deposition and visual injury of tomato plants at the distances tested.

Deposition data from the field study are reported in Table 4.5. During the course of the testing, the wind was within the acceptable range for testing field drift treatments, i.e. within 30 degrees perpendicular to the driveline (ASABE 2009a) (Table 4.4). Overall, the deposition of the rhodamine dye was similar for each nozzle type at a given downwind distance. Beyond 16 m, deposition measurements were below the detectable limit of the fluorometry procedures utilized in the study. Field measurements of drift using techniques established in the EPA DRT guidelines (EPA 2015) have previously reported poor resolution of detection at relatively far downwind distances (Fritz et al. 2011). Utilizing additional collection media and methods, such as dynamic air samplers at various ground heights, can improve the efficiency of drift experiments (Arvidsson et al. 2011). Direct comparisons between the LSWT and field deposition data were not possible due to different operating conditions and equipment, which included environmental conditions, number of nozzles on the boom, distances at which collectors were placed, etc. However, the nozzle types were similar between the two studies, and both studies indicated drift of the Enlist Duo® herbicide was similar for a very coarse and extremely coarse spray classification.

Conclusions

This study was designed to measure the drift potential of the Enlist Duo® herbicide using three air-inclusion nozzles. The use of tomato plants as indicators of potential damage resulting from off-target movement was also utilized in the LSWT. Field drift data resulted in little to no detection of the tracer dye beyond 16 meters for each nozzle tested, which would likely correspond to little or no plant damage beyond this distance based on wind tunnel observations of plant damage at similar dose levels. The results of this dataset suggest that utilizing a nozzle which generates a very coarse or extremely coarse spray classification based on ASABE standards (ASABE 2009b) will result in equivalent drift levels of Enlist Duo®. Based on these results, an applicator utilizing the Enlist Duo® herbicide can expect to minimize drift and damage to nearby vegetation by utilizing a very coarse or extremely coarse spray quality. Careful attention to nearby susceptible species is still warranted to minimize or fully prevent damage.

Table 4.1. Droplet size distribution of the three nozzles applying Enlist Duo® herbicide at 276 kPa. $Dv_{0.1}$ is the percent of the spray volume of which the droplets are of the given diameter and below. $Dv_{0.05}$ is the volume median diameter of the spray. Vol<141 is the percent of the spray solution that contains droplets 141 µm in diameter or less. The spray classifications is based on guidelines established in the ASAE S572.1 standard. Numbers followed by the same letter in the same column for each nozzle are not different ($P \leq 0.05$).

Nozzle[a]	Enlist Duo® concentration[b]	$Dv_{0.1}$		$Dv_{0.05}$		Vol<141 µm		Spray Classification[c]
		µm				%		
AIXR	Wind Tunnel	234	A	452	B	2.1	A	VC
	Field	229	A	458	A	2.4	A	VC
TDXL	Wind Tunnel	282	A	523	B	1.0	B	EC
	Field	262	B	537	A	1.6	A	EC
ULD	Wind Tunnel	309	A	578	B	0.7	A	EC
	Field	315	A	605	A	0.8	A	EC

[a]All nozzles were designated 110° spray angle and 3.8 L/min flow rate

[b]Experiment Enlist Duo® concentrations: wind tunnel=2.8 %v/v, field=5.95 %v/v

[c]VC=very coarse, EC=extremely coarse

Table 4.2. Deposition (PPM) of the rhodamine tracer dye at five downwind distances in a LSWT in North Platte, NE. The tank mixture was Enlist Duo® at 2.8 %v/v and the rhodamine tracer dye at 0.25 %v/v. The three nozzles tested were manufacturer designated 110º spray angle and flow rate of 3.8 L/min at 276 kPa. Numbers followed by the same letter in the same row or column are not different using the Tukey-Kramer test (P≤0.05).

	AIXR		TDXL		ULD	
Distance	Deposition					
m	ppm					
1.5	0.05	A	0.04	B	0.04	BC
3.0	0.03	BC	0.03	C	0.03	C
6.1	0.02	D	0.02	D	0.02	D
9.1	0.02	D	0.02	D	0.02	D
12.2	0.02	D	0.02	D	0.02	D

Table 4.3. Visual injury (%) of the tomato indicator plants at five downwind distances in a LSWT. The tank mixture was Enlist Duo® at 2.7 %v/v and the rhodamine tracer dye at 0.25 %v/v. The three nozzles tested were manufacturer designated 110º spray angle and flow rate of 3.8 L/min at 276 kPa. Numbers followed by the same letter in the same row or column are not different using the Tukey-Kramer test ($P \leq 0.05$).

	AIXR		TDXL		ULD	
Distance	Visual injury					
m	%					
1.5	98	A	97	A	98	A
3.0	98	A	95	AB	97	A
6.1	92	BC	89	C	89	C
9.1	89	C	80	DEF	83	D
12.2	82	DE	77	F	79	EF

Table 4.4. Weather data for the field drift experiment near Advance, IN. The metrics were averaged over the duration of the application and replication for the given nozzle.

Nozzle[a]	Wind Direction	Wind Speed	Temperature	Relative Humidity
	ø	m/s	Celsius	%
AIXR	298	2.2	23.4	75.6
TDXL	303	2.3	23.0	75.0
ULD	306	1.4	23.4	75.0

[a]Nozzles were designated as 110º spray angle and flow rate of 3.8 L/min at 276 kPa

Table 4.5. Deposition (PPM) of the rhodamine tracer dye at ten downwind distances in a field setting near Advance, IN. The tank mixture was Enlist Duo® at 5.95 %v/v and the rhodamine tracer dye at 0.25 %v/v. The three nozzles tested were manufacturer designated 110º spray angle and flow rate of 3.8 L/min at 276 kPa. Numbers followed by the same letter in the same row or column are not different using the Tukey-Kramer test ($P \leq 0.05$).

	AIXR		TDXL		ULD	
Distance	Deposition					
m	ppm					
3	0.03	A	0.02	AB	0.03	A
8	0.01	C	0.01	BC	0.00	C
16	0	C	0	C	0	C
31	0	C	0	C	0	C
38	0	C	0	C	0	C
46	0	C	0	C	0	C
61	0	C	0	C	0	C
69	0	C	0	C	0	C
77	0	C	0	C	0	C
90	0	C	0	C	0	C

Figure 4.1 Representative tomato (Solanum lycopersicum) plants sprayed in the low-speed wind tunnel with an AIXR 11004 nozzle at 276 kPa with Enlist Duo® at a 2.8 % v/v concentration. From left to right, the plants were untreated, 1.5, 3.0, 6.1, 9.1, and 12.2 meters downwind of nozzle.

CHAPTER 5

MEASURING THE EFFECT OF SPRAY PLUME ANGLE ON THE ACCURACY OF DROPLET SIZE DATA

Abstract

Analysis of droplet size data using laser diffraction allows for quick and easy assessment of droplet size for agricultural spray nozzles and pesticides. However, operation and setup of the instrument and test system can potentially influence the accuracy of the data. One of the factors is the orientation of the spray plume relative to the laser beam. The common practice is to orientate the nozzle such that the nozzle orifice's long axis is 90 degrees from the laser beam. Some wind tunnels are designed in a manner such that the spray plume impinges with the walls or the design of the nozzle may necessitate a deviation from this standard practice to obtain a measurement in some situations. The objective of this research was to determine the influence spray plume orientation had on measured droplet size spectra in a low-speed wind tunnel. The orientation of the nozzle tested was 45, 60, 75 and 90 degrees in rotation relative to the laser beam. Four nozzles (AIXR11005, AI11005, TT11005 and XR11005) were evaluated using three different spray solutions. Treatments were evaluated using a laser diffraction system. The results indicate that spray plume orientation does not have an effect on droplet size data for these nozzles, regardless of spray solution. The data from these tests will aid in the standardization of laser diffraction use in low-speed wind

tunnels and increase the repeatability of measurements between different spray testing laboratories.

Introduction

With an increased emphasis on managing off-target movement of sprays in agricultural applications, it is essential to understand the spray particle size distribution from spray nozzle by operating pressure by spray solution combinations. Understanding the spray droplet size distribution provides tremendous information for applicators on how to mitigate one major component of off-target movement (Hewitt 2000; Maybank et al. 1978). Additionally, having the right droplet size can also play a critical role in ensuring the maximum pesticide efficacy in agricultural pesticide applications (Knoche 1994; Miller and Butler Ellis 2000; Nuyttens, D. et al. 2007; Omar et al. 1991; Reed and Smith 2001). Unfortunately, mitigating off-target movement of pesticide applications and maximizing pesticide efficacy do not always coincide. For many commercial pesticides, as the droplet size increases, the off-target movement of the pesticide decreases and the pesticide efficacy also decreases.

There is a need for strict operating procedures when analyzing pesticide droplet spectra to ensure data gathered in a laboratory translates to in-field situations. For analysis of agricultural sprays, a number a factors can influence the accuracy of droplet size measurements, including selection of measuring device, operation of the measuring environment (e.g. wind speed and stability of the air), and user defined parameters for the experiment. Spatial sampling instruments (e.g. Malvern or Sympatec) are common for measuring droplet size in agricultural sprays, because they allow for line of sight calculations of droplet size in the entire spray volume (Dodge et al. 1987), within a short timeframe and using reduced test volumes (Hewitt 1994). In opposition, temporal sampling instruments (e.g. PDPA) include droplet velocities in measurement calculations, and several authors have demonstrated the differences between these systems in droplet size measurements (Arnold 1990; Chapple et al. 1995; Dodge 1987; Dodge et al. 1987; Tuck et al. 1997). With regards to operating environment, Hewitt (2000) (Hewitt and Valcore 1995) demonstrated that the ratio of air flow to liquid flow should ideally be 1:1 to avoid overestimation of larger or smaller droplets using spatial sampling laser diffraction device (e.g. Malvern or Sympatec). In addition, user defined factors, such as: adjuvant inclusion (Butler Ellis et al. 1997; Hoffmann, W.C. et al. 2008; Holloway et al. 2000; Miller and Butler Ellis 2000; Stainier et al. 2006), nozzle selection (Hewitt et al. 1994; Nuyttens, D. et al. 2007), or flow rate (Giles et al. 1995) have an influence on the measured droplet sizes.

