HERBICIDE APPLICATION TECHNOLOGY IMPACTS ON HERBICIDE SPRAY CHARACTERISTICS AND PERFORMANCE

by

Cody F. Creech

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Cody F. Creech, Ph.D.

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Adviser: Greg R. Kruger

Pesticide drift and the inherent risks associated with the application of pesticides in agriculture have been attracting the attention from the public sector as well as the scientific community. In an effort to reduce pesticide drift, efforts have been made to implement drift reduction technologies (DRTs). These technologies aim to mitigate off-target spray deposition through methods such as reducing the proportion of small droplets in sprays (e.g. improved nozzle or tank mix designs), shielding the spray from wind displacement (e.g. through the placement of hoods, shrouds, shields or cones over the nozzles), or improving the spray trajectory towards the target. However, spray drift is a complex research topic that includes environmental and equipment variables, and many application parameters that make it difficult to test all possible interactions. The full effect of DRTs on the biological efficacy of herbicides is not well understood and much of the research into DRTs is at relatively early stages, particularly for application systems common in the US.

The objectives of this research were: 1) evaluate and further expand a database of droplet size and spray spectra data using herbicides and adjuvants commonly used in ground applications in Nebraska, 2) conduct greenhouse and field studies to evaluate the impact of factors that influence droplet size on the biological efficacy of herbicides, and

3) evaluate the effect of DRTs as they relate to canopy penetration, retention, and how that correlates with weed control efficacy.

This research has refined and expanded the current understanding of how changes in herbicide spray droplet size spectra impact biological efficacy in the field. This research has also expanded the understanding of how application parameters such as nozzle type, spray pressure, and tank mixture interact and influence the efficacy of the herbicide being applied. The results will be disseminated to herbicide applicators through a variety of means to aid in the decision making process of what is a complex system.

For Natalie, Hunter, Brooklyn, and Gage.

My biggest supporters and motivation. I could not have done this without you.

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CHAPTER 1

Literature Review

Herbicides continue to play a critical role in weed control for many growers in the United States. Herbicide drift occurs with every herbicide application. Herbicide drift from agricultural applications is a source of environmental contamination which has potential human health impacts, and can cause damage to non-target plants, animals, and other natural resources. Herbicide use in the United States between 1996 and 2011 increased by an estimated 9% or 240 million kilograms (Benbrook 2012). Van den Berg et al. (1999) estimated that up to 50% of the herbicide applied could be lost into the environment when applications are made in poor conditions. Heightened risk of public health and other non-targets can be expected as a result of more intensive herbicide use. As herbicide use has increased, public awareness and concern about agricultural herbicide use has increased creating the need to regularly re-evaluate weed control and herbicide application practices (Wallace and Bellinder 1992).

Herbicide Technology in Crops

The introduction of herbicide-resistant crops was promoted as a way to simplify weed management and increase weed control efficacy (Martinez-Ghersa et al. 2003). This includes development of dicamba-resistant, 2,4-D-resistant, and 4-Hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor-resistant soybeans that are being developed by U.S. companies and will soon be available to growers pending regulatory approval. Once approved, the dicamba-, 2,4-D-, and HPPD-resistant technology will enable the use of dicamba, 2,4-D, or HPPD-inhibitors with glyphosate tank-mixtures for preplant burndown, at planting, and in-season applications (Davis 2012). Growers have readily adopted herbicide-resistant crops; thereby increasing the choices of herbicides, number of hectares, and timings applications could be made for a number of given crops. For example, the adoption of glyphosate-resistant soybeans [*Glycine max* (Merr.) L.] increased from 17% of US soybean hectares in 1997 to 68% in 2001 and 93% in 2010 (Fernandez-Cornejo et al. 2014). The adoption of this technology may have also facilitated changes in crop production practices such as increased use of no-till and strip-till (Young 2009). Such changes in crop production systems and use of specific chemicals within a crop for weed control could increase grower dependence upon chemical weed control (Radosevich et al. 1992). The integration of herbicide-resistant crops has resulted in increased usage of nonselective herbicides allowing growers more herbicide options later in the growing season, thereby increasing the chance that off-target movement of herbicides could damage non-tolerant crops and other sensitive vegetation.

Droplet Generation

The process of generating droplets is called atomization. The droplet is the transport vehicle of the active ingredient from the moment it forms until it reaches the target site. Spray application is a composite process involving a series of stages beginning at the nozzle with droplet formation, travel to the plant surface, droplet impaction and retention on the leaf surface, deposit formation, plant uptake, and biological response (Brazee et al. 1991; Ebert and Downer 2008; Merritt et al. 1989; Reichard 1988). Droplets can be formed through pressure, centrifugal forces, air shear, vibration, or electrostatic charges as described in (PISC 2002). This work will focus on droplets generated through pressure by forcing the spray liquid through a small orifice of a nozzle tip as such is the most common type of droplet formation in agricultural herbicide applications in the United States. These nozzles are known as hydraulic and are available in a number of different types such as flat fan, cone, or deflector. When the liquid emerges under pressure from the orifice of a flat fan nozzle, it does so as sheets which atomize from wavy rim disintegration or ligament breakup to form droplets.

The spray droplet size spectra of agricultural nozzles are important because they can affect spray deposition and drift (Taylor et al. 2004). Agricultural nozzles generally produce droplets ranging in diameter from a few to greater than 1,000 μm (Bouse et al. 1990). Droplet size has been identified as one of the most important factors influencing drift potential of herbicide applications (Whisenant et al. 1993; Yates et al. 1976). Etheridge et al. (1999) described droplets less than 200 μm as being most susceptible to drift while Yates et al. (1985) characterized driftable droplets as those being less than 150 μm in diameter. The diameter of a spray droplet is significant as a 100 μm diameter water droplet can travel 7.5 times further off-target (to the point of deposition) than a 500 μm droplet in 5 km h^{-1} wind speed (Bode 1987). Droplets generated by an agricultural nozzle, regardless of size, can move off-target provided other application factors, namely wind speed, speed of travel, and boom height, afford the opportunity. Spray droplet size is also recognized as a determining factor for herbicide efficacy (Knoche 1994). When a droplet impacts a plant surface, it will either be retained through adhesion, bounce, shatter, or roll off. Droplets that are not retained can continue through the canopy and may be retained on a lower leaf or may impact the ground (Schou et al. 2012).

Definition of Herbicide Drift

Herbicide drift can be classified by one of two mechanisms in which herbicides move downwind, namely particle drift and vapor drift. Vapor drift occurs when herbicide molecules within a treatment zone evaporate into the air from a sprayed surface where the spray droplets had previously settled and move downwind outside the treatment zone as vapor. It only occurs for a few semi volatile active ingredients and when environmental conditions are conducive to volatilization. This kind of drift can occur more than 12 hours after application and is more likely to occur when temperatures are high (Matthews 2008). Vapor drift is mainly related to the herbicide's chemical properties, the air temperature and/or formulation and less to the type of application and equipment used.

The second type of drift, particle drift, has been defined by the Environmental Protection Agency (EPA) as the physical movement of a herbicide containing particle through the air at the time of application or soon thereafter to any site other than that intended for application (EPA 1999). This work will focus mainly on particle drift; therefore, any future references to drift will reference particle drift as described by the definition of the EPA above. Herbicide drift occurs when fine droplets produced by nozzles of spray equipment stay suspended in the air and are then transported by air currents until they deposit on the ground or contact an off-target surface. Numerous factors can combine to influence the magnitude of drift including atmospheric conditions, application equipment design and application parameters, and spray physical properties and formulation (Salyani and Cromwell 1992). These factors, coupled with the variability of field trials, have made testing the full range of application drift possibilities impossible.

Mechanisms of Drift

The mechanisms by which spray droplets become detrained from moving toward the target site are complex. When applications are made using a conventional ground application sprayer, nozzles are directed downward to the target site from a height of 45 to 60 cm above the target. Many applications are even higher with high speed high clearance sprayers making applications with heights up to 1.25 m. The spray leaves the nozzle at an initial velocity normally in the range of 15-25 m s^{-1} before breaking up into droplets (Dombrowski and Johns 1963). Jörgensen (2003) described a vortex that develops as the downward spray and forward movement of the nozzles creates an air current that moves downward following the spray which creates a depression around the nozzle that is filled by air coming from up the front and back of the nozzle. This vortex caused by the nozzles is able to divert spray particles from their intended trajectory depending on their momentum. Droplets located at the edges of the spray are more likely to be affected by the vortex and displaced downwind (Young 1990). Droplets that are small enough to be influenced by the vortex or prevailing wind may move off target until they either settle or completely evaporate.

Consequences of Spray Drift

Spray drift may result in undesirable chemicals being deposited in areas that ultimately result in serious consequences. The amount of drift which can be tolerated is dependent upon many factors namely the quantity of the active ingredient that drifts, where it gets deposited, and what is located within that area. Spray drift can damage sensitive plants as well as adjoining crops (de Snoo and de Wit 1998; Nordby and

Skuterud 1974). Environmental contamination may occur to open sources of water if a substantial amount of herbicide drift accumulates in such an area. Also of high concern is the health risks for humans and animals associated with herbicide exposure either directly or indirectly. Herbicide drift is also a cause for increased regulation by governing bodies (Hewitt 2000). Off-target herbicide movement not only impacts the surrounding environment, but may also reduce weed control in the target area (Johnson et al. 2006). The unintended drift within and out of a treatment area may result in an uneven spray distribution or a lower dose than required to effectively control certain target plants. An applicator could also over-apply a herbicide in an attempt to compensate for expected losses or a similar result could occur at a labeled dose rate from drift settling in an area within the treated area which could result in crop damage or other environmental impacts. Thus, spray performance is both environmentally and economically important.

Drift Reduction Technologies (DRTs)

In an attempt to reduce herbicide drift, efforts have been made to implement drift reduction technologies (DRTs). These technologies aim to mitigate off-target spray deposition through methods such as reducing the proportion of small droplets in sprays through the use of innovative nozzle designs and formulations, hoods or shields to protect the spray from wind displacement, and boom height controllers to release the spray close to the target (Lund et al. 2000; Nordby and Skuterud 1974; Wolf et al. 1993; Yates et al. 1976). Air induction nozzles are effective at reducing herbicide drift by limiting the number of fine droplets, over a wide range of spray pressures, that could potentially move off-target (Etheridge et al. 1999). These nozzles vary in design but usually consist of a pre-orifice, one or two air-induction ports, a mixing chamber, and an exit orifice that is larger than the pre-orifice. The air-induction ports permit air to enter the chamber and reduce the pressure of the liquid. The pre-orifice insert determines the flow rate of the liquid prior to exiting the larger exit orifice thus reducing spray velocity producing larger droplets.

Another method used to reduce off-target herbicide movement is the use of drift control adjuvants. These adjuvants are often classified as spray modifiers in that they may increase the viscosity of the spray to reduce the number of small droplets (Monaco et al. 2002). Other drift control adjuvants function more as an invert suspension or emulsifier to improve the sheet breakup mechanism which reduces fines. For this reason, many applicators will include a drift control adjuvant in the herbicide tank-mixture to attempt to reduce off-target movements near sensitive areas (VanGessel and Johnson 2005). Spray drift control adjuvants are not believed to directly affect herbicide efficacy, but rather make the herbicide application process more efficient by reducing losses through drift (McMullan 2009).

DRT Impact on Herbicide Efficacy

While increasing the spray droplet size of a herbicide application may be effective at mitigating off-target movement (Bode 1987), increasing the spray droplet size of an application can impact herbicide efficacy (Knoche 1994). It is generally assumed that contact herbicides may be more adversely affected than systemic herbicides to increasing spray droplet size. Knoche (1994) observed an increase in contact herbicide efficacy in 58% of the studies he reviewed. Conversely, glyphosate, a systemic herbicide, has increased adsorption and translocation when applied using larger droplets (Feng et al. 2003; Liu et al. 1996). Small droplets provide greater coverage (Ramsdale and Messersmith 2001) than large droplets on plant surfaces which is especially important for contact-type herbicides (Hislop 1987; McKinlay et al. 1972; Merritt and Taylor 1977; Prokop and Veverka 2003). More recent research has found no change or increased efficacy of systemic herbicides as droplet size increased (Etheridge et al. 2001; Feng et al. 2003).

Objectives

Applicators are tasked with selecting appropriate spraying equipment components and parameters for a specific application from a seemingly endless array of choices. Droplet size is dependent upon the interaction of nozzle type and size, properties of the spray liquid, and the pressure at which the liquid leaves the nozzle orifice (Klein and Johnson 2002). Furthermore, pesticide and surfactant concentration, as they relate to carrier volume, have been shown to modify droplet size (Bouse et al. 1990; Hall et al. 1993). The objectives of this research were: 1) evaluate and further expand a database of droplet size and spray spectra data using herbicides and adjuvants commonly used in ground applications in Nebraska, 2) conduct greenhouse and field studies to evaluate the impact of droplet size on the biological efficacy of herbicides, and 3) evaluate the effect of DRTs as they relate to canopy penetration, retention, and thereby weed control efficacy.

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CHAPTER 2

Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics

Abstract

Recent concerns regarding herbicide spray drift and its subsequent impact on the surrounding environment and herbicide efficacy have prompted applicators to focus on methods to reduce the off-target movement of herbicides. Herbicide applications are complex processes and as such, few studies have been conducted that consider multiple variables that impact the droplet size spectra of herbicide sprays. The objective of this study was to elucidate the effects of nozzle type, orifice size, herbicide active ingredient, pressure, and carrier volume on the droplet spectra of herbicide sprays. Droplet size spectrum data were collected on 720 combinations of spray application variables which included six spray tank mixes (five herbicide mixtures and water alone), four carrier volume rates, five nozzle types, two orifice sizes per nozzle type, and three operating pressures. The laboratory study was conducted using a Sympatec laser diffraction instrument to determine the droplet size spectrum for each treatment combination. When averaged over each main effect, nozzle type had the greatest impact on droplet size. Droplet size rankings for nozzles, ranked smallest to largest using the $D_{v0.5}$ values, were the XR, TT, AIXR, AI, and TTI nozzle with 176% change in $D_{v0.5}$ values from the XR to the TTI nozzle. On average, increasing the nozzle orifice size from a 11003 orifice to a 11005 caused an increase of 8% in the $D_{v0.5}$ value. When compared to the water treatment, cloransulam (FirstRate®) did not change the $D_{v0.5}$ value. Clethodim (Select Max®), glyphosate (Roundup PowerMax®), lactofen (Cobra®), and glufosinate (Ignite®)

caused a reduction in the mean $D_{v0.5}$ value for water of 5, 11, 11, and 18%, respectively. Increasing the pressure of AIXR, TT, TTI, and XR nozzles from 138 to 276 kPa and the AI nozzle from 276 to 414 kPa caused a decrease in the $D_{v0.5}$ value of ~25%. Increasing the pressure from 276 to 414 kPa and from 414 to 552 kPa for the same nozzle group and AI nozzle caused a decrease in the $D_{v0.5}$ value of ~14%. Carrier volume rate had the least effect on the $D_{v0.5}$ value. Increasing the application volume rate from 47 to 187 L ha^{-1} caused an increase in the $D_{v0.5}$ value of only 5%, suggesting that the droplet sizes of the herbicides tested in this study were not highly dependent on the delivery application volume rate. The impact on droplet size of the variables examined in this study in order of highest to lowest impact were nozzle, operating pressure, herbicide, nozzle orifice size, and application volume rate.

Introduction

Herbicides continue to play a critical role in weed control for many growers in the United States. Pesticide use in the United States between 1996 and 2011 has increased by an estimated 7% or 404 million pounds (Benbrook 2012). In 2011, nearly 6 billion pounds of pesticides were applied in the United States. Van den Berg et al. (1999) estimated that up to 50% of applied pesticides could be lost due to volatilization and drift. The integration of herbicide-resistant crops has resulted in increased usage of nonselective herbicides allowing growers more herbicide options later in the growing season, thereby increasing the chance that off-target movement of herbicides could damage non-tolerant crops and other sensitive vegetation. Off-target herbicide movement not only impacts the surrounding environment, but may also reduce weed control in the target area (Johnson et al. 2006). Thus, spray performance is both environmentally and economically important. As pesticide use has increased, public awareness and concern of the risks associated with off-target movement of pesticides to public health and the environment has creating the need to re-evaluate weed control and pesticide application practices (Pimentel 2005).

The spray droplet spectra of agricultural nozzles is important because it affects spray deposition and drift (Taylor et al. 2004). Droplet size has been identified as one of the most important factors influencing drift potential of herbicide applications (Whisenant et al. 1993; Yates et al. 1976). Apart from not spraying on windy days and maintaining the spray boom as close to the ground as possible without jeopardizing the spray pattern, the quality of spray generated by agricultural nozzles is the primary variable applicators can manipulate to reduce potential drift. Agricultural nozzles generally produce droplets ranging in diameter from 10 to greater than 1,000 µm (Bouse et al. 1990). Etheridge et al. (1999) described droplets less than 200 µm as being most susceptible to drift while Yates et al. (1985) characterized driftable droplets as those being less than 150 µm in diameter. The diameter of a spray droplet is significant as a 100 µm diameter droplet can travel 7.5 times further off-target than a 500 µm droplet in 5 km h^{-1} wind speed (Bode 1987). Droplets generated by an agricultural nozzle, regardless of size, can move off-target provided other application factors, namely wind speed, speed of travel, and boom height, afford the opportunity.

Spray droplet spectra may also impact the biological efficacy of the herbicide applied. A meta-analysis conducted by Knoche (1994) revealed an increase in herbicide performance in 71% of the experiments reviewed when droplet size decreased.

Decreasing droplet size had no effect on performance in 20% of the experiments, while in 9% of the cases reviewed herbicide efficacy decreased. Large droplets are poorly retained on the leaf surface and have minimal coverage while small droplets are prone to drift and evaporation (Spillman 1984). In theory, herbicide applications made with a narrow spray droplet distribution should be more efficient if the average or median droplet size being sprayed is the most efficacious droplet diameter known for the herbicide being applied (Hartley and Graham-Bryce 1980). Numerous studies have evaluated droplet size as it relates to drift and efficacy; however, results often show no consistent trend and in some instances, have been contradictory (Knoche 1994). This is not surprising due in large part to the complex nature of the spray application process. Spray application is a composite process involving a series of stages beginning at the nozzle with droplet formation, travel to the plant surface, droplet impaction and retention on the leaf surface, deposit formation, plant uptake, and biological response (Brazee et al. 1991; Ebert and Downer 2008; Merritt et al. 1989; Reichard 1988). A change that occurs at any one stage interacts with the other application factors and, as many stages are interrelated, subsequent stages and spray performance may be affected.

Applicators are tasked with selecting appropriate spray application equipment and parameters for a specific application from a seemingly endless array of choices. Droplet size is dependent upon the interaction of nozzle type and size, properties of the spray liquid, and the pressure at which the liquid leaves the nozzle orifice (Klein and Johnson 2002). Furthermore, pesticide and adjuvant concentration, as they relate to carrier volume, have been shown to modify droplet size (Bouse et al. 1990; Hall et al. 1993). Spray nozzle classification in ASABE standards is determined by spraying water or water with a surfactant through reference nozzles (ASABE 2009); however, other spray properties that may affect droplet size should be considered by the end user. Previous research on spray droplet spectra of agricultural nozzles is limited and often focused on a small number of application parameters and interactions that could impact the droplet size spectrum (Bouse et al. 1990; Czaczyk et al. 2012; Miller and Butler Ellis 2000; Nuyttens et al. 2007a; Nuyttens et al. 2009; Van De Zande et al. 2002). Researchers and applicators do not have access to sufficiently comprehensive data or models to select appropriate nozzles, pressures and application volume rates to achieve an optimum droplet size spectrum. Therefore, the objective of this study was to elucidate the effects of nozzle type, orifice size, herbicide active ingredient, pressure, and application volume rate on the droplet size spectrum of the spray.

Materials and Methods

This experiment was conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center of the University of Nebraska-Lincoln in North Platte, Nebraska during 2011 and 2012 using a static spray chamber (Figure 1). The chamber is approximately 0.9 m wide, 1.8 m long, and 1.4 m tall. It consists of a stainless steel basin to collect the spray solution, clear polycarbonate sides with an access door to perform maintenance and change nozzles, holes for the laser and traverse, and a stainless steel exhaust hood which uses a low speed fan to vent spray vapors.

The methods of this study were consistent with the Spray Nozzle Classification by Droplet Spectra Standard which defines the means for relative nozzle comparison based on droplet size and the classification of spray nozzles (ASABE 2009). The droplet size spectrum for each treatment was determined using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany). The laser is controlled by WINDOX 5.7.0.0 software (Sympatec Inc., Clausthal, Germany) which was operated on a computer adjacent to the chamber. This laser/lens combination was capable of detecting droplets in the size range of 0.5 to 3,700 µm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser (smaller of the laser housings in Figure 1) and a receiver housing containing the lens and detector element. The two laser housings were separated 1.2 m apart on either side of the static chamber and mounted on an aluminum optical bench rail outside of the chamber but connected through the inside of the chamber to ensure proper laser alignment. The optical bench rail had a plastic Astroturf door mat (GrassWorx, St. Louis, MO) placed over the top of the bench rail that passed through the inside the chamber to absorb and deflect spray droplets to prevent rebounding and re-measurement of spray droplets with the laser. The spray plume was oriented perpendicular to the laser beam and traversed through the laser beam by means of a mechanical linear actuator. The actuator moves the nozzle at a constant speed of 0.2 m/s such that the entire spray plume would pass through the laser beam. The nozzle orifice was offset by 30 cm from the laser beam and the laser beam was 38 cm above the bottom on the basin.

Commercial formulations of five commonly used soybean herbicides (Table 2.1) were mixed separately with tap water as a carrier in 11 L stainless steel containers and applied at application volume rates of 47, 94, 140, and 187 L ha^{-1}. Additionally, adjuvants typically used with these herbicides were added in an effort to use treatments which would be representative of those commonly be used by commercial applicators in Nebraska ground applications (Table 2.1). Nozzles used included the Teejet Air Induction Flat Spray Tip (AI), Teejet Air Induction Extended Range Flat Spray Tip (AIXR), Turbo Teejet Wide Angle Flat Spray Tip (TT), Turbo Teejet Induction Flat Spray Tip (TTI), and Teejet Extended Range Flat Spray Tip (XR) (Spraying Systems Co. Wheaton, IL). Each nozzle was evaluated at both the 03 and 05 orifice sizes and only 110˚ angle rated nozzles were used in this study. Nozzle evaluations were conducted at 138, 276, and 414 kPa for the AIXR, TT, TTI, and XR nozzle. The AI nozzle is not recommended for use at pressures below 207 kPa, and therefore it was only tested at pressures of 276, 414, and 552 kPa. In addition to the five herbicides used in this study, water alone was sprayed and the droplet size spectra were measured with all the nozzle, orifice size, and pressure combinations.

Measurements of the various spray solutions were performed within one hour after mixing. Previous research has investigated the relationship between ambient air temperature and liquid atomization (Miller and Tuck 2006; Spillman 1984), and concluded a relationship exists, therefore, air temperature at the time of testing was recorded. Testing was conducted in an insulated, environmentally controlled room with an air temperature of approximately 20°C with relative humidity of 65 ± 5%. Before any measurements were taken, the alignment of the laser diffraction system was checked and adjusted as needed to assure correct alignment. After the appropriate nozzle was affixed on the carriage of the mechanical traverse and the spray solution canister was attached and pressurized, the procedure was as follows: 1) focusing of the laser on the diode array (automated by the Sympatec instrument), 2) manual purging of the lines of air and water while verifying the spray pressure at the nozzle through a pressure gauge connected to the nozzle tip by a capillary, 3) manual initiation of data collection (turn laser on), 4) automated traversing of the spray pattern across the laser beam (data collection automatically stops when the laser exits the spray pattern according to user-defined setup of the spray "trigger" condition based on a lower obscuration value of 0.5) 5) manual stopping of the spray, 6) automated computer calculation of the droplet size spectrum through inversion of the associated diode light diffraction matrix, and automated recording of the data, and 7) manual inspection of the data for validity. A valid reading was assessed as one where there was a full droplet size/ volume distribution without truncation or unusual additional peaks in the data which would trigger the decision to repeat steps 1-7 until the data were acceptable.

Statistical Analysis. Volumetric droplet size spectra data were analyzed using ANOVA with Proc Mixed procedure (method = REML) (Littell et al. 2006) in SAS version 9.3 (SAS Institute Inc., Cary, NC) as a 6 x 4 x 5 x 2 x 3 factorial arrangement of treatments. The model included the fixed effects of herbicide, application volume rate, nozzle type, nozzle orifice size, and spray pressure with all possible interactions as dependent variables. Replication was considered a random effect. Mean treatment effects were compared using Tukey's studentized range test (HSD) and an alpha value of $P < 0.05$ was considered significant. Given the large number of comparisons, Tukey's HSD was used to reduce the chance of type I errors (Steel and Torrie 1980). A single traverse of the spray pattern through the laser beam was used as the experimental unit.

Results and Discussion

The interaction of nozzle, orifice size, spray mixture, pressure, and carrier volume were significant ($P < 0.0001$, ANOVA not shown) for each measurement parameter. All lesser interactions and main effects were also significant ($P < 0.0001$). Due to the large number of treatment combinations (720), only a few discrete simple effects will be discussed. The main effects of each level of nozzle, orifice size, herbicide, pressure, and carrier volume is also presented to simplify and facilitate the discussion of the results. A similar approach was used by Etheridge et al. (1999) who had a four-way interaction and 180 treatment combinations when investigating the spray droplet size spectra and patterns of four venturi-type nozzles.

The $D_{v0.5}$ represents the droplet size diameter of equal of lesser value comprising 50% of the total spray volume. Similarly, the $D_{v0.1}$ and $D_{v0.9}$ values are the droplet size diameters of equal or lesser value comprising 10 and 90%, respectively, of the total spray volume. The relative span (RS) is a dimensionless value indicative of the uniformity of the spray droplet size spectrum and is defined as:

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

A RS value that approaches one would be preferred if a droplet diameter is known to maximize herbicidal biological efficacy as it demonstrates balance, uniformity, and a narrow spray droplet spectrum. In addition, the percentages of spray volume contained in droplets less than 105, 150, and 210 µm and greater than 730 µm was reported ($V<105$, $V<150$, $V<210$, and $V>730$, respectively). These fixed values ($V<105$, $V<150$, $V<210$, and $V>730$) allow for comparison of spray droplet distributions across different treatment variables, with an emphasis on spray volume contained in small droplets.

The static spray chamber (Figure 2.1) was used to compare the relative differences in spray droplet spectrum among treatments evaluated in this study. While droplet size numbers are presented, they are not absolute and are used as relative values to compare treatments. Fritz et al. (2014) concluded that using an appropriate measurement distance and sufficient air stream velocity in a wind tunnel could reduce spatial bias to within a variance of normal spray measurement. Over-estimation of fine droplets is possible using a static spray chamber caused by small droplets being suspended in the air and re-sampled; however, reference nozzles and curves were used and curves were created (Figure 2.2) to define spectrum quality as described by ASABE (2009). These reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Nozzle Type Effects. When averaged over the other application variables (orifice size, herbicide, pressure, and carrier volume), the AI, AIXR, and TTI nozzles, which were developed and designed to produce relatively coarse sprays had the largest $D_{v0.1}$, $D_{v0.5}$. and $D_{v0.9}$ values (Table 2.2). The XR nozzle is considered a standard flat fan and neither the XR nor TT nozzles have air induction components because they were originally designed to produce Fine and Medium spray qualities. Both air induction and pre-orifice technologies are used with the AI, AIXR and TTI nozzles, in order to produce coarser sprays. Pre-orifice technologies function by positioning a small orifice at the top of the nozzle. As the liquid passes through this first (or “pre”) orifice, there is a pressure reduction prior to the liquid reaching the second and final orifice through which it exits and forms a sheet of liquid and subsequent spray. The pressure reduction prior to the liquid exiting the final nozzle orifice increases the diameter of the spray droplets as the spray breakup length increases. Air induction technologies build upon the pre-orifice concept by having one or two air inlets that introduce air into the nozzle body after the pre-orifice. The air mixes with the spray liquid to further decrease the pressure of the spray solution, thus increasing the mean droplet size as the liquid exits the nozzle orifice. Previous research has suggested that in addition to the pressure reduction afforded by air induction nozzles, the air mixes with the liquid within the nozzle and air is encapsulated within the droplets as it exits the nozzle orifice thereby increasing droplet size The amount of air depends on the nozzle design and tank mix physical properties such as dynamic surface tension (Dorr et al. 2013).

Nozzles ranked by $D_{v0.5}$ from smallest to largest were the XR, TT, AIXR, AI, and TTI (Table 2.2). The $D_{v0.5}$ value was 157% larger when comparing the XR to the TTI nozzle. This represents moving from a Medium spray droplet classification to an Extremely Coarse spray classification as determined using reference curves generated at the PAT Lab (Figure 2.2) per ASAE S572.1 (ASABE 2009). These results are also confirmed by the V<105 value which is representative of the spray volume percentage which is likely to move off-target under unfavorable conditions. The V<105 value decreased as the $D_{v0.5}$ increased (Table 2.2). The XR and TT nozzle had much higher values V<105 values (17 and 10%, respectively) compared to the other nozzles (Table 2.2). This was also the case for the V<150 and V<210 values. The TTI nozzle, which had the greatest $D_{v0.5}$ value, had 28% of its spray volume above 730 µm while all other nozzles had V>730 values less than 8% (Table 2.2). Etheridge et al. (1999) evaluated the XR and AI nozzles in addition to the Delavan Raindrop Ultra (RU) (Delevan Spray Technologies, Monroe, NC), Greenleaf TurboDrop (TD) (Greenleaf Technologies, Covington, LA) and Lurmark Ultra Lo-Drift (LM) (Lurmark LTD, Cambridge, UK) nozzles using glufosinate, glyphosate, and paraquat formulations. The RU, TD, and LM nozzles are considered venturi-type nozzles in that they use air-induction technology to increase droplet diameter. Similar to our results, the XR nozzle had the smallest $D_{v0.5}$ value (173 µm) and the venturi-type nozzles had the largest values.

The AI and AIXR nozzles performed similarly with the AIXR having a slightly smaller droplet diameter ($D_{v0.5}$ values of 442 and 426, respectively) (Table 2.2). Other parameters, including RS, were similar (Table 2.2). Although the RS was 1.16 and 1.14 for the AI and AIXR nozzles, respectively, greater variation was observed when the intersecting points of $D_{v0.5}$ and V<105 values were plotted (R^2 = 0.68 for AI 11003 and R^2 = 0.85 for AIXR 11003) (Figure 2.3). The low R^2 value for droplets from the AI nozzle indicates it responds more uniformly to changes in spray solution and is more variable particularly for lactofen and glufosinate (data not shown). The AIXR nozzle is often preferred by applicators over the AI nozzle due to its compact size (less prone to breaking) and similar droplet size performance to the AI. This research demonstrates another benefit of the AIXR nozzle in that it responds more consistently to changes in spray mixtures and other application parameters. The greatest R^2 values for droplet size when averaged over both orifice sizes were obtained from the TT and XR (R^2 values = 0.91 and 0.97, respectively) nozzles that have no air technology (Figure2.3). However, both TT and XR nozzles have RS values of 1.48 and 1.39, respectively, indicating a relative lack of uniformity within the spray droplet size spectrum.

Nozzle Orifice Size Effects. Droplet diameters for each of the $D_{v0.1}$, $D_{v0.5}$. and $D_{v0.9}$ values increased 8% as the orifice size increased from a 03 to a 05 orifice (Table 2.2).

Similarly, the percentage of droplets less than V<105, V<150, and V<210 decreased 31, 30, and 26 %, respectively (Table 2.2). Similar results were observed by Etheridge et al. (1999) and Womac et al. (1997) who found that decreasing orifice size increased the V<205 value within the same nozzle (note that V<205 is not the same parameter used in this study). Furthermore, Figure 2.3 illustrates higher correlation between the $D_{v0.5}$ and V<105 values for nozzles that use air induction and/or pre-orifice technologies which include the AI, AIXR, and TTI, when increasing the orifice size. The R^2 values obtained using the TT and XR nozzles actually decreased slightly (0.92 to 0.91 and 0.98 to 0.96, respectively) when increasing from a 03 to a 05 orifice. It should be noted that in many instances, the TTI nozzle performed erratically compared to the other nozzles. In many cases, increasing the orifice size actually decreased droplet diameter produced by the TTI nozzle (data not shown). Etheridge et al. (1999) observed similar irregularities when characterizing the spray spectrums of other venturi nozzles. In their study, the RU and TD nozzles increased the V<205 as the orifice size increased from 015, 03, and 04 . Etheridge et al. (1999) hypothesized that these unexpected results are likely due to liquid flow turbulence within the nozzle. Although the TTI nozzle may produce a reduced droplet diameter as the orifice size increases, it still produces the largest spray droplet diameters of any of the nozzles tested (Table 2.2). In general, reduction of droplets that are most prone to drift can be achieved by increasing the nozzle orifice size. In addition to reducing the spray volume of a given nozzle contained in droplets with a diameter less than 210 μm, the RS value decreased from 1.26 to 1.24 for 03 and 05 orifice sizes, respectively, which indicates a slightly narrower spray spectrum (Table 2.2).

