The Effect of Spray Parameters on the Application of Enlist Duo

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THE EFFECT OF SPRAY PARAMETERS ON THE APPLICATION OF ENLIST DUO

by

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EFFECT OF SPRAY PARAMETERS ON THE APPLICATION OF ENLIST DUO

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The emergence of new weed control challenges, along with shifts in weed management strategies and cultural practices, has resulted in an increased reliance on chemical weed control in United States (US) cropping systems. As a result, numerous weed species have evolved resistance to herbicides such as glyphosate, thus prompting the development of new weed control systems designed to aid growers in managing resistant weeds. While these new weed control options may give growers additional management options, the high sensitivity of broadleaf crops, fruits, and vegetables to products containing 2,4-D or dicamba increases the potential for herbicide drift resulting from application of these herbicides to damage non-target susceptible plants. As a result, herbicide labels for new products such as Enlist Duo contain specific application requirements for both application and meteorological factors aimed at minimizing application drift potential. Drift reduction for ground application of herbicide is typically centered combinations of agricultural nozzle types and spray pressures designed to increase the droplet size distribution of the applied solution, as larger droplets are less prone to off-target movement in the form of spray particle drift. However, the mechanisms by which herbicide droplets drift is a complex process, and is influenced by may application and meteorological factors. Additionally, while minimizing drift should be a goal for all applications, an ideal application of herbicide must also deposit and retain active ingredient on leaf surfaces as well as transfer a lethal dose of herbicide to its
intended targets.

The objectives of this research were to 1) evaluate the droplet size, droplet initial exit velocity, and drift potential of two venturi-type nozzles in laboratory conditions and 2) determine the influence of nozzle type on the drift potential of a field application of Enlist Duo herbicide.
For my best friend and love of my life, Erin.

You are my today, my tomorrow, and my everything.
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CHAPTER 1

Literature Review

Herbicides continue to be an important component of agricultural weed management strategies in the United States, as evidenced by their application to nearly 97% of corn and soybean acres from 2014-2015 (USDA NASS, 2014-2015). The introduction of herbicide-tolerant crops increased the use of herbicides in row crop agriculture with a 20% increase in use from 1971-1982 (Zimdahl 2007), and a 9% increase in use from 1996-2011 (Benbrook 2012). The wide-spread adoption of glyphosate-tolerant crops played large role in this increase, as the amount of glyphosate applied per year in the United States increased by 27.5 million kg from 1995 to 2005 (Young 2009). While herbicide-tolerant crops allow for more-efficient weed control and simplify the weed management process (Martinez-Ghersa et al. 2003), the potential development of resistant species increases, particularly in areas where weeds have endured repeated exposure to herbicides with the same mode of action (Burnside 1992). The increased potential risks from this effect is evident in soybean production, as the number of active ingredients applied on 90% of US soybean hectares declined from 11 in 1995 to only one single ingredient, glyphosate, in 2002 (Young 2009). As of 2015, glyphosate resistance was confirmed in 32 weed species worldwide (Heap 2015). These weed management challenges led to the development of new technologies designed to ease the management of herbicide-resistant and hard to control weeds.

New Herbicide-Crop Technology
Attempting to combat resistant weeds, farmers have turned to both cultural practices and the use of multiple herbicides. These practices have had positive, but limited success as they add cost to production systems, effective herbicides are not always readily available, and more intensive tillage is often not possible to implement in larger production acres (Purdue Extension 2012). Responding to these management challenges, new herbicide-crop technologies such as corn and soybean cultivars, tolerant to glyphosate and dicamba or 2,4-D, will soon be available for commercial release. These novel weed control systems offer a potential increase in control of both resistant broadleaf weeds and tough to control grasses, as each herbicide will be used in a tank-mixture or pre-mixture with glyphosate (Davis 2012). These technologies also allow for a wider application window throughout the growing season, offering farmers more use options and flexibility (Purdue Extension, 2012). Broadleaf crops tolerant to glyphosate and synthetic auxin herbicides will be the first of these new technologies to be utilized.

One of these technologies, Roundup Ready 2 Xtend (Monsanto), received regulatory approval for use in 2017. This system consists of crops tolerant to both glyphosate and dicamba herbicides and the ability for multiple, in-season applications of dicamba (Xtendimax herbicide) to Xtend corn, soybean, and cotton. Currently, Roundup Ready Xtend herbicide, a pre-mixture of glyphosate and dicamba, is awaiting regulatory approval. Another similar technology, and the focus of this research, is the Enlist Weed Control System (Dow AgroSciences). This new herbicide-crop technology features corn, soybean, and cotton cultivars tolerant to both glyphosate and 2,4-D, allowing for the use of Enlist Duo herbicide, a pre-mixture of glyphosate and 2,4-D choline, to control troublesome and herbicide-resistant weeds. The Enlist Weed Control System is scheduled to be available for limited release in 2017.
Enlist Duo Herbicide

Enlist Duo herbicide is a pre-mixture of glyphosate \([N-(phosphonomethyl) glycine, \text{dimethylammonium salt}]\) and 2,4-D (2,4-dichlorophenoxyacetic acid, choline salt). This product contains 195 g ae L\(^{-1}\) of 2,4-D choline and 205 g ae L\(^{-1}\) of glyphosate with a recommended use rate of 1,640 to 2,185 g ae ha\(^{-1}\). Enlist Duo may be applied POST at various crop growth stages to control broadleaf weeds and grasses in Enlist corn, soybean, and cotton. Though available literature notes the propensity of 2,4-D herbicides to move off-target during or after application (Grover et al. 1972; Renne and Wolf 1979), the choline salt \((C_{13}H_{19}Cl_2NO_4)\) was developed to be less prone to drift and volatilization than other forms of 2,4-D (Minnesota Department of Agriculture 2015). The Enlist Duo herbicide label addresses spray drift management, listing application requirements for factors such as wind direction and speed, nozzle selection, and protection of sensitive areas.

While this herbicide is new to the market, it’s components are not. Glyphosate was first synthesized by Dr. Henri Martin in 1950 but was not tested as a herbicide until 1970 (Franz et al. 1997). Since its commercial introduction in 1974, glyphosate \([N-(phosphonomethyl)glycine],\) is considered to be the most important herbicide of its time. Glyphosate is a broad spectrum, non-selective, anionic herbicide that is active in several cationic formulations such as the sodium, isopropylamine, potassium, and diammonium salts. Glyphosate has a unique mode of action, as it is the only molecule that is highly effective at inhibiting the enzyme 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS) of the shikimate pathway (Duke et al. 2008). Though it is unknown how inhibition of this pathway kills susceptible plants, many assume that insufficient
aromatic amino acid production to maintain necessary protein synthesis is the primary effect (Duke et al. 2008). Glyphosate’s mechanism of action is an enzyme (EPSP) found only in plants, making it an ideal herbicide. However, the non-selective nature of glyphosate resulting in the destruction of crops upon application limited its initial use to non-crop and orchard production systems (Dill 2005).