Spatially generated data from a wind tunnel are subject to a variety of factors that can impugn accuracy. For example, vignetting of the measurement is a concern when the particle field is at a sufficient distance from the lens, resulting in scattered light that cannot be intercepted. This will produce a measurement bias towards large particles (Wild and Swithenbank 1986). This issue can be of particular concern when testing with wide angle (e.g. 110°) ground nozzles. While multiple facilities in the US are equipped with particle size analyzers, and some include wind tunnels, to measure the droplet sizes of agrochemicals, differences in their setup for droplet size analysis is to be expected.

Therefore, proper setup of a particle size analyzer is critical for accurate and repeatable data generation.

The objective of this research is to determine if spray plume orientation in a low-speed wind tunnel has an impact on droplet size measurements. The authors hypothesize that by changing the orientation of the spray plume from hydraulic nozzles in the wind tunnel, the measurements from laser diffraction will be altered because the spray plume will change distances from the lens potentially resulting in vignetting. As wind tunnels are being developed which rely on laser diffraction instruments to determine spray particle size, understanding how nozzle orientation affects spray droplet size measurements will be critical to ensuring the quality of the data being collected and potentially being compared between facilities.

Materials and Methods

Testing for this experiment was conducted at the Pesticide Application Technology Laboratory in North Platte, Nebraska. Data were collected in a low speed wind tunnel (LSWT) which consists of the following components: a 5.6 kW axial flow fan, an expansion chamber, a honeycomb straightener used to produce laminar air flow, and eight 1.2 x 1.2 x 2.4 m sections. A scrubber system and 7.5 kW electric axial flow fan was attached to the terminal section for removing spray droplets and vapors from the exhausted air (Figure 5.1).

The droplet spectrum for each treatment was analyzed using a Sympatec Helos/Vario KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany). This lens is capable of detecting droplets in a range from 18 to 3750 µm. The laser is comprised of two housings, an emitter housing containing the optical box and the source of the laser and a receiver housing containing the lens and detector element. The whole system was separated across the wind tunnel section and mounted on a custom-built aluminum stand which sat on the outside of the wind tunnel. The width of the spray plume was traversed through the laser beam by means of a linear actuator. The distance from the nozzle tip to the laser was set at 30.5 cm.

The treatments used in this experiment, which included four nozzles and three spray solutions in a factorial arrangement of treatments, are listed in Table 5.1. The nozzles were chosen because they are widely used in the US and because of the different features that classify the nozzle as flat fan (XR and TT) or venturi type (AIXR and AI). The LSWT was operated at 6.7 m/s, as measured by a hot wire anemometer set eight feet upstream of the nozzle, for each treatment. Nozzles were operated at 276 kPa. The spray plume orientation was determined by using a protractor and level, with the 90º orientation relative to the laser beam serving as the standard measurement. Each treatment consisted of at least three replications. Statistical analysis of the data were conducted using a mixed model ANOVA (PROC MIXED) in SAS v9.2 with replication set as a random factor. A Tukey adjustment was utilized with α=0.05 for the mean separation tests.

Results and Discussion

Differences in average optical concentration levels were generally only present between the standard orientation, 90°, and the 45° orientation for each spray solution by nozzle combination. This indicates that at the largest angle, 45°, a greater number of particles were passing through the collimated laser beam (Figure 5.2). The optical concentration did not exceed 5% for any of the nozzle by spray solution by plume orientation combinations (Table 5.2). It has been noted that at optical obscurations levels of 40-50% and higher (Triballier et al. 2003), multiple light scattering will diminish measurement accuracy. This is usually a matter of concern in highly dense sprays or when a high proportion of the laser's volume is obscured (Gülder 1990). In these scenarios, the forward scattered light will have greater refractive angles, causing an overestimation in the small droplet population (Agrawal et al. 2008; Triballier et al. 2003). Examination of the percent of droplets less than 100 µm in Table 5.2 indicates more sub-100 µm for many treatments with the plume angled, relative to the 90° orientation. In light of the optical concentration results, the authors do not believe this is a result of multiple light scattering, but rather a result of better capturing the entire plume width in our LSWT with these nozzles. Our results indicate that multiple light scattering will unlikely be an issue when testing with common ground nozzles and spray solutions in wind tunnels constructed similar to the one used in the study.

The volume median diameter (VMD) and relative span (RS) were not different between spray plume orientation within nozzle and spray solution combinations, except the water treatment using the AI11005 nozzle (Table 5.2). Therefore, the authors do not believe vignetting of measurements occurred in this experiment. It should be noted that orientating the spray plume to an angle which places particles beyond the maximum measurement zone of the particle size analyzer may bias measurements due to vignetting.

In regards to the system used in this experiment, the maximum working distance is 1132 mm using the R7 lens based on the manufacturers recommendations (Sympatec 2009). With a spray plume orientation of 45°, the furthest edge of the plume was approximately 1016 mm from the lens. Thus, if using spray plum angles greater than 45° with wide angle ground nozzles is necessary to make a measurement, care should be taken to avoid vignetting.

The results of our experiment indicate that spray plume orientation did not have an effect on precision of spray droplet data using a particle size analyzer. Therefore, based on these results and our observations during the study, the spray plume orientation of a nozzle can be orientated up to 45° in order to traverse the entire plume. Care should be taken to avoid fouling the lens on the measurement device and to observe if any spray impingement occurs on the sidewalls, which could impact data accuracy. The Pesticide Application Technology Laboratory in North Platte will choose the minimum angle necessary to fully traverse the spray plume for all future experiments. This data will be useful for standardization of experiments involving particle size analyzers and low speed wind tunnels. In addition, it will be helpful for increasing repeatability of data amongst different testing laboratories

Table 5.1. List of treatments including nozzles and spray solutions used to determine if spray plume orientation has an effect on droplet size measurements in a low-speed wind tunnel.

Nozzle	Solution	Plume Orientation
		° (degree)
AI11005	Water	90, 75, 60, 45
AI11005	Glyphosate[a] + AMS[b]	90, 75, 60, 45
AI11005	Glyphosate + DRT adjuvant[c]	90, 75, 60, 45
AIXR11005	Water	90, 75, 60, 45
AIXR11005	Glyphosate + AMS	90, 75, 60, 45
AIXR11005	Glyphosate + DRT adjuvant	90, 75, 60, 45
TT11005	Water	90, 75, 60, 45
TT11005	Glyphosate + AMS	90, 75, 60, 45
TT11005	Glyphosate + DRT adjuvant	90, 75, 60, 45
XR11005	Water	90, 75, 60, 45
XR11005	Glyphosate + AMS	90, 75, 60, 45
XR11005	Glyphosate + DRT adjuvant	90, 75, 60, 45

[a]Glyphosate was included at 32 oz/acre

[b]AMS was included at 5 % volume/volume

[c]DRT adjuvant was included at 2 oz/1 qt glyphosate

Table 5.2. Droplet size characteristics for four hydraulic nozzles tested at four different orientations in a low speed wind tunnel using water, glyphosate + AMS, and glyphosate + DRT adjuvant. Letters following numbers in the table indicate significant differences at the alpha = 0.05 level using Tukey's multiple pairwise comparisons within each nozzle type.

Nozzle	Treatment	Orientation	C_{opt}		VMD[a]		<100 µm		RS[b]	
		°	%		µm		%			
AI11005	Glyphosate + AMS	45	5.1	a	621	bc	0.44	ab	1.16	a
AI11005	Glyphosate + AMS	60	4.7	ab	622	bc	0.43	abc	1.16	a
AI11005	Glyphosate + AMS	75	4.3	bc	601	bc	0.43	abc	1.09	a
AI11005	Glyphosate + AMS	90	4.2	cd	594	c	0.44	a	1.07	a
AI11005	Glyphosate + DRT adjuvant	45	3.8	de	657	ab	0.05	d	1.00	a
AI11005	Glyphosate + DRT adjuvant	60	3.0	f	616	bc	0.06	d	0.92	a
AI11005	Glyphosate + DRT adjuvant	75	3.3	f	630	abc	0.05	d	0.97	a
AI11005	Glyphosate + DRT adjuvant	90	3.1	f	630	abc	0.06	d	0.97	a
AI11005	Water	45	4.0	cd	684	a	0.16	d	1.09	a
AI11005	Water	60	3.2	f	650	abc	0.16	d	1.01	a
AI11005	Water	75	3.4	ef	661	ab	0.21	cd	1.05	a
AI11005	Water	90	3.2	f	622	bc	0.22	bcd	0.97	a
AIXR11005	Glyphosate + AMS	45	4.8	a	496	**b**	0.92	**a**	1.16	**a**
AIXR11005	Glyphosate + AMS	60	4.2	b	506	**b**	0.97	**a**	1.19	**a**