Herbicide Effects. On average, the addition of herbicides to a water carrier decreased the $D_{v0.1}$ values by 3%, $D_{v0.5}$ values 9%, and $D_{v0.9}$ values 11% (Table 2.2). The $D_{v0.5}$ values for herbicides tested ranked largest to smallest averaged over other experimental variables were water, cloransulam, clethodim, glyphosate, lactofen, and glufosinate (Table 2.2). The addition of glufosinate reduced the $D_{v0.5}$ value 18% from 425 µm to 359 µm when compared to water alone. As a result, glufosinate had the highest percentage of spray volume less than V105, V150, and V210 (10.5, 19.0, and 29.9%, respectively) (Table 2.2). These results are similar to Etheridge et al. (1999) who found the $D_{v0.5}$ value of glufosinate to be 399 µm, which was the lowest for the three herbicides they tested and it represented a 15% decrease in the $D_{v0.5}$ value from glyphosate. Lactofen and glyphosate had $D_{v0.5}$ values 11% lower than water, clethodim was 5% lower, and cloransulam had no change. Although cloransulam had a similar $D_{v0.5}$ compared to water (424 and 425 µm, respectively), the $D_{v0.1}$ and $D_{v0.9}$ values were very different (Table 2.2). Cloransulam had $D_{v0.1}$ and $D_{v0.9}$ values of 199 and 621 µm which were much narrower than the $D_{v0.1}$ and $D_{v0.9}$ values of water (173 and 690 µm, respectively) (Table 2.2). This is also evident when comparing the RS values of water and cloransulam (1.30 and 1.03 µm, respectively) (Table 2.2). The droplet spectrum of cloransulam, although having almost identical $D_{v0.5}$ values to water alone, was more closely centered around the $D_{v0.5}$ value with a RS of 1.03 having both fewer Fine and Coarse droplets (Table 2.2). Although RS values ranged from 1.03 to 1.47 (Table 2.2), all herbicides had similar R^2 values ranging from 0.96 to 0.98 (Figure 2.4). In contrast to cloransulam, glufosinate produced the highest RS value of 1.47 while also having one of the highest R^2 values of 0.97 (Table 2.2, Figure 2.4). Although clethodim produced a lower $D_{v0.5}$ value than water, its $D_{v0.1}$ value was 5% higher than water and its $D_{v0.9}$ was 10% lower (Table 2.2). As such, clethodim had a more uniform droplet size spectrum having an RS of 1.15 which was much lower than water 1.30 (Table 2.2). These results indicate that the addition of herbicides to a spray mixture can alter the spray droplet spectrum, and in some cases, may cause a change in droplet size classification. As such, herbicide applicators should be aware that droplet size classifications based on water alone should be used as a guide because these classifications are likely not completely accurate when applying herbicides.

Pressure Effects. As expected, the droplet diameter of every combination of nozzle, orifice size, herbicide, and carrier volume decreased as the pressure increased (Table 2.2). The $D_{v0.5}$ value decreased 25% when increasing the pressure of AIXR, TT, TTI, and XR nozzles from 138 to 276 kPa and the AI nozzle from 276 to 414 kPa (475 µm to 380 µm) (Table2). The $D_{v0.5}$ value decreased 14% when increasing pressure from 276 to 414 and from 414 to 552 kPa for the same nozzle group and AI nozzle (380 µm to 332 µm) (Table 2.2). Increasing pressure from 138 to 414 kPa for AIXR, TT, TTI, and XR nozzles and from 276 to 552 kPa for the AI nozzle nearly triples the percentage of fine droplets (V<210 values = 15.0 and 30.6%, respectively) (Table 2.2). In addition, the RS value increased from 1.13 to 1.35 when pressure increased from 138 to 414 kPa for AIXR, TT, TTI, and XR nozzles and from 276 to 552 kPa for the AI nozzle (Table 2.2). As pressure increased, R^2 values increased from 0.90 to 0.96 (Figure 2.5). Decreasing droplet diameter as a result of increasing pressure has been observed and well documented in many previous studies (Czaczyk et al. 2012; Etheridge et al. 1999; Nordby and Skuterud 1974; Nuyttens et al. 2007a). As such, avoiding high pressures is vital to reducing the driftable fines. However, applying herbicides at low pressures may produce unsatisfactory spray patterns that have uneven distribution across the width of the spray pattern (Etheridge et al. 1999). Thus, avoiding the extreme maximum or minimum nozzle pressure specifications is advised.

Carrier Volume Effects. In nearly every case, droplet diameter increased as the spray mixture became more diluted as carrier volume increased. When averaged across other experimental variables, increasing the carrier volume from 47 to 187 L ha^{-1} increased the $D_{v0.5}$ value 5% from 383 to 404 µm (Table 2.2). Although the impact of carrier volume on droplet diameter is less than the other variables, it still reduced the volume percentage of fine droplets described by V<105 from 7.6 to 6.8% when increasing the carrier volume from 47 to 187 L ha^{-1} (Table 2.2). However, it should be noted that in some instances, some nozzle, orifice size, pressure, and herbicide combinations performed erratically (data not shown). When this occurred, larger carrier volumes that typically would have larger droplet diameters were observed to have smaller droplet sizes. For example, this occurred with the TTI nozzle with both orifice sizes and all pressures. Instances that were less common occurred with the AI11005 and TT11005 at 276 and 138 kPa, respectively, and the AIXR11005 at 276 kPa. The R^2 values decreased as carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1} (R^2 = 0.66, and 0.62, respectively) (Figure 2.6). Other research has shown that changing the carrier volume, which not only dilutes the herbicide but any surfactant in the formulation, modifies spray droplet diameter (Anderson et al. 1983; Arnold 1983; Bouse et al. 1990; Nuyttens et al. 2007a).

The spray application variables examined in this study, in order of greatest to least impact on spray droplet diameter were nozzle, pressure, herbicide, orifice size, and carrier volume. Johnson et al. (2006) concluded that the use of drift-reducing nozzles to mitigate herbicide drift is less expensive than including a drift control adjuvant with each spray application. However, it is the opinion of the authors that spray solution, including the active and additives, must be considered to maximize efficacy and minimize drift in herbicide applications.

An exponential relationship between $D_{v0.5}$ and V<105 values existed and is illustrated in Figures 3-6. One would expect that a linear relationship would exist between the $D_{v0.5}$ and V<105 values. However, since the relationship is exponential, by identifying the point of tangency, one could identify the best combination of application variables to maximize the total volume of spray comprised of droplets of biological beneficial diameter that are also less prone to drift. In addition, these same figures illustrate how rapidly the V<105 can decrease when utilizing application parameters that promote larger droplet diameters. In this study, the most extreme $D_{v0.5}$ values observed for any of the treatments was 123 µm for glufosinate using the XR11003 at 414 kPa and 47 Lha^{-1} and 847 µm for cloransulam using the TTI11003 at 138 kPa and 94 L ha^{-1}. Any of the variables examined in this study, when examined singularly, may not have a large impact on the droplet spectrum of the spray. However, any combination of the variables examined in this study could potentially change the spray droplet spectra significantly. For example, using the AIXR11003 nozzle at 276 kPa should produce a very coarse nozzle classification (349-428 µm) as described in the TeeJet Technologies nozzle catalog when spraying water (Spraying Systems Co. 2011). Those same application parameters produced a 405 µm $D_{v0.5}$ value in this study which is a coarse droplet classification according to the PAT Lab reference curves. The addition of glufosinate at

140 L ha^{-1} to those same application parameters reduced the $D_{v0.5}$ value 22% (317 µm), which is similar to the 18% reduction of the $D_{v0.5}$ value from water to glufosinate averaged over all other variables reported in Table 2.2. The reduction in the $D_{v0.5}$ value caused by adding glufosinate reduced the droplet classification to medium (Figure 2.2). Thus, understanding the relationship of the variables examined in this study on spray droplet spectrum, approximations of droplet spectra could be created by growers and applicators for a number of different application scenarios.

Results of this research are being correlated to biological performance to better understand where the potential changes seen in droplet diameter translate to actual biological effect. As more focus is put on increasing droplet size to reduce herbicide drift, it is imperative to maintain biological efficacy of herbicides. Due to the wide variation in droplet sizes observed in this study, it is clear that no single nozzle will perform best under all conditions or scenarios. It is important to document how variations in droplet diameter influence biological efficacy of herbicides in future studies.

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Table 2.1. Source of materials used in spray droplet spectra characterization experiment in North Platte, NE.

Common name	Trade name	Treatment rate (kg ai or ae ha^{-1}, or v/v)[a]	Manufacturer
Clethodim	SelectMax	0.14[b]	Valent USA Corporation, Walnut Creek, CA, www.valent.com
Cloransulam	FirstRate	0.02	Dow AgroSciences, Indianapolis, IN, www.dowagro.com
Glufosinate	Ignite	0.49	Bayer Crop Science LP, Research Triangle Park, NC, www.bayer.com
Glyphosate	Roundup PowerMax	0.87[c]	Monsanto Corporation, St. Louis, MO, www.monsanto.com
Lactofen	Cobra	0.22	Valent USA Corporation, Walnut Creek, CA, www.valent.com
Ammonium sulfate	Bronc	5.0[d]	Wilbur-Ellis Company, Fresno, CA, wilburellis.com
Crop oil concentrate	Crop Oil Concentrate	0.5[e]	Helena Chemical Company, Collierville, TN, www.helenachemical.com

[a] Abbreviations: ae, acid equivalent; ai, active ingredient; v/v, volume percent concentration.

[b] Active ingredient of clethodim, cloransulam, glufosinate, and lactofen were used.

[c] Acid equivalent of glyphosate was used.

[d] Ammonium sulfate was added to all five herbicides (v/v).

[e] Added to cloransulam and lactofen at rate listed in table (v/v). Added to clethodim at 2.34 L ha^{-1}.

Table 2.2. Spray characteristics pooled over nozzle, orifice size, herbicide, pressure, and carrier volume.

Variable		$Dv_{0.1}$[a]	$Dv_{0.5}$	$Dv_{0.9}$	V<105	V<150	V<210	V>730	RS
		µm			%				
Nozzle	AI	187	442	693	3.6	7.4	13.7	7.2	1.16
	AIXR	186	426	664	4.0	8.4	15.2	7.1	1.14
	TT	115	293	538	10.1	20.7	34.5	1.9	1.48
	TTI	262	588	878	1.3	3.3	7.2	28.3	1.06
	XR	95	229	402	16.6	29.3	46.0	0.1	1.39
	HSD[b]	1.1	2.8	3.7	0.1	0.1	0.1	0.3	0.006
Orifice size	11003	162	381	611	8.1	15.6	26.0	8.1	1.26
	11005	175	411	659	6.2	12.0	20.7	9.8	1.24
	HSD	0.4	0.6	1.7	0.1	0.1	0.1	0.1	0.003
Herbicide	Clethodim	181	404	627	5.6	11.5	20.6	7.5	1.15
	Cloransulam	199	424	621	4.5	9.5	17.9	9.5	1.03
	Glufosinate	137	359	634	10.5	19.0	29.9	8.6	1.47
	Glyphosate	155	382	640	8.5	16.1	26.1	8.7	1.35
	Lactofen	168	379	599	6.3	12.8	22.9	6.1	1.18
	Water	173	425	690	7.3	13.8	22.5	13.2	1.30
	HSD	1.0	1.5	4.2	0.1	0.1	0.1	0.3	0.007
Pressure	Low	214	475	727	3.8	8.2	15.0	15.6	1.13
	Medium	159	380	616	7.3	14.3	24.3	7.0	1.26
	High	133	332	562	10.2	18.9	30.6	4.1	1.35
	HSD	0.7	0.9	2.4	0.04	0.1	0.1	0.2	0.004
Carrier volume	47	163	383	618	7.6	14.7	24.7	8.0	1.26
	94	169	397	639	7.1	13.8	23.3	9.0	1.26
	140	170	398	638	7.0	13.5	22.9	9.0	1.24
	187	172	404	645	6.8	13.2	22.4	9.7	1.24
	HSD	0.8	1.1	3.1	0.05	0.1	0.1	0.2	0.005

[a] Abbreviations: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values represent the droplet diameter at which 10, 50 and 90% of the total spray volume, respectively, is comprised of droplets of equal or lesser diameter. V<105, V<150, V<210, and V>730 values represent the percentages of spray volume contained in droplets less than 105, 150, and 210 µm and greater than 730 µm. RS is the relative span of the spray droplet spectrum.

[b] Tukey's studentized range test (HSD) mean separation technique at the 5% significance level.

Figure 2.1. Static chamber and Sympatec laser diffraction system used to characterize sprays of 720 treatment combinations.

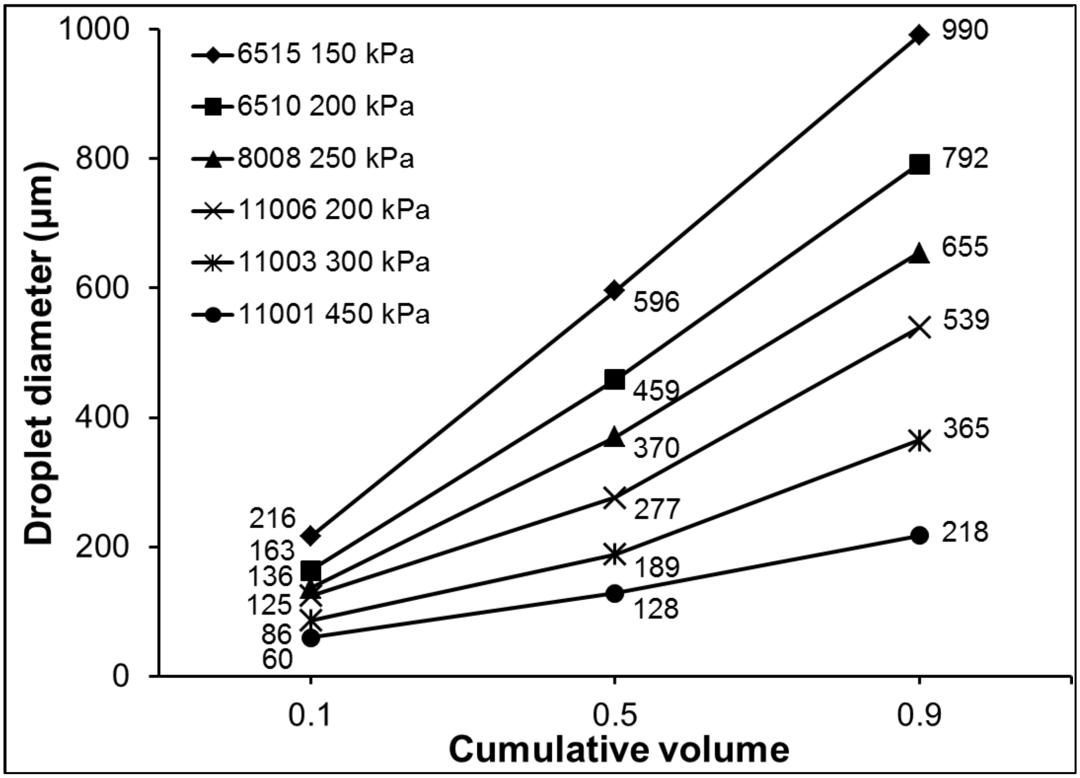

Figure 2.2. Reference curves generated with water at the Pesticide Application Technology Laboratory and spray classification categories as defined by ASAE S572.1 as areas under each curve.

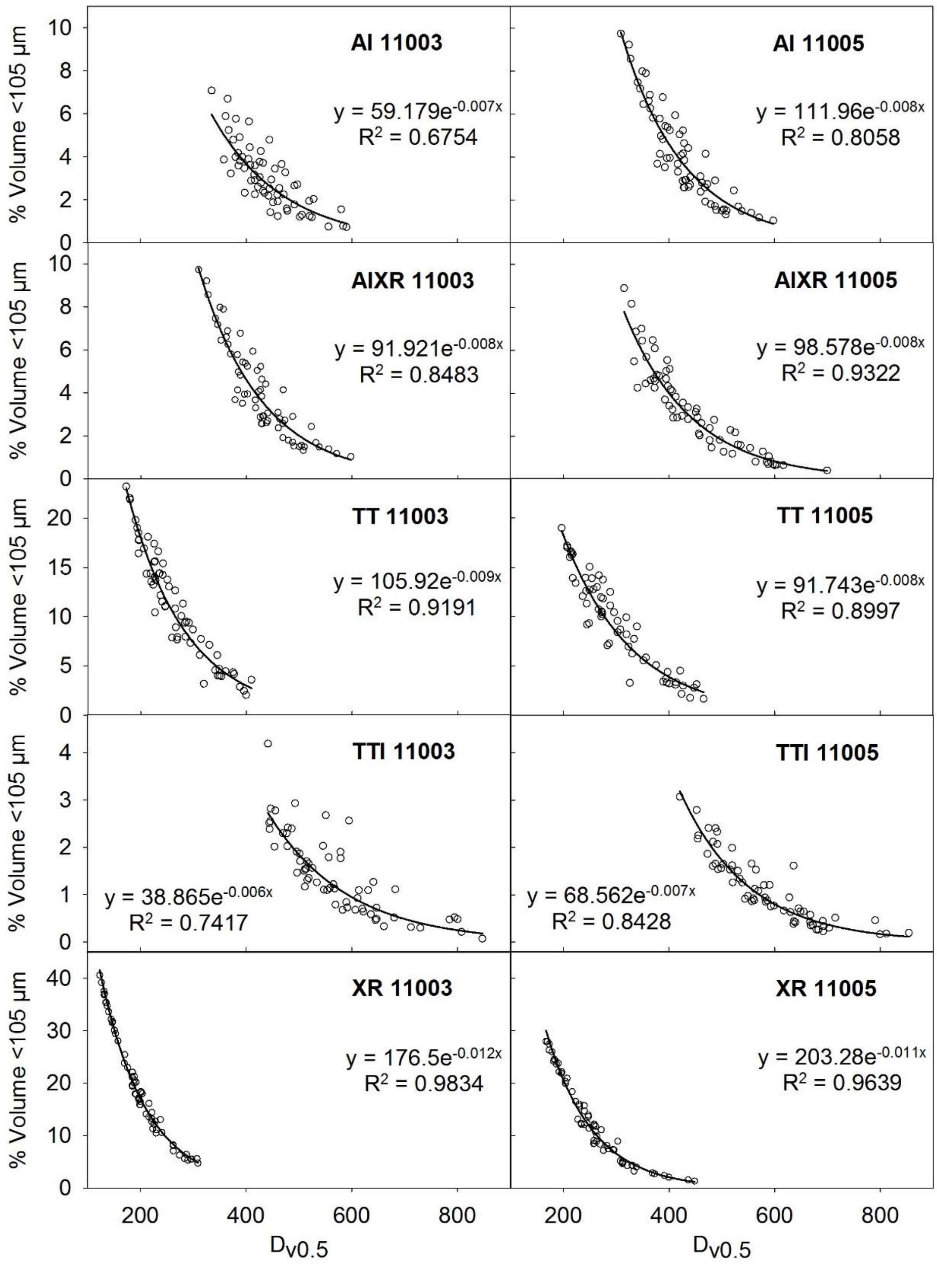

Figure 2.3. The percentage of liquid volume contained in droplets smaller than 105 µm as related to $D_{v0.5}$ for each nozzle type and orifice size using different spray solutions, carrier volumes, and pressures.

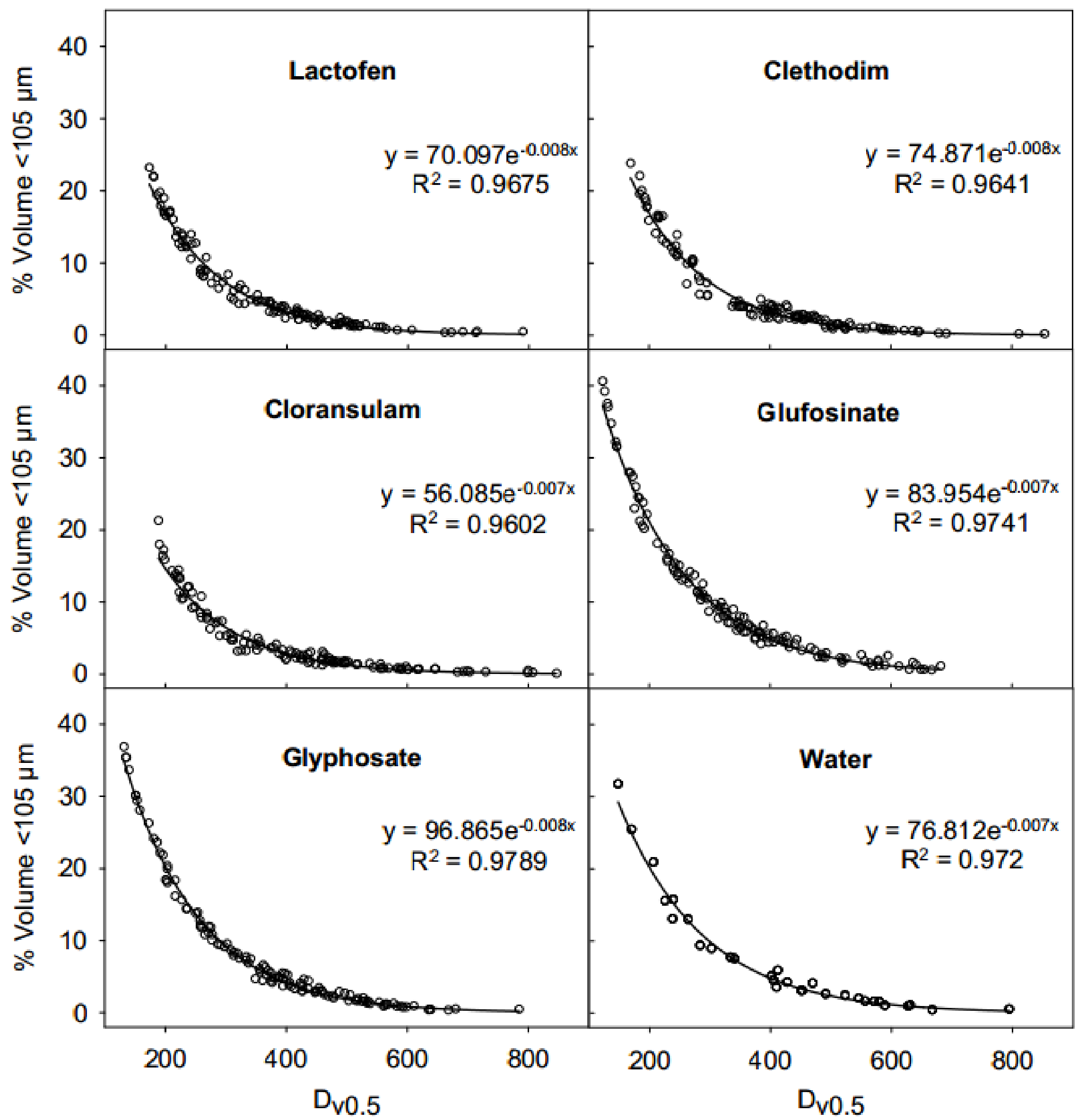

Figure 2.4. The percentage of liquid volume contained in droplets smaller than 105 µm as related to $D_{v0.5}$ for each spray solution using different nozzle types, orifice sizes, carrier volumes, and pressures.

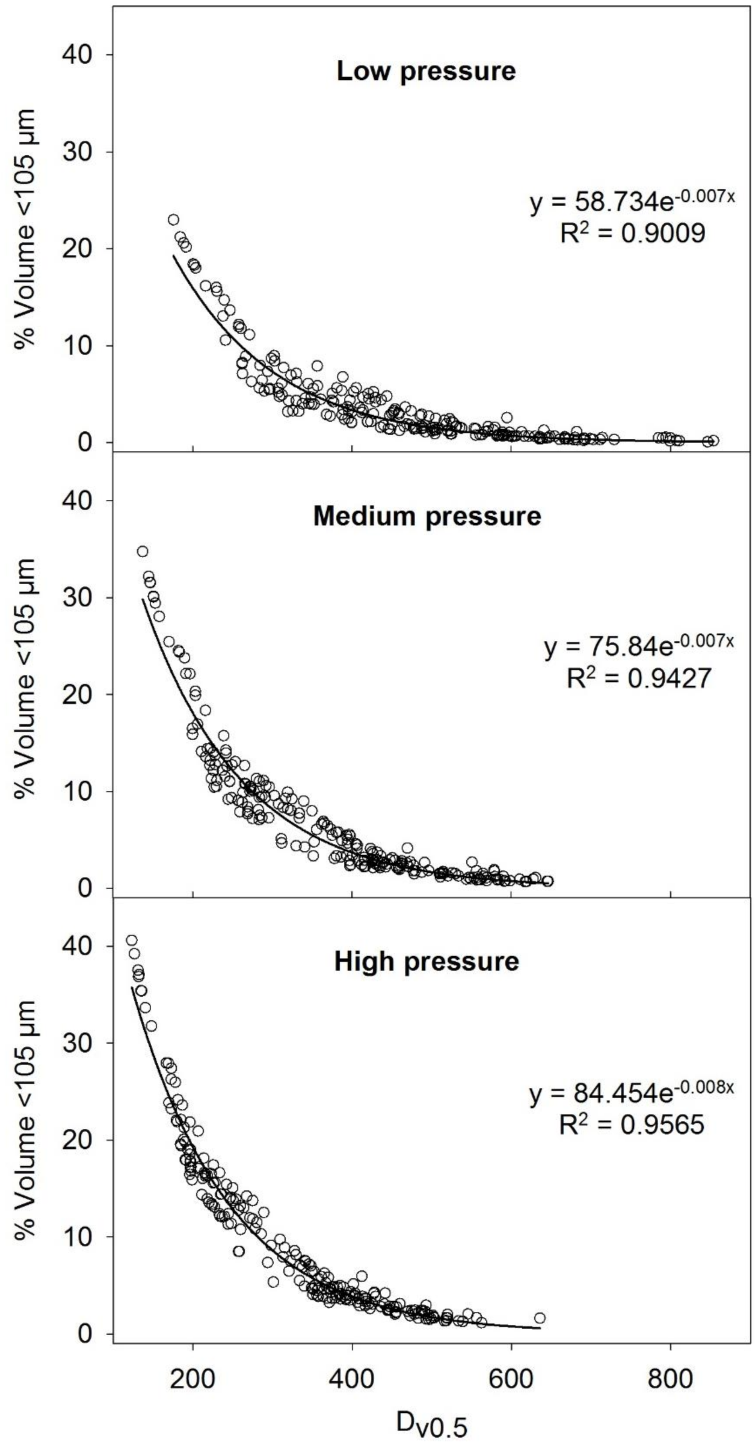

Figure 2.5. The percentage of liquid volume contained in droplets smaller than 105 µm as related to $D_{v0.5}$ for each pressure using different spray solutions, nozzle types, orifice sizes, and carrier volumes.

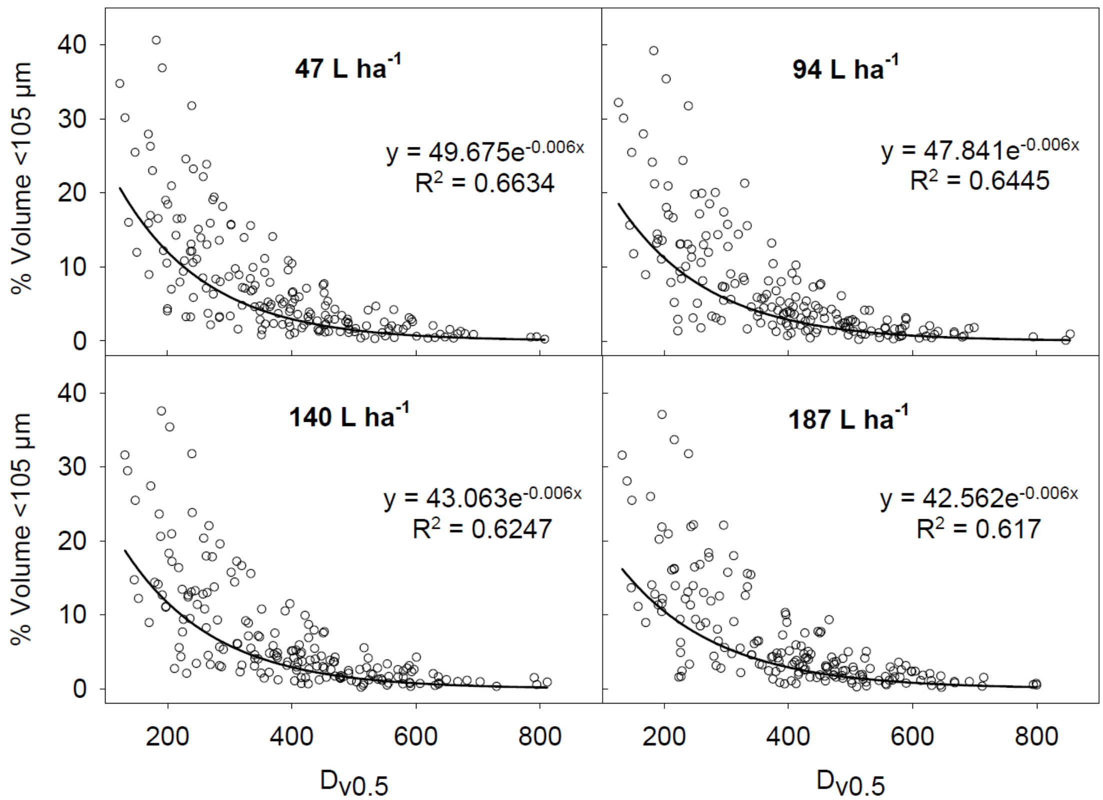

Figure 2.6. The percentage of liquid volume contained in droplets smaller than 105 µm as related to $D_{v0.5}$ for each carrier volume using different spray solutions, nozzle types, orifice sizes, and pressures.

CHAPTER 3

Herbicide Spray Penetration into Corn and Soybean Canopies with Air-Induction Nozzles and a Drift Control Adjuvant

Abstract

Herbicide penetration into a crop canopy is necessary for a herbicide application to reach a target weed species when applications are made after crop emergence. When crops are actively growing, they can be injured by off-target herbicide movements. Many drift reduction technologies aim to eliminate the smaller droplets that occur with some sprays because these small droplets can move off-target in the wind. The impact of such drift reducing technologies on herbicide penetration into the canopy has not been fully investigated. This study evaluated the canopy penetration and efficacy of glyphosate treatments applied using four nozzle types (XR, AIXR, AITTJ, and TTI), two carrier volume rates (94 and 187 L ha^{-1}), and glyphosate applications with and without a commercial drift reducing adjuvant. Applications were made to corn and soybean fields near North Platte and Big Springs, NE. Glyphosate was applied at 1.26 kg ae ha^{-1} with ammonium sulfate at 5% v/v. A rhodamine dye was added (0.025% v/v) to the spray tank of each mix as a tracer. Mylar™ cards were placed in the field above canopy, in the middle canopy, and on the ground for corn and above and below canopy for soybean. Five cards were at each position in the canopy arranged across the crop row. Data were transformed to represent the percent reduction of the spray collected relative to what was recovered at the top of the canopy. The addition of a drift reducing adjuvant did not impact canopy penetration. Doubling the carrier volume increased the amount of penetration proportionally and as such the percent reduction was not different. The TTI

nozzle had the greatest amount of spray penetration (28%) in the soybean canopies and the XR nozzle had the greatest amount (50%) in the corn canopies. Deposition across the row, beginning in-between the row crop and ending in the row of the crop was 44, 18, and 8% for soybean and 59, 50, 36% for corn. For both crops, more than half of the herbicide application was captured in the crop canopy. Proper nozzle selection for canopy type can increase herbicide penetration and increasing the carrier volume will increase penetration proportionally.

Introduction

Off-target movement of herbicides occurs with every herbicide application. Van den Berg et al. (1999) estimated that up to 50% of the herbicide applied could be lost into the environment when applications are made in poor conditions. Herbicide drift from agricultural applications is a source of environmental contamination which has potential adverse human health impacts and can cause damage to non-target plants, animals, and other natural resources. Herbicide use in the United States between 1996 and 2011 has increased by an estimated 9% or 240 million kilograms (Benbrook 2012). At the same time, public awareness and concern about agricultural herbicide use has increased along with efforts to mitigate off-target movement of herbicides and to re-evaluate weed control and herbicide application practices.

Agricultural nozzles generally produce droplets ranging in diameter from <10 to >1,000 µm (Bouse et al. 1990). The diameter of a spray droplet is significant for transport and fate. For example, a 100 µm diameter droplet can travel 7.5 times further off-target than a 500 µm droplet in 5 kph wind speed when released from a typical boom height of

0.5 m (Bode 1987). Creech et al. (2015a) evaluated application variables that impact spray droplet size and concluded that nozzle type, operating pressure, herbicide solution, nozzle orifice size, and carrier volume, in order of greatest impact to least, all impact droplet size. In addition to the factors evaluated by Creech et al. (2015a), other application and environmental factors could also impact droplet size. Herbicide applications are a complex process involving a series of stages beginning at the nozzle with droplet formation, followed by travel to the plant surface, droplet impaction and retention on the leaf surface, deposit formation, plant uptake, and biological response (Brazee et al. 1991; Ebert and Downer 2008; Merritt et al. 1989; Reichard 1988). A change that occurs at any one stage interacts with the other application factors and, as many stages are interrelated, subsequent stages and spray performance are affected.

In an attempt to reduce herbicide drift, efforts have been made to implement drift reduction technologies (DRTs). These technologies aim to mitigate off-target spray deposition through methods such as reducing the proportion of small droplets in sprays through the use of innovative nozzle designs and formulations, hoods or shields to protect the spray from wind displacement, and boom height controllers to release the spray close to the target (Lund et al. 2000; Nordby and Skuterud 1974; Wolf et al. 1993; Yates et al. 1976). Because spray drift is a complex research topic that includes both environmental and equipment variables in addition to the many application parameters, it is difficult to test all possible interactions. Pesticide drift models, most notably AGDISP, have been developed to aid in risk assessment and decision making associated with herbicide applications (Bilanin et al. 1989; Woodward et al. 2008). While many factors that impact herbicide drift have become better understood, the full effect of DRTs on the delivery of the herbicide to the target and ultimate performance have not been fully investigated and are not as easily quantified for use in models.

Air induction nozzles are effective at reducing herbicide drift by limiting the number of fine droplets, over a wide range of spray pressures, that could potentially move off-target (Etheridge et al. 1999). These nozzles vary in design but usually consist of a pre-orifice, one or two air-induction ports, a mixing chamber, and an exit orifice that is larger than the pre-orifice. The air-induction ports permit air to enter the chamber and reduce the pressure of the liquid. The pre-orifice insert determines the flow rate of the liquid prior to exiting the larger exit orifice thus reducing spray velocity to producing larger droplets. While increasing the spray droplet size of an herbicide application may be effective at mitigating off-target movement (Bode 1987), increasing the spray droplet size of an application can impact herbicide efficacy (Knoche 1994). It is generally assumed that contact herbicides may be more adversely affected than systemic herbicides to increasing droplet spray droplet size. Knoche (1994) observed an increase in contact herbicide efficacy in 58% of the studies he reviewed. Conversely, glyphosate, a systemic herbicide, has increased adsorption and translocation when applied using larger droplets (Feng et al. 2003; Liu et al. 1996). The effect of droplet size on herbicide efficacy is herbicide and species dependent and results can be highly variable (Creech et al. 2015c).