Developed during World War II, 2,4-D was one of the first herbicides used in the United States (Tu et al. 2001). The basic form of 2,4-D is 2,4--dichlorophenoxyacetic acid, but it is often formulated as an inorganic salt, amine or ester (WHO, 1984). These herbicides exert selective action, preferentially against dicot weeds in cereal crops, and are translocated systemically in the plant (Grossmann 2010). 2,4-D herbicides are foliarly active and enter plants through open stomata and the leaf cuticle. When applied, 2,4-D is quickly absorbed and translocated from older leaves to actively growing areas of the plant. 2,4-D acts by mimicking the growth hormone auxin, which causes uncontrolled growth, and eventually death, in susceptible plants (Tu et al. 2001). Auxins generally regulate cell division and elongation and developmental processes including vascular tissue and floral meristem differentiation, leaf initiation, senescence, apical dominance and root formation (Grossman 2010). While low auxin concentrations may stimulate growth and development, high concentrations disturb growth and lethally damage susceptible plants.

**Glyphosate and 2,4-D Use**
As of 1995, glyphosate was the seventh most commonly used herbicide in US agricultural crop production with 11-13 million kg ai applied (Aspelin et al. 1997). By 2007, glyphosate was the most commonly used herbicide agricultural herbicide in the US with 81-84 million kg ai applied (Grube et al. 2011). Additionally, glyphosate use increased slightly in non-agricultural sectors, as around 8 million kg ai was applied in 1995 versus 11 million kg ai in 2007 (Aspelin et al. 1997; Grube et al. 2011). The widespread adoption of glyphosate-tolerant soybean (Roundup Ready Soybean) following their introduction in 1996 is the cause of the dramatically expanded use of glyphosate (Figure 1.1). In the year 2000, 54% of all soybean, 61% of all cotton, and 25% of all corn in the US were glyphosate-tolerant whereas by 2016, 94%, 93%, and 92% of all US soybean, cotton, and corn were glyphosate-tolerant (USDA ERS 2016).

2,4-D has become a mainstay in agriculture, forestry, and lawn care due to its effectiveness at selectively eliminating broadleaf plants (Munro et al. 1992). Use of 2,4-D herbicide in US crop production has steadily increased: in 1995, 2,4-D was the sixth most used herbicide with 14-16 million kg ai applied whereas 2,4-D was the fifth most used herbicide with 11-13 million kg ai applied in 2007. In terms of non-agricultural use, 2,4-D was the most commonly used herbicide in the US for decades, with its use expanding from nine million kg ai applied in 1995 to 14 million kg ai in 2007 (Aspelin et al. 1997; Grube et al. 2011). Though 2,4-D was historically used PRE in corn-soybean systems, its use in such systems has recently increased (Figure 1.2). This is likely due to shifts in weed species composition as continued use of glyphosate has results in growing populations of resistant or tough-to-control weeds such as Conyza Canadensis (L.) Cronq, Lactuca serriola (L.), Kochia scoparia (L.) Schrad, Xanthium strumarium (L.), Chenopodium album (L.), and several Amaranthus subspecies (Shaner 2000). Additionally, it is hypothesized that increased use in corn-soybean cropping systems is partially
due to 2,4-D’s increased application flexibility in comparison to alternative pre-emergence herbicide options; a shortened planting restriction, for example, allows growers to switch crops early in the growing season if planting is delayed.

**Droplet Generation**

Atomization, the process of reducing a liquid to fine particles, is how spray droplets are generated. There are five droplet creation methods: forcing spray liquid under pressure through small orifices, subjecting liquid to centrifugal energy, air shear, utilizing vibrational energy, and electrical charge via electrostatic nozzles (PISC 2002). These methods expend energy on spray liquid to overcome surface tension and viscous forces and to increase spray liquid surface area to form droplets via sheet break-up, ligament break-up, and direct droplet formation (PISC 2002; Ebert and Downer 2008). This research focuses on creating droplets by forcing spray liquid through a small nozzle orifice. These nozzles, available as flat fan, air induction, twin fluid, and hollow or full cone, are called hydraulic nozzles. Spray liquid applied through a hydraulic nozzle emerges as a liquid sheet, and atomizes either as rim, perforated sheet, or wavy-sheet disintegration (Ebert and Downer 2008). The purpose of the spray droplet is to deliver active ingredient to application target sites. After spray droplet generation and formation, the process of delivering droplets is complex and contains many different stages: travel to plants and subsequent impaction, droplet retention, deposit of active ingredient, plant uptake, and plant biological response (Reichard 1988; Ebert and Downer 2008; Creech et al. 2015). The stages of droplet delivery, spray coverage, application efficacy, and drift potential are impacted by the droplet size distribution of a spray solution. Therefore, the droplet size spectra of hydraulic
nozzles are important, as selecting nozzles to meet specific needs can limit the amount of herbicide lost to drift and maximize the efficacy of the application (Yates et al. 1985; Bouse et al. 1990; Taylor et al. 2004).

Measuring Droplet Size Distribution

Measuring drift is typically done in a wind tunnel, and focuses on measuring the droplet size distribution (DSD) of the spray, and can include measuring downwind deposition and/or airborne flux of drifting spray particles. The DSD is typically measured by either laser diffraction, imagery, or phase doppler based systems (Hewitt 1997). Drift reduction can then be determined by comparing droplet data to sprays produced by standard reference nozzles such schemes outlined by British Crop Protection Council (Nuyttens et al. 2007) or the American Society of Agricultural Engineers (ASAE 2009). These reference nozzles establish droplet size classification categories, allow for comparison between laboratories, and are typically included in any droplet sizing work (Fritz et al. 2014; Fritz and Hoffman 2016). The standard developed by the American Society of Agricultural Engineers classifies nozzles as very fine (<100 mm), fine (100-175 mm), medium (175-250 mm), coarse (250-375 mm), very coarse (375-450 mm), or extremely coarse (>450 mm) (ASAE 2009). Mean droplet diameter is then used to characterize agricultural sprays, with the amount of spray drift typically related to the percentage of fine spray droplets (Hilz and Vermeer 2013).