AIXR11 005	Glyphosate + AMS	75	4.2	b	496	**b**	0.88	**a**	1.14	**a**
AIXR11 005	Glyphosate + AMS	90	3.9	bc	498	**b**	0.87	**a**	1.16	**a**
AIXR11 005	Glyphosate + DRT adjuvant	45	3.7	cd	536	a	0.23	**b**	1.00	**b**
AIXR11 005	Glyphosate + DRT adjuvant	60	2.9	fg	526	a	0.24	**b**	0.96	**b**
AIXR11 005	Glyphosate + DRT adjuvant	75	3.0	efg	537	a	0.23	**b**	1.02	**b**
AIXR11 005	Glyphosate + DRT adjuvant	90	3.3	de	536	a	0.20	**b**	1.11	**ab**
AIXR11 005	Water	45	3.7	cd	541	a	0.38	**b**	1.04	**b**
AIXR11 005	Water	60	3.2	ef	519	**ab**	0.41	**b**	1.00	**b**
AIXR11 005	Water	75	2.6	g	544	a	0.34	**b**	1.05	**b**
AIXR11 005	Water	90	2.8	fg	537	a	0.41	**b**	1.05	**b**
TT1100 5	Glyphosate + AMS	45	4.2	a	490	a	2.1	a	1.48	a
TT1100 5	Glyphosate + AMS	60	3.8	bc	463	ab	2.2	a	1.42	ab
TT1100 5	Glyphosate + AMS	75	3.4	cde	447	abc	2.3	a	1.37	abc
TT1100 5	Glyphosate + AMS	90	3.4	cde	450	abc	2.1	a	1.35	abc
TT1100 5	Glyphosate + DRT adjuvant	45	4.2	ab	396	cd	1.7	**bc**	1.24	bc

TT1100 5	Glyphosate + DRT adjuvant	60	3.1	e	364	d	1.9	**b**	1.12	c
TT1100 5	Glyphosate + DRT adjuvant	75	3.2	de	407	bcd	1.6	**cd**	1.32	abc
TT1100 5	Glyphosate + DRT adjuvant	90	3.1	e	399	bcd	1.6	**cd**	1.23	abc
TT1100 5	Water	45	4.4	a	409	bcd	1.7	**bc**	1.19	bc
TT1100 5	Water	60	3.6	cd	418	**bc**	1.7	**bc**	1.23	abc
TT1100 5	Water	75	2.0	g	448	abc	2.1	**a**	1.20	bc
TT1100 5	Water	90	2.6	f	436	abc	1.7	**c**	1.28	abc
XR1100 5	Glyphosate + AMS	45	5.6	a	272	a	8.7	a	1.39	a
XR1100 5	Glyphosate + AMS	60	5.2	a	268	a	8.6	ab	1.35	ab
XR1100 5	Glyphosate + AMS	75	4.6	bc	277	a	8.6	ab	1.36	ab
XR1100 5	Glyphosate + AMS	90	4.2	cd	264	a	8.4	b	1.30	abc
XR1100 5	Glyphosate + DRT adjuvant	45	4.0	d	299	a	3.0	e	1.09	bcd
XR1100 5	Glyphosate + DRT adjuvant	60	3.1	e	316	a	**2.0**	h	1.02	d
XR1100 5	Glyphosate + DRT adjuvant	75	3.3	e	307	a	**2.3**	g	1.03	cd
XR1100 5	Glyphosate + DRT adjuvant	90	2.9	e	302	a	2.8	f	1.08	bcd

XR1100 5	Water	45	4.7	b	315	a	3.9	d	1.17	abcd
XR1100 5	Water	60	3.9	d	317	a	3.9	d	1.18	abcd
XR1100 5	Water	75	3.1	e	312	a	3.9	d	1.16	abcd
XR1100 5	Water	90	3.1	e	303	a	3.9	d	1.19	abcd

[a]VMD=Volume median diameter

[b]RS=Relative span. Defined as (Dv90-Dv10)/Dv90.

Figure 5.1. The low-speed wind tunnel used at the Pesticide Application Technology Laboratory in North Platte, NE. The axial flow fan at right is the source of the wind, which travels through the expansion chamber, air straightener, and 1.2 x 2.4 m sections. The scrubber system (not pictured) sits at the terminal end of the tunnel, 14.6 m from the air straightener.

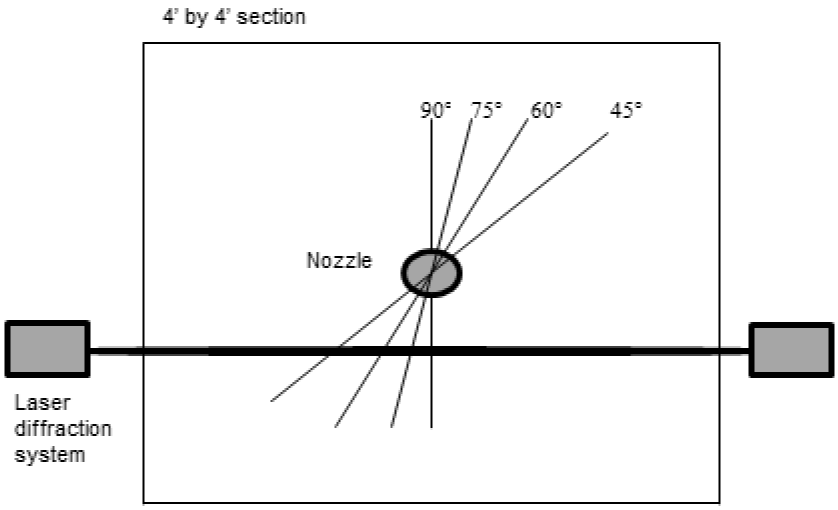

Figure 5.2. An illustration of the four spray plume orientations used in this study. Not drawn to scale.

CHAPTER 6

A COMPARISON OF AN UNHOODED AND HOODED SPRAYER FOR PESTICIDE DRIFT REDUCTION

Abstract

Management of drift from pesticide applications is important for human and environmental health concerns. It is also necessary to ensure the adequate dosage of the pesticide meets the target species(s). A variety of factors can affect the drift potential of a pesticide application, including nozzle selection, solution chemistry, and application equipment. In the present study, a comparison of two ground sprayers, one with a hood and one without a hood, is made using three common ground nozzles in the US. The hooded sprayer reduced the drift potential of the pesticide application for all nozzles tested. In addition, higher spray coverage under the boom was measured when using the hooded sprayer. The results of this study indicate that incorporating a hood will lead to reduced drift potential from a pesticide application.

Introduction

Management of pesticide drift from ground applications is necessary to help reduce risks associated with human and environmental exposure. In the US, pesticides serve as a major component of crop production. In 2012, herbicides, insecticides, and fungicides were applied to 98, 18, and 11 percent of soybean acreage, respectively, with the most commonly applied herbicide being glyphosate(Nass 2012b). The benefits of pesticide use is well documented in regards to productivity increases; however, the combination of rising input prices (Nass 2012a), weed resistance management (Powles and Yu 2010), and government regulations regarding drift reduction techniques (EPA 2006) are causing growers to reevaluate pesticide application methods. With respect to pesticide drift, growers are faced with unwanted damage to sensitive species, complaints, legal ramifications, and profit loss(Hewitt 2000). A key aspect of government regulations regarding drift reduction will be field evaluations of the proposed method or technology.

Assessing drift reduction technologies (DRTs) in a field environment is critical for establishing the DRTs potential, labeling requirements, and potential for crop injury. Over the years, the knowledge gained from such studies has been used to develop computer modeling programs for evaluating the potential for pesticide drift, especially those from aerial applications (Teske et al. 2011). The use of wind tunnels is another option for drift assessment; however, evaluating the pesticide drift from ground based applications in a low speed wind tunnel is an on-going area of development (Fritz et al. 2009). When the proposed DRT consists of sprayer modification, e.g. hooded sprayer, the upcoming US EPA regulations will most likely require a field evaluation to be performed (Hewitt 2012).

Using hooded sprayers during ground applications has the potential to minimize pesticide drift, especially when combined with other DRTs, e.g. drift retardant adjuvants or low drift nozzles. Fehringer and Cavaletto (1990) demonstrated the capacity of using a simple hood and curtain to reduce spray drift over a conventional spray boom. For this study, a spray solution of water soluble dye through a single nozzle design reduced downwind drift up to 275% over the open boom design. In a wind tunnel study, two hooded sprayer designs (a double foil and triple foil shield) reduced drift up to 76% when measured using collection cans under the sprayer, and these results were dependent upon nozzle orifice size and spray pressure (Sidahmed et al. 2004). A study involving a variety of hooded sprayer designs and nozzle setups further demonstrate the potential for hoods to reduce spray drift (Ozkan et al. 1997). Shielded individual nozzles proved successful for reducing spray drift in wind speeds up to 30 km/h (Maybank et al. 1990), although this approach would limit the user from easily switching nozzles which is important for custom application businesses.

In the current market of increasing input prices and government regulations regarding pesticide applications, growers will need effective methods for drift reduction. While multiple DRTs exist, and combinations thereof will likely provide the greatest drift reducing potential, it is likely growers will look towards efficient approaches that provide consistent performance. With this in mind, the objective of the current research was to evaluate the drift reduction potential of a newly designed hooded sprayer system versus an unhooded system in a field environment. The application procedures were developed to mimic those realized in a normal application scenario, specifically spray solutions, nozzle types, and weather conditions that are common to the Corn Belt of the US. The authors hypothesized that a combination of low-drift nozzles and a hooded sprayer would result in the greatest drift reduction over a flat fan nozzle in an unhooded sprayer. The data from this study can aid sprayer manufacturers and government bodies for developing and testing hooded sprayers for pesticide drift reduction.