Another method used to reduce off-target herbicide movement is the use of drift control adjuvants. These adjuvants are often classified as spray modifiers in that they may increase the viscosity of the spray to reduce the number of small droplets (Monaco et al. 2002). Other drift control adjuvants function more as an invert suspension or emulsifier to improve the sheet breakup mechanism which reduces fines. For this reason, many applicators will include a drift control adjuvant in the herbicide tank-mixture to attempt to reduce off-target movements near sensitive areas (VanGessel and Johnson 2005). Spray drift control adjuvants are not believed to directly affect herbicide efficacy, but rather make the herbicide application process more efficient by reducing losses through drift (McMullan 2009).

Research on herbicide efficacy is typically conducted under ideal situations that limit interference from other variables. For example, a researcher would prefer to avoid a situation where a spray application must pass through a crop canopy to reach the target weed species. Growers have readily adopted herbicide-resistant crops; thereby increasing the choices of herbicides, number of hectares, and timings applications could be made for a number of given crops. For example, the adoption of glyphosate-resistant soybeans [*Glycine max* (Merr.) L.] increased from 17% of US soybean hectares in 1997 to 68% in 2001 and 93% in 2010 (Fernandez-Cornejo et al. 2014). A crop canopy can intercept the spray reducing the effective dosage on target plants and increasing deposition variability within and among weeds (Wolf et al. 1996). The primary reason applicators use DRTs is to try to reduce off-target movement of herbicides during application. The objective of this research is to explore other potential benefits that may exist. The primary objective of this research was to evaluate the impacts of air-induction nozzles and a drift control adjuvant on canopy penetration and deposition of a glyphosate application in corn and soybean. The secondary objective was to determine if glyphosate efficacy was impacted by reduced deposition when applied to target plants in corn.

Materials and Methods

The study was conducted near Big Springs and North Platte, NE in irrigated corn and soybean fields in 2014. The Big Springs site (41.16ºN, 102.02ºW) was located on a Kuma loam soil (fine-silty, mixed, superactive, mesic Pachic Argiustolls) located approximately 16 km north northeast of Big Springs, NE. The North Platte site was located at the West Central Research and Extension Center near North Platte NE (41.09°N, 100.77°W) on a Cozad silt loam soil (coarse-silty, mixed, mesic, Typic Haplustolls). The Big Springs locations have historically been a no-till corn-soybean rotation. The North Platte corn location was continuous no-till and the soybean location was a corn-soybean no-till rotation. Corn and soybean were sown in adjacent fields at each location.

The corn cultivar was 106 day Pioneer® 35K09AM1 sown at 76,000 seeds ha^{-1} in early May. The soybean cultivar was Pioneer® 92Y70 with a 2.7 maturity was sown at 475,000 seeds ha^{-1} in mid-May. Both corn and soybean used in this study were glyphosate-resistant and planted in 76 cm rows. Supplemental irrigation was provided at the Big Springs location using center pivot irrigation systems for both corn and soybean. Supplemental irrigation was provided through a sub-irrigation system and lateral move irrigation system for corn and soybean, respectively, in North Platte. The use of irrigation provided uniform germination and growth of the corn and soybean. Common cultural methods were employed to maintain the study areas free of pests which resulted in very little insect, weed, or disease pressure.

Treatments were applied when corn was near the V10 growth stage and soybeans were near the R3 stage. Detailed measurements were made of canopy structure within the central portion each plot. This included plant height, plant density, canopy width, and leaf area. Corn height measurements were 1.0 to 1.2 m and soybean heights were near 0.75 cm. The corn and soybean canopies had mean respective canopy widths of 1 m and 75 cm. The leaf area indices (LAIs) for corn plots at the Big Springs and North Platte locations ranged from 6.6 to 12 and 4.6 to 9.9, respectively. The LAIs for the soybean at Big Springs and North Platte were from 2.7 to 4.9 and 3.7 to 5.3, respectively.

Glyphosate (Roundup PowerMAX®, Monsanto Company, St. Louis, MO, 63167) was applied at 1.26 kg ae ha^{-1} with ammonium sulfate (AMS, Bronc®, Wilbur-Ellis Company, Fresno, CA, 93755) at 5% v/v. In addition, a rhodamine dye (intracid rhodamine WT, Cole Palmer Instrument Company, Vernon Hills, IL, 60061) was added at 0.25% v/v as a tracer. The treatment factors were carrier volume, drift control adjuvant, and nozzle type. The desired application volume rates were 94 and 187 L ha^{-1}. Apart from changing the glyphosate concentration in the tank-mix when changing carrier volume from 94 to 187 L ha^{-1}, all other application variables remained the same except for the application speed which decreased from 16 to 8 km h^{-1}. The nozzle types evaluated in this study were the AIXR, AITTJ, TTI, and XR nozzles (Spraying Systems, Wheaton, IL, 60189) with 110 degree spray angles and 1.9 L/min exit orifices (rated for this flow rate at the reference and operational pressure of 276 kPa). The final treatment variable was a drift reduction adjuvant (In-Place®, Wilbur-Ellis Company, Fresno, CA, 93755) applied at a rate of 1 part adjuvant to 4 parts herbicide.

The experimental design used for the soybeans was a split-plot design with four replications. The experimental design for the corn was a split-split plot design also with four replications. The whole plot factor for both experiments was the entire plot area treated with the spray mixture. The sub-plot factor for both experiments was the section of sprayer boom which had the same nozzles. At the Big Springs location, treatments were applied using a John Deere 4830 self-propelled sprayer (John Deere, Moline, Illinois, 61265) with a stainless steel tank and 30 m stainless steel boom. The North Platte treatments were applied using an older model 3-point tractor mounted 18 m sprayer (Schaben Industries, Columbus, NE, 68601). Applications were made 60 cm above the crop canopy with nozzles spaced 76 cm apart. Each spray boom was divided into five equal sections (subplots) with each section having one type of nozzles affixed. The fifth section on the spray boom was capped and therefore would not be sprayed. This section served as the control for the study. The corn studies were conducted on July 1 and July 11 in North Platte and Big Springs, respectively. Air temperature, relative humidity, and wind speed were on average 18 C, 64%, 12 km h^{-1}, and 21 C, 75%, and 14 km h^{-1} for North Platte and Big Springs, respectively. The soybean studies were conducted on August 1 and August 9 in North Platte and Big Springs, respectively. Air temperature, relative humidity, and wind speed were on average 21 C, 60%, 6 km h^{-1}, and 23 C, 75%, and 8 km h^{-1} for North Platte and Big Springs, respectively.

Canopy penetration and deposition of the spray was measured using Mylar cards that were 10 cm x 10 cm (Grafix Plastics, Cleveland, OH, 44137). Five Mylar cards were centered at 0, 19, 38, 57, and 76 cm distances across the board and fastened to a board using a staple. The board would then be positioned within the designated area of the crop near the center of a nozzle section so that the Mylar cards at 0 and 76 cm were positioned on the crop rows (Figure 3.1). The Mylar card at 38 cm would then be in the middle of the two rows of the crop (Figure 3.1). In both the corn and soybeans within each nozzle section, a board with five cards was placed at the top of the canopy. The board was high enough so that none of the crop canopy would impede the spray from deposition on the cards. The board was held in position by a fiberglass fence post driven into the ground and the other end inserted into a drilled hole in the bottom of the board. In the corn, an additional board with Mylar cards was positioned within each nozzle section in the middle of the canopy approximately 45 cm above the ground using a shorter fence post (Figure 3.1). Both corn and soybean then had a board with Mylar cards placed on the ground. The different levels of collection stations were radically separated to avoid interference in collecting spray deposition. In summary for the soybean, each nozzles' section of the spray boom had a set of Mylar cards below the canopy on the ground and above the canopy for a total of 10 cards or 50 cards per whole plot. The corn had the same 10 cards plus an additional five cards in the middle of the canopy for 75 cards per whole plot (Figure 3.1). With the additional set of cards in the corn, the position of the cards in the canopy, low vs middle, was considered the sub-sub plot in the experimental design for the corn.

After the plots had been sprayed, all Mylar cards were collected within 10 minutes. The cards were placed individually into pre-labeled clean plastic recloseable bags. After the cards from one nozzle section were collected and bagged, they were placed in a large paper sack and placed into a dark container to prevent photodegredation of the dye. After spraying a plot, the sprayer operator would switch the nozzle sections on the spray boom so every replication had a different randomization of the nozzle sections across the spray boom. The operator would wait until the previous plot was collected before spraying the subsequent plot and ensure the samples were collected soon after spraying.

The Mylar cards were taken to the Pesticide Application Technology Laboratory (PAT Lab) in North Platte, NE to extract and analyze dye concentration using fluorometry techniques. Each bag containing a Mylar card had 40 ml of distilled water added using a bottle top dispenser (Model 60000-BTR, LabSciences, Inc., Reno, NV, 89510). The bag was then resealed and the Mylar card was rubbed to release any dye from the Mylar card into the liquid in the bag. After the dye was successfully suspended in the liquid, a 2 ml sample was drawn with a pipette to fill a glass cuvette. The cuvette was placed in a rhodamine/phycoerythrin module inside a fluorometer (Trilogy Laboratory Fluorometer, Turner Designs, Sunnyvale, CA, 94085) and fluorescence data were collected at 24 C. Some samples were further diluted using additional distilled water to bring the raw fluorescence unit readings within the required range for known response of the calibrated fluorometry system.

In addition to Mylar cards, plants were grown and used in the corn study as biological indicators to evaluate the impact of the corn canopy and the experimental treatments on herbicide efficacy in the bottom of the canopy. No biological indicator plants were used in the soybean study because the density of the soybean canopy was high. The biological indicator plants were glyphosate-susceptible Asgrow® A3253 soybeans grown in 10 x 10 x 10 cm pots filled with Professional Growers Mix (Ball Horticulture Company, West Chicago, IL, 60185) grown in a greenhouse at the PAT Lab. Plants were seeded approximately one month prior to conducting each corn experiment at both field location and were watered as needed. Plants received supplemental nutrition

(Scotts Miracle-Gro® LiquaFeed® All Purpose, The Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol™ DS 300W, Illumitex, Austin, TX, 78735) was provided to ensure 14 h days. Plants were 15 to 20 cm tall when treated in the field. On the day the study was conducted, five plants were placed on the ground in each nozzle section between two rows, spaced the same as the Mylar cards at 0, 19, 38, 57, and 76 cm. After the study had been completed, the plants were transported back to the greenhouse. Visual estimations of injury were recorded at 7, 14, 21, and 28 days after treatment (DAT) using a scale of 0 – 100 where 0 = no control and 100 = plant death. At 28 DAT, plants were destructively sampled by clipping the plant at the soil surface and recording the fresh weights. These samples were then dried at 40 C for 7 days following which dry weights were recorded.

The spray droplet size spectrum for each treatment combination was evaluated in 2014 using the low speed wind tunnel at the PAT Lab. The system and process used to collect the spray droplet data has been described extensively by Creech et al. (2015b). The particle size measurement system and software output allow classification of the spray droplet size spectrum using the ASABE standard S572 (ASABE 2009). The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Statistical Analysis. With differences in application timing and sampling methods, corn and soybean results were analyzed separately. The deposition rates were calculated as a percent of the applied rate as determined from the amount of spray deposited on the Mylar cards above the canopy. The Mylar cards from the nozzle section on the spray boom that was capped did not have a significant amount of recovered tracer dye (data not shown). This indicated minimal movement of spray between nozzle sections and the results from the capped section were not used in the final analysis. Deposition data from the field studies were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute, Cary, NC 27513). Data from the field locations were combined and analyzed together with replication nested within location and considered a random effect as suggested by Carmer et al. (1989) as no significant effect for either the corn or soybean studies existed. LS means were compared for significant fixed effects at an alpha level of 0.05.

For the soybean plants that were used as biological indicator plants of herbicide efficacy in the greenhouse study, the analysis of visual injury data was performed using repeated measures which allowed for pooling of means across rating intervals. The Akaike information criterion with a correction for finite sample sizes (AICc) was used, as suggested by Burnham and Anderson (2002), to select the appropriate covariance model to use in the repeated measure analysis. The AICc indicated the default covariance model used by GLIMMIX best fitted the data, so this was used for repeated measure analysis. In addition, the Kenward-Rogers degree-of-freedom approximation procedure was used to account for instances of missing data from plants that were damaged during transport to and from the field sites. The analysis for the estimations of visual injury had replication nested within location designated as a random effect in the model. Percent biomass reduction for treated experimental units was calculated using both the fresh and dry weights relative to the average biomass of the non-treated control plants in the study as:

$$Percent\ biomass\ reduction = \left((\bar{C} - B/\bar{C})\right) 100 \ [1]$$

where $\bar{C}$ is the mean biomass of the non-treated control replicates, and B is the biomass of an individual experimental unit after being treated. Values for injury ratings and biomass reduction were compared using GLIMMIX in SAS (Littell et al. 2006). LS means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

Spray Droplet Size. The droplet size spectra of each treatment are presented in Table 3.1. The XR nozzle had the smallest $D_{v0.5}$ values. Without the DRT the XR nozzle had a Fine spray and nearly 20% of the spray volume was contained in droplets less than 150 µm (Table 3.1). With the addition of the DRT, the XR nozzle had a Medium spray and less than 7% of the spray volume was contained in droplets less than 150 µm (Table 3.1). A similar reduction in spray volume less than 150 µm occurred with the AIXR nozzle with a mean decrease from 3.4 to <1.7% (Table 3.1). The four treatments with the AIXR nozzle remained a Very Coarse spray although the $D_{v0.5}$ value increased (Table 3.1). Without the DRT, the AITTJ produced larger spray droplets than the AIXR having an Extremely Coarse spray. The TTI nozzle had the largest spray droplets with an average $D_{v0.5}$ value of 726 µm and spray volume less than 150 µm below 1% (Table 3.1). However, the addition of the DRT to the AITTJ and the TTI reduced each nozzle's spray from Extremely Coarse to Ultra Coarse, and Very Coarse to Extremely Coarse, respectively. Creech et al. (2015a) reported the TTI nozzle was often highly variable for droplet size spectra and did not always produce the same trends established by other nozzles as application parameters changed. The AIXR, AITTJ, and TTI nozzles utilize venturi technology whereas the XR nozzle is standard hydraulic nozzle. The likely cause of the difference in spray droplet size when using the DRT is the incorporation of a turbulence chamber in the AITTJ and TTI nozzle designs. This chamber mixes air with the spray liquid causing a turbulence that can render the DRT ineffective. Another unique characteristic of the AITTJ and TTI nozzles is the angle of the spray leaving the nozzle orifice. The spray from XR and AIXR nozzles exits the orifice perpendicular to the ground whereas the spray from a TTI nozzle exits forward 15 degrees offset from vertical and the AITTJ has two exit orifices with one spraying 30 degrees forward and the other 30 degrees backward of perpendicular. While the spray angle should not be the cause of the decrease in droplet size when using the AITTJ or TTI nozzles with a DRT, an angled spray could increase deposition (Richardson 1987) or herbicide efficacy (Jensen 2009). These differences in droplet size due to nozzle type and response to DRT adjuvant in addition to considering the potential implications of spray angles will add clarity to the deposition and efficacy results.

Spray Deposition in Corn. The height of the collector position in the corn canopy had an effect (P = 0.0029) on the amount of spray deposition collected. The Mylar cards positioned 45 cm above the ground collected nearly 50% of the total applied rate (Figure 3.2). The corn leaves above these Mylar cards accounted for 75% of the total leaf area of the entire corn plant, on average (data not shown). The collectors positioned near the ground collected nearly 42% of the total applied rate which was less than the middle collectors (Figure 3.2). Similarly, Zhu et al. (2004) reported a dramatic decrease in spray deposition in peanut canopies from top to bottom. Although the middle collectors were positioned near the center of the corn plant, the majority of the corn leaf area is toward the top of the plant competing for light. Once past the upper portion of the canopy, the majority of the remaining spray droplets will reach the ground.

The distance of the Mylar cards between the corn rows also had an effect ($P < 0.001$) on the amount of spray deposition collected. The cards positioned in the middle of the two rows, centered 38 cm from each row, had the greatest spray deposition (59%) (Figure 3.3). Mylar cards 19 cm from either row had 50% deposition and Mylar cards positioned within the corn row had deposition of 36% (Figure 3.3). The decrease in deposition closer to the corn row was also manifested in the decrease in efficacy observed with the biological indicator plants. Visual ratings of the indicator plants placed in the corn rows had on average 7% less injury than plants placed toward the center of the rows ($P < 0.0001$) (Figure 3.4). Weed species growing near the middle away from corn rows would have greater access to light and other resources making them more competitive compared to a weed growing near a corn row. It is hypothesized that a greater amount of herbicide spray deposition would be required to control the weeds with access to better resources. The plants used in this study as biological indicator plants were in the field for only a few hours and had access to adequate and equal resources. Thus, it is unknown if similar differences would have been observed had the indicator plants been subjected to inter-plant competition.

A significant interaction ($P = 0.0036$) between spray mixture and nozzle type impacting deposition rates at different canopy regions was observed. The AITTJ, AIXR, and XR nozzles all had greater spray deposition when DRT was used in the 94 L ha^{-1}

spray mixture (Figure 3.5). When the DRT was used at 187 L ha^{-1} with those same nozzles, the deposition decreased compared to the spray mixture at the same carrier volume with no DRT (Figure 3.5). The DRT used is marketed as a product to reduce the volume of small droplets which increases deposition and coverage on the target surface (Anonymous 2013d). Our results indicate that the use of a DRT with air-induction nozzles with turbulence chambers may not always perform as expected, producing smaller sized droplets (Table 3.1) and in the case of the TTI nozzle, did not improve spray deposition (Figure 3.5). Because the spray droplet size of the AITTJ nozzle decreased with the addition of the DRT to the spray solution, it produced a spray quality nearly identical to the AIXR nozzle with the DRT (Table 3.1). With nearly the same spray quality as the AIXR with DRT, the AITTJ with its dual front and rear facing spray fans was not able to increase deposition compared to the AIXR nozzle (Figure 3.5). The AITTJ with its dual fans is marketed as a nozzle to provide good coverage and penetration (Anonymous 2011). In theory, coverage and deposition should be mutually exclusive. If the aim of the herbicide application is to target weeds below a crop canopy, having a good level of coverage on the crop canopy will not provide deposition on weed targets below the canopy. The visual injury ratings of the biological indicator plants had an interaction ($P = 0.021$) between spray mixture and nozzle. The results did not correlate well with the spray deposition results in Figure 3.5 with the 187 L ha^{-1} treatment without the DRT being a good example (Figure 3.6). The XR nozzle, which had the greatest proportion of small spray droplets among the nozzles evaluated and a vertical spray fan, had greater deposition at the bottom of the canopy (Figure 3.5). Using a greater carrier volume generally did not increase the percent of spray deposition recovered across the different treatments (Figure 3.5). This indicated that doubling the carrier volume essentially increased the amount of spray deposition proportionally keeping the percentage reported in Figure 3.5 the same. Although the 187 L ha^{-1} with DRT application had a low spray deposition in Figure 3.5, the efficacy reported in Figure 3.6 was greater than most other treatments.

The wet and dry weight reductions of the biological indicator plants both had a spray mixture main effect ($P = 0.004$ and $P < 0.001$, respectively) presented in Figure 3.7. Greater wet weight reductions were observed when using 94 L ha^{-1} without DRT and 187 L ha^{-1} with DRT (Figure 3.7). Dry weight reductions were greatest using 94 L ha^{-1} without DRT and 187 L ha^{-1} with DRT though not different than 187 L ha^{-1} without DRT (Figure 3.7). At 35%, dry weight reductions at 94 L ha^{-1} with DRT had the smallest weight reduction. These results generally confirm to the injury ratings presented in Figure 3.6. There was a nozzle main effect for wet weight reduction ($P = 0.0306$) and the AIXR had a wet weight reduction (69%) that was greater than the AITTJ nozzle (62%) (Figure 3.8). On average, the AIXR nozzle had 48% spray deposition compared to 44% for the AITTJ and this was reflected in the wet weight reductions of the indicator plants.

Spray Deposition in Soybean. There was an interaction between the distance of the Mylar cards between soybean rows and nozzle type ($P < 0.001$) on the amount of spray deposition collected. The cards positioned in the middle of the two rows had the greatest spray deposition at 56, 45, 41, and 36% compared to other collector positions closer to the soybean row for the TTI, XR, AIXR, and AITTJ nozzles, respectively (Figure 3.9). At the time of application, the soybean canopies were nearly closed. Thus, if a target weed was growing near the center of the two rows, it would receive about 50% of the intended application on average or half the rate. Mylar cards positioned within the soybean rows collected 8% of the applied herbicide rate (Figure 3.9). In most instances, the TTI nozzle had the greatest spray deposition followed by the XR, AIXR, and AITTJ. Similar to the results observed in the spray deposition into the corn canopy, the AITTJ with its dual angled sprays did not increase deposition in the bottom of the soybean canopy. It is likely that the AITTJ had greater coverage on the upper portion of the soybean canopy which limited the amount of spray to infiltrate through the canopy to ground level. Richardson (1987) concluded that droplet trajectories that are not vertical were more effectively captured in plant canopies because of the increase in the quantity of foliage in their path. This would explain why a nozzle with an angled spray similar to the TTI or AITTJ might have less deposition in the lower levels of a fully developed plant canopy.

There was a spray mixture and nozzle type interaction (P = 0.004) (Figure 3.10). The TTI nozzle at 94 L ha^{-1} had the greatest deposition at 40% and no other differences existed. There was a general trend in deposition increasing as carrier volume increased and when DRT was used. Although differences across nozzle types were not present, the deposition when using the TTI nozzle tended to be higher than the AITTJ nozzle. Zhu et al. (2004) reported less spray deposition in peanut canopies using an XR nozzle and observed higher deposition using a twin jet nozzle compared to a hollow cone nozzle. When a droplet impacts a plant surface, it will either be retained through adhesion, bounce, shatter, or roll off. Larger droplets produced by the TTI nozzle are more likely to not be retained on the first surface they contact due to their size (unpublished data).

Droplets that are not retained can continue through the canopy and may be retained on a lower leaf or may impact the ground (Schou et al. 2012).

Additional research is needed to evaluate the growth stage of crops on spray penetration to evaluate if application technology recommendations need to change during the growing season. The link between spray deposition and biological efficacy needs to be explored further with crop/weed inter-plant competition taken into consideration. Research is also need to evaluate contact herbicides to determine if the trends in spray deposition and biological efficacy for systemic herbicides are similar.

The applications made into both corn and soybean canopies were conducted with robust canopies to maximize differences in treatment factors. Such an application would represent a worst case scenario for herbicide application and would also be similar to a late season rescue application aimed at controlling weed escapes. The goals of a herbicide application and the location of the target pests should dictate the method of the application. Our results demonstrated the negative impact turbulence chambers in nozzle designs can have on the droplet size when using certain DRTs to try to increase spray droplet size. Spray deposition in corn was greatest using the XR and AIXR nozzles that had vertical spray patterns. The TTI nozzle had the greatest spray deposition in soybean. The AITTJ nozzle consistently had the low spray deposition compared to the other nozzles because more spray was captured in the upper portion of the crop canopy. Differences in the amount of spray deposition collected across the row were also present.

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Table 3.1. Droplet size spectrum statistics for glyphosate sprays applied with different nozzle types at two carrier volumes with and without a drift control adjuvant.

Nozzle[a]	Carrier volume	Drift control adjuvant	Droplet diameter[b]				Spray classification[c]
			$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	V<150	
	L ha^{-1}		———	µm	———	%	
AITTJ11005	94	no	269	585	981	1.7	XC
	94	yes	257	506	803	1.8	VC
	187	no	283	602	980	1.5	XC
	187	yes	266	509	788	1.6	VC
AIXR11005	94	no	216	465	778	3.8	VC
	94	yes	261	505	789	1.8	VC
	187	no	231	485	783	3.0	VC
	187	yes	260	509	804	1.6	VC
TTI11005	94	no	369	808	1355	0.5	UC
	94	yes	324	646	1007	0.7	XC
	187	no	377	803	1284	0.5	UC
	187	yes	325	645	1002	0.7	XC
XR11005	94	no	108	246	439	21.1	F
	94	yes	166	312	482	7.0	M
	187	no	109	252	442	20.2	F
	187	yes	171	319	490	6.5	M

[a] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

[b] $D_{v0.X}$ represents droplet diameter below which 0.x of the spray volume is contained in smaller droplets. V<150 represents the spray volume contained in droplets with diameter below 150 µm.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory based on the ASAE S572.1 standard, where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, and XC= Extremely Coarse.

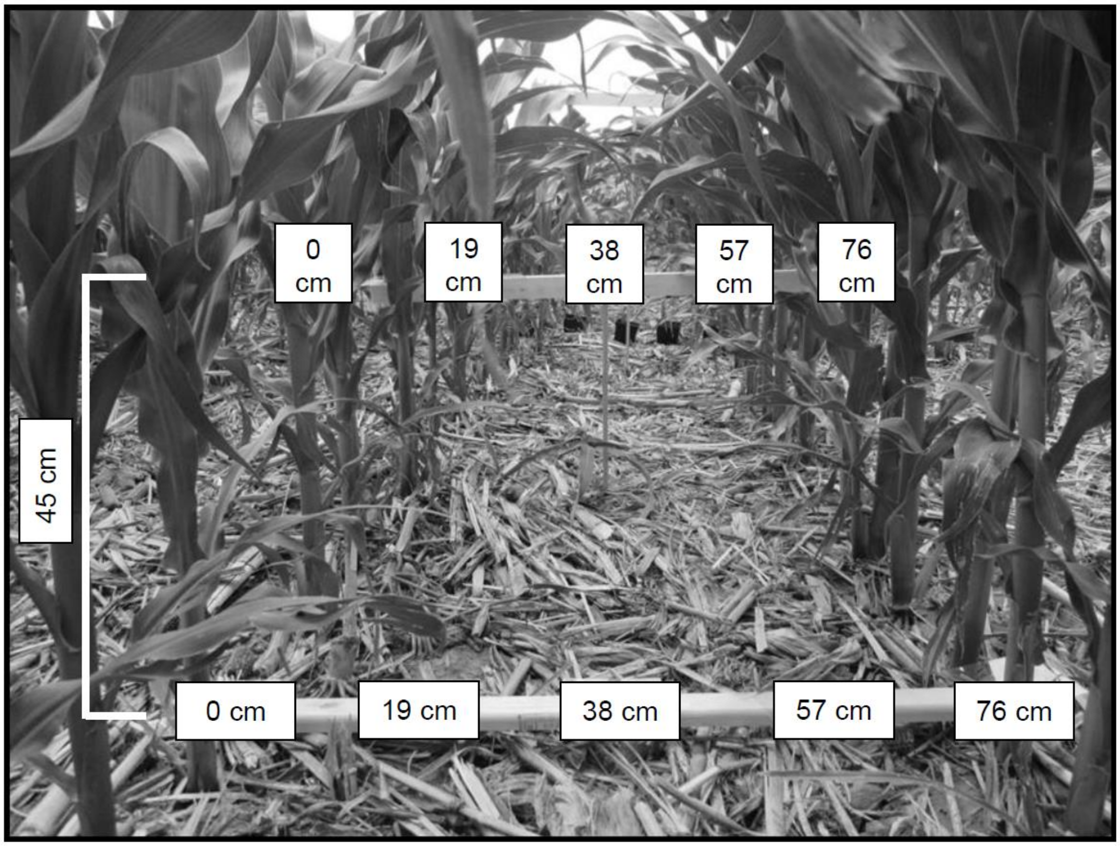

Figure 3.1. Position of middle and bottom Mylar card collectors in 76 cm corn rows. The collectors were fastened to boards and the middle collectors positioned on a single fiberglass fencepost approximately 45 cm above the bottom collectors. The Mylar card collectors above the canopy (not shown) had the same spacing and was also aligned with the crop rows. Also visible further down the rows are the black pots containing the biological indicator plants spaced the same as the Mylar cards.

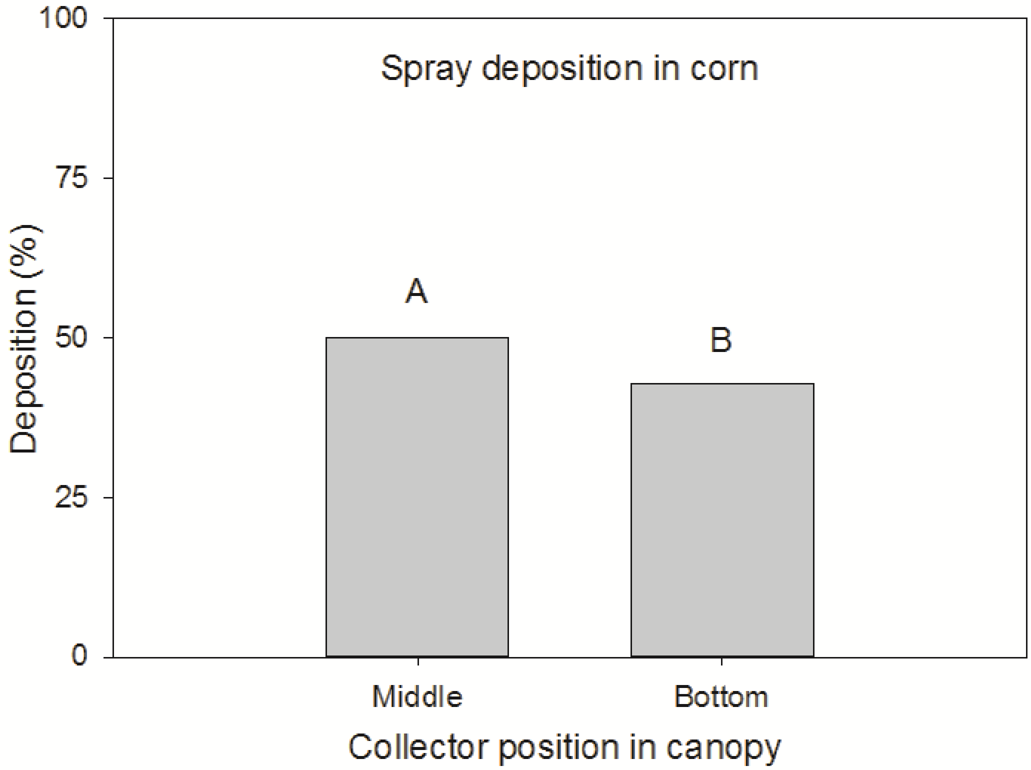

Figure 3.2. Spray deposition on Mylar cards as influenced by collector height position in a corn canopy. Mylar cards were positioned on the ground and 45 cm above the ground. Letters indicate significant differences (α=0.05) across collector position height in the corn canopy.

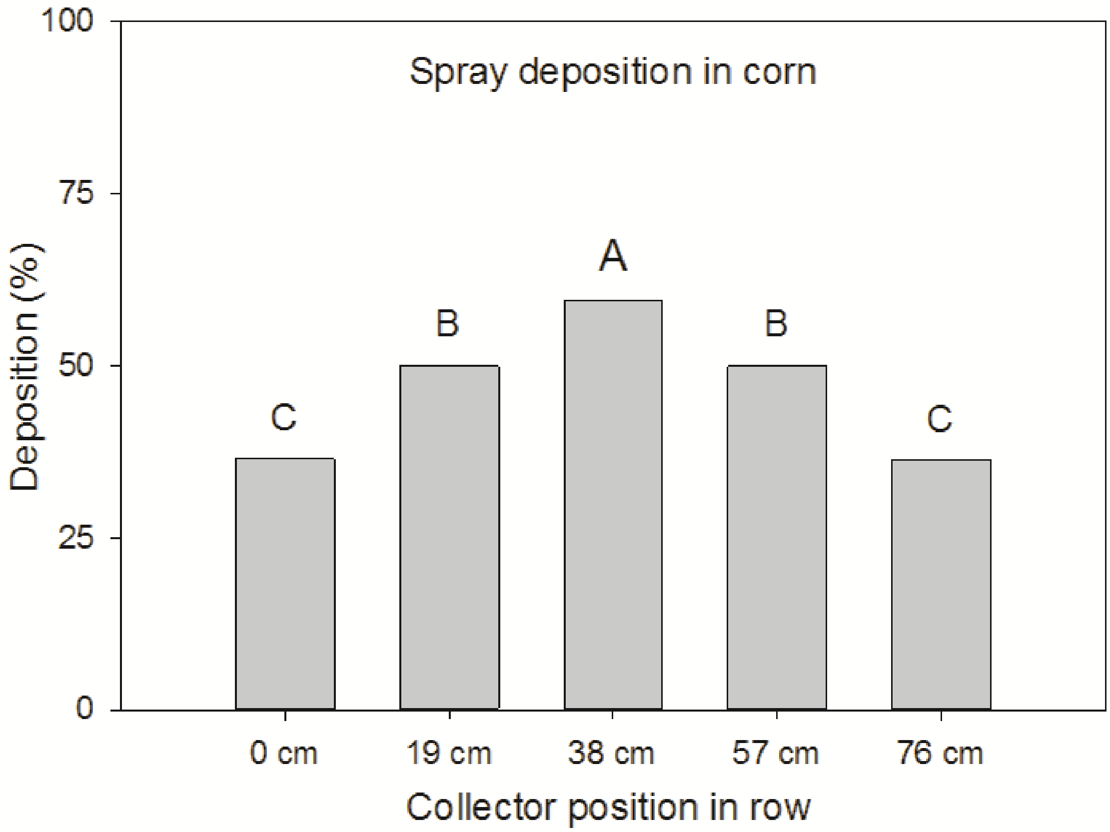

Figure 3.3. Spray deposition on Mylar cards as influenced by collector position across a corn row. Mylar cards were positioned on the ground and 45 cm above the ground at 0, 19, 38, 57, and 76 cm with the 0 and 76 cm Mylar cards positioned directly in the corn rows. Letters indicate significant differences (α=0.05) across collector position across the corn row.