Factors Affecting Droplet Size Distribution
Droplet size distribution is a measure of nozzle performance, and is one of the many factors that influences the efficiency of the herbicide application process (Miller and Butler Ellis 2000). Nozzle selection greatly influences spray droplet size (Derksen et al. 1999), with each nozzle tip producing a varying range of droplet sizes as influenced by the nozzle orifice size and shape (Mueller and Womac 1997; Etheridge et al. 1999), the physical properties of the spray liquid (M.C. Butler Ellis et al. 2001; Lan et al. 2008; Ferguson et al. 2015), and the operating spray pressure (Mueller et al. 1997). Numerous studies have explored the complex relationship between nozzle type and these additional influencing factors that determine the droplet size spectrum generated. Etheridge et al. (1999) applied several different herbicides (paraquat, glyphosate, glufosinate) through four venturi-type nozzles (Delavan Raindrop Ultra - RU, Greenleaf Turbodrop – TD, Lurmark Ultra Lo-Drift - LM, Spraying Systems AI Teejet – AI) with varying orifice sizes and at a range of operating pressures. The results indicated that drift-reducing venturi nozzles produce larger droplets than a standard flat-fan nozzle, that different herbicides may produce varying droplet size distributions independent of nozzle type, reducing nozzle orifice size produces smaller droplets, and increasing operating pressure results in a larger proportion of small spray droplets. A similar study conducted by Creech et al. (2015) examined the same application parameters with the addition of carrier volume. The results support the work of Etheridge (1999), and showed that though the effect of carrier volume on droplet diameter is less than other variables, droplet diameter increases as the spray mixture became more diluted at higher carrier volumes.

*Impact of Droplet Size on Efficacy*
Spray droplet size is a crucial factor in a herbicide’s application efficacy. A review of the effects of droplet size on weed control (Knoche 1994) showed that decreasing droplet size generally increased canopy penetration, improved droplet impaction and herbicide retention, and increased the efficiency of biological response. When examining the effect of droplet size on efficacy, it is critical to consider the herbicide’s mode of action. While droplet size spectra typically do not influence the efficacy of systemic herbicides, fine droplets increase the efficiency of contact herbicides (Prokop and Veverka 2003; Feng et al. 2003). However, applicators can reduce carrier volume and/or increase droplet size with both contact and systemic herbicides without reducing herbicide efficacy (Ramsdale and Messersmith 2001; Wolf 2000). The efficiency of an application is also influenced by droplet retention, absorption, and translocation of active ingredient to target plants. While differences in these factors was examined for multiple droplet sizes (Feng et al. 2003), environmental and leaf morphology effects on spray deposition are typically not considered (Smith and Luttrell 1997; Shaw et al. 2000). Optimal droplet size for herbicide efficacy is species-dependent given variations in leaf morphology and structures such as leaf hairs, protrusions, and cuticular wax (De Ruiter et al. 1990). When spray droplets impact leaf surfaces, they can be retained via adhesion or lost due to shatter, bounce, and rolling off. Though larger droplets may result in less deposition due to these factors (Smith et al. 2000), the amount of surfactant present in herbicide formulations or from adjuvants added to the tank increases the retention of larger spray droplets (De Ruiter et al. 1990; Spillman 1984; Reichard 1988).
Herbicide Drift

Herbicide drift is typically classified as either vapor drift or spray particle drift. The former occurs when a volatile herbicide changes from either a solid or liquid state to a gaseous state, and subsequently moves from the target area (Dexter 1995). Vapor drift may move long distances over extended periods of time depending on the environmental conditions. This type of drift typically occurs if temperatures are high, and humidity is low, and can occur more than 12 hours after herbicide application (Matthews 2016). The vapor pressure of a formulation, along with environmental conditions, directly influence this type of off-target movement.

Much like the process of applying herbicides, attempting to define spray particle drift is a complex endeavor. The US Environmental Protection Agency (EPA) defines spray drift as the “physical movement of a pesticide through the air at the time of application or soon thereafter, to any site other than the one intended for application” (EPA 1999). Spray particle drift has been defined as “drift that occurs when wind causes spray droplets to be displaced from their intended flight path into non-target areas” (Wolf et al. 1993). Henceforth, references to drift will refer to the physical movement of spray droplets from the treatment site following their generation during ground application.

When an application generates many fine spray droplets, spray particle drift is likely to occur. Smaller droplets have lesser terminal settling velocities than larger droplets due to less mass and smaller cross-sectional areas, and thus are carried in the direction of the wind for greater distances prior to deposition. An application’s spray particle drift potential is influenced by a number of factors, including wind speed and direction, relative humidity, air temperature, and volume of small droplets (Bouse et al. 1990). While application efficiency may increase with
a greater number small droplets, these smaller droplets represent a significant drift hazard (Yattes et al. 1976; Whisenant et al. 1993). While droplets generated by nozzles commonly used in agriculture range in size from ~50 µm to greater than 1,000 µm (Bouse et al. 1990; Ebert and Downer 2008), those smaller than 150 µm (Yates et al. 1985) to 200 µm in diameter (Whisenant et al. 1993; Etheridge et al. 1999) are the most susceptible to drift. Recent droplet sizing work conducted for this research shows that for nozzles approved for use with Enlist Duo herbicide, less than 0.1% of the total spray volume was contained in droplets with a diameter of 50 microns.

*Herbicide Drift Mechanisms*

The physical process by which spray particles move off- is complex. While a fraction of herbicide dosage is lost to the atmosphere during application, the total amount of herbicide not reaching its intended target depends on application technique and environmental conditions (Van Den Berg et al. 1999). Weather conditions can directly affect the amount of spray drift resulting from herbicide application (Craig 1998). High wind speeds, coupled with low relative humidity’s and high temperatures, produces conditions conducive to drift (Hanna and Schaefer 2008). Beyond meteorological conditions, the physical setup and operational parameters of the sprayer further influence the transport and fate of an applied spray (Nordby and Skuterud 1974). Conventional ground application sprayers typically apply herbicide from nozzles positioned around 50 centimeters above target plants, though this height may increase at high application speeds. Dombrowski and Johns (1963) found that spray droplets exit from nozzles at velocities ranging from 15 to 25 m s$^{-1}$. Once droplets are generated, their rate of fall can be predicted using
Stokes’ Law; the rate of fall (or how long a particle remains in the air) is proportional to the radius of particles and is modified by entrainment in a mobile air mass (Felsot 2005). Stokes’ Law states that as a sphere falls, its velocity increases until it reaches terminal velocity, drag force is balanced by gravitational force, as a function of droplet diameter. Spillman (1984) noted droplets tend to move in the mean direction of winds, with droplets small than 100 µm being carried near horizontal, particularly in higher wind speeds, while droplets several hundred microns in diameter fall in a near vertical manner as the gravitational forces far outweigh the drag forces. The process of a ground application itself can influence spray movement as moving nozzle(s) create a trailing spray plume or cloud with a vortex developing from the downward movement of spray droplets and forward movement of the nozzle (Gohlich 1983; Jorgensen 2003), which in turn creates an air depression around the nozzle that can divert spray droplets as air moves to fill the void (Young 2009).