Materials and Methods

This experiment was conducted at the Dryland Research Farm in North Platte, NE (41.052342N, -100.746646W) in early fall of 2012 and late summer of 2013. For the trial conducted in 2012, the field site was a wheat stubble field, with stubble height being approximately eight inches. The field was gently sloped uphill towards the west, northwest. An area of 183 meters by 105 meters was designated as the experimental site within this field and encompassed the gentle uphill slope. For the trial conducted in 2013, the field site was a soybean field next to a wheat stubble field with soybean canopy height approximately six inches (growth stage V3) at the time of the experiment. The field was flat with no tall features (trees, buildings, etc.) within 100 meters in any direction. Similar to the 2012 trial, an area of 183 meters by 105 meters was designated as the experimental site within this field.

Prior to the time of the experiment, drift collection stations were placed in the experimental area. Twenty-seven stations were placed downwind of the application zone in three transects, with each transect serving as a replication in analysis of the data. In 2012, the collection media was plastic petri dishes (ø 150mm) placed at the top height of the wheat stubble (Fig. 6.1). The collection media for 2013 was plastic mylar cards (101 mm by 101 mm) (Fig. 6.2), and the decision to switch collection media was based on research that demonstrated a higher collection efficiency of mylar cards over petri dishes (unpublished data). The downwind collection stations in 2013 were placed into the adjacent wheat stubble field, and the collection height was set at eight inches. The application zone contained nine collection stations (in-swath stations), and one collection stations were placed upwind of the application zone (Fig. 6.3).

In order to discern the drift reduction capabilities of a hooded sprayer, two sprayers (Willmar Fabrications, LLC, Willmar, MN) 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 1136 liter 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 the nozzle height was set at 91 cm above the ground level for both sprayers. The wind skirt on the hooded sprayer was set approximately two inches into the wheat or soybean canopy. The height for each sprayer was maintained throughout the study via the sprayers' guide wheels and the tractors' hitch system. The hooded sprayer design used in 2012 is shown in Fig. 6.4. The hood was constructed of molded, polymer plastic that surrounded the nozzles. The hood sections reached approximately 30.5 cm below the nozzle orifices, and a plastic curtain reached a further 10.2 cm below the plastic hood. During the trial in 2012, it was noticed that the design of the hood interfered with the spray plume of the nozzles, particularly those with an angled exit trajectory, e.g. the TTI nozzle (TeeJet Technologies, Wheaton, IL, USA). For this reason, the hood design was slightly modified for the 2013 trial, to widen the area underneath the nozzle orifices (Fig. 6.5). No interference of hood and nozzle plume was observed in the 2013 trial.

The treatments for this experiment are listed in Table 6.1. The spray solution consisted of Roundup PowerMax (540 g ae/L, Monsanto, St. Louis, MO) at a rate of

2.34 L ha^{-1}, Bronc AMS (Wilbur-Ellis, San Francisco, CA) at 5 % vol/vol, and rhodamine dye (intracid rhodamine WT, Cole Parmer Instrument Company) at 0.25 % vol/vol. The desired application rate was 94 L ha^{-1} for each treatment. Each nozzle was run at 290 kPa and travel speed was 12.8 to 14.4 km h^{-1}. The volume median diameter for each spray is listed in Table 6.1, and the data were collected at the University of Nebraska-Lincoln Pesticide Application Technology Laboratory using established techniques (Henry, Ryan et al. 2014). Just prior to an application, the petri dishes or mylar plates were placed on each collection station. The targeted wind velocity was between 8.04 to 24.1 km h^{-1} and +/- 30° of being perpendicular to the driveline before applying a treatment. The meteorological conditions were recorded by an on-site weather station with an accompanying data logger set to record temperature, wind speed, wind direction, and relative humidity. When necessary, the driveline and treatment zone was shifted to maintain the +/- 30° wind direction target. The weather data for each respective treatment is listed in Table 6.2. A single application along the driveline was made for each treatment, and each treatment was repeated twice. All petri dishes or mylar plates were collected 5 minutes after the end of the application, placed into clean plastic bags, and placed into a container to prevent photodegredation of the dye. In 2013, water sensitive cards (52mm by 72mm, Spraying Systems Co., Wheaton, IL, USA) were placed in the driveline for each treatment to measure spray coverage. The cards were analyzed using DropletScan™ v2.5 (Lonoke, AR, USA).

The collection media were taken to a laboratory to extract and analyze dye concentration using fluorometry techniques. Reagent alcohol (Fisher Scientific, Fair

Lawn, NJ) was diluted with distilled water to a final concentration of 50%. In 2012, 60 mL of this alcohol solution was added to each petri dish, in 20 mL increments, using a bottle top dispenser (Model 60000-BTR, LabSciences, Inc.). The rinsate was then decanted into a sterile polyethelyne bottle, and a 1 mL sample was drawn to fill a glass cuvette. In 2013, 60 milliliters of this alcohol solution was added to bag containing a mylar plate, in 20 mL increments, using the same bottle top dispenser. The bag was vigorously shaken to remove any dye from the mylar plate and 1 mL sample was drawn to fill a glass cuvette. Fluorescence data were collected using a fluorometer (Model T200, Turner Designs) with a rhodamine/phycoerythrin module installed.

The deposition rates were calculated as a percent of the applied rate, which was measured as the amount of spray deposited in the driveline for each treatment. The fluorescence of the 50% alcohol solution was measured and recorded to serve as the background signal for the fluorescence measurements. This value was subtracted from each reading, and the corrected value was used for statistical analysis. All data were subjected to ANOVA using PROC MIXED in SAS (Sas 2013) with replication set as a random variable. Means were separated using a Tukey adjustment with alpha set to 0.10.

Results and Discussion

The ambient air temperature and relative humidity were uniform throughout the experiment. The wind velocity and direction were within the targeted range, except Treatment 5. During this treatment, the wind velocity reached 37.3 km h^{-1}, the highest recorded wind velocity during the experiment. In addition, the wind direction shifted close to the 30 degree tolerance of being perpendicular to the drivelines which may partially explain the lack of drift reduction observed with the hooded sprayer for this nozzle.

Deposition data is presented in Table 6.3. The sprayers are compared within each nozzle type. The TTI nozzle produced the lowest amount of downwind deposition, overall. This is to be expected because this nozzle produced the largest droplets from the three nozzles tested (Table 6.1). At all distances downwind, except four and eight meters, measured drift was higher for the hooded sprayer than the unhooded sprayer. This is likely a result of two determining factors. First, the wind velocity reached the highest recorded level for this treatment, and the average wind velocity was approximately 4.8 km h^{-1} higher than for Treatment 6. In addition, during the course of the experiment, it was observed that the spray plume from the TTI nozzle impacted the backside of the hood. While it is not understood why, it seems likely that the increased drift with the hood is due to this interference. The researchers speculate that this may be due to shattering droplets leading to decreased droplet sizes. Based on this observation, the hood's design was altered to accommodate spray nozzles with angled plumes for the 2013 experiment (Fig. 6.5).

Measured deposition was less than one percent when using the hooded sprayer and AIXR nozzles at all downwind distances. At four, eight, and 32 meters downwind, deposition was less using the hooded sprayer as compared to the unhooded sprayer. At the other distances, no differences between deposition of the hooded and open boom were observed. Wind velocity and the maximum recorded wind velocity were higher during the application using the hooded sprayer with AIXR nozzles than the unhooded sprayer with AIXR nozzles.

The XR nozzle produced the highest levels of downwind deposition in this experiment. At 4 and 8 meters downwind, measured deposition levels were 2.05 and 1.37 percent of the total volume applied, respectively, for the unhooded sprayer utilizing XR nozzles. These were the highest measured values in this experiment in 2012. At all measured downwind distances, deposition amounts for the hooded sprayer were either less than or similar to the open sprayer. When applied with a hooded sprayer, the measured deposition from the XR nozzle was similar to that of the hooded sprayers with the AIXR or TTI nozzles.

During the course of the experiment, the ambient air temperature rose 5 degrees, reaching a maximum of 27 °C for treatment six. Relative humidity decreased from 72 percent to 46 percent. The wind velocity and direction were within the targeted range for all treatments. The average wind speed was greatest for treatment two at 13.2 km h^{-1} and lowest for treatment 1at 11.2 km h^{-1}. The range of wind speed observed, and the maximum gust speeds, were within appropriate application guidelines for the pesticide label for all treatments.

Deposition data is presented in Table 6.4. Overall, the applications made using the hooded sprayer had the least amount of downwind deposition, regardless of nozzle type. When using the TTI nozzle, the inclusion of the hood decreased deposition at downwind distances of 45 and 105 meters. At the other distances, the deposition rate was similar to the unhooded sprayer. There was no measured deposition at 4,8, 16, 32, 45, and 105 meters when using the hooded sprayer and TTI nozzles.

Similar to the TTI nozzle, measured deposition was less than one-tenth of a percent when using the hooded sprayer and AIXR nozzles. For the majority of measured distances, deposition was less for the hooded sprayer than the unhooded sprayer. There was no measured drift at 8, 16, 32, 45, and 75 meters with the hooded sprayer and AIXR nozzle setup.

The XR nozzle again produced the highest levels of downwind deposition observed in this experiment in 2013. At the nearest five distances, the deposition rate of the hooded sprayer was less than that of the unhooded sprayer, and the deposition rates were similar between the two sprayers at the four furthest distances. As in 2012, the deposition rates for the hooded sprayer with the XR nozzles were similar to that of the hooded sprayers with the AIXR and TTI nozzles.