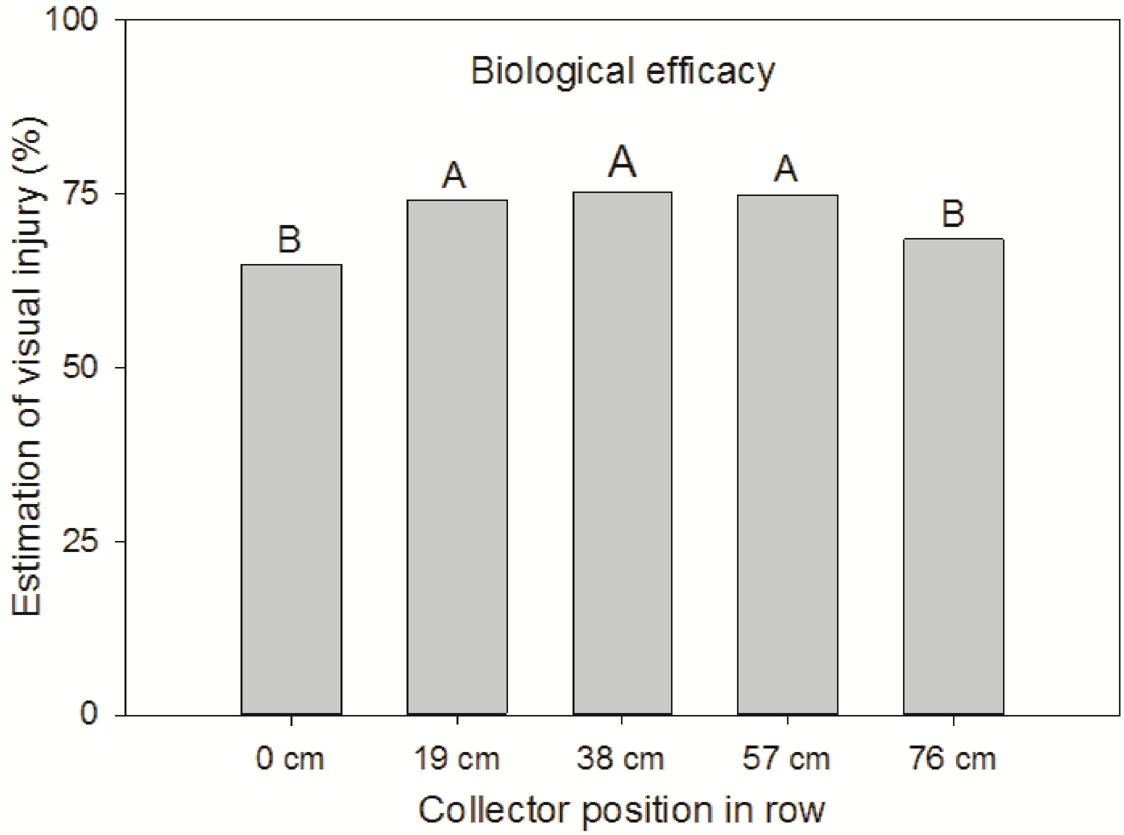

Figure 3.4. Estimation of visual injury ratings of biological indicator plants as influenced by their position on the ground. Plants were spaced at 0, 19, 38, 57, and 76 cm across the corn row with the 0 and 76 cm positioned directly in the corn rows. Letters indicate significant differences (α=0.05) across collector position across the corn row.

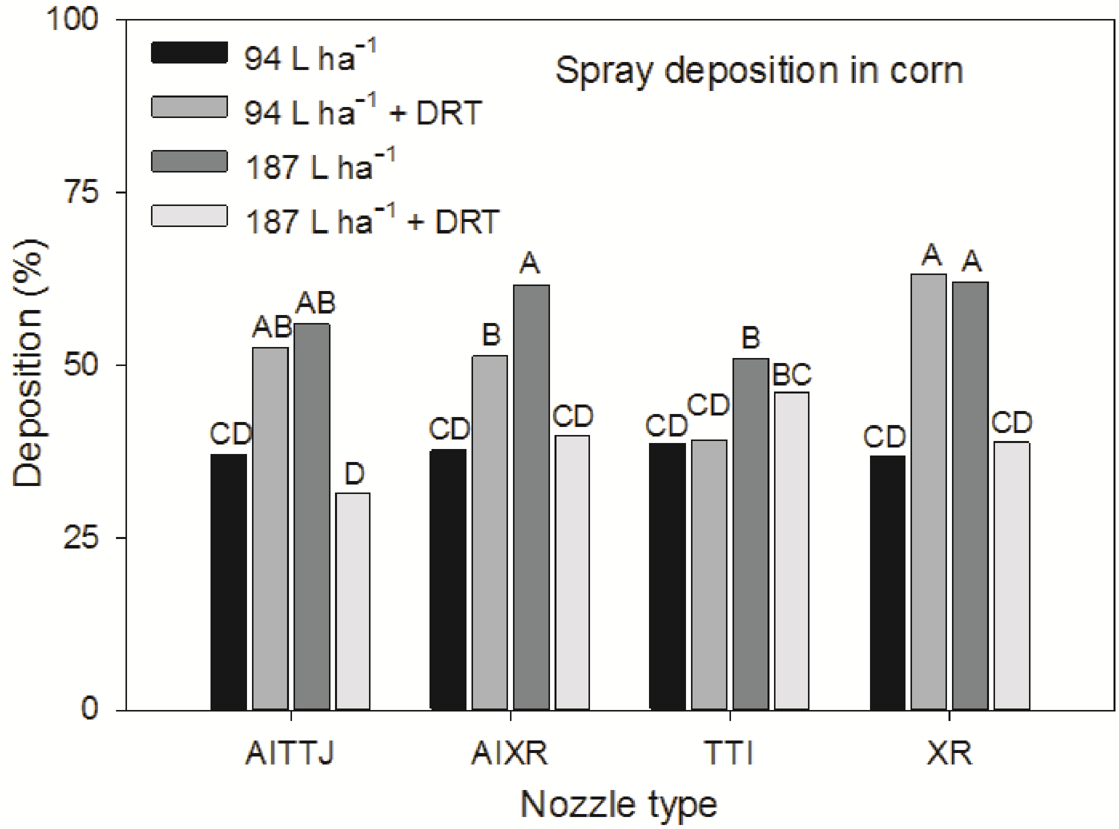

Figure 3.5. The interaction of spray mixture and nozzle type on spray deposition into a corn canopy. The spray mixture included two carrier volumes with and without a drift reduction adjuvant (DRT). Letters indicate significant differences (α=0.05) across nozzle type and spray mixture.

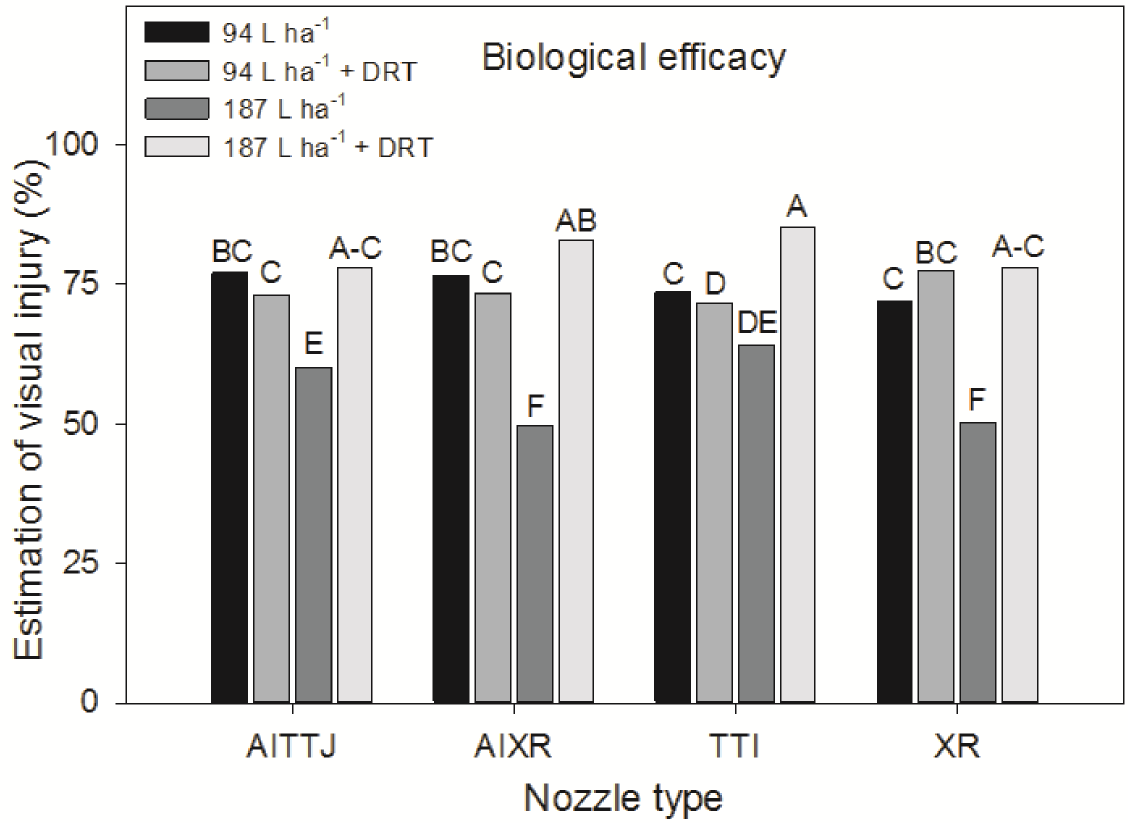

Figure 3.6. Estimation of visual injury ratings of biological indicator plants as influenced by the interaction of spray mixture and nozzle type in a corn canopy. The spray mixture included two carrier volumes with and without a drift reduction adjuvant (DRT). Letters indicate significant differences (α=0.05) across nozzle type and spray mixture.

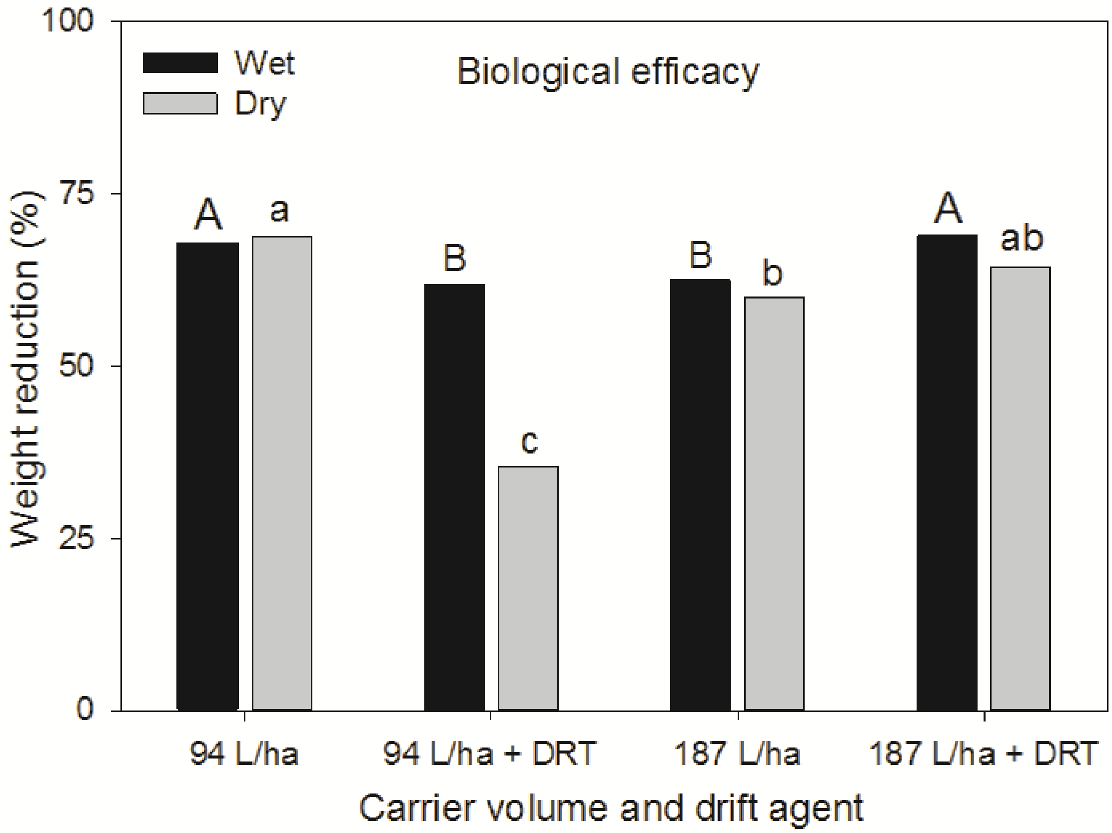

Figure 3.7. Wet and dry weight reductions of biological indicator plants as influenced by spray mixture in a corn canopy. The spray mixture included two carrier volumes with and without a drift reduction adjuvant (DRT). Letters indicate significant differences (α=0.05) across spray mixtures and within wet or dry weight reductions.

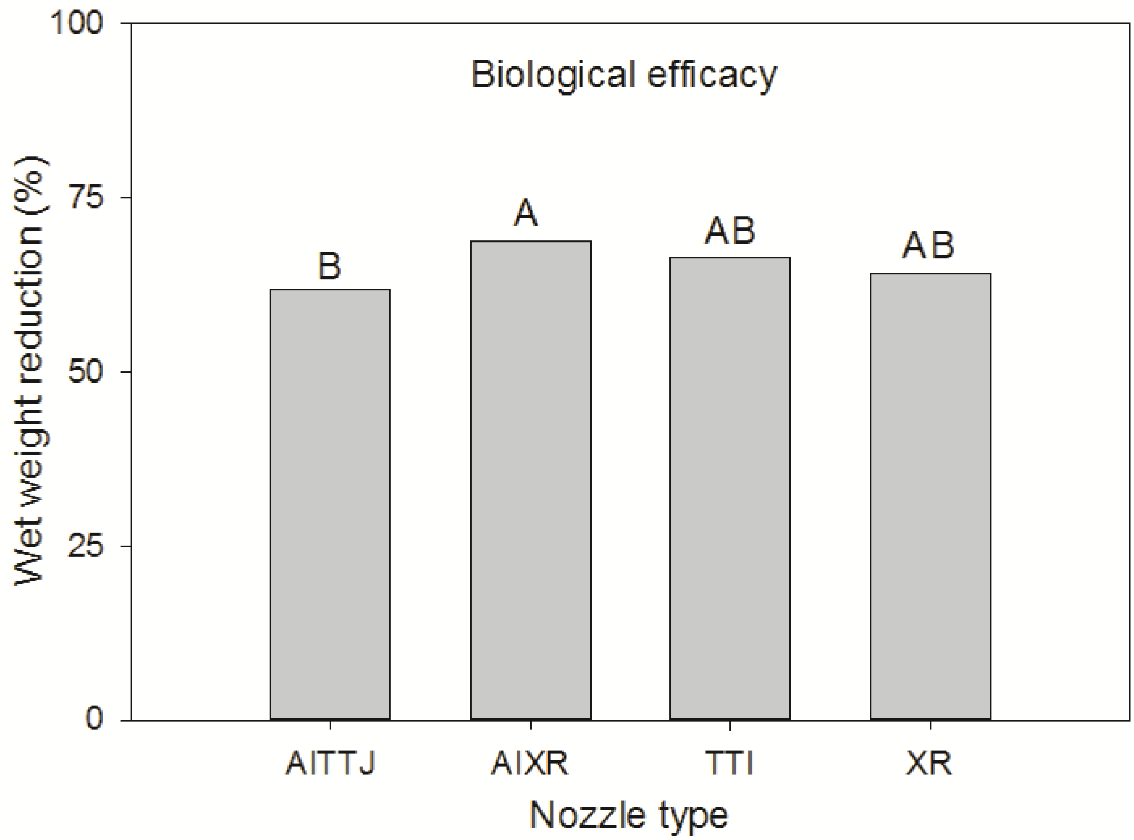

Figure 3.8. Wet weight reduction of biological indicator plants as influenced by nozzle type in a corn canopy. The spray mixture included two carrier volumes with and without a drift reduction adjuvant (DRT). Letters indicate significant differences (α=0.05) across nozzle type.

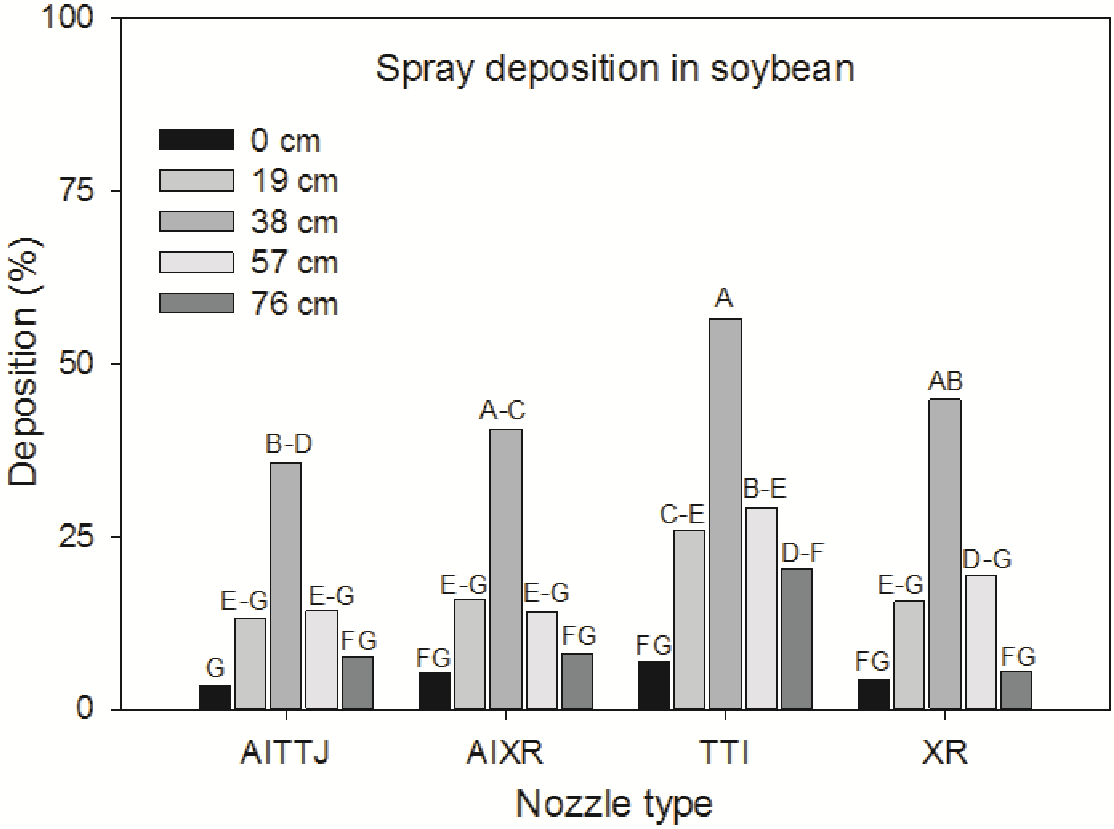

Figure 3.9. The interaction of collector position across a soybean row and nozzle type on spray deposition into a soybean canopy. Mylar card collectors were spaced at 0, 19, 38, 57, and 76 cm across the soybean row with the 0 and 76 cm positioned directly in the soybean rows. Letters indicate significant differences (α=0.05) collector position and nozzle type.

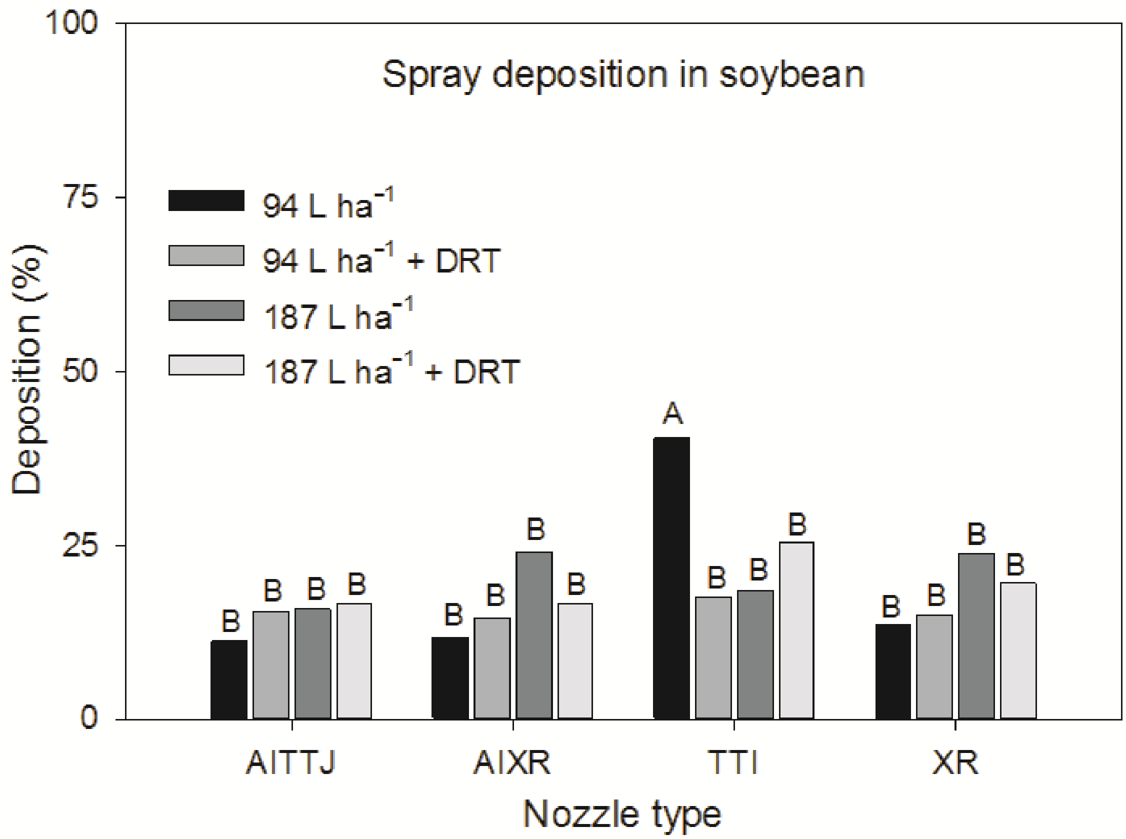

Figure 3.10. The interaction of spray mixture and nozzle type on spray deposition into a soybean canopy. The spray mixture included two carrier volumes with and without a drift reduction adjuvant (DRT). Letters indicate significant differences (α=0.05) across nozzle type and spray mixture.

CHAPTER 4

The Impact of Spray Droplet Size on the Efficacy of 2,4-D, Atrazine, Chlorimuron-methyl, Dicamba, Glufosinate, and Saflufenacil

Abstract

Herbicide application methods are generally less effective than they could as only a small amount of the active ingredients reach the intended targets. Consequently, environmental contamination and/or loss of profitability may occur. Selecting the appropriate application parameters and equipment can allow applicators to increase the efficiency of their applications. The objective of this research was to evaluate the effect of droplet size on the efficacy of six commonly used herbicides applied to different plant species. Atrazine (1.12 kg ai/ha), cloransulam-methyl (0.18 g ai/ha), dicamba (0.14 kg ae/ha), glufosinate (0.59 kg ai/ha), saflufenacil (12.48 g ai/ha), and 2,4-D (0.20 kg ae/ha) were applied using an XR11003 nozzle at 138, 276, and 414 kPa and a AI11003 nozzle at 207, 345, and 483 kPa. Each herbicide and nozzle/pressure combination was evaluated for droplet size spectra at the Pesticide Application Technology Lab, West Central Research and Extension Center, University of Nebraska-Lincoln in North Platte, NE. The treatments were applied at 131 L/ha to seven plant species. Results varied depending on the herbicide and the plant species. Control when using 2,4-D was observed to be generally greater for all species except common lambsquarters and in some instances soybean as droplet size increased. Control using atrazine was generally minor as droplet size changed and no clear pattern existed. An increase in efficacy may be achieved for most species evaluated if cloransulam-methyl is applied using Fine droplets. Dicamba and glufosinate efficacy was generally greatest when Medium and Very Coarse spray

droplets were used. Conversely, saflufenacil efficacy was generally greatest when using a Fine or Extremely Coarse spray. These results demonstrate the importance of selecting an appropriate nozzle and pressure to mitigate potential drift while maintaining the efficacy of the herbicide application.

Introduction

The introduction of herbicide-resistant crops was promoted as a way to simplify weed management and increase weed control efficacy (Martinez-Ghersa et al. 2003). The adoption of this technology may have also facilitated changes in crop production practices such as increased use of no-till and strip-till (Young 2009). Such changes in crop production systems and use of specific chemicals within a crop for weed control could increase grower dependence upon chemical weed control (Radosevich et al. 1992). Herbicide use has increased 240 million kilograms between 1996 and 2011 driven in large part by the adoption of herbicide-resistant crops (Benbrook 2012). As herbicide use increases, the likelihood of damage to neighboring crops or other sensitive plant species increases. Apart from not spraying on windy days or with high booms, increasing the spray droplet size is the most common approach to reduce off-target movement during herbicide application (Bird et al. 1996; Carlsen et al. 2006; Nuyttens et al. 2007b).

Atomization of liquids is commonly used in herbicide applications to deliver a lethal dose of chemical to the target plant species. A recent study by Creech et al. (2015a) concluded that nozzle type, operating pressure, herbicide solution, nozzle orifice size, and carrier volume, in order of greatest impact to least, all impact droplet size. Agricultural nozzles used for atomization today create a spectrum of droplets with varying diameters.

A herbicide spray application with a narrow droplet size distribution should be more efficient, as small droplets which are prone to particle drift and evaporation, and large droplets which can be poorly retained, are eliminated (Knoche 1994). To optimize a droplet size for a target species requires an understanding of the biology and morphology of the target species as well as an understanding how the herbicide best performs (Combellack 1984).

Numerous studies have been conducted on the effects of droplet size using different herbicides on select plant species and their results have been summarized in a meta-analysis (Knoche 1994). Of the studies evaluated by Knoche (1994), herbicide efficacy increased as droplet size decreased in 71% of the experiments, 22% had no change, and 7% had decreased efficacy. Small droplets provide greater coverage (Ramsdale and Messersmith 2001) than large droplets on plant surfaces which is especially important for contact-type herbicides (Hislop 1987; McKinlay et al. 1972; Merritt and Taylor 1977; Prokop and Veverka 2003). As droplet size decreased in the meta-analysis, efficacy of contact-type herbicides increased in 58% of the studies, had no change in 19%, and decreased in 23% (Knoche 1994). Similarly, systemic herbicide efficacy increased in 76% of the studied, had no change in 24%, and no studies had decreased efficacy (Knoche 1994). More recent research has found no change or increased efficacy of systemic herbicides as droplet size increased (Etheridge et al. 2001; Feng et al. 2003).

The appropriate droplet spectrum required for a herbicide depends on the amount of coverage needed and the size and structure of the target weed species (Derksen et al. 1999; Zhu et al. 2004). When a droplet impacts a plant surface, it will either be retained through adhesion, bounce, shatter, or roll off. Droplets that are not retained can continue through the canopy and may be retained on a lower leaf or may impact the ground (Schou et al. 2012). Monocotyledons predominantly have a vertical structure and are more likely to retain smaller droplets than larger droplets (Knoche 1994). Nairn et al. (2014) observed lower adhesion of droplets to hairy leaves due to an increase in the incidence of droplet shatter. Growing conditions can alter the wettability of a plant and decrease droplet retention on the leaf surface (Forster and van Leeuwen 2010). The ability of spray droplets to remain on a plant surface determines the quantity of herbicide potentially available to be taken up by the plant. Herbicide performance increased more frequently on difficult-to-wet species as droplet size decreased in the meta-analysis than easy-to-wet species (Knoche 1994).

Understanding the impacts of spray droplet size on herbicide efficacy is important as applicators move to increase droplet size as a means to mitigate herbicide drift. The objective of this study was to evaluate the effect of droplet size on the efficacy of six commonly used herbicides applied to different plant species that are either considered weeds or have characteristics of different weeds in either plant architecture and/or morphology.

Materials and Methods

A greenhouse study was conducted at the Pesticide Application Technology Laboratory (PAT Lab) located at the West Central Research and Extension Center in North Platte, NE. Soybean [*Glycine max* (L.) Merr.], tomato (*Solanum lycopersicum* L.), shattercane [*Sorghum bicolor* (L.) Moench ssp. arundinaceum (Desv.) de Wet & Harlan], corn (*Zea mays* L.), velvetleaf (*Abutilon theophrasti* Medik.), sunflower (*Helianthus annus* L.) and common lambsquarters (*Chenopodium album* L.) were grown in SC10 cone-tainer cells (Stuewe and Sons Inc., Corvallis, OR 97389) filled with Baccto Professional Grower's Mix (Michigan Peat Company, Houston, TX 77098) which is a growing Medium limed to 5.5 to 6.5 pH consisting of 75 to 85% sphagnum peat moss and 15 to 25% perlite. Plants were seeded at different intervals beginning in August through September of 2013 and were watered as needed. Plant received supplemental nutrition once per week by watering with Scotts Miracle-Gro® LiquaFeed® All Purpose (The Scotts Company, Marysville, OH, 43041) plant fertilizer. The experiment was conducted twice, separated temporally; representing two experimental runs. Treatments were applied throughout October and November, when plants reached a height of 15 cm, using a generation III single track research spray chamber (DeVries Manufacturing, Hollandale, MN 56045). The materials used described in Table 4.1 and application parameters described in Table 4.2 were used to apply the treatments to the greenhouse study. Corn, shattercane, and soybean had two, four, and five herbicides applied, respectively, because not all of the herbicides evaluated were effective at controlling these species. Visual estimations of control were collected at 7, 14, and 28 days after treatment (DAT) using a scale of 0 to 100% where 0 = no control and 100 = plant death. At 28 DAT, plants were clipped at the soil surface and fresh weights were recorded. These samples were then dried and dry weights were recorded.

The spray droplet spectrum for each herbicide and carrier volume combination was evaluated using the low speed wind tunnel at the PAT Lab in North Platte, NE. 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). The laser is controlled by WINDOX 5.7.0.0 software (Sympatec Inc., Clausthal, Germany) which was operated on a computer adjacent to the wind tunnel. This lens is capable of detecting droplets in a range from 9 to 3700 µm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser and a receiver housing containing the lens and detector element. The two laser housings were separated (1.2 m) on each side of the wind tunnel and mounted on an aluminum optical bench rail that connected underneath of the wind tunnel to ensure proper laser alignment. The spray plume was oriented perpendicular to the laser beam and traversed through the laser beam by means of a mechanical linear actuator. The actuator would move the nozzle at a constant speed of 0.2 m/s such that the entire spray plume would pass through the laser beam. The distance from the nozzle tip to the laser was 30 cm. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by ASAE 572.1 (ASABE 2009) (Table 4.3). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Statistical Analysis. The experiment was arranged as a randomized complete block design with five replications. Each species was analyzed separately because treatments were applied separately to each species. The analysis of visual control data was completed using repeated measures which allowed for pooling of means over rating intervals. The Akaike information criterion with a correction for finite sample sizes (AICc) was used, as suggested by Burnham and Anderson (2002), to select the appropriate covariance model to use in the repeated measure analysis. The AICc indicated the default covariance model used by GLIMMIX fit the data the best and was therefore used in the analysis. Replication nested within run was designated as a random effect in the model.

Percent biomass reduction for treated experimental units was calculated using both the fresh and dry weights relative to the average biomass of the non-treated control plants in each study as:

$$Percent\ biomass\ reduction = \left((\bar{C} - B/\bar{C})\right) 100\ [1]$$

where $\bar{C}$ is the mean biomass of the non-treated control replicates, and B is the biomass of an individual experimental unit after being treated. Values for biomass reduction were compared using a generalized linear mixed model analysis of variance (GLIMMIX) procedure of SAS (Littell et al. 2006). Replication nested within run was designated as a random effect in the model. LS means for both estimation of visual control and weight reductions were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

2,4-D. Fine to Medium sprays (Table 4.3) controlled common lambsquarters better than Very Coarse droplets (Table 4.4). Ennis and Williamson (1963) also observed a reduction in common lambsquarters control with 2,4-D as droplet size increased from 75 to 240 µm. Differences in common lambsquarters control is likely as a result of the structure of the leaf surface, which is composed of crystalline epicuticular wax, which makes it difficult to wet (Harr et al. 1991) such that larger spray droplets would not remain on the leaf surface as easily as smaller droplets. Common sunflower control was very high with all treatments, and as a result, few differences were observed as droplet size increased (Table 4.4). The Very Coarse spray (AI nozzle at the low operating pressure) had greater control than the Medium spray (XR nozzle at the high pressure) (Table 4.3 and 4.4). Similarly, McKinlay et al. (1972) reported diminishing control of common sunflower as 2,4-D droplet size increased from 100 to 400 μm. Soybean control was greatest with Very Coarse sprays and control decreased with Fine and Extremely Coarse sprays (Table 4.4). Tomato wet weight reduction (WWR) of 91% and dry weight reduction (DWR) of 79% resulting from Extremely Coarse spray treatments were greater than the WWR (66%) and DWR (58%) of the Very Coarse spray applications (Table 4.4). The only significant difference in control observed with velvetleaf was between the Fine (XR @276 kPa) and Very Coarse (AI @ 345 kPa) sprays which rated at 60 and 72%, respectively (Table 4.4). Generally, greater control when using 2,4-D was observed to be generally greater for all species except common lambsquarters and in some instances soybean when droplet size was increased.

Atrazine. Atrazine had a high level of control when applied to common lambsquarters and common sunflower and no differences in control were observed as droplet size increased (Table 4.5). Shattercane control was greatest when applied using a Medium spray, with a visual control rating of 11% (Table 4.5). Fine spray applications (XR @ 276 kPa) had the lowest WWR and DWR at 87 and 89%, respectively (Table 4.5). Medium spray application resulted in the lowest control ratings, WWR, and DWR for tomatoes, with the exception of the WWR and DWR resulting from a Fine spray (XR @ 276 kPa) for which there was no statistical difference (Table 4.5). Velvetleaf had a maximum rating of 81% with a Coarse spray (Table 4.5). Atrazine's dependence on droplet size tends to be less than the other herbicides evaluated in this research. Although some differences were observed, they were generally minor with no clear pattern emerging.