Consequences of Herbicide Drift

While the costs associated with pesticide use are significant, damage due to off-target movement can be as, or more, substantial. Spray particle drift can damage neighboring crops as well as nearby sensitive plant species (de Snoo and De Wit 1998; Nordby and Skuterud 1974). The impact of spray drift is a function of the toxicity of the herbicide, the distance of sensitive plants from the application site, the impacted species’ level of susceptibility, and potential “fitness” levels of exposed plants (Marrs and Frost 1997). De Snoo and van der Poll (1998) showed that late-season, field-wide application of broad-spectrum herbicides resulted in deposition and subsequent damage to ditch-bank vegetation. Marrs et al (1989) determined that
for the application of broad-spectrum herbicides, in both high and low wind speeds, the maximum safe distance at which no lethal effects were observed was 6 meters downwind from the sprayer. No lethal damage was observed beyond 6 and it was concluded that a downwind buffer zone of 6-10 meters would likely sufficiently protect sensitive areas. This initial buffer zone was expanded as a result of additional work showing greater target species capture of drifting particles and increased plant sensitivity (Marrs et al. 1993; de Snoo and De Witt 1998; Longley et al. 1996). Herbicide toxicity is an important factor as well, as certain modes of action are very active even at low concentrations. Some fruits, vegetables, and broadleaf crops are sensitive to dicamba and 2,4-D at rates as low as 1 g ha$^{-1}$ (Auch and Arnold 1978; Johnson 1947). Buffer zones will play an important role in spray drift management when using new herbicide-crop technologies containing growth regulator herbicides such as dicamba and 2,4-D.
Objectives

New herbicide-crop technologies will provide an additional weed management tool for growers across the US. These technologies, such as the Enlist Weed Control System, also create concern regarding off-target movement of herbicide and subsequent damage to sensitive non-target plants. Spray particle drift is dependent upon factors such as droplet size, spray liquid properties, operating pressure, applicator equipment setup, and environmental conditions (Bouse et al. 1990; Nordby and Skuterud 1974). The objectives of this research were: 1) evaluate the effects of nozzle type and wind speed on droplet size and droplet initial exit velocity of spray particles moving off-target in a wind tunnel, 2) conduct field studies to determine the spray particle drift resulting from an application of Enlist Duo herbicide, and 3) evaluate the effect of nozzle type, orifice size, and operating pressure on the efficacy of Enlist Duo on resistant and tough-to-control weed species.
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Figure 1.1. Estimated agricultural use of glyphosate in the US by crop, years 1992-2014.

Figure 1.2 Estimated agricultural use of 2,4-D in the US by crop, years 1992-2014.
CHAPTER 2

Droplet Size and Deposition of Enlist Duo in a Wind Tunnel

Abstract

Spray particle drift, or the physical movement of spray particles off-target, is influenced by factors including wind speed and direction, boom height, droplet initial exit velocity, and spray droplet size. Droplet size is affected by nozzle type, operating pressure, orifice size, and tank solution composition. The potential adverse impacts resulting from spray drift is dependent upon the location of susceptible plants relative to the site of application and the susceptibility of the impacted species. The objective of this study was to determine droplet size, droplet initial exit velocity, and the droplet size and deposition of Enlist Duo applied through two drift reduction type nozzles in laboratory conditions. The study was conducted in low-speed wind tunnels at the Pesticide Application Technology (PAT) Lab in North Platte, NE and the Aerial Application Technology Research Unit (USDA ARS) in College Station, TX. Enlist Duo herbicide, a premixture of 2,4-D choline and glyphosate, was applied at a rate of 592.36 g ae ha\(^{-1}\) glyphosate and 557.51 g ae ha\(^{-1}\) 2,4-D with a carrier volume of 140 L ha\(^{-1}\) through either an AIXR11004 or TDXL11004 nozzle operated at 276 kPa. A Sympatec HELOS/KR laser diffraction instrument was used for droplet sizing measurements, and a LaVision SprayMaster system was used for initial velocity measurements. The wind tunnel was operated 8.1, 16.1, and 21.1 km hr\(^{-1}\) for drift evaluation, and collection stations were placed 0, 1.5, 3, 6, 9, and 12 m downwind of the nozzle. Mylar cards and strings were used to collect deposition and airborne spray flux, and water sensitive cards were used to collect the droplet size of drifting spray. The study showed that between nozzle types, the TDXL11004 produced a spray with a larger \(D_{v0.5}\) value and a smaller
volume of spray contained in droplets < 141 µm than the AIXR11004. The drift deposition and
droplet size was impacted by wind speed, as higher wind speed resulted in greater downwind
deposition and larger particles moving off-target. Additionally, Enlist Duo through the
TDXL11004 nozzle at the 21 km hr\(^{-1}\) wind speed resulted in the collection of larger spray
droplets at downwind distances (1.5 and 3 m) and more airborne drift than the AIXR11004
nozzle. The TDXL also generated droplets with lower initial exit velocity profiles than the
AIXR, as the nozzle design of the TDXL reduces internal pressure near the exit orifice. In
conclusion, this study showed that while drift deposition was the same between nozzle types, the
TDXL11004 resulted in more airborne spray flux and larger droplets moving downwind than the
AIXR11004 at the 21 km hr\(^{-1}\) wind speed despite generating a coarser spray quality. For an
Enlist Duo solution applied through two drift-reduction type nozzles, the generation of larger
spray droplets did not necessarily result in less spray particle drift. Therefore, a better
understanding of initial exit velocity profiles of sprays generated by such nozzles may be crucial
in making accurate drift potential assessments.

**Introduction**

Herbicides continue to be an important component of agricultural weed management
strategies. In 2008, more than 230,000,000 kg of pesticide were applied in the US, with
herbicides accounting for 78% of total pesticide use (USDA ERS 2014). Van den Berg et al.
(1999) noted that the fraction of herbicide dosage that misses its intended target may be as high
as 50% depending upon application conditions. Continued reliance on chemical weed control has
raised public awareness about the effects of herbicide use and its off-target movement. Increased
public concern and media emphasis on pesticide application has contributed to a heightened public awareness of ecological concerns, especially with regards to pesticide drift (Pimentel et al. 2005). These concerns have increased greatly with the wide-spread adoption of herbicide-tolerant crops.