Percent coverage of the spray application was measured for each treatment using WSC (Fig. 6.6). The hooded sprayer had more coverage than the open sprayer, regardless of nozzle type. The treatment with the highest coverage was the hooded sprayer using the XR nozzle, while the treatment with the least coverage was the unhooded sprayer with the XR nozzle.

Conclusions

The results of this experiment highlight the potential of utilizing a hooded sprayer design to minimize pesticide drift. From this experiment, the authors conclude:

- A hooded sprayer is capable of reducing pesticide drift, even when making an application with a “fine” spray quality
- The design of a hood should not interfere with the spray plume. If an interference occurs, the drift potential is markedly increased
- Spray coverage was improved when using a hooded sprayer, as measured by WSC

It should be noted that none of the treatment resulted in zero downwind deposition at all measured distances in this experiment. When compared to an unhooded sprayer with XR nozzles, the percent reduction in deposition for the treatments ranged from 0 to 100 percent in 2012 and 2013; however, there were instances of a percent increase in measured deposition in both years even when using a hooded sprayer (Tables 6.5 and 6.6). This could be due to a number of reasons. It is possible a greater wake effect is produced by the hood leading to unstable air near the sprayer. Any droplets that escape the hood can be influenced by this stable air and pushed downwind. Future work involving different plant canopies and heights, as well as efficacy screens of weed species will help to further advance the potential of a hooded sprayer for use in row crop systems in the US.

Acknowledgments

The authors would like to thank the efforts of the team of graduate students, technicians, and undergraduate students and their contributions to this study. We also thank the team of engineers for their work towards designing and building the hooded and unhooded sprayer systems.

Table 6.1. List of treatments used in this experiment for both 2012 and 2013.

Treatment	Nozzle[a]	Boom	VMD[b]	Spray Classification[c]
1	XR11003	Hooded	203	Fine
2		Open		
3	AIXR11003	Hooded	428	Coarse
4		Open		
5	TTI11003	Hooded	704	Ultra Coarse
6		Open		

[a] Spraying Systems, Wheaton, IL

[b] Volume Median Diameter

[c]Spray classifications are defined using ASABE S572.1

Table 6.2. Meteorological data for each treatment. Data were logged by an on-site weather station placed approximately 50 meters southwest of the application zone. The data logger recorded at 15 second intervals and data presented is average over the duration of the each treatment.

Treatment	Air temperature	Relative humidity	Wind speed[a]	Wind direction
	°C	%	km h^{-1}	
		2013		
1	22	72	11.2 (14)	17
2	27	47	13.2 (16.7)	25
3	23	65	13 (15.2)	33
4	27	46	12.2 (17.3)	12
5	22	69	13.8 (18.1)	30
6	27	46	11.9 (13.5)	45
		2012		
1	26	19.3	14.9 (20.1)	128
2	26	19.4	13 (18.7)	128
3	26	19.9	16.9 (25.4)	117
4	27	18.9	13 (20.7)	121
5	26	20.0	17.5 (37.3)	94
6	26	22.1	12.4 (26)	113

[a] Numbers listed in parentheses were observed maxima wind speed for each treatment

Table 6.3. Deposition amounts determined as a percent of the applied rate for each nozzle tested in 2012. Differences in a nozzle by boom pair are noted in bold font.

Nozzle	Boom	Distance Downwind								
		4	8	16	32	45	60	75	90	105
		meters								
XR	Hooded	**0.35**	**0.29**	0.68	**0.03**	**0.03**	**0.03**	0.30	0.08	0.13
	Open	**2.05**	**1.37**	0.90	**1.05**	**0.27**	**0.34**	0.42	0.08	0.10
AIXR	Hooded	**0.21**	**0.14**	0.28	**0.08**	0.10	0.09	0.16	0.07	0.11
	Open	**0.66**	**0.74**	0.48	**0.41**	0.13	0.17	0.19	0.07	0.04
TTI	Hooded	0.18	0.07	**0.16**	**0.15**	**0.28**	**0.23**	**0.15**	**0.06**	**0.16**
	Open	0.14	0.10	**0.03**	**0.00**	**0.00**	**0.00**	**0.00**	**0.01**	**0.00**

Table 6.4. Deposition amounts determined as a percent of the applied rate for each nozzle tested in 2013. Differences in a nozzle by boom pair are noted in bold font.

Nozzle	Boom	Distance Downwind								
		4	8	16	32	45	60	75	90	105
						meters				
XR	Hooded	**0.05**	**0.00**	**0.01**	**0.00**	**0.00**	0.00	0.02	0.00	0.06
	Open	**1.73**	**0.61**	**0.15**	**0.06**	**0.02**	0.04	0.04	0.02	0.05
AIXR	Hooded	**0.04**	**0.00**	**0.00**	**0.00**	**0.00**	0.02	**0.00**	0.02	0.02
	Open	**0.86**	**0.30**	**0.10**	**0.03**	**0.04**	0.05	**0.06**	0.01	0.03
TTI	Hooded	0.00	0.00	0.00	0.00	**0.00**	0.06	0.01	0.02	**0.00**
	Open	0.04	0.02	0.08	0.00	**0.08**	0.08	0.09	0.01	**0.03**

Table 6.5. Percent reduction in drift compared to the XR11003 flat fan nozzle with an open boom in 2012. Negative values represent an increase in drift.

Nozzle	Boom	Distance Downwind								
		4	8	16	32	45	60	75	90	105
		meters								
XR	Hooded	82.9	78.8	24.4	97.1	88.9	91.2	28.6	0.0	-30.0
	Open	0	0	0	0	0	0	0	0	0
AIXR	Hooded	89.8	89.8	68.9	92.4	63.0	73.5	61.9	12.5	-10.0
	Open	67.8	46.0	46.7	61.0	51.9	50.0	54.8	12.5	60.0
TTI	Hooded	91.2	94.9	82.2	85.7	-3.7	32.4	64.3	25.0	-60.0
	Open	93.2	92.7	96.7	100.0	100.0	100.0	100.0	87.5	100.0

Table 6.6. Percent reduction in drift compared to the XR11003 flat fan nozzle with an open boom in 2013. Negative values represent an increase in drift.

Nozzle	Boom	Distance Downwind								
		4	8	16	32	45	60	75	90	105
						meters				
XR	Hooded	97.1	100.0	93.3	100.0	100.0	100.0	50.0	100.0	-20.0
	Open	0	0	0	0	0	0	0	0	0
AIXR	Hooded	97.7	100.0	100.0	100.0	100.0	50.0	100.0	0.0	60.0
	Open	50.3	50.8	33.3	50.0	-100.0	-25.0	-50.0	50.0	40.0
TTI	Hooded	100.0	100.0	100.0	100.0	100.0	-50.0	75.0	0.0	100.0
	Open	97.7	96.7	46.7	100.0	-300.0	-100.0	-125.0	50.0	40.0

Fig. 6.1. A drift collection station used for the trial in 2013. A mylar cards is held in place by a paperclip on a metal platform, which is held up by a metal pole and clip. The mylar cards were placed at a level just above the wheat stubble.

Fig. 6.2. A drift collection station used for the trial in 2012. A petri dish is held in place by tape to a wooden platform, which is held up by a fiberglass pole and clip. The petri dishes were placed at a level just above the wheat stubble.

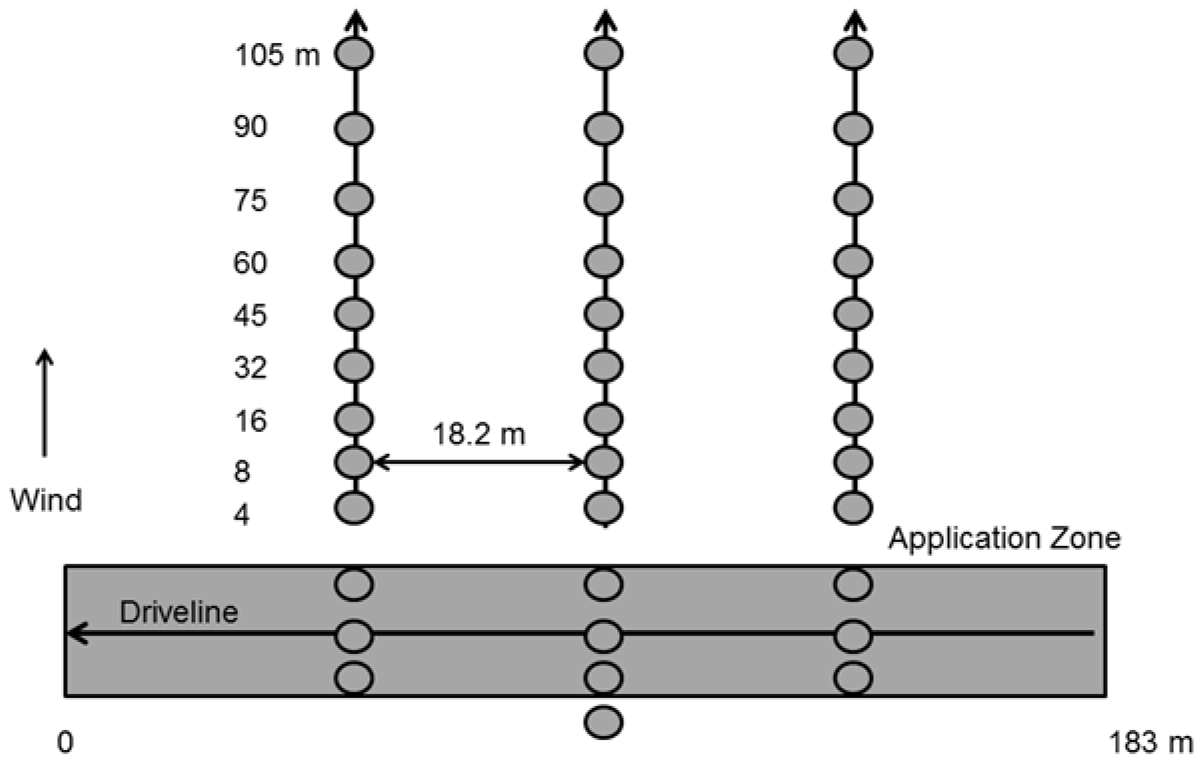

Fig. 6.3. Field layout used for this experiment. Each dot represents a collection station. Twenty-seven stations were placed downwind from the application zone at the designated distances. Nine stations were placed within the applications zone, and one station was placed upwind of the application zone.