Cloransulam-methyl. Cloransulam-methyl had a visual control rating of 18% when applied using Fine sprays but only 9% control when applications were made using Extremely Coarse sprays (Table 4.6). Control results of common sunflower showed no consistent pattern relative to spray classification used (Table 4.6). Shattercane and tomato showed greatest control when Fine sprays (XR @ 414 kPa) were used; however, these differences were not as prevalent in the WWR and DWR data (Table 4.6). Only significant differences in the WWR were observed with 81% control resulting from Medium spray applications compared to only 63% control with Fine spray applications (Table 4.6). Sikkema et al. (2008) reported no difference in cloransulam-methyl efficacy when applied using a flat fan nozzle that produced small droplets and an air induction nozzle that produced larger droplets when applied to common lambsquarters or velvetleaf. In most instances, our data suggest that an increase in efficacy may be achieved for most species if cloransulam-methyl is applied using small droplets but the data is highly variable.

Dicamba. Dicamba applications to common lambsquarters had a rating of 40% using a Medium spray which was greater than the 31% rating from the largest Extremely Coarse spray (Table 4.7). The finest spray had the least control of common sunflower with a rating, WWR, and DWR of 84, 94, and 75%, respectively (Table 4.7). Soybean control was also greater in some instances when using a Medium spray (WWR at 85%) or a Very

Coarse spray (DWR at 74%) (Table 4.7). Similarly, tomato control was greatest when applied using a Very Coarse spray (85%) and decreased when Fine (74 and 73%) and Extremely Coarse (72%) were used (Table 4.7). No difference in velvetleaf control was observed as droplet size changed in response to dicamba (Table 4.7). For all the species where a difference in efficacy was observed, dicamba efficacy was generally greatest when Medium and Very Coarse spray droplets were used (Table 4.7). Dicamba can cause severe injury to neighboring susceptible species if moved off-target by particle drift (Weidenhamer et al. 1989). Environmental concerns and liability for off-target dicamba particle drift has driven applicators to implement drift reduction practices to mitigate the potential for drift. Increasing the spray droplet size can minimize off-target herbicide movement (Etheridge et al. 1999). Our results indicate that a reduction in dicamba efficacy can occur if the spray droplet size is too large. Thus, a balance between mitigating drift and dicamba efficacy should be considered. Using drift reduction technologies that produce a narrow droplet size distribution and reduce fine droplets that are prone to drift and large droplets that are may be detrimental to efficacy is recommended.

Glufosinate. No difference in control was observed using glufosinate as the spray classification changed for either common sunflower or velvetleaf (Table 4.8). Shattercane and soybean had differences in the ratings only. Glufosinate applied to shattercane using a Very Coarse spray (AI nozzle @ 483 kPa) had a greater rating (97%) than the Medium spray and the Very Coarse spray which both had ratings of 93% (Table 4.8). The Extremely Coarse spray applied to soybean (78%) was greater than Fine sprays and Very Coarse sprays that had ratings near 63% (Table 4.8). Corn and tomato had increasing control as droplet size increased in most instances with corn having the greatest control using an Extremely Coarse droplet (Table 4.8). Common lambsquarters had reduced control using a Very Coarse spray and continued the trend of having greater control using smaller spray qualities (Table 4.8). Glufosinate is a non-selective herbicide normally characterized as a contact herbicide due to its limited translocation within a plant indicating the adequate coverage is an important aspect to achieve control. Etheridge et al. (2001) found droplet size to be negatively correlated with glufosinate and paraquat performance. Creech et al. (2015b) suggested using a carrier volume of 140 L ha^{-1} and making application with Medium to Coarse sprays when applying glufosinate. The results in Table 4.8 generally support that assertion that applying glufosinate within that range will provide favorable results for most target weed species.

Saflufenacil. Saflufenacil provided excellent control of common sunflower, tomato, and velvetleaf (Table 4.9) at each spray classification evaluated. The only major difference observed was at Medium spray quality on velvetleaf (81% DWR) which was less than the Fine spray (95% DWR) (Table 4.9). In addition, common lambsquarters and shattercane had no differences in saflufenacil control as droplet size increased (Table 4.9). Corn had greatest control using Extremely Coarse droplets, though not different than the finest droplets applied (78 and 64% DWR, respectively) (Table 4.9). Soybean control with saflufenacil was greatest using a Very Coarse spray (Table 4.9). The effects of spray qualities on the efficacy of saflufenacil are less than most of the other herbicides evaluated in this research.

This research highlights the specificity needed to maximize herbicide efficacy through proper selection of spray classification for different plant species and how it changes among herbicides. Decisions on which spray droplet spectrum to use for a herbicide application should be based on mitigating off-target particle drift and the weed species that are in the target area. Excessively focusing on reducing spray drift by increasing the spray droplet size may result in unsatisfactory control of specific weed species. For example, dicamba can cause severe injury to neighboring plants due to off-target movement. For this reason, applicators should apply dicamba using large spray qualities that reduce drift. However, our results indicate a reduction in efficacy when droplets in dicamba sprays get too large. Thus, using herbicide application technologies that minimize the volume of fine droplets in dicamba applications to reduce the risk of off-target movement yet also minimize excessively large droplets in the spray that are less efficacious should be utilized. Understanding the factors that impact droplet size and the ideal droplet size for specific herbicides and weed species will aid in the decision making process of applicators when considering the most efficacious manner to apply a herbicide treatment.

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Table 4.1. Source of materials used to evaluate the impact of spray droplet size on herbicide efficacy.

Common name	Trade name	Treatment rate	Manufacturer
2,4-D	2,4-D LV4®	0.20 kg ae/ha	Winfield Solutions, LLC, St. Paul, MN, 55164
Atrazine	AAtrex 4L®	1.20 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, 27419
Cloransulam-methyl	FirstRate®	0.18 g ai ha^{-1}	Dow AgroSciences LLC, Indianapolis, IN, 46268
Dicamba	Clarity®	0.14 kg ae ha^{-1}	BASF Corporation, Research Triangle Park, NC, 27709
Glufosinate	Liberty®	0.59 kg ai ha^{-1}	Bayer Crop Science LP, Durham, NC, 27709
Saflufenacil	Sharpen®	12.48 g ai ha^{-1}	BASF Corporation, Research Triangle Park, NC, 27709
Ammonium sulfate	Bronc®	5.00% v/v[a]	Wilbur-Ellis Company, Fresno, CA, 94596
Crop oil concentrate	R.O.C. ®	1.00% v/v [b]	Wilbur-Ellis Company, Fresno, CA, 94596
Non-ionic surfactant	R-11®	0.25% v/v [c]	Wilbur-Ellis Company, Fresno, CA, 94596
Methylated seed oil	Super Spread®	1.00% v/v [d]	Wilbur-Ellis Company, Fresno, CA, 94596

[a] Ammonium sulfate was added to glufosinate and saflufenacil.

[b] Crop oil concentrate was added to atrazine and cloransulam-methyl.

[c] Non-ionic surfactant was added to 2,4-D and dicamba.

[d] Methylated seed oil was added to saflufenacil.

Table 4.2. Application parameters used to achieve different ranges in application droplet size.

Nozzle type	Pressure	Application speed	Application volume
	kPa	km h^{-1}	L ha^{-1}
XR11003[a]	414	7.8	132
XR11003	276	6.4	132
XR11003	138	4.5	132
AI11003	483	8.9	132
AI11003	345	7.2	132
AI11003	207	5.6	132

[a] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.3. Spray volume diameters below which droplets of equal or smaller size constitute 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume, percent spray volume less than 141 μm, relative span, and classification category for each herbicide and treatment combination used in this study. The relative span is a dimensionless parameter indicative of the uniformity of the distribution of the droplet sizes of the spray.

			Spray droplet distribution				Relative span	Classification category[a]
Herbicide	Nozzle	Pressure	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	V<141		
		kPa	μm			%		
2,4-D	XR11003[b]	414	111	219	351	18.9	1.09	F
	XR11003	276	128	246	389	13.3	1.06	F
	XR11003	138	160	303	468	6.7	1.02	M
	AI11003	483	244	462	694	1.7	0.97	VC
	AI11003	345	275	518	795	1.0	1.00	VC
	AI11003	207	327	613	920	0.5	0.97	XC
Atrazine	XR11003	414	115	225	353	17.3	1.06	F
	XR11003	276	133	257	394	11.6	1.01	F
	XR11003	138	174	325	475	5.4	0.93	M
	AI11003	483	234	451	688	2.5	1.01	C
	AI11003	345	270	505	752	1.5	0.95	VC
	AI11003	207	336	608	880	0.6	0.89	XC
Cloransulam-methyl	XR11003	414	117	228	355	16.7	1.05	F
	XR11003	276	137	262	403	10.9	1.02	F
	XR11003	138	180	331	482	4.9	0.91	M
	AI11003	483	254	472	693	1.8	0.93	VC
	AI11003	345	293	533	794	1.1	0.94	VC
	AI11003	207	360	637	908	0.5	0.86	XC

Dicamba	XR11003	414	93	204	348	26.0	1.25	F
	XR11003	276	103	229	390	20.8	1.25	F
	XR11003	138	127	279	465	13.0	1.21	M
	AI11003	483	245	491	770	2.1	1.07	VC
	AI11003	345	270	539	819	1.5	1.02	XC
	AI11003	207	332	653	989	0.7	1.01	XC
Glufosinate	XR11003	414	78	186	333	32.4	1.37	F
	XR11003	276	87	206	359	27.0	1.32	F
	XR11003	138	114	250	420	16.6	1.22	M
	AI11003	483	225	470	762	2.9	1.14	VC
	AI11003	345	248	516	816	2.3	1.10	VC
	AI11003	207	302	628	978	1.3	1.08	XC
Saflufenacil	XR11003	414	113	224	352	17.8	1.07	F
	XR11003	276	133	257	398	11.8	1.03	F
	XR11003	138	173	324	478	5.3	0.94	M
	AI11003	483	240	456	679	2.0	0.96	VC
	AI11003	345	277	514	770	1.2	0.96	VC
	AI11003	207	340	622	916	0.5	0.93	XC

[a] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, and XC= Extremely Coarse.

[b] Teejet Technologies, Spraying Systems Co., Wheaton, IL 627 03.

Table 4.4. Response of different species to 2,4-D applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			2,4-D[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa	%		
Common lambsquarters	XR11003[d]	414	47 ab	48	55
	XR11003	276	49 a	47	54
	XR11003	138	51 a	40	57
	AI11003	483	46 ab	39	49
	AI11003	345	42 b	32	43
	AI11003	207	48 ab	40	52
Common sunflower	XR11003	414	92 ab	97	84
	XR11003	276	94 ab	99	94
	XR11003	138	90 b	96	83
	AI11003	483	95 a	99	91
	AI11003	345	94 ab	98	91
	AI11003	207	93 ab	98	91
Soybean	XR11003	414	40 c	27 b	25 b
	XR11003	276	44 cb	40 b	37 ab
	XR11003	138	46 abc	28 b	26 b
	AI11003	483	56 a	43 a	40 a
	AI11003	345	51 ab	37 b	32 ab
	AI11003	207	46 cb	28 b	27 b
Tomato	XR11003	414	68	80 abc	68 bc
	XR11003	276	74	88 ab	72 ab
	XR11003	138	69	78 bc	62 bc
	AI11003	483	75	77 bc	69 abc
	AI11003	345	64	66 c	58 c
	AI11003	207	76	91 a	79 a
Velvetleaf	XR11003	414	67 ab	41	37
	XR11003	276	60 b	46	42
	XR11003	138	61 ab	42	36
	AI11003	483	69 ab	50	46
	AI11003	345	72 a	52	36
	AI11003	207	67 ab	44	38

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.5. Response of different species to atrazine applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			Atrazine[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa	%		
Common lambsquarters	XR11003[d]	414	93	95	90
	XR11003	276	94	96	91
	XR11003	138	94	97	93
	AI11003	483	93	97	94
	AI11003	345	94	97	93
	AI11003	207	94	98	93
Common sunflower	XR11003	414	98	99	95
	XR11003	276	98	99	96
	XR11003	138	98	100	98
	AI11003	483	98	99	97
	AI11003	345	98	99	96
	AI11003	207	98	100	97
Shattercane	XR11003	414	8 b	22 ab	26 ab
	XR11003	276	7 b	20 ab	28 ab
	XR11003	138	11 a	28 a	33 a
	AI11003	483	7 b	14 b	16 b
	AI11003	345	7 b	18 ab	19 ab
	AI11003	207	7 b	22 ab	27 ab
Soybean	XR11003	414	91	94 a	96 a
	XR11003	276	86	87 b	89 b
	XR11003	138	92	95 a	93 ab
	AI11003	483	92	96 a	96 a
	AI11003	345	90	92 ab	93 ab
	AI11003	207	93	96 a	95 ab
Tomato	XR11003	414	71 a	91 a	90 a
	XR11003	276	65 a	82 ab	81 ab
	XR11003	138	42 b	69 b	70 b
	AI11003	483	80 a	94 a	91 a
	AI11003	345	70 a	92 a	89 a
	AI11003	207	81 a	95 a	92 a

Velvetleaf	XR11003	414	78 ab	67	73
	XR11003	276	77 ab	68	74
	XR11003	138	71 b	56	61
	AI11003	483	81 a	58	60
	AI11003	345	72 b	66	70
	AI11003	207	77 ab	62	68

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.6. Response of different species to cloransulam-methyl applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			Cloransulam-methyl[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa		%	
Common lambsquarters	XR11003[d]	414	18 a	8	12
	XR11003	276	14 ab	7	11
	XR11003	138	11 ab	6	12
	AI11003	483	10 ab	4	6
	AI11003	345	10 ab	13	18
	AI11003	207	9 b	12	15
Common sunflower	XR11003	414	97	99	94 a
	XR11003	276	95	98	89 ab
	XR11003	138	96	99	92 ab
	AI11003	483	97	98	87 b
	AI11003	345	97	99	94 a
	AI11003	207	96	99	92 ab
Shattercane	XR11003	414	30 a	55 a	59 a
	XR11003	276	12 b	18 b	26 b
	XR11003	138	18 b	32 ab	40 ab
	AI11003	483	11 b	26 b	33 ab
	AI11003	345	16 b	32 ab	42 ab
	AI11003	207	17 b	25 b	28 b
Tomato	XR11003	414	69 a	85 a	83 a
	XR11003	276	51 b	67 b	68 b
	XR11003	138	52 b	75 ab	76 ab
	AI11003	483	54 b	77 ab	77 ab
	AI11003	345	48 b	75 ab	77 ab
	AI11003	207	51 b	80 ab	77 ab
Velvetleaf	XR11003	414	82	72 ab	69
	XR11003	276	79	63 b	62
	XR11003	138	83	81 a	71
	AI11003	483	82	68 ab	67
	AI11003	345	86	76 ab	70
	AI11003	207	86	72 ab	70

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.7. Response of different species to dicamba applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			Dicamba[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa	%		
Common lambsquarters	XR11003[d]	414	34 bc	35	49
	XR11003	276	38 ab	31	41
	XR11003	138	40 a	31	46
	AI11003	483	35 bc	25	39
	AI11003	345	37 bc	35	45
	AI11003	207	31 c	29	41
Common sunflower	XR11003	414	84 b	94 b	75 b
	XR11003	276	95 a	99 a	92 a
	XR11003	138	92 ab	97 ab	82 ab
	AI11003	483	95 a	99 a	91 a
	AI11003	345	93 a	97 ab	86 ab
	AI11003	207	92 ab	96 ab	83 ab
Soybean	XR11003	414	73	78 ab	65 b
	XR11003	276	73	74 ab	66 ab
	XR11003	138	81	85 a	70 ab
	AI11003	483	78	83 ab	74 a
	AI11003	345	73	72 b	67 ab
	AI11003	207	77	80 ab	67 ab
Tomato	XR11003	414	74 b	65	71
	XR11003	276	73 b	63	71
	XR11003	138	79 ab	75	77
	AI11003	483	85 a	83	81
	AI11003	345	77 ab	70	67
	AI11003	207	72 b	71	69
Velvetleaf	XR11003	414	32	25	26
	XR11003	276	32	22	28
	XR11003	138	32	25	26
	AI11003	483	35	22	24
	AI11003	345	31	21	26
	AI11003	207	41	32	33

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.8. Response of different species to glufosinate applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			Glufosinate[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa		%	
Common lambsquarters	XR11003[d]	414	97 a	95 a	90 a
	XR11003	276	93 abc	95 a	91 a
	XR11003	138	85 c	86 a	86 a
	AI11003	483	89 bc	89 a	85 a
	AI11003	345	72 d	63 b	60 b
	AI11003	207	94 ab	94 a	90 a
Common sunflower	XR11003	414	97	99	95
	XR11003	276	97	99	95
	XR11003	138	98	99	94
	AI11003	483	98	100	97
	AI11003	345	98	99	94
	AI11003	207	97	99	94
Corn	XR11003	414	60 b	83 ab	87
	XR11003	276	59 b	81 ab	85
	XR11003	138	64 b	83 ab	86
	AI11003	483	69 ab	80 b	82
	AI11003	345	66 b	86 ab	89
	AI11003	207	77 a	95 a	91
Shattercane	XR11003	414	95 abc	94	93
	XR11003	276	94 abc	91	90
	XR11003	138	93 c	92	87
	AI11003	483	97 a	98	95
	AI11003	345	93 bc	89	88
	AI11003	207	97 ab	98	96
Soybean	XR11003	414	65 bc	58	59
	XR11003	276	63 bc	48	50
	XR11003	138	70 abc	52	55
	AI11003	483	76 ab	70	68
	AI11003	345	62 c	42	47
	AI11003	207	78 a	62	64

Tomato	XR11003	414	85 b	91 ab	88 ab
	XR11003	276	88 ab	89 b	80 b
	XR11003	138	92 ab	97 a	92 a
	AI11003	483	94 a	97 ab	94 a
	AI11003	345	85 b	93 ab	87 ab
	AI11003	207	92 ab	97 a	94 a
Velvetleaf	XR11003	414	72 c	40 b	42 b
	XR11003	276	82 b	50 ab	50 ab
	XR11003	138	81 b	50 ab	49 ab
	AI11003	483	90 a	64 a	68 a
	AI11003	345	85 ab	55 ab	56 ab
	AI11003	207	87 ab	59 ab	59 ab

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 4.9. Response of different species to saflufenacil applied in increasing spray droplet sizes using different nozzles and pressures conducted in a greenhouse experiment in North Platte, NE. The spray droplet classification increased from Fine with the XR nozzle at 414 kPa to Extremely Coarse with the AI nozzle at 207 kPa.

			Saflufenacil[a]		
Species	Nozzle	Pressure	Rating	WWR[b]	DWR[c]
		kPa			
Common lambsquarters	XR11003[d]	414	61	52	60
	XR11003	276	60	51	54
	XR11003	138	59	66	72
	AI11003	483	58	62	66
	AI11003	345	56	52	54
	AI11003	207	60	64	68
Common sunflower	XR11003	414	99	100	99
	XR11003	276	99	100	98
	XR11003	138	99	100	98
	AI11003	483	99	100	98
	AI11003	345	99	100	99
	AI11003	207	99	100	98
Corn	XR11003	414	40 ab	55 ab	64 ab
	XR11003	276	32 b	38 b	49 b
	XR11003	138	34 b	48 b	59 b
	AI11003	483	37 b	41 b	52 b
	AI11003	345	39 b	47 b	57 b
	AI11003	207	49 a	68 a	78 a
Shattercane	XR11003	414	41	57	59
	XR11003	276	39	54	59
	XR11003	138	40	49	52
	AI11003	483	44	64	66
	AI11003	345	46	65	68
	AI11003	207	38	55	59
Soybean	XR11003	414	53 ab	28 b	28 b
	XR11003	276	43 c	28 b	27 b
	XR11003	138	45 bc	30 b	30 b
	AI11003	483	50 bc	35 ab	37 ab
	AI11003	345	69 a	55 a	53 a
	AI11003	207	42 c	18 b	20 b

Tomato	XR11003	414	98 a	98 ab	92
	XR11003	276	96 b	96 b	92
	XR11003	138	98 a	99 a	93
	AI11003	483	98 a	99 a	95
	AI11003	345	98 a	99 a	95
	AI11003	207	98 a	99 a	96
Velvetleaf	XR11003	414	99	99	95 a
	XR11003	276	99	97	90 ab
	XR11003	138	99	95	81 b
	AI11003	483	99	97	86 ab
	AI11003	345	99	96	84 ab
	AI11003	207	99	96	88 ab

[a] Means within each species and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

[d] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

CHAPTER 5

Performance of Post-Emergent Herbicides Applied at Different Carrier Volume Rates

Abstract

Post-emergent weed control in soybean in the United States is difficult as weed resistance to herbicides has become more prominent. Herbicide applicators have grown accustomed to low carrier volume rates that are typical with glyphosate applications. These low carrier volumes are efficient for glyphosate applications and allow applicators to treat a large number of hectares in a timely manner. Alternative modes-of-action may require greater carrier volumes to effectively control weeds. Glyphosate, glufosinate, lactofen, fluazifop-P, and 2,4-D were evaluated in field and greenhouse studies using 47, 70, 94, 140, 187, and 281 L ha^{-1} carrier volumes. Spray droplet size spectra for each herbicide and carrier volume combination were also measured and used to determine their impact on herbicide efficacy. Glyphosate efficacy was maximized using 70 to 94 L ha^{-1} carrier volumes using droplets classified as Medium. Glufosinate efficacy was maximized at 140 L ha^{-1} and decreased as droplet diameter decreased. For 2,4-D applications, efficacy increased when using carrier volumes equal to or greater than 94 L ha^{-1}. Lactofen was most responsive to changes in carrier volume and performed best when applied in carrier volumes of at least 187 L ha^{-1}. Carrier volume had little impact on fluazifop-P efficacy in this study and efficacy decreased when used on taller plants. Based on the data, applicators should use greater carrier volumes when using contact herbicides in order to maximize herbicide efficacy.

Introduction

Weed control using foliar-applied herbicides requires impaction and retention of spray droplets on the target plant surface (Hislop 1987). Previous studies have established that herbicide spray applications are effective yet could be more efficient because in many cases only a small fraction of the active ingredient applied is necessary to achieve the biological response desired in the targeted plants (Caseley et al. 1990; Graham-Bryce 1977; Matthews 1977). Generally, herbicide performance is directly related to the amount of active ingredient on the target plant. Thus, spray solution characteristics and application parameters are critical in determining the efficacy of a herbicide application. The carrier volume of a foliar-herbicide application is one of the components of a spray solution that can impact herbicide performance (Knoche 1994). The influence of carrier volume on the efficacy of foliar-herbicides needs to be understood to make the most effective applications possible.

The adoption of glyphosate-resistant soybeans [*Glycine max* (Merr.) L.] has been extremely rapid increasing from 17% of US soybean hectares in 1997 to 68% in 2001 and 93% in 2010 (Fernandez-Cornejo et al. 2014). Reliance on this technology has reduced the use of integrated weed management practices, such as tillage and use of other mode-of-action herbicides in many crop production systems (Shaner 2000). Glyphosate-resistant technology simplified weed management and reduced herbicide expense for soybean producers by allowing application of a non-selective herbicide postemergence to soybean (Shaner 2000). Glyphosate-resistant weeds have since evolved at a high rate due to selection pressure applied to weed populations by the extensive use of glyphosate within corn, soybean, and cotton production systems (Johnson et al. 2009). In response to increasing glyphosate resistance, alternative weed management strategies are being incorporated that use various herbicide modes-of-action. This includes development of dicamba-resistant, 2,4-D-resistant, and HPPD-inhibitor-resistant soybeans that are being developed by U.S. companies and will soon be available to growers pending regulatory approval. Once approved, the dicamba-, 2,4-D-, and HPPD-resistant technology will enable the use of dicamba, 2,4-D, or HPPD-inhibitors with glyphosate tank-mixtures for preplant burndown, at planting, and in-season applications (Davis 2012).

Glyphosate has developed into a global herbicide because it allows low cost and effective weed control while being relatively environmentally benign (Baylis 2000). One component of glyphosate applications that increased its adoption among applicators was that plant response and subsequent control often increased as carrier volumes decreased whereas the performance of other herbicides generally decreases as carrier volume decreases (Knoche 1994). Herbicide programs that rely primarily on glyphosate for weed control often used carrier rates as low as 50 L ha^{-1} and in some instances less. This is a benefit to the applicator because the amount of water and time required for an application is reduced and more hectares are sprayed with each tank load. Conversely, many herbicides other than glyphosate often need a higher carrier volume for maximum efficacy. Applications that minimize carrier volumes to maximize the hectares sprayed with each tank may have a negative consequence because low volume applications usually require smaller orifice nozzles that, in turn, produce finer spray droplets and increase the potential for spray drift (van de Zande et al. 2003) unless drift reduction technologies are used such as low release heights.

Spray applications are complex processes beginning in the spray tank with the spray solution and continue until the herbicide reaches the target. Major components of this process that impact the efficacy of the application include the tank-mixtures, droplet formation, droplet travel to the plant, impaction and retention on the leaf or soil surface, uptake of the active ingredient, and the biological response (Brazee et al. 1991; Merritt et al. 1989; Reichard 1988). At any stage in the process, something could occur that has an effect on subsequent stages in the process and spray performance may be affected. In a meta-analysis of 110 previously published studies, Knoche (1994) reported decreasing carrier volume at constant droplet size increased herbicide efficacy in 24% of the experiments, 32% were unaffected by decreasing carrier volume, and in 44% of the experiments, reduced efficacy was observed due to decreasing carrier volume. Knoche (1994) concluded that carrier volume effects are dependent upon the herbicide being applied.

The primary objective of this study was to determine the influence of carrier volume on the biological efficacy of four different postemergence herbicides commonly used for weed control in soybean, each with a differing mode of action. The secondary objective was to evaluate the droplet size spectrum of each treatment in order to further understand efficacy data.

Materials and Methods

Spray Droplet Data Collection. The spray droplet size spectrum for each herbicide and carrier volume combination was evaluated in a low speed wind tunnel at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and

Extension Center in North Platte, NE. The wind tunnel uses an axial flow fan to generate and move air flow from the fan into an expansion chamber, through a honeycomb straightener for laminar air flow, and then through eight 1.2 x 1.2 x 2.4 m adjoining sections. The droplet size spectrum for each treatment was measured using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) positioned on the last section of the tunnel downwind from the fan. The laser was linked with WINDOX 5.7.0.0 software (Sympatec Inc., Clausthal, Germany) operated on a computer adjacent to the laser. The R7 lens measured droplets in a dynamic size range from 0.5 to 3750 μm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser and a receiver housing containing the lens and detector element. The two laser housings were separated (1.3 m) on each side of the wind tunnel and mounted on an aluminum optical bench rail that connected underneath the wind tunnel to allow proper laser alignment. The spray plume was oriented perpendicular to the laser beam and was entirely traversed through the laser beam at 0.2 m/s using a mechanical linear actuator. The distance from the nozzle tip to the laser was 30 cm. A scrubber system and axial flow fan were attached to the last section to remove spray droplets and vapors from the exhausted air that passed through the wind tunnel. The laser measures light diffraction from all spray particles crossing its beam. The WINDOX computer software is able to classify the spray droplet spectrum in a number of different categories to compare the spray droplet spectra of different treatments. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by ASAE S572.1 (ASABE 2009) (Table 5.3 and 5.4). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Field Studies. Field studies were conducted at sites near Brule, David City, Lexington, O'Neill, and Platte Center, Nebraska in 2012 to demonstrate the effect of different carrier volumes on the biological efficacy of commonly used soybean herbicides. Each field location was arranged as a randomized complete block design with four replications. The Brule site (41.16ºN, 102.02ºW) was located on a Kuma loam soil (fine-silty, mixed, superactive, mesic Pachic Argiustolls) located approximately 16.1 km north northeast of Big Springs, NE. The David City site (41.25ºN, 97.14ºW) was located on a Hastings silt clay loam soil (fine, smectitic, mesic Udic Argiustolls) located approximately 0.8 km west of David City, NE. The Lexington site (40.82ºN, 99.74ºW) was located on a Rusco silt loam soil (fine-silty, mixed, superactive, mesic Oxyaquic Argiustoll) located approximately 3.2 km north of Lexington, NE. The O'Neill site (42.47ºN, 98.59ºW) was located on a O'Neill fine sandy loam soil (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplustoll) located approximately 4.8 km northeast of O'Neill, NE. The Platte Center site (41.52ºN, 97.49ºW) was located on a Shell silt loam soil (fine-silty, mixed, superactive, mesic Cumulic Haplustolls) located approximately 1.6 km south of Platte Center, NE.

The Brule location had a natural emerging population of kochia [*Kochia scoparia* (L.) Schrad.] that was evenly distributed across the plots (15 to 25 plants m^{-2}). The Brule site also had Russian-thistle (*Salsola tragus* L.) present at 10 to 15 plants m^{-2}. The David

City site had a natural emerging population of confirmed glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) that was evenly distributed across the plots (20 to 30 plants m^{-2}). Glufosinate, glyphosate, lactofen, and 2,4-D (Table 5.1) were applied with five carrier volumes (Table 5.2) at each location. In addition, recommended adjuvants were added to each tank-mixture at the suggested labeled rates (Table 5.1). Treatments were applied using the operating parameters described in Table 5.2 using a CO_2-pressurized backpack sprayer with a six nozzle boom having nozzles spaced 50 cm apart and boom height at approximately 50 cm above the weed canopies. Each plot was approximately 3 m wide and 6.5 m long. The Brule location was treated when kochia and Russian-thistle were 10 to 20 cm tall and the David City location was treated when giant ragweed was approximately 5 to 8 cm tall. The treatments were the same as those used at the other locations described hereafter with the exception of the rate of glyphosate used (1.26 kg ae ha^{-1} in Brule and David City; 0.87 kg ae ha^{-1} in Lexington, O'Neill, and Platte Center) (Table 5.1). Visual estimations of control were collected at 14 and 28 days after treatment (DAT) using a scale of 0 – 100 where 0 = no control and 100 = plant death.

Plots at Lexington, O'Neill, and Platte Center were established by seeding glyphosate-susceptible corn (*Zea mays* L.) and soybean, grain-type amaranth (*Amaranthus hypochondriacus* L.), and velvetleaf (*Abutilon theophrasti* Medik.), in rows spaced 76 cm apart, on July 23, 20, and 19, respectively. These species were chosen because of seed availability, ease to germinate and grow in an uncontrolled field setting, wide range of physiological characteristics, and low disposition to persist in the field long-term. These species are also representative in morphology and biology of other weedy species that can be found in Nebraska soybean fields. Plots at these locations were irrigated as needed using a center pivot irrigation system to ensure uniform germination and growth. Treatments were applied as described previously on August 3 at the Platte Center and O'Neill sites and August 10 at Lexington site when the corn was approximately 20 cm tall and the other seeded species averaged 10 to 15 cm tall. Although corn and soybean were in treated plots, herbicide phytotoxicity to corn in 2,4-D plots and soybean in lactofen plots were not recorded. Plots were rated in the same manner as the Brule and David City locations.

Greenhouse Study. A greenhouse study was conducted at the PAT Lab using the same treatments and application parameters that were used in the field studies (Tables 5.1 and 5.2). In addition to the field treatments, Fluazifop-P, and another carrier volume, 280 L ha^{-1}, were used in the greenhouse study and noted in Tables 1 and 2. Fluazifop-P treatments were only applied to grass species and 2,4-D was only applied to broadleaf species. Corn, flax (*Linum usitatissimum* L.), grain amaranth, shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.)], soybean, tomato (*Solanum lycopersicum* L.), and velvetleaf were grown in SC10 cone-tainer cells (Stuewe and Sons Inc., Corvallis, OR 97389) filled with potting mix (Baccto Professional Grower's Mix, Michigan Peat Company, Houston, TX 77098) consisting of 75 to 85% sphagnum peat moss and 15 to 25% perlite with a pH of 5.5 to 6.5. Although flax and tomatoes are not considered weedy species, they were included because tomatoes are highly responsive to herbicides and flax has small leaves similar in morphology and biology to other weeds that can be found in Nebraska soybean fields. Plants were seeded at different intervals beginning in August through September of 2013 and were watered as needed. Plants received supplemental nutrition (Scotts Miracle-Gro® LiquaFeed® All Purpose, The

Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol^{TM} DS 300W, Illumitex, Austin, TX, 78735) was provided to ensure 14 h days. Herbicide treatments were applied at two growth stages when plants from each species were either 15 or 30 cm tall. The experiment was conducted twice, separated temporally; therefore, each species had two experimental runs for each height or four runs for each species. Treatments were applied throughout October and November using a single nozzle track sprayer (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN 56045). An individual plant in a cone-tainer was an experimental unit. Visual estimations of control were collected at 7, 14, and 28 DAT using the aforementioned scale of 0 to 100%. At 28 DAT, plants were destructively sampled by clipping the plant at the soil surface and recording the fresh weights. These samples were then dried at 40 C for 7 days following which dry weights were recorded.

Statistical Analysis. The droplet size spectrum analysis was conducted as a factorial arrangement of treatments within a randomized complete block design with three replications for each treatment combination. Each traverse of the spray pattern through the laser beam represented a replication and produced data for the droplet size parameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ in accordance to ASAE S572.1 (ASABE 2009). Droplet size spectrum data were analyzed using the PROC Mixed procedure (method = REML) (Littell et al. 2006) in SAS v9.3 (SAS Institute Inc., Cary, NC, 27513) with replication as the random variable. Mean treatment effects were compared using Tukey's studentized range test (HSD) at the 0.05 significance level. Tukey's HSD was used to reduce the chance of type I errors (Steel and Torrie 1980).