An ideal application of herbicide should efficiently deposit and retain active ingredient on leaf surfaces as well as transfer a lethal dose of herbicide to the intended target (Ebert and Downer 2008) while also minimizing off-target losses in the form of spray particle drift (Nuyttens 2007). Spray droplet size has been shown to greatly impact both herbicide efficacy and the propensity of spray droplets to move off-target. The droplet size spectra of hydraulic nozzles are then critically important because they affect spray particle drift (Yates et al. 1985; Taylor et al. 2004).

In an effort to mitigate herbicide off-target movement, drift reduction technologies have been developed with the goal of minimizing the amount spray moving off target during application. These technologies include new nozzle designs, pulse-width modulation spray systems, hooded sprayers to aid in droplet deposition, and boom height controllers (Nordby and Skuterud 1974; Pierce and Ayers 2001; Wolf et al. 1993; Yates et al. 1976). Agricultural nozzle manufactures have introduced various venturi-type nozzles designed to mitigate spray particle drift. The purpose of these nozzles is to reduce the volume of spray contained in small drift-prone droplets, such as those smaller than 141 µm in diameter, and create larger droplets than standard flat-fan nozzles (Derksen et al. 1999). While design may vary, drift-reduction nozzles typically utilize pre-orifice chambers, air-induction ports, a mixing chamber, and an exit orifice. Coarser sprays are generated due to the venturi effect, as the flow-metering pre-orifice constricts liquid flow and reduces internal liquid pressure near the exit orifice. Some nozzles feature the
same pre-orifice design with the addition of an air-induction port to draw air into the nozzle, thus producing spray droplets that may contain air pockets (Butler Ellis et al. 2002). Studies have shown that while air-induction nozzles are effective at reducing herbicide drift by producing coarser sprays (Arnold 1990; Combellack et al. 1996), droplet size was mainly determined by the size of the exit orifice and not the inclusion of air into spray droplets (Butler Ellis et al. 2002; Guler et al. 2007). Additionally, several studies have shown that drift-reducing venturi nozzles produce larger droplets, and a smaller proportion of drift-prone droplets, than a standard flat-fan nozzle across a wide range of operating pressures (Etheridge et al. 1999; Mueller and Womac 1997; Wolf et al. 1999).

While nozzle type is certainly important, there are other factors that affect droplet size and resulting spray particle drift potential. The proportion of small droplets generated is often the result of the interaction between nozzle type and orifice size (Mueller and Womac 1997; Etheridge et al. 1999), the physical properties of the spray liquid (Miller and Butler Ellis 2000; Butler Ellis et al. 2001; Lan et al. 2008; Ferguson et al. 2015) and the use of adjuvants (Yates et al. 1976; Spanoghe et al. 2007), operating pressure (Mueller et al. 1997; Nordby and Skuterud 1974), and droplet velocity (Nuyttens et al. 2009). This research focused on the effects nozzle type, wind speed, droplet initial exit velocity and their interaction have on spray particle drift.

Spray particle drift is determined various ways, including measuring droplet size distribution (DSD) in a wind tunnel and determining downwind deposition and/or airborne flux of drifting spray particles in controlled or field environments. The DSD is typically measured by either laser diffraction, imagery, or phase doppler based systems (Hewitt 1997; Dodge et al. 1987). Drift reduction schemes, such as those outlined by the British Crop Protection Council (Nuyttens et al. 2007) or the American Society of Agricultural Engineers (ASAE 2009), have
consisted of comparing droplet data generated by such methods to sprays produced by standard reference nozzle. Various wind tunnel drift studies have been conducted in an effort to avoid time consuming field drift assessments. Monofilament line was placed both horizontally and vertically to collect both deposition and airborne flux in a study conducted by Taylor et al. (2004). The results of this study demonstrated that a decrease in droplet size, as well as in increase in wind speed and boom height, resulted in an increase in drift. Al Heidary et al. (2014) used collection tubes to calculate the amount of spray collected at downwind distances, and determined that greater than 90% of the spray volume is collected within 9 meters of the nozzle. Derksen et al. (1999) used three types of collection materials (plastic tray and cloth ground targets for deposition and nylon screens to measure airborne flux) to measure drift in a low-speed wind tunnel and concluded that drift risk is reduced when using low-drift nozzles compared to flat-fan nozzles under identical conditions.

Spray droplet velocity has been shown to be a key factor in determining both efficacy and drift potential (Miller and Butler Ellis 2000). In terms of drift potential, the distance spray particles move off-target tends to decrease as droplet size and initial exit velocity increase (Ozkan 1998). Droplet velocity is influenced by spray solution (Butler Ellis and Tuck 1999), nozzle type (Nuyttans et al. 2007; Miller et al. 2008), spray adjuvants (Hollway et al. 2000), and operating pressure (Fritz et al. 2014). Droplet velocity must be considered when using spatial droplet sizing techniques such as laser diffraction to ensure that experimental error is minimized (Frost and Lake 1981; Fritz et al. 2014). Droplet velocity can be measured with a phase droplet particle analyzer (PDPA) laser-based measurement system (Dodge et al. 1987) or with imaging software (Miller et al. 2008, Fritz et al. 2014).
The objectives of this study were to determine the droplet size spectrum and initial exit velocity profile a solution of Enlist Duo herbicide as influenced by nozzle type as well as to examine the drift potential of each nozzle type as influenced by droplet size, droplet initial exit velocity, wind speed, and downwind collection distance. Additionally, the horizontal spray deposition and airborne spray flux, droplet size of drifting spray particles, and the biological impact of Enlist Duo drift on sensitive crop species was examined as well.

Materials and Methods

This experiment was conducted at the Pesticide Application Technology Laboratory (PAT Lab) located in North Platte, NE and the Aerial Application Technology Research Unit (USDA ARS) in College Station, TX. Droplet sizing work and evaluation of drift were conducted in a low speed wind tunnel (PAT Lab) measuring 1.2 m wide, 1.2 m tall, and 12 m long. Droplet velocity measurements were conducted in a low-speed wind tunnel with identical dimensions at the Aerial Application Technology Research Unit (AAT) laboratory.