Fig. 6.4. The hood design used in the 2012 trial. The hood consisted of molded plastic extending approximately 30.5 cm below the nozzle orifices, and the plastic curtain extended approximately 10.2 cm below the hood.

Fig. 6.5. The hood design used in the 2013 trial. The area under the hood was widened to decrease the chance of interference of the hood with the spray plume.

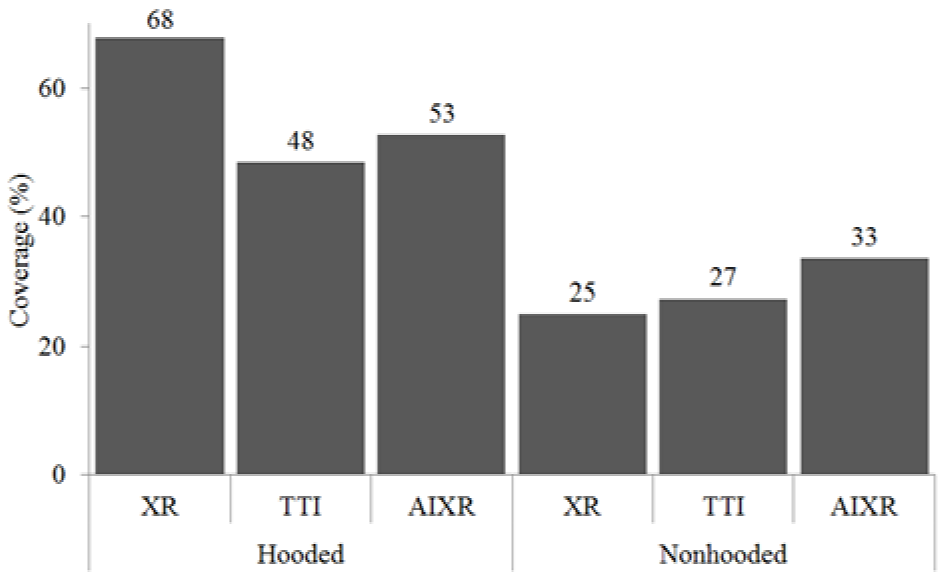

Fig. 6.6. Percent coverage using water sensitive cards (WSC) placed in swath. Each treatment contained three WSCs and the graphs are the average. The WSCs were evaluated using DropletScan v2.4

CHAPTER 7

AN EVALUATION OF THREE DRIFT REDUCTION ADJUVANTS FOR AERIAL APPLICATION OF PESTICIDES

Abstract

Preventing pesticide drift from aerial applications is important for environmental and application efficiency reasons. Proper analysis of drift reduction technologies or techniques is an essential component of the drift prevention process. In the current study, three drift reduction adjuvants were tested with two herbicides under several application conditions used by rotary-wing and fixed-wing aircraft in the U.S. Data were collected using a high speed wind tunnel and laser diffraction equipment. The results of this study indicated that application conditions was largest driver of the droplet size distribution and drift potential. Further analysis in a drift prediction program, AGDISP indicate no differences among the treatments. This study highlighted the importance of testing drift reduction technologies or techniques from multiple viewpoints.

Introduction

Application of pesticides is nearly ubiquitous with cropping systems in the US. Over 90 percent of corn, soybean, and cotton acres planted in the US are genetically modified, where herbicide-tolerance and insect-resistance traits comprise the main categories of this technology. . Growers have long been able to apply the herbicide glyphosate (N-(phosphonomethyl) glycine) to their tolerant crops for broad spectrum weed control, and they will soon have the capacity to apply growth regulator herbicides such as dicamba (3,6-dichloro-O-anisic acid) and 2,4-D ((2,4-dichlorophenoxy) acetic acid).

Pesticide application methods have evolved from rudimentary techniques and equipment to being more technology driven through the use of GPS, flow rate controllers, field mapping, etc. Aerial application of pesticides provides the opportunity for pest control at critical times and it is commonly used in row crops, pastures, and forestry systems. Advances in aircraft design allow the application of a range of products at speeds of 257 km h^{-1}, considerably reducing application times less. However, higher application increased potential for the development of smaller droplets in the spray and therefore increases off-target movement.

The widespread use of pesticides has been raising questions regarding human and environmental safety (Shirangi et al. 2011)(Hewitt 2000). In the US, the EPA initiated programs for evaluating application technologies to mitigate pesticide drift (EPA 2015). Evaluations for aerial applications have been performed for a number of years by a collection of private, public, and government researchers. The net result of this research has culminated in the creation of a computer modeling program for drift prediction, AGDISP. This model is based on the principles of Gaussian dispersion into an atmosphere, but also utilizes Langragian techniques to incorporate the wake effects of aerial applications (Teske et al. 2002). Validation of this model in a field application scenario has been met with success (Teske et al. 2011), while other researchers contend the methodologies for drift collection need refinement to achieve results comparable to AGDISP (Fritz et al. 2011). A key element of this model is the knowledge of the droplet size distribution to obtain confidence in the drift prediction (Fritz et al. 2011; Teske et al. 2011). Spray particle sizes can be obtained by a variety of methods, though a common technique is the use of laser diffraction systems in wind tunnels constructed to simulate the application scenario (Hoffmann et al. 2008).

Similarly to ground applications, aerial applications can be performed with wide variety of solution chemistries, nozzle types, and operational procedures to maximize pesticide efficacy and reduce off-target movement. Investigations of commercially available technologies for drift reduction will benefit the applicator, the environment, and the public at large. Therefore, the objective of this study was to evaluate the performance of three drift reduction adjuvants (DRAs) in combination with two herbicide formulations across a range of airspeeds common to aerial applications. The authors hypothesized that all DRAs would reduce drift potential as measured by droplet size distribution and AGDISP modeling.

Materials and Methods

All data for this research was generated in a high speed wind tunnel at the Pesticide Application and Technology Laboratory (PAT Lab) in North Platte, NE. The wind tunnel is comprised of a 149 kW electrical motor, which powers a forward-curve centrifugal fan. The fan outlet measures 0.3 by 0.3 meters and opens into enclosed sections measuring 1.2 by 1.2 meters and a total length of 4.9 meters. The boom and nozzle delivery system is immediately downwind of the outlet. The boom and nozzle were traversed vertically through the airstream by a linear actuator. The measurement zone was situated 0.5 meters downwind of the nozzle tip. Particle size measurements were made using a Sympatec HELOS/VARIO KF (Sympatec Inc., Clausthal-Zellerfeld, Germany) using the manufacturer denoted R6 lens. This lens is capable of measuring droplets from 9 to 1,750 μm. At least three replications were performed per treatment, with a replication being a single traverse of the spray plume through the measurement zone.

Two herbicide products were used: Base Camp Amine 4 (2,4-dichlorophenoxyacetic acid, dimethylamine salt, 46.8%, Wilbur-Ellis, San Francisco, CA USA) and Roundup PowerMax (potassium salt of *N*-(phosphonomethyl)glycine,48.7%, Monsanto, St. Louis, MO USA). Each herbicide was tested alone or in combination with one DRAs. The drift reduction adjuvant 1 (DRA #1) is composed of modified vegetable oil, amine salts of organic acid, and organic acid, 100%, DRA #2 is composed ofmodified vegetable oil, aliphatic mineral oil, amine salts of organic acids, aromatic acid, 100%, and DRA #3 is composed of phytobland base oil, tall oil fatty acids,N,N-Bis-2-(omega-hydroxypoloxyethylene/polyoxypropylene) ethyl alkylamine, 100%). The applied rates were 1 part of DRA #1 to 4 parts of herbicide, 292 mL ha^{-1} (0.25%v/v) DRA #1 was premixed with the herbicides prior to the addition of water, whereas DRAs #2 and #3 were added last in the mixing order. The carrier volume for each treatment was 94 L ha^{-1}. The two nozzles tested were at an 80° flat fan with a 03 orifice and a 40° flat fan with a 15 orifice. The tips were held with a CP11-TT (Transland, LLC, Wichita Falls, TX) nozzle body that was attached to a CP-06 swivel parallel to the airstream. The CP11-TT body has an inherent deflection, which gives the actual nozzle tip 8° downward orientation relative to the airstream. The nozzle was placed at approximately 9 cm below the airfoil boom, and a pressure of 276 kPa was applied to three operational airspeeds of 129, 193 and 257 km h^{-1}. The airspeed of 129 km h^{-1} was representative of the rotary-wing (helicopter) applications, while the airspeeds of 193 km h^{-1} and 257 km h^{-1} represented the speed for fixed wing applications in the U.S.

The treatments were arranged in a factorial design, and the factors in this experiment were herbicide, adjuvant, nozzle type, and airspeed. Data for this experiment were subjected to ANOVA using either PROC GLM or PROC MIXED in SAS 9.3. (SAS, Cary, NC, USA) based on the model options inherent in each procedure. Replication was set as a random class variable for analysis. Data were separated by airspeed for statistical analysis. The data were further separated by herbicide type and nozzle type in PROC MIXED. Means were separated using the TUKEY procedure with the level of Type I error set at 0.05.