Control rating data from the field studies were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute, Cary, NC 27513). Non-treated controls were included in each field study for visual rating reference only and were not included in analysis of data. David City and Brule sites were each analyzed separately as each site had different weed species. Analysis for each site had replication designated as a random effect in the model. Lexington, O'Neill, and Platte Center control rating data were analyzed together with replication nested within location and considered a random effect as suggested by Carmer et al. (1989). The analysis was performed using repeated measures which allowed for pooling of means over rating intervals. The Akaike information criterion with a correction for finite sample sizes (AICc) was used, as suggested by Burnham and Anderson (2002), to select the appropriate covariance model to use in the repeated measure analysis. The AICc indicated the default covariance model used by GLIMMIX best fit the data and was used for repeated measure analysis conducted for both field and greenhouse studies. The Kenward-Rogers degree-of-freedom approximation procedure was used for the Lexington, O'Neill, and Platte Center analysis due to some instances of missing data. Pearson's correlation coefficient (r) was used to evaluate relationships between the response variables carrier volume and droplet size.

For the greenhouse study, treatments were applied to each weed species and size separately. Therefore, each species and size was analyzed separately. Each experiment was arranged as a randomized complete block design with five replications. Estimation of visual control data for the greenhouse studies had replication nested within run designated as a random effect in the model. Percent biomass reduction for treated experimental units was calculated using both the fresh and dry weights relative to the average biomass of the non-treated control plants in each study as:

$$Percent\ biomass\ reduction = \left((\bar{C} - B/\bar{C})\right) 100\ [1]$$

where $\bar{C}$ is the mean biomass of the non-treated control replicates, and B is the biomass of an individual experimental unit after being treated. Values for biomass reduction were compared using a generalized linear mixed model analysis of variance (GLIMMIX) procedure of SAS (Littell et al. 2006). LS means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

Droplet Size. A significant herbicide by carrier volume interaction of spray droplet size was present ($P < 0.001$) for the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ droplet size parameters. Estimated means from each of the droplet size parameters were sorted by herbicide to simplify the presentation of results (Table 5.4). The largest $D_{v0.5}$ values were observed at the highest application volume rate (281 L ha^{-1}) for all herbicides tested except lactofen and glufosinate which had similar $D_{v0.5}$ values at 47 L ha^{-1} (Table 5.4). As carrier volume increased from 47 to 94 L ha^{-1}, the $D_{v0.5}$ values of 2,4-D and lactofen decreased almost 60 µm yet remained within the Fine spray classification (Table 5.4). The droplet classification of glufosinate and glyphosate also stayed at a Fine classification as $D_{v0.5}$ values decreased 68 and 67 µm, respectively, and fluazifop-P had the greatest decrease at 74 µm keeping it at a Fine classification (Table 5.4). $D_{v0.5}$ values then increased as carrier volumes increased from 94 to 281 L ha^{-1} maintaining the Fine spray classification for 2,4-D, lactofen, and glufosinate and moving droplet classification to Medium for fluazifop-P.

The $D_{v0.1}$ and $D_{v0.9}$ values followed a similar pattern as the $D_{v0.5}$ values, initially decreasing, and then increasing as carrier volume increased (Table 5.4). The changes in droplet size resulted from the application parameters used to achieve each carrier volume (Table 5.2) and how these parameters interacted with each herbicide and carrier volume. The objective of collecting and analyzing of the spray droplet data in this study was not to describe the effects of carrier volume on droplet size because unless a variable rate approach such as Pulsed Width Modulation or the addition of more nozzles to the boom or a slower spraying speed (or multiple applications to the same treatment area) is employed to vary the rate, droplet size will be a function of the required larger orifice sizes for higher flow rates. Rather, the objective was to describe how the operating parameters impacted spray droplet size and provide insight into some instances where differences in results cannot be explained by the simple change in carrier volume. Droplet size has been shown to increase as herbicide concentration was diluted by increasing carrier volumes where larger orifice nozzles and higher water to product ratios are involved (Creech et al. 2015a). When averaged over different herbicides, nozzles, nozzle tip sizes, and pressures, increasing carrier volume from 47 to 187 L ha^{-1} increased the $D_{v0.5}$ value 5% from 383 to 404 µm (Creech et al. 2015a).

Field Studies. Weed species was removed from the model used to analyze the Brule location as it did not have any significant interactions ($P = 0.6574$). Means from the Brule data presented in Table 5.5 were estimated using the herbicide by carrier volume interaction ($P < 0.0001$) and were sorted by herbicide. No differences were observed among treatments as carrier volume increased using 2,4-D at the Brule location (Table 5.5). Glyphosate treatments at Brule provided the greatest control when applied at 47, 70, 140, and 187 L ha^{-1} with 95, 93, 92, and 94% control, respectively (Table 5.5). The lowest level of control was observed when applications were made at 94 L ha^{-1} (86%) though observed control was not different from control following application volumes of 70 and 140 L ha^{-1} (Table 5.5). Weed control from glufosinate was greatest at 140 L ha^{-1} (62%) followed by control following application at 47 and 187 L ha^{-1} (50 and 49%, respectively); although observed control was not different than that observed following applications made at 70 and 94 L ha^{-1} (59 and 51% respectively) (Table 5.5). Control of kochia and Russian-thistle increased from 18 to 42% as carrier volume increased from 94 to 187 L ha^{-1}, respectively, when using lactofen (Table 5.5).

A herbicide by carrier volume interaction (P = 0.0086) was present at David City. Therefore, means were calculated using the herbicide by carrier volume interaction and the resulting estimated means were sorted by herbicide (Table 5.6). No difference in control was observed among carrier volumes when using 2,4-D, glufosinate, or glyphosate when applied to glyphosate-resistant giant ragweed (Table 5.6). Visual estimations of control from lactofen treatments increased from 59 to 82% when increasing carrier volume from 94 to 187 L ha^{-1}, respectively. Control following lactofen application at 187 L ha^{-1} (82%) was not different than control observed following application at 70 L ha^{-1} (73%) (Table 5.6). Increasing the carrier volume when using lactofen from 47 to 187 L ha^{-1} resulted in 141% increase in control from 34 to 82%, respectively (Table 5.6).

The Lexington, O'Neill, and Platte Center data were pooled across location as no significant interactions with location were present. A significant herbicide by carrier volume by species interaction was present (P = 0.0243). Estimated means were sorted by herbicide and species in Table 5.7 to simplify the presentation of the results. Results from 2,4-D on corn and lactofen on soybean were omitted from the analysis due to lack of control based on visual estimates. The only species to respond to changes in carrier volume when using glyphosate at these locations was the grain-type amaranth. The least control at 88% was observed following application at 47 L ha^{-1} which was less than control following application at 70 L ha^{-1} (95%) (Table 5.7). The greatest control of grain amaranth when using 2,4-D was observed when applications were made at a 140 L ha^{-1} (93%) (Table 5.7). This observed control of 93% following 2,4-D application was not different from 94 or 187 L ha^{-1} which resulted in 84 and 89% control, respectively (Table 5.7). Soybean control increased to 68% when applying 2,4-D at 94 L ha^{-1}; however, control was not different than that observed following 2,4-D applied at 140 or 187 L ha^{-1} which resulted in 84 and 89% control, respectively (Table 5.7). No differences in velvetleaf control were observed due to changing carrier volumes when using 2,4-D (Table 5.7). Visual estimation of control was generally greatest when applying glufosinate using carrier volumes greater than 94 L ha^{-1} for the four species (Table 5.7). Amaranth, corn, and soybean control was highest when applying glufosinate at 94, 140, and 187 L ha^{-1} (82, 88, and 87%, 88, 87, and 85%, and 95, 93, and 88%, respectively) although soybean control following application at higher carrier volumes were not different than control observed following applications at 94 L ha^{-1} (86%). Velvetleaf control was greatest when applying glufosinate in 140 and 187 L ha^{-1} carrier volumes (90 and 89%, respectively). Greater control was observed at these locations generally when lactofen was applied at 94, 140, and 187 L ha^{-1} to amaranth, corn, and velvetleaf (Table 5.7). Grain amaranth and velvetleaf control was greatest when application were made at

94, 140, and 187 L ha^{-1} (99, 99, and 100%, and 76, 84, and 85%, respectively) and corn control was greatest at 187 L ha^{-1} (44%) (Table 5.7).

Greenhouse Study. The greenhouse data, as described previously, were analyzed separately by species and size. A significant ($P < 0.05$) herbicide by carrier volume interaction was present for each of the species. Therefore, data were sorted by herbicide as previously described in the field components of this experiment. In addition, results from the 15 cm tall weed species were not presented in table form to simplify the presentation of the results. Nearly all the results from the 15 cm tall species were similar to the 30 cm tall results and any differences worth noting will be mentioned in the following text.

Control of corn with glyphosate according to the dry weight reduction (DWR) was less at the two smallest carrier volumes than the greater volumes (Table 5.8). Conversely, shattercane wet weight reduction (WWR) and DWR was lower when using higher carrier volumes. The response of other species to glyphosate when increasing carrier volume was more variable and no clear trend was observed (Table 5.8).

Soybean control and weight reduction was generally greatest when 2,4-D was applied at the highest carrier volume, 281 L ha^{-1} (Table 5.9). In contrast, velvetleaf was not impacted by changes in carrier volume at the field locations or consistently in the greenhouse (Tables 6 and 8). Grain amaranth displayed little response to changes in carrier volume in the greenhouse (Table 5.9). Tomato control ratings decreased dramatically at 281 L ha^{-1} when using 2,4-D. Runoff likely decreased the amount of 2,4-D on the leaf surface due to the morphology of tomato plants. Although both the wet and dry weight reductions for tomato in Table 5.9 fail to corroborate the control ratings, it should be noted that elongation and swelling of the stems was observed on both tomato and velvetleaf. Therefore, weight often increased as a result of the 2,4-D application and the visual control rating may be a better measure of the effectiveness of 2,4-D for some plant species. Flax control was also generally greater at lower carrier volumes as illustrated by the DWR (Table 5.9). Pearson's correlation coefficients were not significant ($P < 0.05$) for droplet size and any of the response variables related to 2,4-D indicating that droplet size is not as important as other factors in the application process.

When applying glufosinate treatments, the highest carrier volume (281 ha^{-1}) provided the best control in the greenhouse (60% DWR) (Table 5.10). Although other species in the greenhouse were adequately controlled with higher application volumes, no obvious correlation was observed (Table 5.10). Pearson's correlation revealed that a number of the species responded more to the changes in droplet size than changes in carrier volume (data not shown). Nearly all the glufosinate response variables had significant ($P < 0.05$) r values (0.86-0.99) when evaluated the correlation between control and droplet size. Therefore, these results suggest glufosinate efficacy increases as droplets size increases.

Wet and dry weight reductions of 15 cm tall corn and shattercane were greatest when lactofen applications were made at 281 L ha^{-1} (data not shown). Velvetleaf also responded to high carrier volumes in the greenhouse with greatest control being observed most often following applications at 187 and 281 L ha^{-1} (Table 5.11). Grain amaranth did not show a similar response to the field studies as a high level of control was achieved across carrier volumes in the greenhouse (Table 5.11). The greatest control of flax was when applications were made at 94 to 281 L ha^{-1}. Tomato control was inconsistent and did not produce an increasing pattern of control as carrier volume increased (Table 5.11). In addition, WWR and DWR were generally lower for the 30 cm tall plants compared to 15 cm tall plants (data not shown).

Fluazifop-P ratings, WWR, and DWR were nearly all greater than 90% for 15 cm corn and shattercane exempt for some of the corn results (data not shown). Hence, little difference was observed when using fluazifop-P to control corn and shattercane although corn DWR following applications at 47 L ha^{-1} was lower than most carrier volumes (Table 5.12). Corn DWR following applications to 30 cm plants was greatest when applications were made at 187 and 281 L ha^{-1} which resulted in 78 and 79% reductions, respectively (Table 5.12).

Results from the Brule location showed no correlation to changes in carrier volume. Glyphosate control was highly related to $D_{v0.5}$ values (r = 0.98, P < 0.0001). Other studies have evaluated droplet size effects on glyphosate efficacy and concluded that larger droplets increase absorption and translocation of glyphosate (Feng et al. 2003; Liu et al. 1996). In contrast, Ramsdale et al. (2003) found grasses were controlled equally following applications using a standard flat fan nozzle that produce small droplets and drift reducing nozzles that produce larger droplets. Greenhouse results for glyphosate summarized in Table 5.8 and in the data not shown of the 15 cm tall plants shows applications made to 30 cm plants resulted in reduced control and greater response to changes in carrier volume. Applications to tomato resulted in decreased efficacy when applications were made at 281 L ha^{-1} (Table 5.8). Sandberg et al. (1978) reported reduced glyphosate efficacy caused by spray runoff can occur at spray volumes above 190 L ha^{-1}. Similarly, runoff was observed from tomato plants after the glyphosate application at 281

L ha^{-1} which is likely related to the morphology of the tomato plants. Moreover, Ramsdale et al. (2003) concluded the amount of surfactant in formulated glyphosate was insufficient when applied in volumes of 94 L ha^{-1} or greater and that additional surfactant enhanced glyphosate efficacy. Thus, spraying glyphosate at rates of 94 L ha^{-1} or greater provides little additional benefit and is not recommended as reductions in efficacy could occur.

A previously conducted study evaluating droplet size effects on 2,4-D efficacy concluded that greater control of *Beta vulgaris* L. is achieved when using smaller droplets (65 µm) as compared to larger droplets (411 or 530 µm) (Ennis and Williamson 1963). Similarly, McKinlay et al. (1972) reported decreasing control of *Helianthus annuus* L. as droplet sized increased from 100, 200, and 400µm. McKinlay et al. (1972) observed leaf cells collapse and eventually die following applications using 400 µm droplets and hypothesized the collapsed leaf cells limited the amount of translocation of 2,4-D into the plant. McKinlay et al. (1972) did use diesel fuel as a carrier and it is likely that the phytotoxicity of the diesel injured the plant cells and not the 2,4-D itself. 2,4-D treatments used in this study were similar in droplet size, with $D_{v0.5}$ values ranging from 172 to 251 µm (Table 5.4). Large differences in droplet size were noted in studies by Ennis and Williamson (1963) and McKinlay et al. (1972) and differences in 2,4-D efficacy were observed. Similar to the increase in amaranth and soybean control observed using 2,4-D at the Lexington, O'Neill and Platte Center locations as carrier volume increased, Smith (1946) concluded carrier volumes between 122 and 234 L ha^{-1} and Medium to Coarse droplets provided the best control for 2,4-D. As no droplet size and efficacy correlation was observed in this work, 2,4-D applications should be made using carrier volumes between 94 and 281 L ha^{-1} using Medium to Coarse droplets to deliver the 2,4-D to the intended target as recommended by (Smith 1946). Moreover, care should be given to ensure few droplets above 400 µm are produced as previous work has shown decreases in 2,4-D efficacy (Ennis and Williamson 1963; McKinlay et al. 1972).

Glufosinate is a non-selective herbicide normally characterized as a contact herbicide due to its limited translocation within a plant. Although glyphosate and glufosinate have similar chemical properties, glufosinate translocation is minimal compared to glyphosate (Beriault et al. 1999). Etheridge et al. (2001) observed increased glufosinate efficacy on common cocklebur (*Xanthium strumarium* L.) when increasing carrier volumes from 50 to 100 L ha^{-1}. In the same study, Etheridge et al. (2001) found droplet size to be negatively correlated with glufosinate and paraquat performance. Other research has found environmental factors, namely humidity, to affect the amount of glufosinate translocated within plants (Anderson et al. 1993; Coetzer et al. 2009). They found glufosinate efficacy increased as humidity increased. How this relates to carrier volume and droplet size has yet to be studied and could be important when choosing a droplet classification to use to apply glufosinate. The results from our study generally support using a carrier volume of 140 L ha^{-1} and making application with Medium to Coarse spray droplets.

Visual control resulting from lactofen applications increased at the field locations as carrier volume increased. Similarly, Berger et al. (2014) found applications of lactofen to 15-20 cm Palmer amaranth (*Amaranthus palmeri* S. Wats.) provided less control than when applied to 5-10 cm tall plants. In addition, they observed less control of 15-20 cm Palmer amaranth when making applications at 94 L ha^{-1} as compared to applications made at 187 or 281 L ha^{-1}. Moreover, they evaluated both XR and AI nozzles and discovered that although the XR nozzle provided greater coverage, no difference in lactofen efficacy was observed. Our research results agree with the findings of Berger et al. (2014) in that lactofen provides best control when the target species are smaller than 15 cm and when using carrier volumes greater than 187 L ha^{-1}. Likewise, we observed no impact of droplet size on lactofen efficacy.

Chandrasena and Sagar (1989) found applications volumes of 100 and 200 L ha^{-1} provided similar efficacy when applying fluazifop-P and efficacy decreased as carrier volume increased to 400 and 800 L ha^{-1}. Similarly, Smeda and Putnam (1989) concluded application volumes of 187 L ha^{-1} provided better control than application volumes of 374 L ha^{-1}. Fluazifop-P efficacy increased as carrier volume increased in a low carrier volume study using volumes of 10, 30, 50 and 100 L ha^{-1} (Rogers 1989). Chandrasena and Sagar (1989) also evaluated the impact of droplet size on fluazifop-P efficacy and concluded 780 µm droplets resulted in greater efficacy than 990 or 1240 µm droplets. Our operating parameters created much smaller droplets with modest variations among treatments compared to those used by Chandrasena and Sagar (1989) and we observed no droplet size effect on efficacy.

The impacts of carrier volume and to lesser extent, droplet size, on the performance of foliar-applied herbicides were evaluated in this study to provide a better understanding of the influence of spray application factors on herbicide efficacy. Carrier volume requirements depend on the mode-of-action of the herbicide being applied and is impacted by the size and structure of the intended weed target. When applicators use products other than glyphosate for weed control, it is important to understand the application requirements of the products that are being applied and what can be done to maximize efficacy. The herbicides evaluated in this study responded to changes in carrier volume and the response observed was often herbicide specific as well as plant species specific. Increased application volumes result in more being transported and sprayer tanks filled more often to spray fewer hectares; however, the increase in herbicide efficacy can have a positive impact on crop yield and help reduce the rate of spread of herbicide-resistant weeds because of reduced selection pressure from greater weed control.

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Table 5.1. Source of materials used in carrier volume study.

Common name	Trade name	Treatment rate	Manufacturer
Fluazifop-P	Fusilade DX®	0.07 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, 27419
Glufosinate	Liberty®	0.59 kg ai ha^{-1}	Bayer Crop Science LP, Durham, NC, 27709
Glyphosate	Roundup PowerMax®	0.87 or 1.26 kg ae ha^{-1}[a]	Monsanto Corporation, St. Louis, MO, 63141
Lactofen	Cobra®	0.11 kg ai ha^{-1}	Valent USA Corporation, Walnut Creek, CA, 94596
2,4-D	Weedone®	0.20 kg ae ha^{-1}	Nufarm Americas, Alsip, IL, 60803
Ammonium sulfate	Bronc®	5.0 or 2.5% v/v[b]	Wilbur-Ellis Company, Fresno, CA, 94596
Crop oil concentrate	R.O.C. ®	1.0% v/v [c]	Wilbur-Ellis Company, Fresno, CA, 94596
Non-ionic surfactant	R-11®	0.25% v/v [d]	Wilbur-Ellis Company, Fresno, CA, 94596

[a] Brule and David City were treated with 1.26 kg ae ha^{-1} glyphosate; Lexington, O'Neill, Platte Center with 0.87 kg ae ha^{-1} glyphosate.

[b] Ammonium sulfate was added to glufosinate and glyphosate at 5% v/v and to lactofen and 2,4-D at 2.5% v/v.

[c] Added to fluazifop-P and lactofen.

[d] Added to 2,4-D.

Table 5.2. Application parameters used to achieve different carrier volumes.

Carrier volume	Nozzle type	Pressure	Application speed
L ha^{-1}		kPa	km h^{-1}
47	XR11001[b]	103	7.7
70	XR11001	138	6.4
94	XR11001	276	6.4
140	XR110015	276	6.4
187	XR11002	276	6.4
280[a]	XR11003	276	3.2

[a] Only used in the greenhouse study.

[b] Teejet Technologies, Spraying Systems Co., Wheaton, IL 62703.

Table 5.3. Spray droplet diameters generated from reference nozzles as described in ASAE S572.1 volume diameters used to determine spray droplet classifications.

	Droplet size		
Nozzle	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$
		µm	
11001	61	135	1061
11003	117	260	422
11006	168	369	608
8008	200	442	740
6510	239	526	865
6515	314	663	1061

Table 5.4. Volume diameters below which droplets of equal or smaller size constitute 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume for each herbicide and carrier volume combination used. Spray classification determined in accordance with ASAE S572.1 standards from reference curves created using the same methods to determine treatment droplet data.

Herbicide	Volume	Droplet size			Spray classification
		$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	
	L ha^{-1}		μm[a]		
2,4-D	47	114 b	229 b	367 b	Fine
	70	104 c	206 d	343 c	Fine
	94	90 d	172 e	281 d	Fine
	140	103 c	204 d	354 c	Fine
	187	114 b	221 c	352 c	Fine
	281	129 a	251 a	407 a	Medium
Fluazifop-P	47	136 b	252 b	379 b	Medium
	70	122 c	227 d	351 d	Medium
	94	93 e	178 f	283 e	Fine
	140	111 d	212 e	350 d	Fine
	187	125 c	237 c	364 c	Medium
	281	143 a	275 a	423 a	Medium
Lactofen	47	89 a	202 a	358 a	Fine
	70	75 b	176 b	323 b	Fine
	94	62 c	144 d	270 c	Fine
	140	67 c	160 c	325 b	Fine
	187	76 b	178 b	317 b	Fine
	281	87 a	205 a	366 a	Fine
Glufosinate	47	98 ab	227 a	378 b	Fine
	70	95 b	201 b	352 c	Fine
	94	77 d	159 d	281 e	Fine
	140	89 c	187 c	352 c	Fine
	187	95 b	200 b	341 d	Fine
	281	102 a	227 a	392 a	Fine
Glyphosate	47	127 b	243 b	372 b	Medium
	70	118 c	222 d	348 c	Medium
	94	93 e	176 f	281 d	Fine
	140	109 d	210 e	350 c	Fine
	187	122 bc	233 c	358 c	Medium
	281	140 a	271 a	420 a	Medium

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 5.5. Estimation of visual control values derived from a repeated measures analysis using ratings conducted at 14 and 28 (DAT) of Russian-thistle and glyphosate-resistant kochia with various herbicides and carrier volumes near Brule, NE.

	Control			
Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
L ha^{-1}	% [a,b]			
47	32	15 c	50 b	95 a
70	32	17 c	59 ab	93 ab
94	31	18 c	51 ab	86 b
140	33	28 b	62 a	92 ab
187	27	42 a	49 b	94 a

[a] Treatments applied to 10 to 20 cm tall kochia and Russian-thistle.

[b] Means within a column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 5.6. Estimation of visual control for glyphosate-resistant giant ragweed 28 days after treatment with various herbicides and carrier volumes near David City, NE.

	Control			
Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
L ha^{-1}		% [a,b]		
47	70	34 c	63	63
70	68	73 ab	48	68
94	86	59 b	58	51
140	77	61 b	41	68
187	76	82 a	54	55

[a] Treatments applied to 5 to 8 cm tall giant ragweed.

[b] Means within a column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 5.7. Estimation of visual control values derived from a repeated measures analysis using ratings conducted at 14 and 28 (DAT) with various herbicides and carrier volumes pooled across studies conducted near Lexington, O'Neill, and Platte Center, NE.

		Species			
Herbicide	Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
	L ha^{-1}	% [a,b]			
Amaranth	47	83 b	84 b	71 bc	88 b
	70	82 b	92 b	70 c	95 a
	94	84 ab	99 a	82 ab	92 ab
	140	93 a	99 a	88 a	93 ab
	187	89 ab	100 a	87 a	92 ab
Corn	47		24 b	79 bc	98
	70		23 b	76 c	98
	94		29 b	88 a	98
	140		32 b	87 ab	97
	187		44 a	85 abc	97
Soybean	47	46 c		86 abc	96
	70	52 bc		81 c	98
	94	68 a		95 a	96
	140	65 ab		93 ab	97
	187	61 abc		88 abc	98
Velvetleaf	47	55	52 b	69 b	95
	70	59	57 b	74 b	94
	94	59	76 a	77 b	96
	140	58	84 a	90 a	93
	187	63	85 a	89 a	95

[a] Treatments applied to 10 to 15 cm tall plants.

[b] Means within each species and herbicide followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 5.8. Estimation of visual control ratings and wet and dry weight reductions of 30 cm tall plant species to glyphosate applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Glyphosate[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	49 a	91 a	67 b
	70	45 ab	88 ab	69 b
	94	40 ab	87 ab	70 ab
	140	31 b	84 b	73 ab
	187	34 ab	88 ab	76 a
	281	36 ab	88 ab	77 a
Flax	47	70 ab	54 c	47 c
	70	68 ab	62 abc	55 bc
	94	62 b	49 c	44 c
	140	81 a	71 ab	69 c
	187	79 a	80 a	82 a
	281	72 ab	60 bc	61 ab
Grain amaranth	47	21 bc	87 b	82 ab
	70	11 cd	96 a	91 a
	94	29 ab	88 b	81 b
	140	32 ab	93 ab	89 ab
	187	10 d	94 ab	91 a
	281	37 a	96 a	91 a
Shattercane	47	77 a	81 a	78 a
	70	73 ab	76 ab	72 ab
	94	72 ab	73 abc	75 a
	140	59 ab	57 c	60 bc
	187	55 b	57 c	53 c
	281	64 ab	63 bc	65 abc
Soybean	47	25 a	25	38
	70	18 b	23	25
	94	16 b	22	18
	140	17 b	18	20
	187	11 c	23	16
	281	20 ab	21	18

Tomato	47	54 a	64	56 ab
	70	67 a	71	61 a
	94	55 a	53	48 ab
	140	61 a	57	39 b
	187	54 a	59	53 ab
	281	28 b	49	39 ab
Velvetleaf	47	17 ab	67 a	71 a
	70	14 ab	26 abc	48 ab
	94	8 b	5 bc	29 ab
	140	12 ab	2 c	12 b
	187	22 a	40 abc	41 ab
	281	17 ab	51 abc	63 ab

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

Table 5.9. Estimation of visual control ratings and wet and dry weight reductions of 30 cm tall plant species to 2,4-D applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		2,4-D[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Flax	47	57 a	53 a	58 a
	70	40 b	48 a	43 abc
	94	45 ab	47 a	55 a
	140	36 b	25 b	38 abc
	187	37 b	32 ab	30 c
	281	40 ab	37 ab	34 bc
Grain amaranth	47	56 ab	99	92
	70	59 ab	99	94
	94	44 b	99	94
	140	55 ab	99	94
	187	43 b	99	92
	281	69 a	99	92
Soybean	47	49 bcd	40 b	42 b
	70	43 cd	47 b	42 b
	94	40 d	31 b	34 b
	140	51 bc	45 b	46 b
	187	54 b	44 b	38 b
	281	76 a	78 a	69 a
Tomato	47	77 ab	72 ab	48 bc
	70	63 b	58 b	39 c
	94	79 a	81 a	67 a
	140	79 a	74 ab	62 ab
	187	79 a	70 ab	44 bc
	281	38 c	83 a	70 a
Velvetleaf	47	71 ab	74 ab	58
	70	73 a	71 ab	47
	94	75 a	77 a	58
	140	75 a	76 a	54
	187	56 b	59 ab	44
	281	84 a	50 b	44

[a] Means within each herbicide and column followed by the same letter are not significantly different at the P ≤ 0.05 level using least-squares means.
[b] Abbreviation: WWR, wet weight reduction.
[c] Abbreviation: DWR, dry weight reduction.

Table 5.10. Estimation of visual control ratings and wet and dry weight reductions of 30 cm tall plant species to glufosinate applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Glufosinate[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}		%	
Corn	47	20 bc	45 b	17 d
	70	22 bc	34 b	28 cd
	94	21 bc	21 c	36 bc
	140	23 b	43 b	43 b
	187	17 c	19 c	45 b
	281	30 a	59 a	60 a
Flax	47	61 ab	46 b	62 ab
	70	71 a	64 a	66 ab
	94	49 b	31 b	51 b
	140	61 ab	50 ab	71 a
	187	68 a	68 a	72 a
	281	69 a	69 a	63 ab
Grain amaranth	47	90 a	99 a	96 a
	70	87 ab	98 a	95 ab
	94	70 c	95 b	90 b
	140	73 c	98 a	93 ab
	187	76 bc	98 a	96 a
	281	93 a	99 a	97 a
Shattercane	47	65 a	62 a	75
	70	50 b	40 b	66
	94	40 b	53 ab	66
	140	45 b	49 ab	69
	187	47 b	60 ab	63
	281	64 a	56 ab	75
Soybean	47	79 ab	76 a	77 a
	70	64 cd	63 abc	64 abc
	94	60 d	52 bc	57 bc
	140	67 bcd	67 ab	70 ab
	187	63 cd	47 c	50 c
	281	81 a	75 a	76 a

Tomato	47	91 a	90 a	76 a
	70	71 bc	54 c	58 b
	94	79 abc	81 ab	67 ab
	140	64 c	68 bc	54 b
	187	86 a	77 ab	73 a
	281	41 d	78 ab	68 ab
Velvetleaf	47	76 a	73 a	71
	70	66 b	68 ab	68
	94	50 c	42 b	63
	140	47 c	55 ab	51
	187	63 bc	50 ab	60
	281	89 a	71 a	51

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

Table 5.11. Estimation of visual control ratings and wet and dry weight reductions of 30 cm tall plant species to lactofen applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Lactofen[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	13	12 bc	11
	70	13	7 c	12
	94	14	9 bc	18
	140	14	13 bc	18
	187	16	24 a	21
	281	15	18 abc	22
Flax	47	82 bc	58 b	54 b
	70	80 c	54 b	53 b
	94	87 ab	65 ab	61 ab
	140	87 ab	63 ab	57 b
	187	88 ab	61 ab	75 a
	281	94 a	78 a	77 a
Grain amaranth	47	95 ab	99	96
	70	96 ab	98	95
	94	93 ab	99	95
	140	89 b	98	94
	187	95 ab	99	96
	281	98 a	99	96
Shattercane	47	23 b	20 bc	25 b
	70	25 ab	17 c	24 b
	94	28 ab	43 a	37 ab
	140	26 ab	33 ab	44 a
	187	35 a	30 abc	44 a
	281	36 a	39 a	44 a
Tomato	47	68 b	53 b	59 ab
	70	75 ab	64 ab	52 b
	94	66 b	54 b	50 b
	140	63 b	60 ab	58 ab
	187	84 a	57 ab	58 ab
	281	42 d	81 a	76 a

Velvetleaf	47	64 c	56 ab	72 a
	70	69 bc	49 b	53 b
	94	71 bc	52 b	55 ab
	140	77 b	61 ab	60 ab
	187	70 bc	74 ab	65 ab
	281	93 a	76 a	69 ab

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

Table 5.12. Estimation of visual control ratings and wet and dry weight reductions of 30 cm tall plant species to fluazifop-P applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Fluazifop-P[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	49	92 ab	64 d
	70	46	90 b	70 cd
	94	51	91 ab	71 cd
	140	58	95 a	72 bc
	187	42	90 ab	78 ab
	281	54	95 ab	79 a
Shattercane	47	59	62 ab	57 abc
	70	55	62 ab	58 abc
	94	58	67 ab	65 a
	140	50	57 ab	50 bc
	187	50	51 b	48 c
	281	57	70 a	60 abc

[a] Means within each herbicide and column followed by the same letter are not significantly different at the P ≤ 0.05 level using least-squares means.

[b] Abbreviation: WWR, wet weight reduction.

[c] Abbreviation: DWR, dry weight reduction.

CHAPTER 6

Increased Dicamba, Fluazifop-P, Glyphosate, and Lactofen Efficacy Using Adjuvants

Abstract

The activity of postemergence herbicides is often limited by the inability of the herbicide to adequately cover or penetrate the leaf surface. Adjuvants can alter spray quality, increase spray retention on the leaf surface, and increase the efficacy of herbicide applications. The lack of regulation, large number of available adjuvants, and the complexity of the herbicide application process have made choosing the best adjuvant difficult in the US. The objective of this study was to evaluate the impact of different types of adjuvants on herbicide efficacy and spray quality when applied with four herbicide active ingredients. The treatments consisted of a non-surfactant loaded glyphosate (0.79 kg ae ha^{-1}), fluazifop-P (0.07 kg ai ha^{-1}), lactofen (0.11 kg ai ha^{-1}) and dicamba (0.14 kg ae ha^{-1}). Each herbicide was applied alone and in combination with a non-ionic surfactant (NIS, 0.25% v/v), crop oil concentrate (COC, 1% v/v), methylated seed oil (MSO, 1% v/v), high surfactant oil concentrate (HSOC, 1% v/v), ammonium sulfate (AMS, 5% v/v), or a drift reduction adjuvant (DRA, 0.3 L ha^{-1}). Treatments were applied in field studies and in the greenhouse to different plant species. In addition, the droplet size spectrum for each treatment combination was determined using a laser diffraction system. Glyphosate efficacy increased by 30 and 35% averaged across species with the addition of NIS and AMS under field conditions, respectively. Lactofen, dicamba, and fluazifop-P efficacy increased 40, 22, and 41% with the addition of COC under field conditions. While other adjuvants also increased herbicide performance, the

rate of increase was different for each herbicide and plant species specific. For all herbicides tested, the addition of adjuvants generally increased the droplet size with the exception of NIS and in some instances MSO, which slightly reduced or maintained droplet size. The use of adjuvants can increase herbicide performance and should be considered for use if they are recommended on the herbicide label and have been proven effective. Further research is needed to understand when and where adjuvants will be effective over a wide range of conditions.