Droplet Size Measurements

Methods for droplet size measurements were consistent with the Spray Nozzle Classification by Droplet Spectra Standard, which categorizes agricultural nozzles based on droplet size (ASABE 2009). The droplet size spectrum of Enlist Duo was determined using a Sympatec HELOS/KR (Sympatec, INC. Pennington, NJ, USA) laser diffraction instrument (Figure 2.1) with an R7 lens (Sympatec Inc., Clausthal, Germany) capable of measuring droplets ranging in size from 1 to 3,500 µm, controlled by WINDOX 5.7.0.0 software (Sympatec Inc., Clausthal, Germany). The laser consists of an emitter housing, which contains the source of the
laser, and the receiver housing, which contains the lens and detector element. These two
components are located 1.2 m apart on either side of the wind tunnel and are mounted on an
aluminum connecting rail to maintain laser alignment. A single nozzle is mounted with the spray
plume oriented perpendicular to the laser beam. The spray plume is then traversed through the
laser beam via a linear actuator that moves the nozzle at 0.72 m s\(^{-1}\), ensuring that the entire spray
cloud passes through the laser beam. At least three complete traverses (replications) for each
nozzle were made for statistical analysis. The nozzle is positioned 30 cm from the laser beam,
and measurements are made at a wind velocity of 21 km hr\(^{-1}\) (Fritz et al. 2014). The treatments in
this study were compared using the \(D_{v0.1}\), \(D_{v0.5}\), and \(D_{v0.9}\), which represents droplet sizes such
that 10, 50, and 90% of the spray volume is in droplets smaller than \(D_{v0.1}\), \(D_{v0.5}\), and \(D_{v0.9}\).
Additionally, the percentage of spray volume contained in droplets 150 microns in diameter and
smaller diameter were evaluated. Spray classifications used in this study are from reference
curves developed under the study measurement conditions based on the standard ASAE 572.1
(ASABE 2009). The Teejet Air Induction Extended Range Flat Spray Tip (AIXR) (Spraying
Systems Co. Wheaton, IL) and the Greenleaf TurboDrop® XL Flat Spray Tip (TDXL)
(Greenleaf Technologies, Covington, LA) were evaluated at the 04 orifice size and 110° spray
angle. Enlist Duo ™, mixed at a use rate of 592 g ae\(^{-1}\) of glyphosate and 557 g ae\(^{-1}\) 2,4-D, was
applied through both nozzles at an operating pressure of 276 kPa and a carrier volume of 140 L
ha\(^{-1}\).

**Wind Tunnel Drift Measurement**

Enlist Duo herbicide (Dow AgroSciences, Indianapolis, IN) was applied in the low-speed
wind tunnel (Figure 2.2) at the PAT Laboratory to evaluate spray deposition, airborne spray flux,
and droplet size of resulting spray particle drift as well as the impact of drift on susceptible crop
species. The wind tunnel uses an axial fan (Hartzell Inc., Piqua, OH) located at the front of the tunnel to generate air flow. Drift was evaluated at wind speeds of 8, 16, and 21 km hr\(^{-1}\). Wind speed was measured upwind of the traverse at nozzle height using a portable anemometer (Nielsen-Kellerman Inc., Kestrel\(^\circ\) 4000, Boothwyn, PA). The herbicide solution was sprayed through a single nozzle, the Teejet Air Induction Extended Range Flat Spray Tip (AIXR) (Spraying Systems Co. Wheaton, IL) and the Greenleaf TurboDrop\(^\circ\) XL Flat Spray Tip (TDXL) (Greenleaf Technologies, Covington, LA), positioned 0.6 meters from the fan outlet. Both nozzles were tested using the 04 orifice size, 110° spray angle, and a spray pressure of 276 kPa. Each replication consisted of 2-second application, controlled by an auto shut-off switch (Intmatic Inc., EI 400C, Spring Grove, IL).

Enlist Duo, a glyphosate DMA and 2,4-D choline solution, was mixed at a use rate of 2.9% v v\(^{-1}\) with a carrier volume of 140 L ha\(^{-1}\). The spray solution consisted of the herbicide, tap water, and a PTSA fluorescent tracer dye (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) (Spectra Colors Corp., Kearny, NJ) added at 0.6 mg ml\(^{-1}\). PTSA is an extremely water-soluble, stable tracer dye that is highly detectible by fluorometry (Hoffman et al. 2014).

Methods for the determination of drift were similar to those presented in ISO Standard 22856 (ISO 2008). Similar methodology has been used in various wind tunnel drift studies (Lund 2000; Walklate and Miller 2000; Derksen et al. 1999). Collection stations and sensitive crops were located both under the nozzle and at 1.5, 3, 6, 9, and 12 meters downwind (Figure 2.2). Collection materials consisted of Mylar\(^\text{TM}\) cards (10 cm x 10 cm) (Grafix Platics, Cleveland, OH) to record spray fallout deposition, water sensitive paper (5 cm x 8 cm) (Spraying Systems, Wheaton, IL, 60189) to record the droplet size of suspended spray droplets collected at each location, and monofilament line (38 cm x 0.2 cm) (Blount Inc., Magnum Gatorline\(^\text{TM}\), Portland,
OR) to collect airborne spray flux. Mylar cards were placed horizontally on the collection stations 25 cm above the tunnel floor. Monofilament lines were horizontally strung across the top of the 50 cm tall collection stations. Water sensitive papers were vertically attached 40 cm above the tunnel floor facing the direction of the wind. Tomato (*Solanum lycopersicum*) and Roundup Ready® soybean (*Glycine max*) and cotton (*Gossypium hirsutum*) plants approximately 30 cm in height were also placed at each distance and sprayed separately from the collection materials.

Collection stations and sensitive crops were removed from the wind tunnel one minute after application to ensure all spray material had traveled downwind. Mylar cards and monofilament line were placed into pre-labeled plastic bags and stored in a dark storage bin to minimize photodegradation (Hoffman et al. 2014). Water sensitive papers were placed in pre-labeled bags and stored in a freezer to prevent moisture contamination. The plants were placed into a greenhouse, and visual injury ratings were assessed at 14 and 21 days after treatment (DAT) using a scale of 0 – 100 where 0 = no control and 100 = plant death. Upon the conclusion of the 21-day study, plants were clipped at the soil surface, fresh weights were recorded, and plants were then dried to determine biomass reduction. Percent dried biomass reduction for treated crop species was calculated using dry weights compared to the average dried biomass from non-treated control plants:

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

where \(\bar{C}\) is the average non-treated control biomass and \(B\) is the biomass of an individual treated experimental unit.

Tracer dye was extracted from Mylar cards and monofilament line in a manner similar to techniques described by Fritz et al. (2011) and Roten et al. (2014). A 10:90 isopropyl alcohol:
distilled water solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV). Mylar cards and monofilament line were each washed with 40 and 25 ml of solution, respectively. Samples were then shaken to release the tracer dye from the samplers. Upon the suspension of dye in the washing solution, a 1.5 ml aliquot from each bag was drawn and placed in a glass cuvette. Each cuvette was then placed into a PTSA module inside a fluorimeter (Turner Designs, Sunnyvale, CA), where ultra-violet light was used to collect fluorescence values. Fluorescence values were then converted into dye concentrations and the amount of spray deposited. These calculations were made assuming a linear response between fluorescence and dye concentration, which was made possible by selecting a PTSA use rate that results in dye deposits falling within the accepted concentration range (Fritz et al. 2011).