After determining the droplet size distributions (DSD) for each treatment, the data were modeled in AGDISP v8.26. This program was made available to the authors by the US Forest Service. For each modeling iteration, the following settings were used:

Application Method: Aerial, Air Tractor 402B, release height of 10 feet, 25 spray lines

Application Technique: user defined DSD

Meteorology: Default values (2.24 m s^{-1} wind speed, perpendicular wind flow to flight path, 29.44 ºC, 80% RH

Spray Material: Water, spray material does not evaporate

Stability: Overcast

Surface: 0 degree uphill and side slope angle

Canopy: None

Surface Details: Surface roughness of 0.04 m

Transport: 0 m

Advanced: All default except default swath offset set to 0 swath

Results and Discussion

An ANOVA overview is presented in Table 7.1 for the dependent variable "%Vol<100 µm", which was one of four dependent variable analyzed in this research. All main effects and interactions thereof are significant at α=0.05. The ANOVA tables for the three other dependent variables (Dv0.1, VMD, and Dv0.9) were significant for all effects and interactions were at α=0.05 (data not shown). The dependent variable "%Vol<100 µm" was selected as an indicator of the fine portion of the spray that is typically most prone to drift. The effect size for each main effect and interaction is also presented in Table 7.1. For the dependent variable "%Vol<100 µm", the main effects that explained the vast majority of the dataset variability were airspeed and nozzle type at 58.3% and 26.0%, respectively (Table 7.1). Airspeed is the dominant factor in DSD for aerial applications. At airspeeds above 129 km h^{-1}, the force of the air movement upon the spray droplets induces a secondary atomization event, typically defined as an air shear effect. This can substantially lower the DSD of the resultant application. When the mean values of all dependent variables across the three tested airspeeds were compared, it was evident that the data displayed the air shear effect. For example, the percent of the spray volume <100 μm for the glyphosate treatments with the CP 4015 averaged 0.6 % at 129 km h^{-1}, while at 193 and 257 km h-1 the averages were 3.2% and 9.3%, respectively (Tables 7.4 and 7.6). Similar trends were also found in other similar comparisons in the dataset.

Nozzle type accounted for 26.0% of the treatment effect for this dataset (Table 7.1). The nozzles tested were different in two important ways. First, the plume angles were 40^o different. The wider spray plume angle of the CP 8003 nozzle resulted in more force upon the entire spray plume versus the narrower angle CP 4015, and hence overall smaller DSD. For example, the VMD of the treatments involving 2,4-D through a CP 4015 nozzle produced VMD's that were twice as large as the sprays through a CP 8003 nozzle (Table 7.2). At 257 km h^{-1}, this effect had a lower magnitude, which can be explained by the air shear effect as described previously. In addition to the spray plume angle of the nozzles, the orifice size had an effect on the DSD. In general, larger the orifice size were associated with larger droplets (Nuyttens, Schampheleire, et al. 2009). The data from this experiment support previous findings.

The DSD of the glyphosate solutions were consistently smaller than the 2,4-D only solutions at a given nozzle by airspeed combination. When using the CP 8003 nozzle at an airspeed of 257 km h^{-1}, the VMD of the glyphosate treatments were 170 μm and below, and the %Vol<100 μm ranged 13.4 to 19.2 % (Table 7.3). The same treatment performed with 2,4-D had VMD values 204 μm or below, and the percent of the spray volume with droplet sizes <100 µm were between 10.4 and 12.1. Overall, the herbicide choice accounted for 6.2% of the treatment variability (Table 7.1). The differences in DSD of the herbicide solutions is likely a result of higher surfactant concentration of glyphosate versus the 2,4-D formulation. The presence of a surfactant in pesticide formulations will decrease the dynamic surface tension when compared to pure water or other solutions containing less surfactant, resulting in modified spray sheet breakup and overall smaller DSD (Hilz and Vermeer 2013).

Adjuvant inclusion had little effect on the DSD of the treatments, particularly as airspeed increased. At 129 km h^{-1} airspeed, representative of rotary-wing applications, adjuvant inclusion had the greatest effect on DSD when using the CP 4015 nozzle (Tables 7.4 and 7.5). At airspeeds representative of fixed-wing applications, inclusion of a DRA had the greatest effect when combined with glyphosate. When included, the DRAs altered the percent of the spray volume <100 µm by approximately 2.5 to 6.0 percent for the glyphosate treatments. This compared to 0.8 to 1.5 %for the 2,4-D treatments. The DRAs behaved disparately across the treatments in this experiment. For example, DRA#3 had the highest VMD at 193 km h^{-1} when combined with CP 4015 nozzle and glyphosate, but had the third lowest VMD when applied with 2,4-D.

The spray classifications reported in Tables 7.2-7.5 are based on established guidelines (ASABE 2009b) using reference nozzle data generated at the PAT Lab. At 257 km h^{-1}, the DRAs had little to no effect on the spray classifications. At 193 km h^{-1}, DRA inclusion resulted in a larger spray classification in four occasions when in combination with glyphosate, however no differences in spray classification were observed with 2,4-D. At 129 km h^{-1}, spray classifications were overall larger when each herbicide was tested with a DRA, but this was only observed for the CP 4015 nozzle. The impact of DRAs on the DSD and spray classifications is important to consider because pesticide label requirements will often define upper or lower limits for DSD and/or spray classification.

Overall, the treatment main effects and interactions were significant ($p<0.05$) (Table 7.1). The dependent variables that explained the most variability in effect size were airspeed, nozzle type, and herbicide, appropriately (Table 7.1). DRA inclusion had little to no effect, and sometimes an undesirable effect, on the dependent variables VMD, Dv0.9, and %Vol<100 µm (Tables 7.2-7.5). Nevertheless, the DRAs increased Dv0.1 and decreased %Vol<100 µm comparatively to treatments without DRA. Adjuvants formulated for drift reduction are often characterized by their ability to alter the lower diameters of droplet distributions, while maintaining the middle to higher droplet diameters (Hilz and Vermeer 2013).

While differences between the drift potential from DRA inclusion in the tank-mixture within each nozzle type by airspeed by herbicide were observed in AGDISP (Table 7.6), the magnitude of differences appears to be unimportant. This is relevant when considering the multiple statistical differences observed in the DSD data. The discrepancy might be explained by the high repeatability of laser diffraction measurements, resulting in low treatment variability and thus ease of mean separation for the DSD data, and the empirical and mathematical framework upon which the AGDISP model was built. The droplet dispersion algorithms of models such as AGDISP do not fully account for near wake or far-field (generally >100 meters) droplet dispersion behaviors (Fritz et al. 2011). Therefore, the AGDISP model predicts less differences between treatments than would otherwise be inferred from DSD data. Based on the AGDISP results, the authors would not anticipate observing differences between treatments in a field experiment.

Conclusions

DRA inclusion had little effect on the DSD and AGDISP modelling for drift potential in this research. At airspeeds below an air shear effect (approximately 129 km h-1), the DRAs had the greatest magnitude of change on the DSD dependent variables, particularly on Dv0.1 and %< 100 µm (Tables 7.4 and 7.5). At airspeeds used by fixed-wing aircraft, the effect of DRA inclusion on the DSD and AGDISP results were minimal.

The results of this research demonstrated that the effectiveness of DRAs into an aerial pesticide application are ultimately dependent upon the operating conditions. Overall, airspeed had the greatest treatment effect. At airspeeds below the air shear effect, the DSD was mostly affected by nozzle type. At higher airspeeds, the DSD could be influenced towards lower drift potential by inclusion of a DRA, particularly when using a narrower angle, higher flow rate nozzle and lower airspeeds in fixed-wing aircraft.

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Table 7.1. ANOVA table of fixed effects and interactions for the dependent variable "<100 µm". Analysis of the Type III fixed effects in PROC GLM of SAS was used to determine significance at $p<0.05$.

Effect	df[a]	F Value	η^{2b}	Pr>F
Herbicide	1	2281.7	0.062	<.0001
Nozzle	1	9569.44	0.260	<.0001
Airspeed	2	10780.2	0.583	<.0001
Adjuvant	3	341.31	0.028	<.0001
Herbicide*Nozzle	1	14.63	0.000	0.0002
Herbicide*Airspeed	2	456.84	0.025	<.0001
Nozzle*Airspeed	2	273.27	0.015	<.0001
Herbicide*Adjuvant	3	136.84	0.011	<.0001
Adjuvant*Nozzle	3	57.46	0.005	<.0001
Adjuvant*Airspeed	6	19.94	0.003	<.0001
Herbicide*Nozzle*Airspeed	2	13.46	0.001	<.0001
Herbicide*Adjuvant*Nozzle	3	22.68	0.002	<.0001
Herbicide*Adjuvant*Airspeed	6	4.45	0.001	0.0005
Adjuvant*Nozzle*Airspeed	6	9.15	0.002	<.0001
Herbicide*Adjuvant*Nozzle*Airspeed	6	6.71	0.001	<.0001

[a]df- degrees of freedom

[b]η^2- total variation being accounted for by given effect

Table 7.2. Droplet Size Distribution (DSD) for the treatment consisting of the herbicide 2,4-D with two aerial nozzles, two airspeeds used by fixed-wing aircraft, and three drift reducing adjuvants. Data were subjected to a TUKEY means separation using PROC MIXED in SAS. Means within each column are not different if followed by the same letter (α=0.05). The two nozzle types and airspeeds were analyzed separately.