Introduction

The development and integration of herbicide-resistant crops into agriculture has been rapid and has led to an increased usage and reliance on non-selective postemergence herbicides (Shaner 2000). In particular, the adoption of glyphosate-resistant soybeans [*Glycine max* (Merr.) L.] increased from 17% of US soybean hectares in 1997 to 68% in 2001 and 93% in 2010 (Fernandez-Cornejo et al. 2014). Glyphosate-resistant technology simplified weed management and reduced herbicide expense for soybean producers by allowing application of a non-selective herbicide postemergence to soybean (Shaner 2000). Although many benefits are afforded by herbicide-resistant technology in crops, some negative consequences have developed. Glyphosate-resistant weeds, for example, have since evolved at a high rate due to selection pressure applied to weed populations by the extensive use of glyphosate within corn, soybean, and cotton production systems (Johnson et al. 2009). Herbicide-resistance in weeds is an evolutionary process that occurs in response to repeated applications of the same herbicide family and as weeds survive, the genetic composition of the weed population changes and weeds become adapted to the intense selection pressure (Jasieniuk et al. 1996). Herbicide resistance can only evolve if a weed survives a herbicide application and successfully sets seed that germinates.

Herbicide applications are inefficient because only a small fraction of the active ingredient applied during an application is required to control the targeted weeds (Caseley et al. 1990; Graham-Bryce 1977; Matthews 1977). This is due to only a small amount of herbicide active ingredient applied will reach the intended target, and only a portion of that will be able to enter the plant (Liu et al. 1996; Sandberg et al. 1980; Wyrill III and Burnside 1976). Less than 70% of glyphosate deposited on a leaf surface will be successfully absorbed by the plant (Wyrill III and Burnside 1976). An adjuvant is any substance added to a spray tank to modify herbicidal activity or application characteristics (Monaco et al. 2002) and they are often added to enhance spray solution characteristics and/or herbicide activity. The most common types of adjuvants can be classified as herbicide activity enhancers (surfactants, oils, organosilicones, and fertilizers), spray modifiers (drift control agents and stickers), and utility agents (compatibility and antifoam agents) (Young 2012). Although adjuvants can significantly impact herbicide efficacy, they are considered to be inactive components of the spray mixture (Monaco et al. 2002).

Many adjuvants are currently available in the U.S. because of the ease to get a new product from initial development to the market with limited restriction due to a lack of regulation, registration, and oversight. The first Compendium of Herbicide Adjuvants was assembled in 1992 with 76 adjuvants from 22 companies (Young 2012). This increased to 687 entries from 38 companies by 2012 (Young 2012) in a time where the opposite is true with herbicides and herbicide companies which have consolidated (Duke 2012). The growth of the adjuvant industry is powered by continued reliance on postemergence herbicides, scientific advancements, successful research, and blending adjuvants with specific herbicides into a single product (Young 2012). Such rapid growth with minimal oversight has caused much confusion with applicators (Zollinger 2009). Zollinger (2009) noted ambiguity and confusion caused by adjuvant terminology, adjuvant and herbicide labels, manufacturer claims, and lack of unbiased research.

The complex interaction among herbicides, adjuvants, plants, and the environment is another area of confusion for applicators. Zollinger (2009) noted many of the following complexities for each component of the complex interaction. He reported that plants have different morphology, leaf surfaces, composition, and cuticle surfaces. Herbicides have different vapor pressures, solubilities, photosensitivities, and emulsifier qualities. Adjuvants do not share similar qualities across the industry, are specific to herbicides, plant species, and environmental conditions, and are influenced by tank-mix partners, rates, and carrier volumes. Environmental conditions like temperature, humidity, light intensity, and soil moisture all influence the plant growing environment and can impact cuticle hydration and thickness, and humectant properties of spray deposits. Underwood (1992) reported applicators apply as many as five adjuvants in a single application. However, the addition of adjuvants to the spray solution is not always beneficial. Penner (1989) showed that some adjuvants antagonize herbicides and reduce weed control.

Herbicide applicators can easily become confused trying to select the most appropriate adjuvant for a specific herbicide or weed species. The objective of this research was to evaluate the impact of adjuvants from different classifications on the efficacy of four commonly used herbicides applied to different plant species. In addition, the study was duplicated in a greenhouse with nearly identical treatments to confirm the findings from the field studies and to evaluate additional species.

Materials and Methods

Field Studies. Field studies were conducted at sites near Minden, Pierce, Waterloo, and York Nebraska in 2013 to determine the effect of different adjuvants on the biological efficacy of commonly used corn (*Zea mays* L.) or soybean herbicides against seeded plant species. Each field location was arranged as a randomized complete block design with four replications. The Minden site (40.51ºN, 99.05ºW) was located on a silt loam textured soil located approximately 8 km west of Minden, NE. The Pierce site (42.18ºN, 97.50ºW) was located on a sandy loam textured soil located approximately 3.2 km southeast of Pierce, NE. The Waterloo site (41.23ºN, 96.28ºW) was located on a sandy loam textured soil located approximately 6.4 km south of Waterloo, NE. The York site (40.89ºN, 97.57ºW) was located on a silty clay loam soil located on the northeast edge of York, NE.

The study locations at each site were prepared and seeded on June 19-20, 2013. The study areas were lightly worked with a cultivator and harrow to remove existing weeds and breakdown crop residue. The seedbed was finished using a small turf seeder (APS 1586 All Purpose Seeder, Land Pride, Salina, KS, 67401) to pack the soil to create a firm seedbed. Seed was then broadcasted manually using a hand spreader to uniformly apply the seeds to the area. Barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], flax

(*Linum usitatissimum* L.), grain amaranth (*Amaranthus hypochondriacus* L.), Palmer amaranth (*Amaranthus palmeri* S. Wats.), and velvetleaf (*Abutilon theophrasti* Medik.) were broadcasted on the prepared 30 by 100 m area at 0.9, 2.3, 0.3, 0.3, and 0.5 kg, respectively. These species were chosen because of seed availability, ease to germinate and grow in an uncontrolled field setting, wide range of physiological characteristics such as leaf type hairiness, and waxiness, and low disposition to persist in the field long-term. After broadcasting the seed, the turf seeder was used again to pack the soil and seed to ensure good soil to seed contact. The study locations were irrigated as needed using a center pivot irrigation system to ensure uniform germination and growth.

Treatments were applied to plots 3 m wide by 8 m long using a CO_2-pressurized backpack sprayer with a six nozzle boom having nozzles spaced 50 cm apart and boom height. Applications were made at approximately 50 cm above the weed canopies with the spray boom pressurized to 207 kPa. The treatments consisted of four herbicides applied alone or as a tank-mixture with six adjuvants. The herbicides and rates used included dicamba (0.14 kg ae ha^{-1}), fluazifop-P (0.07 kg ai ha^{-1}), an unloaded glyphosate (0.79 kg ae ha^{-1}), and lactofen (0.11 kg ai ha^{-1}) (Table 6.1). The adjuvants and rates used were a non-ionic surfactant (NIS, 0.25% v/v), crop oil concentrate (COC, 1% v/v), methylated seed oil (MSO, 1% v/v), high surfactant oil concentrate (HSOC, 1% v/v), ammonium sulfate (AMS, 5% v/v), and a drift reduction agent (DRA, 0.3 L ha^{-1}) (Table 6.1). Dicamba, fluazifop-P, and glyphosate treatments were applied at 94 L ha^{-1} using AIXR110015 nozzles (Teejet Technologies, Spraying Systems Co., Springfield, IL 62703). Lactofen was applied at 187 L ha^{-1} using AIXR11003 nozzles. Treatments were applied on July 16-17, 2013 when plants were 15 to 20 cm tall. Visual estimations of injury were recorded at 7, 14 and 28 days after treatment (DAT) using a scale of 0 – 100 where 0 = no control and 100 = plant death.

Greenhouse Study. A greenhouse study was conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center in North Platte, NE. The same treatments and application parameters that were used in the field studies described previously were followed (Table 6.1). A few minor differences in protocol did exist and will be described hereafter. The species used that were the same were flax, grain amaranth, and velvetleaf. The additional species used in the greenhouse study were corn and shattercane [*Sorghum bicolor* (L.) Moench ssp. arundinaceum (Desv.)]. Plants were grown in SC10 cone-tainer cells that have a volume of 164 cubic cm (Stuewe and Sons Inc., Corvallis, OR 97389) filled with potting mix (Baccto Professional Grower's Mix, Michigan Peat Company, Houston, TX 77098). Plants were seeded from August through September of 2013 and were watered as needed. Plants received supplemental nutrition (Scotts Miracle-Gro® LiquaFeed® All Purpose, The Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol™ DS 300W, Illumitex, Austin, TX, 78735) was provided to ensure 14 h days. Herbicide treatments were applied when plants were 15 to 20 cm tall using a single nozzle track sprayer (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN 56045). Visual estimations of injury were recorded at 7, 14, and 28 DAT using the aforementioned scale of 0 to 100%. At 28 DAT, plants were destructively sampled by clipping the plant at the soil surface and recording the fresh weights. These samples were then dried at 40 C for 7 days following which dry weights were recorded.

The experiment had five replications and was conducted twice, separated temporally. An individual plant was the experimental unit.

Spray Droplet Data Collection. The spray droplet spectrum for each herbicide and adjuvant combination was evaluated in 2013 using a low speed wind tunnel at the PAT Lab. The spray droplet data were collected as described by (Creech et al. 2015b). The laser diffraction instrument is able to assign the spray droplet spectrum in a number of different size categories to compare the spray droplet spectra of different treatments. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by ASAE S572.1 (ASABE 2009) (Table 6.2). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Statistical Analysis. Control rating data from the field studies were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute, Cary, NC 27513). Non-treated controls were included in each field study for visual rating reference only and were not included in analysis of data. Data from the field locations were combined and analyzed together with replication nested within location and considered a random effect as suggested by Carmer et al. (1989). The analysis was performed using repeated measures which allowed for pooling of means over rating intervals. The Akaike information criterion with a correction for finite sample sizes (AICc) was used, as suggested by Burnham and Anderson (2002), to select the appropriate covariance model to use in the repeated measure analysis. The AICc indicated the default covariance model used by GLIMMIX best fit the data and was used for repeated measure analysis conducted for ratings collected from both field and greenhouse studies.

For the greenhouse study, treatments were applied to each weed species separately. Therefore, each species was analyzed separately. Estimation of visual injury data for the greenhouse studies had replication nested within run designated as a random effect in the model. Percent biomass reduction for treated experimental units was calculated using both the fresh and dry weights relative to the average biomass of the non-treated control plants in each study as:

$$Percent\ biomass\ reduction = \left((\bar{C} - B/\bar{C})\right) 100 \text{ [1]}$$

where $\bar{C}$ is the mean biomass of the non-treated control replicates, and B is the biomass of an individual experimental unit after being treated. Values for biomass reduction were compared using a generalized linear mixed model analysis of variance (GLIMMIX) procedure of SAS (Littell et al. 2006). LS means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

There was no significant location interaction from the field study data so location was removed from the fixed effects in the model. The herbicide, adjuvant, and species interaction was significant (P < 0.0001) showing how complicated weed control with herbicides is when all factors are considered. The results from the field studies are presented in tables sorted by herbicide and then species to better evaluate the impact of the different classifications of adjuvants on specific herbicides and species. The greenhouse data were analyzed by species because treatments were not applied to all species at the same time. The greenhouse data had a significant herbicide by adjuvant interaction ($P < 0.0001$) and the results are presented in tables sorted by herbicide. In addition, spray droplet size data and classifications are presented in Table 6.2. Previous research has demonstrated the impact droplet size may have on herbicide efficacy (Creech et al. 2015c; Knoche 1994). The data presented in Table 6.2 shows the impact adjuvants have on spray droplet size and how they can impact spray classifications. While changes in spray classification categories occurred, ASABE categories are quite broad so it is hard to see differences unless there is a large change or the change occurs near the boundary from one category to the next. Understanding these changes in the spray spectrum can aid in understanding changes in efficacy as well as implications on spray drift management.

Adjuvants recommended on the label for use with dicamba to improve efficacy are surfactants, fertilizers, or crop oil concentrates; particularly in dry growing conditions (Anonymous 2013a). The results observed in both the field and greenhouse studies generally agree with these recommendations. The applications in the field studies were applied in July when temperatures were near 32 C. Grain amaranth injury was greatest (33%) when COC was added compared to dicamba alone (27%) (Table 6.3). No other differences were observed when adjuvants were added to dicamba (Table 6.3). In the controlled setting of the greenhouse, velvetleaf control was greatest when AMS or NIS was added to dicamba (Table 6.4). Ratings of dicamba with AMS and NIS applied to velvetleaf were 29 and 28%, respectively (Table 6.4). No difference among adjuvant treatments was observed when applied to grain amaranth (Table 6.4). Flax was not reported in Table 6.4 because of a lack of injury due to the low rate of dicamba used (data not shown). Likewise, barnyardgrass showed little effect from the dicamba applications and is not reported in Table 6.3. Roskamp et al. (2013) observed an increase in redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.) control when tank-mixing AMS with dicamba. The results presented in Table 6.3 and 6.4 indicate an increase in dicamba efficacy can occur with the addition of AMS, COC, or NIS depending upon the environment, plant species, and other application parameters. In addition, it is important to note that none of the adjuvants used decreased the dicamba efficacy compared to the dicamba alone. From a spray droplet size perspective, COC, DRA, and MSO increased the droplet size and AMS and NIS decreased droplet size relative to dicamba with no adjuvant (Table 6.2). This indicates that dicamba is probably highly effective over a wide range of droplet sizes.

Fluazifop-P provides grass weed control in a large number of broadleaf crops. The addition of adjuvants to fluazifop-P, including the DRA, did not have an effect on spray droplet size and all treatments remained in the Coarse classification (Table 6.2). The fluazifop-P label requires applicators add either a COC, NIS, or any other adjuvant that contains Environmental Protection Agency exempt ingredients, is nonphytotoxic to the crop, is compatible with the tank-mixture, and supported locally for use on the target crop through proven field trials and university recommendations (Anonymous 2013c). Fluazifop-P applied alone or with AMS consistently had the lowest control in both the field and greenhouse studies (Table 6.5 and 6.6). Although AMS did not increase fluazifop-P efficacy, liquid nitrogen fertilizer is recommended in soybeans but should not be used as a substitute for COC or NIS (Anonymous 2013c). The addition of COC to fluazifop-P in the field study increased the control of barnyardgrass from 16 and 17% for AMS and fluazifop-P alone, respectively, to 24% (Table 6.5). In the controlled setting of the greenhouse, the benefit of the addition of the COC was not as pronounced (Table 6.6). DWR of corn was greatest when DRA, MSO, and NIS (91, 90, and 90%, respectively) were added to fluazifop-P (Table 6.6). Differences in the control of shattercane were more subtle. Shattercane treated with fluazifop-P and MSO had an estimated visual injury of 79% which was greater than AMS at 64% (Table 6.6). Singh and Mack (1993) evaluated the addition of COC and NIS to fluazifop-P and reported an increase in efficacy over fluazifop-P alone. Likewise, an increase in efficacy with the addition of COC, NIS, and in some instances, MSO, HSOC, and DRA were observed in this study.

Barnyardgrass control with glyphosate in the field studies had the lowest level of injury when applied alone (46%) or with the DRA (59%) compared to the other adjuvants which had control percentages from 64-69% (Table 6.7). Control of corn with glyphosate was greatest in the greenhouse when NIS was added to the tank-mixture. NIS had a rating, WWR, and DWR of 39, 95, and 90%, respectively (Table 6.8). Conversely, glyphosate alone had the lowest WWR and DWR at 19 and 36%, respectively (Table 6.8). Shattercane WWR and DWR were greatest with MSO and NIS with 95% WWR for both and 96 and 97% DWR, respectively (Table 6.8). Flax control with glyphosate in the field study was greatest with NIS (59%), followed by COC and MSO (50 and 48%, respectively), HSOC, AMS, and DRA (43, 38 and 38%, respectively), glyphosate alone (22%) (Table 6.7). Similar results were observed in the greenhouse where flax ratings, WWR, and DWR were the greatest at 50, 89, and 82%, respectively, when NIS was applied with glyphosate (Table 6.8). The control ratings of the amaranth species in the field and greenhouse studies were greatest when AMS was tank-mixed with glyphosate (Table 6.7 and 6.8). NIS and HSOC had increased efficacy compared to glyphosate alone in the field study but was less than AMS (Table 6.7). Velvetleaf control with glyphosate in the field study was also greatest with the addition of AMS (66%) but in the greenhouse the velvetleaf DWR were DRA (82%) and MSO (81%) (Table 6.7 and Table 6.8). This was one of the few examples where control of a species increased with DRA. The DRA used in this study is a deposition and retention agent that reduces the number of droplets less than 100 µm (Anonymous 2013d). The DRA tank-mixed with glyphosate was the only adjuvant to increase the $D_{v0.5}$ value and had the greatest increase in $D_{v0.1}$ value (Table 6.2). The interaction between velvetleaf and DRA that caused this increase will need to be explored in the future to understand the factors responsible. Similar to our results Ramsdale et al. (2003) reported enhanced glyphosate efficacy with AMS and NIS. Ramsdale et al. (2003) concluded that the AMS helped to overcome the antagonism associated with hard water and glyphosate and that the benefit of adding NIS to a glyphosate tank-mixture increases as carrier-volume increases because the amount of NIS in a formulated glyphosate product becomes diluted. Many glyphosate formulations come preloaded with surfactants however the amount included is not disclosed on the labels because surfactants are not active ingredients. The amount of surfactant in the formulation is not generally reported so applicators should be cautious and add surfactant if there are noticeable performance failures that are species specific and cannot be otherwise explained. This may especially be true if they are using higher carrier rates than they had in the past. A significant increase in the control of flax was observed with the addition of NIS. Weed species that have similar characteristics to flax may be aided by the addition of NIS to glyphosate.

Lactofen is a contact herbicide the requires good coverage of small actively growing broadleaf weeds for optimal control (Anonymous 2013b). AMS, COC, MSO, and NIS are recommended and drift reduction adjuvants are not recommended for use with lactofen according to the label (Anonymous 2013b). In the field studies, COC and HSOC consistently increased the efficacy of lactofen across species relative to lactofen applied alone (Table 6.9). Conversely, DRA did not increase the efficacy of any of the species compared to lactofen alone (Table 6.9). In the greenhouse study, a high level of control was observed with grain amaranth and no differences among treatments were distinguished (Table 6.10). For flax, the adjuvants increased control when added to lactofen with the exception of AMS which was no different than lactofen alone (Table 6.10). Velvetleaf control was greatest when lactofen was applied with the DRA (36, 31, and 34% for rating, WWR, and DWR, respectively) (Table 6.10). The increase in efficacy of both glyphosate and lactofen when tank-mixed with a DRA raises questions about the relationship between drift reduction adjuvants and glyphosate or lactofen in velvetleaf.

Adjuvants are intended to improve spray delivery, increase the retention of the spray on plant foliage, and increase foliar penetration (Penner 1989). The end goal is that the addition of each of these factors to the spray process will increase herbicide efficacy and/or selectivity. The aim of this research was to elucidate the impacts of different classifications of adjuvants on the efficacy of dicamba, fluazifop-P, glyphosate, and lactofen. In addition, the impact on the spray droplet spectrum due to the addition of adjuvants to the tank-mix was observed. Each of the herbicides evaluated in this research interacted with the addition of adjuvants. Which adjuvant improved the performance of the herbicide was dependent upon the herbicide being tested, the environment and growing conditions, and the species being targeted. It is important to recognize of the six adjuvants evaluated, none of them reduced efficacy lower than the herbicide without an adjuvant. In that regards, the addition of adjuvants to a spray solution only has upside in terms of herbicide performance with the only negative being cost if no added benefit is gained. Although some adjuvants did not increase herbicide efficacy, there could be other benefits that were not explored or discovered in this study. For example, this study did not evaluate the impact of using multiple adjuvants and possible synergistic or additive effects they may result. Nor were any possible impacts or implications on herbicide drift management considered.

If a herbicide label recommends the use of an adjuvant with a herbicide, one of the recommended adjuvants should strongly be considered to maximize herbicide performance. Once an applicator has decided on an adjuvant that will maximize the application, use of the full recommended rate of the adjuvant is also strongly encouraged. Some adjuvants are advertised to allow the applicator to “reduce the rate” of the pesticide being applied. Reduced herbicide rates can increase the evolution of herbicide resistance (Neve and Powles 2005; Norsworthy et al. 2012). The increased herbicide performance due to the use of adjuvants can potentially slow the evolution of herbicide resistance. Adjuvants should be viewed as tools to improve performance or reduce unintended effects, not to replace the herbicide required for the application. Ultimately, reducing the herbicide rates being applied can lead to variable performance and/or herbicide resistance. The adjuvant market is constantly changing as new products are brought to the market rapidly due to little regulation (Zollinger 2009). The number of available adjuvants, produced by numerous companies with an equal number of claims about their adjuvants creates confusion among applicators that is compounded by vague labels. Applicators should use proven adjuvants to maximize and enhance their herbicide applications when adjuvants are recommended on the herbicide label.

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Table 6.1. Source of materials used in adjuvant study.

Common name	Trade name	Treatment rate	Manufacturer
Dicamba	Clarity®	0.14 kg ae ha^{-1}	BASF Corporation, Research Triangle Park, NC, 27709
Fluazifop-P	Fusilade DX®	0.07 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, 27419
Glyphosate	Touchdown HiTech®	0.79 kg ae ha^{-1}	Syngenta Crop Protection, Greensboro, NC, 27419
Lactofen	Cobra®	0.11 kg ai ha^{-1}	Valent USA Corporation, Walnut Creek, CA, 94596
Ammonium sulfate	Bronc®	5.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Crop oil concentrate	R.O.C. ®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Drift agent	In-Place®	0.3 L ha^{-1}	Wilbur-Ellis Company, Fresno, CA, 94596
High surfactant oil	High Load®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Non-ionic surfactant	R-11®	0.25% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Methylated seed oil	Super Spread MSO®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596

Table 6.2. Volume diameters below which droplets of equal or smaller size constituting 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume for each herbicide and adjuvant combination used. The relative span is a dimensionless parameter indicative of the uniformity of the distribution of the droplet sizes of the spray. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

Herbicide[a]	Adjuvant[b]	Droplet size			Relative span	Spray classification
		$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$		
		µm				
Dicamba	AMS	193	367	578	1.05	Medium
	COC	215	385	569	0.92	Coarse
	DRA	216	389	568	0.90	Coarse
	HSOC	198	383	602	1.06	Medium
	MSO	215	387	565	0.90	Coarse
	NIS	174	358	574	1.11	Medium
	None	201	379	579	1.00	Coarse
Fluazifop-P	AMS	217	389	570	0.91	Coarse
	COC	218	390	566	0.89	Coarse
	DRA	217	390	566	0.89	Coarse
	HSOC	218	405	602	0.95	Coarse
	MSO	204	372	559	0.95	Coarse
	NIS	212	385	581	0.96	Coarse
	None	218	385	558	0.89	Coarse
Glyphosate	AMS	194	374	579	1.03	Medium
	COC	212	386	572	0.93	Coarse
	DRA	220	394	573	0.89	Coarse
	HSOC	180	352	570	1.11	Medium
	MSO	208	377	558	0.93	Coarse
	NIS	191	374	583	1.05	Medium
	None	202	391	592	1.00	Coarse
Lactofen	AMS	240	437	663	0.97	Coarse
	COC	241	437	656	0.95	Coarse
	DRA	245	446	672	0.96	Very Coarse
	HSOC	239	444	682	1.00	Very Coarse
	MSO	226	420	648	1.00	Coarse
	NIS	223	418	658	1.04	Coarse
	None	238	434	659	0.97	Coarse

[a] Dicamba, fluazifop-P, and glyphosate treatments applied at 94 L ha^{-1} using AIXR110015 nozzles. Lactofen treatments applied at 187 L ha^{-1} using AIXR11003 nozzles.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

Table 6.3. Visual estimations of injury of different plant species from applications of dicamba with adjuvants conducted in a field study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

Adjuvant[a]	Spray classification	Flax	Grain amaranth[b]	Palmer amaranth	Velvetleaf
		%			
AMS	Medium	11	31 ab	31	16
COC	Coarse	11	33 a	33	16
DRA	Coarse	13	31 ab	32	17
HSOC	Medium	10	30 ab	30	19
MSO	Coarse	11	30 ab	30	17
NIS	Medium	11	32 ab	33	18
none	Coarse	9	27 b	29	15

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Letters indicate significant differences (α=0.05) within species.

Table 6.4. Visual estimations of injury, wet weights, and dry weights of grain amaranth and velvetleaf from applications of dicamba with adjuvants conducted in a greenhouse study.

		Dicamba[a,b]		
Species	Adjuvant	Rating	WWR	DWR
			%	
Grain amaranth	AMS	45	6	20
	COC	43	2	11
	DRA	43	8	21
	HSOC	42	0	9
	MSO	42	8	27
	NIS	39	0	11
	none	37	0	7
Velvetleaf	AMS	29 a	5	5 a
	COC	19 b	6	0 b
	DRA	25 ab	5	0 b
	HSOC	25 ab	6	0 b
	MSO	23 ab	6	0 b
	NIS	28 a	5	3 a
	none	23 ab	6	0 b

[a] Letters indicate significant differences (α=0.05) within species.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant; WWR, wet weight reduction; DWR, dry weight reduction.

Table 6.5. Visual estimations of injury of barnyardgrass from applications of fluazifop-P with adjuvants conducted in a field study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

Adjuvant[a]	Spray classification	Barnyardgrass[b]
		%
AMS	Coarse	16 c
COC	Coarse	24 a
DRA	Coarse	18 abc
HSOC	Coarse	22 abc
MSO	Coarse	23 ab
NIS	Coarse	18 abc
none	Coarse	17 bc

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Letters indicate significant differences (α=0.05) within species.

Table 6.6. Visual estimations of injury, wet weights, and dry weights of different plant species from applications of fluazifop-P with adjuvants conducted in a greenhouse study.

		Fluazifop-P[a,b]		
Species	Adjuvant	Rating	WWR	DWR
		%		
Corn	AMS	30	90 d	85 c
	COC	29	92 cd	86 c
	DRA	37	96 a	91 a
	HSOC	39	96 ab	88 abc
	MSO	42	97 a	90 a
	NIS	41	96 a	90 ab
	none	33	94 bc	86 bc
Shattercane	AMS	64 b	98 ab	97
	COC	73 ab	99 ab	98
	DRA	68 ab	98 b	97
	HSOC	74 ab	99 ab	98
	MSO	79 a	99 a	98
	NIS	69 ab	99 ab	98
	none	70 ab	99 ab	98

[a] Letters indicate significant differences (α=0.05) within species.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant; WWR, wet weight reduction; DWR, dry weight reduction.

Table 6.7. Visual estimations of injury of different plant species from applications of glyphosate with adjuvants conducted in a field study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

Adjuvant[a]	Spray classification	Barnyardgrass[b]	Flax	Grain amaranth	Palmer amaranth	Velvetleaf
				%		
AMS	Medium	66 a	38 d	90 a	90 a	66 a
COC	Coarse	64 ab	50 b	80 bc	79 bc	47 bc
DRA	Coarse	59 bc	38 d	78 bc	76 bc	47 bc
HSOC	Medium	69 a	43 cd	82 b	80 b	47 bc
MSO	Coarse	67 a	48 bc	78 bc	78 bc	43 c
NIS	Medium	66 a	59 a	83 b	81 b	50 b
none	Coarse	46 c	22 e	75 c	74 c	43 c

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Letters indicate significant differences (α=0.05) within species.

Table 6.8. Visual estimations of injury, wet weights, and dry weights of different plant species from applications of glyphosate with adjuvants conducted in a greenhouse study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

		Glyphosate[a,b]		
Species	Adjuvant	Rating	WWR	DWR
		%		
Corn	AMS	11 de	67 cd	71 cd
	COC	18 bc	75 cd	77 cd
	DRA	11 cde	65 d	71 d
	HSOC	15 bcd	78 c	79 c
	MSO	20 b	87 b	84 b
	NIS	39 a	95 a	90 a
	none	6 e	19 e	36 e
Flax	AMS	3 d	32 c	35 c
	COC	5 cd	27 b	26 d
	DRA	4 cd	28 c	28 cd
	HSOC	8 bc	58 b	54 b
	MSO	10 b	55 b	55 b
	NIS	50 a	89 a	82 a
	none	4 cd	11 d	10 d
Grain amaranth	AMS	54 a	39	40 ab
	COC	49 ab	38	36 b
	DRA	47 ab	45	50 ab
	HSOC	44 ab	57	60 a
	MSO	44 ab	46	49 ab
	NIS	41 b	53	57 ab
	none	41 b	39	35 b
Shattercane	AMS	51 bcd	90 bc	92 bc
	COC	45 cd	90 bc	92 bc
	DRA	54 bc	91 b	92 b
	HSOC	41 d	86 c	86 d
	MSO	59 ab	95 a	96 a
	NIS	66 a	95 a	97 a
	none	44 cd	85 c	87 cd

Velvetleaf	AMS	83 bc	70 ab	71 ab
	COC	84 bc	75 ab	78 ab
	DRA	89 a	79 a	82 a
	HSOC	82 c	67 b	70 ab
	MSO	88 ab	80 a	81 a
	NIS	80 c	66 b	68 b
	none	82 c	73 ab	74 ab

[a] Letters indicate significant differences (α=0.05) within species.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant; WWR, wet weight reduction; DWR, dry weight reduction.

Table 6.9. Visual estimations of injury of different plant species from applications of lactofen with adjuvants conducted in a field study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

Adjuvant[a]	Spray classification	Flax[b]	Grain amaranth	Palmer amaranth	Velvetleaf
			%		
AMS	Coarse	12 bc	45 bcd	45abc	18 c
COC	Coarse	21 a	52 a	51 a	26 a
DRA	Very Coarse	13 bc	42 cd	40 cd	20 bc
HSOC	Very Coarse	19 ab	51 ab	50 a	24 ab
MSO	Coarse	16 abc	46 bc	44 bcd	21 abc
NIS	Coarse	16 abc	47 abc	46 ab	22 abc
none	Coarse	10 c	40 d	39 d	18 c

[a] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Letters indicate significant differences (α=0.05) within species.

Table 6.10. Visual estimations of injury, wet weights, and dry weights of different plant species from applications of lactofen with adjuvants conducted in a greenhouse study. Spray classification was determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray classifications.

		Lactofen[a,b]		
Species	Adjuvant	Rating	WWR	DWR
		%		
Flax	AMS	61 c	60 c	57 b
	COC	96 a	97 a	93 a
	DRA	92 ab	92 ab	86 a
	HSOC	92 ab	91 ab	90 a
	MSO	90 b	90 ab	88 a
	NIS	86 b	82 b	81 a
	none	55 c	59 c	55 b
Grain amaranth	AMS	96	93	92
	COC	96	94	94
	DRA	95	96	95
	HSOC	95	91	91
	MSO	94	97	97
	NIS	94	93	93
	none	94	91	91
Velvetleaf	AMS	24 b	12 ab	14 ab
	COC	25 b	12 ab	14 ab
	DRA	36 a	31 a	34 a
	HSOC	31 ab	31 a	33 ab
	MSO	30 ab	23 ab	26 ab
	NIS	31 ab	22 ab	29 ab
	none	24 b	9 b	12 b

[a] Letters indicate significant differences (α=0.05) within species.

[b] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; DRA, drift reduction agent; HSOC, high surfactant oil concentrate; MSO, methylated seed oil; NIS, non-ionic surfactant; WWR, wet weight reduction; DWR, dry weight reduction.

CHAPTER 7

Dicamba Spray Droplet Retention on Leaves as Influenced by Nozzle Type, Application Pressure, and Adjuvant Type

Abstract

Off-target movement of growth regulator herbicides can cause severe injury to susceptible plants. Apart from not spraying on windy days or with excessive boom heights, making herbicide applications using nozzles that produce large droplets is the preferred method to reducing herbicide drift. Although large droplets maintain a higher velocity and are more likely to reach the leaf surface in windy conditions, their ability to remain on the leaf surface is not well understood. Upon impaction with the leaf surface, droplets may shatter, bounce, roll off, or be retained on a leaf surface. This study was conducted to evaluate how nozzle types, adjuvants, and pressure impact spray retention on a leaf surface. Common lambsquarters and soybean plants were grown inside a greenhouse located at the Pesticide Application Technology Laboratory, West Central Research and Extension Center, University of Nebraska-Lincoln in North Platte, NE. Three nozzles (XR, AIXR, and TTI) were evaluated at 138, 259, and 379 kPa. Dicamba (0.14 kg ae ha^{-1}) was applied alone and with a non-ionic surfactant (NIS), crop oil (COC), methylated seed oil (MSO), silicone, or drift reduction adjuvant (DRA) and contained 1, 3, 6, 8-pyrene tetra sulfonic acid tetra sodium salt as a tracer. Dicamba spray retention when applied using the XR nozzle, which produced the smallest spray droplets, was 1.75 times greater than when applied with the TTI nozzle which had the largest spray droplets. Applying dicamba with MSO resulted in spray retention on leaf surfaces nearly four times the amount achieved when applying dicamba without an adjuvant. The lowest

application pressure (138 kPa) had more than 10% more dicamba spray retention compared to the higher pressures 259 and 379 kPa. By understanding the impacts of these application parameters on dicamba spray droplet retention, applicators can select application parameters, equipment, and adjuvants that will maximize the amount of dicamba spray retained on the target leaf surface while minimizing dicamba spray drift.

Introduction

Glyphosate-resistant weeds have developed in part due to selection pressure applied to weed populations by the extensive use of glyphosate within corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirsutum* L.) production systems (Johnson et al. 2009). In response to increasing glyphosate resistance, alternative weed management strategies including herbicide-resistant crop traits are being integrated that use various herbicide modes-of-action that otherwise would not be an option. This includes development of dicamba-resistant, 2,4-D-resistant, and HPPD-inhibitor-resistant soybeans that are being developed by U.S. companies and will soon be available to growers pending regulatory approval. Once approved, the dicamba-, 2,4-D-, and HPPD-resistant technology will enable the use of dicamba, 2,4-D, or HPPD-inhibitors alone and with other herbicides for preplant burndown, at planting, and in-season applications (Davis 2012). This will give growers the ability to control herbicide-resistant weeds growing within a crop with herbicides that otherwise would injure the crop.