Data were adjusted for dye recovery rate during the wash procedure. This was done by spiking a 10 μl sample from representative tank-mixtures onto six mylar cards. These cards were washed as described above and fluorescence values where then compared to a separate 10 μl sample. The average recovery rates for the mylar cards were 89%. Additionally, dye degradation was calculated, as dye may be quenched at increased concentration and/or affected by the composition of the spray solution (Hoffman et al. 2014). This was accomplished by adding a 10 μl to a known volume of water:isopropyl alcohol solution every hour for 6 hours and comparing the results to the value of a similar solution taken shortly after mixing. The results of the degradation analysis showed minimal degradation of PTSA dye by the Enlist Duo solution.

Water sensitive papers, which are coated with a yellow surface that is stained blue by impacting water droplets, were analyzed with the software program DropletScan™ version 2.5 (WRK of Arkansas LLC., Lonoke, AR) to determine the droplet size of deposited spray particles. This program allows for the accurate measurement of spray droplet impressions, and can
determine statistics such as spray coverage, deposition rate, and spray droplet size. Papers were paced onto a scanner (Epson V600 Photo Scanner, Epson Shinjuku, Tokyo, Japan), scanned and analyzed, and droplet statistics were then recorded. Droplet size was reported as $D_{n0.5}$. It should be noted that DropletScan™ reports stain diameter instead of the diameter of deposited droplets. A spread factor, the diameter of the stain plotted against the actual droplet diameter, was not applied to droplet data presented, as the purpose of this study was to screen treatments for field evaluation.

*Droplet Velocity Measurement*

Droplet velocity was measured in the low-speed wind tunnel at the Aerial Application Technology Research Unit (AAT) Laboratory in College Station, TX. A LaVision SprayMaster (LaVision Inc., Ypsilanti, MI) system in Shadowgraphy mode was used for these measurements, which allows the detection of droplets between ~60 and 2,000 µm in diameter. It accomplishes this by utilizing a double pulsed laser and camera to take two sequential images of the spray droplets eight nanoseconds apart. The images were taken 15.2 cm downstream of the nozzle orifice exit with the wind tunnel operated at a speed of 3.6 km hr$^{-1}$. The measured data was recorded as droplet diameter and mean velocity for each droplet captured.

Droplet size and velocity data generated in this experiment was analyzed using Statistical analysis was conducted using SAS v9.4 (SAS, Cary, NC). The PROC GLIMMIX procedure was used to analyze droplet data from selected nozzles. The spray characteristics analyzed included the percent of the spray volume < 141 µm, $D_{v0.1}$, and $D_{v0.5}$ values. and droplet velocity (m s$^{-1}$). Spray deposition, airborne spray flux, and suspended spray droplet size data were analyzed using PROC GLIMMIX with nozzle type, wind speed, and collection distance arranged in a
completely randomized 2 x 3 x 5 factorial design. Tukey’s mean separation was used to
determine statistical significance with $\alpha=0.05$. Visual injury estimations and percent biomass
reduction were analyzed individually by species using the PROC GLIMMIX procedure, and LS
means were compared at $\alpha=0.05$. Replication was considered a random factor for all analyses.

**Results and Discussion**

The droplet size distribution data for the two nozzles used in this study are presented in
Table 2.1. The spray classification category for the AIXR nozzle was very coarse with the TDXL
nozzle being classified as extremely coarse. The percentage of spray volume < 141 $\mu$m, $D_{v0.5}$,
and $D_{v0.1}$ values were statistically different for each nozzle ($P\leq0.05$), with the AIXR nozzle
producing a smaller droplet size distribution. It should be noted, however, that less than 2% of
the total spray volume consisted of droplets < 141 $\mu$m in diameter for both nozzles.

For the droplet size of suspended spray, ANOVA indicated that both the nozzle type by
wind speed interaction and wind speed by distance interaction were significant ($P\leq0.05$). No
difference in the droplet size of suspended spray particles from the AIXR and TDXL nozzles
was indicated across all wind speeds. The $D_{v0.5}$ of spray droplets collected were different for the
AIXR nozzle as the wind speed increased from 8 to 16 km hr$^{-1}$, but no difference was reported as
wind increased from 16 to 21 km hr$^{-1}$. For the TDXL, no difference in suspended spray droplet
size was reported between wind speeds of 8 to 16 km hr$^{-1}$, but a difference in $D_{v0.5}$ was indicated
as wind increased from 16 to 21 km hr$^{-1}$ (Table 2.2). Across nozzle type, $D_{v0.5}$ increased as the
wind speed increased and decreased at distances further downwind from the nozzle. Differences
in suspended spray droplet size were observed only at downwind distances of 1.5, 3, and 6
meters downwind, with wind speed increasing from 16 to 21 km hr\(^{-1}\) having the greatest impact on the size of suspended spray droplets (Table 2.3). Spray droplets > 200 μm in diameter were collected beyond 1.5 m downwind at the 21 km hr\(^{-1}\) wind speed only. While high wind speeds may move larger droplets off-target, the contained airflow of droplets in the wind tunnel likely contributed to the collection of large spray droplets downwind at the 21 km hr\(^{-1}\) wind speed.

Analysis of spray deposition collected on mylar cards indicated that the wind speed by distance interaction was significant (P≤0.05) and that both nozzle types resulted in the same amount of spray deposition. Deposition rate (μg cm\(^{-2}\)) is the amount of PTSA dye deposited divided by the area of the sampler. The highest wind speed (21 km hr\(^{-1}\)) resulted in more downwind deposition than both the 8 km hr\(^{-1}\) and 16 km hr\(^{-1}\) wind speeds, both of which produced same amount of downwind spray deposition. The collection of PTSA tracer dye was greatest closer to the nozzle, and decreased at further downwind distances (Table 2.4). Less than 0.25 μg cm\(^{-2}\) of dye was deposited at the two furthest downwind distances (9 and 12 m) across all wind speeds.