Nozzle[a]	Wind Speed	Adjuvant	Dv0.1[b]		VMD[c]		Dv0.9[d]		< 100 µm[e]		Spray Classification[f]
	km h⁻¹		µm		µm		µm		%		
CP 4015	193	DRA #1	231	B	455	C	659	C	1.0	B	Coarse
		DRA #2	252	A	508	A	866	A	0.8	B	Coarse
		DRA #3	222	C	470	B	707	B	1.4	AB	Coarse
		none	208	D	452	C	675	BC	1.8	A	Coarse
	257	DRA #1	132	AB	298	B	575	A	5.5	AB	Medium
		DRA #2	136	A	305	B	582	A	5.1	B	Medium
		DRA #3	129	B	298	B	525	B	5.9	A	Medium
		none	133	AB	316	A	599	A	5.6	AB	Medium
CP 8003	193	DRA #1	132	A	257	A	400	A	4.6	B	Medium
		DRA #2	132	A	257	A	404	A	4.6	B	Medium
		DRA #3	122	B	257	A	418	A	6.1	A	Medium
		none	125	B	260	A	421	A	5.7	A	Medium
	257	DRA #1	98	A	202	AB	326	A	10.4	C	Fine
		DRA #2	96	AB	194	B	305	A	11.0	B	Fine
		DRA #3	92	B	197	AB	320	A	12.1	A	Fine

	none	93	A B	204	A	337	A	11.7	A	Fine

[a]Transland, LLC, Wichita Falls, TX USA

[b]Dv0.1- The droplet diameter (µm) at which ten percent of the spray volume contains droplets at the given size and below

[c]VMD- Volume Median Diameter

[d]Dv0.0 The droplet diameter (µm) at which ninety percent of the spray volume contains droplets at the given size and below

[e]<100- The percent of the spray volume containing droplets 100 µm in diameter and below

[f]Spray classifications based on ASABE S572.1 guidelines

Table 7.3. Droplet Size Distribution (DSD) for the treatment consisting of the herbicide glyphosate with two aerial nozzles, two airspeeds used by fixed-wing aircraft, and three drift reducing adjuvants. Data were subjected to a TUKEY means separation using PROC MIXED in SAS. Means within each column are not different if followed by the same letter (α=0.05). The two nozzle types and airspeeds were analyzed separately.

Nozzle[a]	Wind Speed	Adjuvant	Dv0.1[b]		VMD[c]		Dv0.9[d]		< **100** µm[e]		Spray Classification[f]
	km h^{-1}		µm		µm		µm		**%**		
CP 4015	193	DRA #1	176	B	374	A	645	B	2.3	C	Medium
		DRA #2	184	A	379	A	682	A B	1.9	C	Coarse
		DRA #3	164	C	380	A	697	A	3.2	B	Medium
		none	133	D	334	B	588	C	5.5	A	Medium
	257	DRA #1	107	A	245	A	470	A B	8.6	B	Fine
		DRA #2	104	A	230	B	433	B	9.1	B	Fine
		DRA #3	105	A	245	A	462	A B	9.0	B	Fine
		none	98	B	240	A	482	A	10.4	A	Fine
CP 8003	193	DRA #1	122	A	234	A	377	A	5.6	C	Medium
		DRA #2	127	A	232	A	362	A	4.7	D	Medium
		DRA #3	109	B	229	A B	390	A	8.1	B	Medium
		none	103	B	223	B	376	A	9.2	A	Fine
	257	DRA #1	84	A B	169	A	274	A	14.9	C	Fine
		DRA #2	89	A	170	A	269	A	13.4	D	Fine

	DRA #3	79	B	170	A	281	A	16.6	B	Fine
	none	72	C	164	A	279	A	19.2	A	Fine

[a]Transland, LLC, Wichita Falls, TX USA

[b]Dv0.1- The droplet diameter (µm) at which ten percent of the spray volume contains droplets at the given size and below

[c]VMD- Volume Median Diameter

[d]Dv0.0 The droplet diameter (µm) at which ninety percent of the spray volume contains droplets at the given size and below

[e]<100- The percent of the spray volume containing droplets 100 µm in diameter and below

[f]Spray classifications based on ASABE S572.1 guidelines

Table 7.4. Droplet Size Distribution (DSD) for the treatment consisting of the herbicide 2,4-D with two aerial nozzles, one airspeed used by rotary-wing, and three drift reducing adjuvants. Data were subjected to a TUKEY means separation using PROC MIXED in SAS. Means within each column are not different if followed by the same letter (α=0.05). The two nozzle types were analyzed separately.

Nozzle[a]	Wind Speed	Adjuvant	Dv0.1[b]		VMD[c]		Dv0.9[d]		< **100** µm[e]		Spray Classification[f]
	km h^{-1}		µm		µm		µm		**%**		
CP 4015	129	DRA #1	391	B	678	B	910	C	0.0	A	Extremely Coarse
		DRA #2	415	A	732	A	1010	A	0.0	A	Ultra Coarse
		DRA #3	374	C	687	B	964	B	0.1	A	Ultra Coarse
		none	329	D	632	C	887	C	0.2	A	Extremely Coarse
CP 8003	129	DRA #1	141	A	280	A	444	A	3.9	AB	Medium
		DRA #2	146	A	281	A	438	A	3.3	B	Medium
		DRA #3	134	A	273	A	427	A	4.7	A	Medium
		none	144	A	281	A	438	A	3.5	AB	Medium

[a]Transland, LLC, Wichita Falls, TX USA

[b]Dv0.1- The droplet diameter (µm) at which ten percent of the spray volume contains droplets at the given size and below

[c]VMD- Volume Median Diameter

[d]Dv0.0 The droplet diameter (µm) at which ninety percent of the spray volume contains droplets at the given size and below

[e]<100- The percent of the spray volume containing droplets 100 µm in diameter and below

[f]Spray classifications based on ASABE S572.1 guidelines

Table 7.5. Droplet Size Distribution (DSD) for the treatment consisting of the herbicide glyphosate with two aerial nozzles, one airspeed used by rotary-wing aircraft, and three drift reducing adjuvants. Data were subjected to a TUKEY means separation using PROC MIXED in SAS. Means within each column are not different if followed by the same letter (α=0.05). The two nozzle types were analyzed separately.

Nozzle[a]	Wind Speed	Adjuvant	Dv0.1[b]		VMD[c]		Dv0.9[d]		< **100** µm[e]		Spray Classification[f]
	km h^{-1}		µm		µm		µm		**%**		
CP 4015	129	DRA #1	306	A	609	A	1018	A	0.2	B	Extremely Coarse
		DRA #2	277	B	558	B	861	B	0.4	AB	Extremely Coarse
		DRA #3	239	C	529	C	862	B	0.7	AB	Very Coarse
		none	206	D	490	D	776	C	1.6	A	Very Coarse
CP 8003	129	DRA #1	137	AB	274	A	438	A	4.2	B	Medium
		DRA #2	142	A	270	A	424	AB	3.4	B	Medium
		DRA #3	123	BC	249	B	396	B	5.6	A	Medium
		none	121	C	250	B	399	B	6.0	A	Medium

[a]Transland, LLC, Wichita Falls, TX USA

[b]Dv0.1- The droplet diameter (µm) at which ten percent of the spray volume contains droplets at the given size and below

[c]VMD- Volume Median Diameter

[d]Dv0.0 The droplet diameter (µm) at which ninety percent of the spray volume contains droplets at the given size and below

[e]<100- The percent of the spray volume containing droplets 100 µm in diameter and below

[f]Spray classifications based on ASABE S572.1 guidelines

Table 7.6. Results of AGDISP calculations for the fixed-wing treatments.

Nozzle[a]	Airspeed	Solution	Downwind Deposition[b]	Airborne Drift[c]
	km h^{-1}		%	%
CP 4015	193	2,4-D	0.5653	0.1584
		2,4-D + DRA #1	0.3833	0.0507
		2,4-D + DRA #2	0.3165	0.0405
		2,4-D + DRA #3	1.46	0.6022
		Glyphosate	0.7401	0.1305
		Glyphosate + DRA #1	0.7401	0.1305
		Glyphosate + DRA #2	0.6556	0.1024
		Glyphosate + DRA #3	0.9182	0.2663
	257	2,4-D	1.49	0.6753
		2,4-D + DRA #1	1.53	0.5814
		2,4-D + DRA #2	1.42	0.5228
		2,4-D + DRA #3	1.59	0.6678
		Glyphosate	2.63	1.44
		Glyphosate + DRA #1	2.3	0.9857
		Glyphosate + DRA #2	2.47	0.9625
		Glyphosate + DRA #3	2.33	1.09
CP 8003	193	2,4-D	1.72	0.4876
		2,4-D + DRA #1	1.51	0.3002
		2,4-D + DRA #2	1.49	0.2784
		2,4-D + DRA #3	1.8	0.5322
		Glyphosate	2.54	0.8456
		Glyphosate + DRA #1	1.83	0.346
		Glyphosate + DRA #2	1.66	0.2474
		Glyphosate + DRA #3	2.31	0.672
	257	2,4-D	3.08	1.46
		2,4-D + DRA #1	2.88	1.19
		2,4-D + DRA #2	3.07	1.25
		2,4-D + DRA #3	3.23	1.51
		Glyphosate	4.7	2.73

Glyphosate + DRA #1	3.98	1.74
Glyphosate + DRA #2	3.75	1.37
Glyphosate + DRA #3	4.25	2.2

[a]Transland, LLC, Wichita Falls, TX USA

[b,c]Percent of applied rate at 61 meters downwind

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