Dicamba can be used as preplant burndown or postemergence to selectively control broadleaf weeds in grass crops. Broadleaf crops like soybeans are often grown near grain crops and are vulnerable to off-target movement of dicamba. Previous research has reported dicamba drift injury on cotton, soybean, potato (*Solanum tuberosum*), field bean (*Phaseolus vulgaris*), and tomato (*Lycopersicon esculentum*) (Kruger et al. 2012; Lyon and Wilson 1986; Marple et al. 2008; Wall 1994; Weidenhamer et al. 1989). Dicamba is a phenoxy herbicide with injury symptoms that include cupping and curling of leaves as well as stem epinasty. These injury symptoms are easily recognizable and readily manifest the occurrence of phenoxy herbicide drift. A major concern of herbicide-resistant crops is the incidence of off-target movement of herbicides due to increased reliance on and usage of herbicides for weed control within these systems.

Physical herbicide drift occurs when spray droplets are displaced from their intended flight path due to wind. Application variables that can impact herbicide drift include the use of a hooded sprayer boom (Wolf et al. 1993), the use of drift control agents (Bode et al. 1976), or by lowering the spray boom closer to the ground (Combellack et al. 1996). Apart from not spraying on a windy day, the most influential factor related to herbicide drift is droplet size (Bird et al. 1996; Carlsen et al. 2006; Nuyttens et al. 2007b; Ozkan et al. 1997). Larger droplets maintain their direction and momentum longer and are less prone to be displaced by the wind whereas smaller droplets quickly lose their momentum and become suspended in the air (Nuyttens et al. 2009). Creech et al. (2015a) identified nozzle type as the most important factor determining spray droplet size followed by operating pressure, herbicide spray solution, nozzle orifice size, and carrier volume rate. Increasing the spray pressure decreases droplet size yet herbicide drift may decrease depending on nozzle design due to the dominance of droplet velocity (Miller and Smith 1997).

The spray droplet discharged from a nozzle is the vehicle most often used to deliver the herbicide active ingredient to the weed target. The droplet must first travel the distance from the spray boom to the target. Spray droplets leave the nozzle traveling at velocities of 15 to 25 m s^{-1} (Dombrowski and Johns 1963). When a droplet impacts a plant surface, it will either be retained through adhesion, bounce, shatter, or roll off. Droplets that are not retained can continue through the canopy and may be retained on a lower leaf or may impact the ground (Schou et al. 2012). Monocotyledons predominantly have a vertical structure and are more likely to retain smaller droplets than larger droplets (Knoche 1994). Nairn et al. (2014) observed lower adhesion of droplets to hairy leaves due to an increase in the incidence of droplet shatter. Growing conditions can alter the wettability of a plant and decrease droplet retention on the leaf surface (Forster and van Leeuwen 2010). The ability of spray droplets to remain on a plant surface determines the quantity of herbicide potentially available to be taken up by the plant. Herbicide performance increased more frequently on difficult-to-wet species as droplet size decreased in the meta-analysis than easy-to-wet species (Knoche 1994).

Other variables that impact droplet retention include plant morphological characteristics such as leaf angle and pubescence as well as droplet surface tension (Ennis et al. 1952). Retention of spray droplets is more dependent upon dynamic surface tension than equilibrium surface tension (Anderson et al. 1987; De Ruiter et al. 1990). By changing the surface tension of a spray droplet, adjuvants allow spray droplets to spread and remain over a normally repellent leaf surface (Monaco et al. 2002). Thus, adjuvants can increase droplet retention by causing more uniform spreading and wetting of the plant surface and assisting spray droplets to stick to plants (Monaco et al. 2002). For this reason, adjuvants are often added to postemergence spray solutions to enhance spray solution characteristics and/or herbicide activity. Applicators select adjuvants based on many factors namely cost, phytotoxicity risk, compatibility with tank-mix partners, and recommendations from herbicide labels and industry consultants.

In order to mitigate off-target movement of dicamba, herbicide labels recommend applicators use nozzles designed to produce large diameter droplets (Anonymous 2013a). While increasing the spray droplet size of an herbicide application may be effective at mitigating off-target movement (Bode 1987), increasing the spray droplet size of an application can impact herbicide efficacy (Knoche 1994). In addition, the dicamba herbicide label recommends the use of adjuvants and lists many different types that may be used (Anonymous 2013a). While this approach allows an applicator the ability to tailor an application to his/her specific needs, without sufficient knowledge proper selection of the most appropriate adjuvant can be difficult due to the complexity of the system (Zollinger 2009). Although these recommendations are on the dicamba label, researchers have not explored the impact they might have on the retention of spray droplets on their intended targets. The objective of this study was to determine the impact of droplet size, application pressure, and adjuvant type on the spray droplet retention of dicamba. This study will provide applicators with information to allow them to make educated decisions when making dicamba applications.

Materials and Methods

This study was conducted during the fall of 2014 at the Pesticide Application Technology Laboratory (PAT Lab) of the University of Nebraska-Lincoln located at the

West Central Research and Extension Center in North Platte, NE. The study had five replications and two runs separated temporally for each plant species evaluated. A dicamba (0.14 kg ae ha^{-1}) spray solution was applied alone and with a non-ionic surfactant (NIS), crop oil concentrate (COC), methylated seed oil (MSO), silicone based adjuvant, or a drift reduction adjuvant (DRA) (Table 7.1). The AIXR 110025, TTI 110025 and XR 110025 nozzles (Teejet Technologies, Spraying Systems Co., Springfield, IL 62703) were operated at 138, 259, and 379 kPa to deliver 94 L ha^{-1}. A 1, 3, 6, 8-pyrene tetra sulfonic acid tetra sodium salt (PTSA) was added as a tracer dye at 0.6 mg/ml as recommended by Hoffmann et al. (2014) for agricultural sprays. Treatments were applied using a single nozzle track sprayer (Generation III Research Track Sprayer DeVries Manufacturing, Hollandale, MN 56045). Prior to conducting the study, each nozzle and pressure combination was calibrated to ensure equal deposition by mass at the same height and location within the spray pattern that the plant species would be placed. This was completed by using a 15 cm petri dish and making 20 spray passes over the dish. The dish would then be weighed and the speed of the track sprayer would be adjusted until the nozzles each had the same deposition at the target site. This method of calibration was used because it was recognized that simply measuring the output of each nozzle for a period of time would be an insufficient means of calibration for this study because of variations of spray patterns among nozzles at the target site.

Common lambsquarters (*Chenopodium album* L.) and Asgrow® A3253 soybeans were grown in SC10 cone-tainer cells (Stuewe and Sons Inc., Corvallis, OR 97389) that were filled with Professional Growers Mix potting soil (Ball Horticulture Company, West Chicago, IL, 60185). Plants received supplemental nutrition (Scotts Miracle-Gro®

LiquaFeed® All Purpose, The Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol™ DS 300W, Illumitex, Austin, TX, 78735) was provided to ensure 14 h days. Plants were sprayed with dicamba treatments when the two unifoliate leaves were fully developed on soybean plants and when common lambsquarters had at least four large leaves. For each species, this occurred when plants were 15 to 20 cm tall. Prior to spraying the plants, any foliage above the target leaves was clipped and removed to ensure the spray droplets were not impeded from the target leaves.

Plants were placed individually in the center of the track sprayer 50 cm below the tip of the nozzle. In addition, a 15 cm petri dish was placed at the height of the plant canopy to collect spray deposition. This was used to further verify that equal amounts of deposition were applied across all treatment combinations. If any differences were observed, data was corrected to ensure equal comparison across treatment factors and that no bias was present. After a plant was sprayed, it was removed from the track sprayer and treated leaves were clipped into pre-labeled plastic recloseable bags. The leaves were then rinsed immediately with 40 ml of a 9:1 distilled water to isopropyl alcohol solution added using a bottle top dispenser (Model 60000-BTR, LabSciences, Inc., Reno, NV, 89510). This solution provided the maximum recovery of PTSA deposits in a study conducted by Hoffmann et al. (2014). After the PTSA dye was successfully suspended in the liquid, a two ml sample was drawn with a pipette to fill a glass cuvette. The cuvette was placed in a PTSA module inside a fluorometer (Trilogy Laboratory Fluorometer, Turner Designs, Sunnyvale, CA, 94085) and fluorescence data were collected.

Data were corrected to account for differences in leaf area and recovery as follows. After the leaves were rinsed, they were removed from the bags and dried using paper towels. The total leaf area for all leaves used for each plant was determined using an LI-3100 leaf area meter (LI-COR, Lincoln, NE, 68504). To evaluate recovery of the PTSA dye from leaf surfaces, 20 µl of each spray solution was pipetted directly onto leaves of each species and into plastic bags. The leaves were then clipped into plastic bags and rinsed and processed in the same manner as regular leaf samples with 40 ml of distilled water and isopropyl alcohol solution. Bags without leaves were also processed in the same manner. The recovery of PTSA dye from the plant surface was a percentage of the amount observed from bags with no leaves.

The spray droplet spectrum for each treatment combination was evaluated in 2014 using the low speed wind tunnel at the PAT Lab. The system and process used to collect the spray droplet data has been described extensively in a previous manuscript (Creech et al. 2015b). The laser is able to classify the spray droplet spectrum in a number of different categories to compare the spray droplet spectra of different treatments. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The amount of spray volume contained in droplets smaller than 200 µm was also used for comparison. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by ASAE S572.1 (ASABE 2009) (Table 7.1). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Statistical Analysis. Results from common lambsquarters and soybean spray droplet retention on leaf surfaces were analyzed separately because the treatments were applied at different times.

Spray droplet retention rates were calculated as a percent of the applied rate as determined from the amount of spray collected in the adjacent petri dish. Spray droplet retention data from each species were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute, Cary, NC 27513). Data from the runs of each species were combined within each experiment because they did not differ significantly. Replication was nested within run and considered a random effect in the model. LS means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

Spray Droplet Size. The droplet size spectra of each treatment are presented in Table 7.1. In general, the addition of a silicone adjuvant to dicamba produced the smallest spray droplets, followed by MSO, DRA, COC, NIS, and dicamba without an adjuvant. These spray solutions had $D_{v0.5}$ values of 482, 489, 507, 524, 546, and 559 µm, respectively, when averaged over nozzle type and pressure (Table 7.1). The different nozzle types had the greatest variability among $D_{v0.5}$ values when averaged over adjuvant and pressure. The AIXR, TTI, and XR nozzles had average $D_{v0.5}$ values of 505, 812, and 237, respectively (Table 7.1). The difference in spray droplet size among nozzles is also apparent when comparing the amount of spray volume contained in droplets less than 200 µm. The TTI nozzle typically had less than one percent while the XR nozzle had nearly

50% of its spray volume contained in droplets less than 200 µm when applications were made at 379 kPa (Table 7.1). Increasing the application pressure decreased spray droplet size as determined by $D_{v0.5}$ values from 629 µm to 495 and 430 µm averaged across nozzle type and spray solution for 138, 259, and 924 kPa, respectively (Table 7.1). The different combination of variables in the study resulted in spray classifications ranging from Very Fine to Ultra Coarse (Table 7.1). Spray droplets are the means of transportation frequently used in herbicide applications to deliver a lethal dose of chemical to the target plant species. Furthermore, the spray droplet size is highly correlated to the velocity of the droplets (Nuyttens et al. 2009) and the rate of change of size with distance from spray release. Smaller droplets may initially have a high velocity when emitted through the nozzle but their low mass allows them to rapidly decelerate. At the plant location, these small droplets, with their relatively slower velocities, are more readily retained on a leaf surface (Ramsdale and Messersmith 2001). Understanding these principles and the spray droplet characteristics of the treatment variables described in Table 7.1 will give further clarity and reasoning to the results presented hereafter.

Common lambsquarters. Common lambsquarters was used for this experiment because it has a leaf surface composed of crystalline epicuticular wax which makes it difficult to wet (Harr et al. 1991). A significant three-way interaction ($P = 0.0025$) was observed among nozzle type, pressure, and spray solution as they relate to dicamba spray droplet retention on common lambsquarters leaves. Due to the large number of treatment interactions, the many differences will not be covered individually, rather trends will be discussed. The use of adjuvants significantly increased the amount of spray retained on the surface of common lambsquarters (Table 7.3). Of the top ranked 15 treatments for dicamba retention, MSO accounted for six instances, followed by COC, NIS, and silicone with four, three, and two instances, respectively. These 15 highest ranked treatments had an average spray retention of 24% of the applied rate (Table 7.3). Dicamba applied without an adjuvant, ranked near the bottom in comparison to other treatments with adjuvants with less than 10% spray retention on common lambsquarters leaf surfaces (Table 7.3). The addition of DRA to the dicamba solution only moderately increased retention compared to dicamba alone. These two treatments had less than half the dicamba spray retention that the top ranked 15 treatments had. For the most part, the use of NIS and silicone with dicamba was most often ranked near the middle of all the treatments for spray retention.

In most instances, the spray droplet classifications for the dicamba alone and with DRA treatments that were ranked in the last 15 were Coarse, Extremely Coarse, and Ultra Coarse (Table 7.3). The majority of these treatments were applied with TTI and AIXR nozzles. The few exceptions were the treatments applied with the XR nozzle that produced Fine and Medium spray classifications. Although these XR nozzle treatments had smaller spray droplets, it was not enough to overcome the poor retention observed when only using dicamba or dicamba with DRA. Conversely, 10 of the 15 highest ranked treatments for spray retention were applied with XR nozzles that had spray classifications of Very Fine to Medium (Table 7.3). Of the remaining five highest ranked treatments, three were attributed to the AIXR nozzle with Coarse to Extremely Coarse spray classifications and two were applied with the TTI nozzle with Extremely Coarse and Ultra Coarse spray classifications. It would be expected that larger spray droplets would not remain on the leaf surface as easily as smaller droplets.

The treatments with the greatest amount of spray retention were each applied at the lowest pressure evaluated, 138 kPa, although dicamba treatments with NIS applied with the XR nozzle and MSO applied with the AIXR nozzle were not different than some lesser treatments (Table 7.3). Treatments applied at 138 kPa had on average 25% more spray retention on common lambsquarters leaves. Differences between 259 and 379 kPa were more subtle and no general trend was obvious other than they were ranked toward the middle to last in most instances. At 50 cm below the nozzle, Nuyttens et al. (2009) observed an increase in droplet velocity only for droplets greater than 200 µm in diameter. Thus, any reduction in spray droplet retention caused by increasing the application pressure would impact the TTI and AIXR nozzle more which had less than 10% of their spray volume contained in droplets less than 200 µm (Table 7.2). In comparison, the XR nozzle had as much as 59% of its spray volume contained in droplets less than 200 µm and droplet velocity would not have been as important as a variable.

Soybeans. The dicamba spray retention on soybean leaves as influenced by adjuvant, nozzle type, and application pressure was similar to that observed with common lambsquarters. A significant three-way interaction (P = 0.0003) was observed among the three variables as they relate to dicamba spray droplet retention on soybean leaves. The use of adjuvants significantly increased the amount of spray retained on the surface of soybean (Table 7.4). Of the top ranked 15 treatments for dicamba retention in soybean, MSO accounted for eight instances, followed by NIS and silicone with three and COC with one. These 15 highest ranked treatments had an average spray retention of 37% (Table 7.4). Similar to common lambsquarters, dicamba applied without an adjuvant or with DRA occupied the 15 lowest rankings with less than 15% spray retention on average

(Table 7.4). The addition of DRA to the dicamba solution only moderately increased retention compared to dicamba alone. In comparing the spray retention of adjuvants applied with dicamba to soybean and common lambsquarters the biggest difference was that NIS and silicone had greater retention on average than COC on soybean. The opposite is true for common lambsquarters which had greater dicamba droplet retention when using COC.

Of the ten treatments ranked the highest for spray droplet retention, eight were applied using the XR nozzle that produced spray classifications from Very Fine to Medium (Table 7.4). The remaining two positions of the top ten ranked treatments were the AIXR nozzle when applying dicamba with MSO. The TTI nozzle when applying a dicamba and MSO spray solution ranked 11th, 12th, and 13th with spray classifications of Extremely Coarse and Ultra Coarse (Table 7.4). Although the TTI nozzle produces relatively large droplets compared to the other nozzle evaluated, the use of MSO was able to overcome the antagonistic properties of large droplets relating to retention on a leaf surface. The next time the TTI nozzle appears in the table is when applications were made with silicone at 259 kPa. Where the MSO was able to compensate somewhat for the large droplet size of the TTI nozzle, the same is true for the XR nozzle when used with dicamba alone or with DRA. As previously reported, dicamba alone or with DRA performed had very low spray droplet retention on soybean leaves. The highest ranked treatments when using either dicamba alone or with DRA were all achieved when using the XR nozzle producing Fine to Medium spray droplets. Soybean leaves, especially on young plants, are observed to be fairly pubescent. Reduced spray retention has been observed on hairy leaves due to an increase in the incidence of droplet shatter (Nairn et al. 2014). Thus, smaller droplets, with less velocity and momentum, are less likely to shatter and therefore may be more disposed to remain on the leaf surface similar to what was observed with the XR nozzle.

Similar to the results observed with common lambsquarters, spray droplet retention increased on soybean leaves when applied at 138 kPa in most instances (Table 7.4). Smaller spray droplets slow down more quickly compared to larger droplets due to the effect of air drag (Goering et al. 1972). At 50 cm below the nozzle tip, spray droplets 120 μm and smaller have velocities at or less than 2 m s^{-1} (Nuyttens et al. 2009) Spray droplets larger than 400 μm in diameter have a relatively constant velocity as pressure increases (Nuyttens et al. 2009). The TTI nozzle had less than 10% of its spray volume contained in droplets less than 400 μm when averaged across treatments (Table 7.2). Because of this, the impact of increasing application pressure when using the TTI nozzle had no significant effect and in most cases the adjuvant treatments when using the TTI nozzle were ranked almost identically (Table 7.4). Nuyttens et al. (2009) reported that the velocity droplets with diameters between 200 and 400 μm were most responsive to increasing spray pressure 50 cm below the nozzle tip. Because the spray droplet spectrums ranged from Very Fine to Ultra Coarse depending on the treatment, the influence of increasing application pressure varied.

As environmental concerns instigated by the risk of herbicide spray drift shift the pendulum to larger spray droplet sizes, the proper selection and use of adjuvants and operating pressure can aid in ensuring herbicide efficacy is not marginalized. This research will serve as a basis for future studies as researchers attempt to define the ideal nozzle-adjuvant-pressure combination that will maximize herbicide performance by increasing spray droplet retention and transfer of lethal dose to the plant while minimizing off-target movement due to spray drift.

The addition of adjuvants to the dicamba spray solution had the greatest impact on spray droplet retention. Retention increased on average 4.5 and 3.7 times by adding MSO to the dicamba spray solution for common lambsquarters and soybean, respectively. The use of a DRA purportedly reduces the number of fine droplets and increases spray droplet deposition (Anonymous 2013d). While spray droplet deposition is a necessary requirement for herbicide activity on targeted plants, of equal or greater importance is the amount retained on the leaf surface. In this study, the use of the DRA with dicamba increased the amount of spray retained on the leaf surface by 34 and 40% for common lambsquarters and soybean, respectively, when averaged over other treatment variables. Compared to dicamba alone this is a significant increase but compared to other adjuvants the increase was minimal. Whether this increase is due to increased spray deposition, retention, or both is unknown. When applying the spray solutions to leaf surfaces manually to calculate recovery, it was evident that silicone has high spreading capabilities. This would permit the spreading of spray droplets applied to the upper surface of leaves to cover a wide area and spread around the leaf margin to the underside of the leaves. Although this level of spreading was not observed by the other spray solutions, silicone was consistently ranked near the middle of the spray solutions evaluated. Spreading may deflect some of the spray droplet momentum from rebounding or shattering when impacting the leaf surface, however, it may lead to excessive runoff. The adjuvants evaluated were applied at a single rate and were not combined with other adjuvants. Further research is needed to know if other rates or adjuvant combinations can be used to achieve a greater amount of droplet retention.

The interaction between spray solution and nozzle type can change the risk of drift and may impact spray droplet retention and herbicide efficacy in some circumstances (Miller and Butler Ellis 2000). Nozzles are the most influential component of a spray application process in the determination of spray droplet size (Creech et al. 2015a). Retention with the XR nozzle that produces Very Fine to Medium spray droplets was nearly 2 times greater than the TTI nozzle that produced Extremely Coarse to Ultra Coarse spray droplets. This demonstrated the impact droplet size can have on droplet retention. However, it is important to recognize this study was conducted under ideal conditions in a spray chamber with no apprehension for herbicide drift. Under normal field conditions, applicators must weigh the risks of herbicide drift from the application while maintaining high spray droplet deposition, retention, and herbicide efficacy. Bode (1987) reported the significance of the diameter of a spray droplet related to particle drift as a 100 μm diameter droplet can travel 7.5 times further off-target than a 500 μm droplet in 5 kph wind speed. For this reason, the use of an XR nozzle is not justifiable in many scenarios. The same is especially true when applying a product similar to dicamba with a nozzle that produces fine droplets that can cause severe damage to sensitive plants. On the other hand, droplets too large are difficult to retain on a leaf surface or to achieve high number densities of droplets because as one increases droplet diameter by a factor of 2, there is a reduction of 8 x the number of droplets.

Increasing the application pressure had the smallest effect on droplet retention. This may be explained by first understanding that the trend with the nozzle types in this study is that as pressure increases spray droplet size decreases, both of which are counteractive. Secondly, velocities for droplets with diameters between 200 and 400 μm are highly responsive to increasing spray pressure when those velocities are measured at a distance close to that of the ground, i.e. ~50 cm below the nozzle tip (Nuyttens et al. 2009). Thus, changes in application pressure to droplets with diameters below and above that range of droplet sizes would have minimal effect on changing the droplet velocity near the target leaves. Applications made at 138 kPa had greater spray droplet retention than the other pressures. This could be attributed to the fact that herbicide solutions applied at lower pressures have spray droplets beginning at a slower velocity and reach their sedimentation velocity quicker than when sprayed at higher pressures (Nuyttens et al. 2009). In the scenario of making applications at 138 kPa, droplets would impact the leaf surface with relatively low velocity and momentum thus reducing droplet bounce and shatter.

Current and future research at the PAT Lab will identify application parameters and adjuvants that maximize both spray droplet retention on leaf surfaces and herbicide efficacy against a range of weed types including narrow leaf grasses and broad leaf species. The treatments identified will then be evaluated for their propensity to move off-target via particle drift. The objective of this study was to determine the impact of droplet size, application pressure, and adjuvant type on the spray droplet retention of dicamba. This study found that applying dicamba with no additional adjuvant significantly reduced the amount of spray droplets retained on leaf surfaces. The addition of adjuvants, particularly MSO, increased spray retention. This research also found that coarser sprays are poorly retained on leaf surfaces, as compared to finer sprays. Additionally, lower pressure applications increase retention compared to those at higher pressures. Although the use of the XR nozzle should not be used for a dicamba application in the field, it helped to illustrate that smaller droplets are better retained than larger droplets. Based on the results from this research, if applicators use the nozzle and adjuvant types and scenarios in this study, they should consider using Coarse to Extremely Coarse droplets at lower pressures to reduce drift potential while using an MSO or COC to achieve maximum droplet retention on the leaves. By understanding the impacts of these application parameters on dicamba spray droplet retention, applicators can select application parameters, equipment, and adjuvants that will maximize the amount of dicamba spray retained on the target leaf surface while minimizing dicamba spray drift potential.

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Table 7.1. Source of materials used in spray droplet retention study.

Common name	Trade name	Treatment rate	Manufacturer
Crop oil concentrate	R.O.C.®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Dicamba	Clarity®	0.14 kg ae ha^{-1}	BASF Corporation, Research Triangle Park, NC, 27709
Drift agent	In-Place®	0.3 L ha^{-1}	Wilbur-Ellis Company, Fresno, CA, 94596
Methylated seed oil	Super Spread MSO®	1.0% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Non-ionic surfactant	R-11®	0.25% v/v	Wilbur-Ellis Company, Fresno, CA, 94596
Silicone adjuvant	Syl-Coat®	0.95 L ha^{-1}	Wilbur-Ellis Company, Fresno, CA, 94596

Table 7.2. Volume diameters below which droplets of equal or smaller size constitute 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume and percent spray volume less than 200 μm for each adjuvant, nozzle, and pressure combination used. The relative span is a dimensionless parameter indicative of the uniformity of the distribution of the droplet sizes of the spray. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

Adjuvant[a]	Nozzle[b]	Pressure	Droplet size $D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	V<200	Relative span	Spray classification[c]
		kPa		μm		%		
COC	AIXR	138	339	632	924	1.68	0.93	XC
COC	AIXR	259	259	488	715	4.42	0.93	VC
COC	AIXR	379	217	416	616	7.89	0.96	C
COC	TTI	138	584	1010	1366	0.35	0.78	UC
COC	TTI	259	420	770	1099	0.98	0.88	UC
COC	TTI	379	345	670	984	1.79	0.95	UC
COC	XR	138	148	295	483	22.70	1.13	M
COC	XR	259	116	232	382	38.17	1.14	F
COC	XR	379	103	206	343	47.44	1.17	F
DRA	AIXR	138	333	613	882	1.79	0.89	XC
DRA	AIXR	259	261	481	702	4.27	0.92	VC
DRA	AIXR	379	225	423	656	6.99	1.02	C
DRA	TTI	138	537	924	1240	0.32	0.76	UC
DRA	TTI	259	403	735	1046	0.99	0.88	UC
DRA	TTI	379	332	632	944	1.94	0.97	XC
DRA	XR	138	158	308	489	19.41	1.08	M
DRA	XR	259	121	236	394	36.66	1.16	F
DRA	XR	379	104	210	350	46.13	1.18	F
MSO	AIXR	138	277	537	761	4.90	0.90	XC
MSO	AIXR	259	240	450	652	5.67	0.91	VC
MSO	AIXR	379	208	403	622	8.98	1.03	C
MSO	TTI	138	532	927	1309	0.22	0.84	UC
MSO	TTI	259	382	713	1018	1.18	0.89	UC
MSO	TTI	379	315	621	946	2.49	1.01	XC
MSO	XR	138	160	304	465	19.00	1.00	M
MSO	XR	259	124	235	367	35.66	1.03	F
MSO	XR	379	108	209	338	45.99	1.10	F
NIS	AIXR	138	332	661	972	2.39	0.97	XC

NIS	AIXR	259	246	506	810	5.77	1.11	VC
NIS	AIXR	379	207	432	679	9.16	1.09	C
NIS	TTI	138	589	1044	1410	0.21	0.79	UC
NIS	TTI	259	458	860	1244	0.72	0.92	UC
NIS	TTI	379	374	728	1069	1.47	0.96	UC
NIS	XR	138	127	274	468	28.71	1.24	M
NIS	XR	259	101	218	379	43.61	1.27	F
NIS	XR	379	89	194	337	52.44	1.28	F
None	AIXR	138	350	663	964	1.84	0.93	XC
None	AIXR	259	259	513	800	4.73	1.05	VC
None	AIXR	379	215	442	697	8.22	1.09	C
None	TTI	138	618	1094	1480	0.16	0.79	UC
None	TTI	259	465	887	1286	0.65	0.92	UC
None	TTI	379	379	746	1091	1.40	0.95	UC
None	XR	138	136	282	470	25.77	1.18	M
None	XR	259	100	219	380	43.30	1.28	F
None	XR	379	85	188	332	54.78	1.31	F
Silicone	AIXR	138	309	587	862	2.26	0.94	XC
Silicone	AIXR	259	233	449	679	6.23	0.99	VC
Silicone	AIXR	379	201	401	641	9.86	1.10	C
Silicone	TTI	138	511	896	1268	0.33	0.85	UC
Silicone	TTI	259	385	716	1021	1.15	0.89	UC
Silicone	TTI	379	328	637	953	2.09	0.98	XC
Silicone	XR	138	141	267	413	26.81	1.02	F
Silicone	XR	259	114	209	336	46.03	1.06	VF
Silicone	XR	379	98	183	292	58.71	1.06	VF

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

Table 7.3. Spray droplet retention on common lambsquarters leaves as a percent of the total spray volume applied. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

Adjuvant[a]	Nozzle[b]	Pressure	Spray classification[c]	Retention[d]
		kPa		%
COC	XR	138	M	29.2 a
MSO	XR	138	M	29.1 a
NIS	XR	138	M	27.5 ab
MSO	AIXR	138	XC	26.6 ab
MSO	TTI	379	XC	25.4 bc
COC	AIXR	138	XC	25.3 bc
Silicone	XR	379	VF	24.7 b-d
NIS	XR	259	F	22.0 c-e
COC	XR	259	F	21.7 d-f
COC	XR	379	F	21.3 d-f
MSO	AIXR	379	C	21.3 d-f
MSO	TTI	138	UC	21.0 ef
MSO	XR	379	F	20.6 e-g
NIS	XR	379	F	20.6 e-g
Silicone	XR	138	F	20.5 e-g
MSO	AIXR	259	VC	20.2 e-g
Silicone	XR	259	VF	20.0 e-g
COC	AIXR	379	C	19.8 e-g
MSO	XR	259	F	19.3 e-h
COC	TTI	138	UC	19.2 e-h
Silicone	AIXR	138	XC	19.0 e-i
NIS	AIXR	138	XC	18.9 e-i
COC	AIXR	259	VC	18.5 f-j
MSO	TTI	259	UC	17.4 g-k
COC	TTI	379	UC	16.0 h-l
NIS	AIXR	259	VC	15.7 j-m
Silicone	TTI	379	XC	15.1 j-n
COC	TTI	259	UC	14.5 k-o
Silicone	AIXR	379	C	14.1 k-p
DRA	XR	138	M	14.0 k-p
Silicone	AIXR	259	VC	13.3 l-q
NONE	XR	259	F	13.1 l-q

NIS	AIXR	379	C	13.0 l-q
Silicone	TTI	138	UC	12.8 l-q
DRA	XR	379	F	12.7 l-r
NIS	TTI	259	UC	12.6 l-r
NIS	TTI	138	UC	12.4 m-r
Silicone	TTI	259	UC	11.9 n-r
DRA	XR	259	F	11.8 n-s
NONE	XR	138	M	11.6 n-s
NIS	TTI	379	UC	11.4 o-t
NONE	XR	379	F	10.9 p-u
DRA	AIXR	379	C	10.3 q-u
DRA	AIXR	259	VC	10.0 u-w
DRA	TTI	259	UC	9.3 r-w
DRA	AIXR	138	XC	8.4 s-w
NONE	AIXR	259	VC	8.1 t-w
DRA	TTI	138	UC	7.8 u-w
NONE	AIXR	379	C	7.8 u-w
NONE	AIXR	138	XC	7.8 u-w
NONE	TTI	379	UC	7.7 u-w
DRA	TTI	379	XC	7.5 u-w
NONE	TTI	138	UC	6.8 vw
NONE	TTI	259	UC	6.1 w

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

[d] Means followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 7.4. Spray droplet retention on soybean leaves as a percent of the total spray volume applied. Spray classification determined in accordance with ASAE S572.1 standards from reference curves generated using the same methods to determine spray quality of the treatments.

Adjuvant[a]	Nozzle[b]	Pressure	Spray classification[c]	Retention[d]
		kPa		%
NIS	XR	138	M	44.1 a
MSO	XR	138	M	43.5 a
Silicone	XR	379	VF	39.9 ab
MSO	AIXR	138	XC	37.8 bc
COC	XR	138	M	37.5 b-d
NIS	XR	379	F	36.9 b-d
MSO	AIXR	379	C	36.7 b-d
Silicone	XR	138	F	36.2 b-e
MSO	XR	379	F	35.9 b-e
Silicone	XR	259	VF	35.8 b-f
MSO	TTI	379	XC	34.7 c-g
MSO	TTI	138	UC	33.3 c-h
MSO	TTI	259	UC	33.2 d-h
NIS	XR	259	F	31.9 e-i
MSO	AIXR	259	VC	31.9 e-i
MSO	XR	259	F	31.3 f-j
Silicone	AIXR	138	XC	30.9 g-k
COC	XR	379	F	29.3 h-l
DRA	XR	138	M	29.2 h-l
NIS	AIXR	138	XC	28.1 i-m
COC	XR	259	F	27.8 i-m
NIS	AIXR	379	C	27.2 j-m
Silicone	AIXR	379	C	26.6 k-n
COC	AIXR	259	VC	25.9 l-o
NIS	AIXR	259	VC	25.4 l-p
COC	AIXR	138	XC	24.3 m-q
Silicone	TTI	259	UC	23.6 m-r
NIS	TTI	138	UC	23.4 m-r
Silicone	TTI	138	UC	22.9 n-s
NIS	TTI	259	UC	22.6 n-t
Silicone	TTI	379	XC	22.1 n-t
DRA	XR	379	F	21.8 o-t

COC	TTI	259	UC	21.7 o-t
COC	AIXR	379	C	21.6 o-u
Silicone	AIXR	259	VC	20.8 p-v
COC	TTI	138	UC	20.3 q-v
NIS	TTI	379	UC	19.9 r-w
COC	TTI	379	UC	19.6 r-w
None	XR	379	F	18.6 s-w
DRA	XR	259	F	18.5 t-w
None	XR	259	F	17.3 u-x
None	XR	138	M	17.1 v-x
DRA	TTI	138	UC	15.5 w-y
DRA	TTI	379	XC	13.1 x-z
DRA	AIXR	259	VC	13.0 x-z
DRA	AIXR	138	XC	12.6 yz
None	AIXR	379	C	12.6 yz
DRA	TTI	259	UC	12.4 yz
DRA	AIXR	379	C	12.4 yz
None	AIXR	259	VC	11.6 yz
None	AIXR	138	XC	11.3 yz
None	TTI	138	UC	11.2 yz
None	TTI	379	UC	9.9 z
None	TTI	259	UC	9.1 z

[a] Abbreviations: COC, crop oil concentrate; DRA, drift reduction agent; MSO, methylated seed oil; NIS, non-ionic surfactant.

[b] Nozzles used were 110025, Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[c] Spray classification categories were derived from reference curves generated at the Pesticide Application Technology Laboratory per ASAE S572.1 where VF = Very Fine, F = Fine, M = Medium, C = Coarse, VC = Very Coarse, XC = Extremely Coarse, and UC = Ultra Coarse.

[d] Means followed by the same letter are not significantly different at $\alpha = 0.05$.