Mean visual injury ratings of soybean, cotton, and tomato taken at 21 DAT averaged across wind speed and nozzle type ranged from 57 to 17, 70 to 20, and 79 to 30 percent from 1.5 m to 12 m downwind, respectively. ANOVA indicated the main effects for wind speed and downwind distance were significant (P≤0.05) for each species; higher injury ratings were observed with an increase in wind speed, and ratings decreased as downwind distance from the nozzle increased. The nozzle by wind speed interaction was also significant (P≤0.05) for soybean, with the TDXL nozzle resulting in higher visual injury than the AIXR at the 8 km hr\(^{-1}\) wind speed only (Figure 2.4). Observed injury symptoms included stem swelling and cracking, cupping of leaves, epinasty, and reduced plant height.
Percent biomass reduction across all wind speeds and nozzle types ranged from -8 to 37, 20 to 70, and 2 to 53 percent from 12 m to 1.5 m downwind for soybean, cotton, and tomato respectively. The distance main effect was significant for all three species, wind speed main effect was significant for tomato and soybean, and the nozzle main effect was significant for soybean only (P≤0.05). Smaller biomass reduction values were observed as downwind distance increased, and ANOVA indicated that percent biomass reduction was not different across nozzle type and wind speed for all species at 9 and 12 meters downwind (Table 2.7). Overall, larger biomass reduction values were observed as wind speed increased: Mean biomass reduction values across nozzle type and downwind distance at 8, 16, and 21 km hr$^{-1}$ were -0.08, 9.4, and 15.2 percent for soybean and 16.5, 29.0, and 32.0 percent for tomato. The effect of nozzle type on biomass reduction was significant in soybean only, with ANOVA indicating that Enlist Duo applied through the TDXL nozzle resulted in more biomass reduction than the AIXR (P=0.0073). In general, the greatest amount of biomass reduction was observed at distances of 1.5 and 3 meters downwind at wind speeds of 16 and 21 km hr$^{-1}$ (Figures 2.5, 2.6).

Overall, visual injury ratings indicated injury was greatest to tomato, and that damage to both cotton and tomato was extensive across all distances. Additionally, minimal damage was done to soybean across all treatments. Biomass reduction values indicated the greatest reduction in biomass occurred to cotton, followed by tomato, and that Enlist Duo drift increased the biomass of soybean plants when applied at the 8 km hr$^{-1}$ wind speed. This is likely due to the effects of the 2,4-D component of Enlist Duo herbicide, as stem swelling on tomato plants may have led to higher fresh and dry weights. While the application of Enlist Duo herbicide in a low-speed wind tunnel resulted in significant injury to cotton and tomato, little damage was observed in soybean. While it is generally accepted that crops such as tomato and cotton are very
susceptible to 2,4-D, the minimal amount of injury to soybean plants was encouraging, as laminar flow of spray droplets in a wind tunnel results in larger amounts of droplets moving downwind than typically seen in a field drift assessment.

Airborne spray flux was also measured on monofilament line, and ANOVA indicated that both the nozzle type by wind speed interaction and wind speed by distance interaction were significant (P≤0.05). The TDXL nozzle resulted in more airborne spray flux than the AIXR nozzle, averaged across all distances, at the 21 km hr⁻¹ wind speed only, and the highest wind speed resulted in nearly twice the airborne spray collected downwind when compared to the lower wind speeds (Table 2.5). While no differences in airborne spray flux at downwind distances were observed at 8 km hr⁻¹, the 16 km hr⁻¹ wind speed resulted greater deposition at 1.5 m downwind and differences were reported up to 6 m downwind at 21 km hr⁻¹ (Table 2.6). Less than 2 μg cm⁻² of dye was recovered beyond 9 m downwind across all wind speeds.

Of the spray deposition collected downwind from the nozzle, 85% of the total dye collected was recovered from 0-9 meters downwind. This supports the findings of field and wind tunnel drift studies that observed a majority of spray particle drift being accounted for within 0-10 meters downwind from the site of application (Marrs et al. 1989; de Snoo and De Witt 1998; Al Heidary et al. 2014). While wind speed affected the amount of airborne drift from both nozzles, the highest wind speed increased the amount of spray moving downwind for the TDXL nozzle only. This same trend was observed for the droplet size data, as differences in droplet size and deposition for the AIXR nozzle were observed only as wind speed increased from 8 to 16 km hr⁻¹ whereas differences for the TDXL nozzle were observed as wind speed increased from 16 to 21 km hr⁻¹. Downwind deposition from the TDXL is similar to data recorded in a wind tunnel study conducted by Derksen et al. (1999). Data from this study showed that a
TurboDrop® (TD11002) nozzle, despite producing a significantly coarser spray and fewer driftable fines, resulted in more deposition up to 3 meters downwind than both a flat-fan (XR11002) and Turbo TeeJet® (TT11002) nozzle when operated in an 18 km hr\(^{-1}\) wind. Increases in airborne spray flux from a nozzle which generates coarser spray droplets may be explained by initial exit velocity profiles.

The initial exit velocity profiles for the AIXR11004 and TDXL11004 nozzles at 276 kPa were measured for a solution of Enlist Duo herbicide, and the droplet velocity profiles for both nozzles are reported in Table 2.8. ANOVA indicated that the AIXR generated droplets with larger initial exit velocity values than TDXL at any given droplet diameter. The highest mean velocity values, 12.3 and 10.2 m s\(^{-1}\), were observed for droplets between 800 and 1,000 μm for the AIXR and the TDXL nozzles. Droplets smaller than 100 μm had mean velocities of 10.6 across both nozzle types, but droplets between 100 and 200 μm in diameter had velocities of 6.6 and 5.8 m s\(^{-1}\) for the AIXR and TDXL, respectively. Droplets larger than approximately 200 μm in diameter had velocities of 9.8 m s\(^{-1}\) for the AIXR and 8.8 m s\(^{-1}\) for the TDXL. The mean initial exit velocity, averaged across all droplet diameters, was 10.6 m s\(^{-1}\) for the AIXR compared to 9.2 m s\(^{-1}\) for the TDXL.

Droplet initial exit velocity is an important component in determining herbicide drift potential. Upon formation, droplets are slowed due to drag forces reach an equilibrium with ambient wind conditions. Small, slow-moving droplets tend to lose initial exit velocity quicker than coarse, fast-moving droplets: As droplet size and velocity increase, the distance spray particles drift tends to decrease (Zhu et al. 1994; Ozkan 1998). Large droplets are dominated by the effects of gravity upon generation, which leads to a near vertical downward trajectory and a reduction in drift potential. Dorr et al. (2013) examined the effect of various application factors
such as nozzle design, operating pressure, and spray liquid properties on spray characteristics such as initial exit velocity. It was concluded that operating pressure and nozzle type had the greatest influence on initial exit velocity. Additionally, it was noted that while the TTI nozzle produced the coarsest droplets, it resulted in lower initial exit velocity values than all nozzles examined in the study. This supports the velocity data recorded in this study, as the TDXL, though producing a coarser spray quality, resulted in a lower initial velocity than the AIXR nozzle.

Initial exit velocity, combined with wind speed, is likely to have influenced the amount of spray drift collected downwind and size of spray droplets moving off-target observed in this research. Zhu et al. (1994) predicted that droplets as large as 300-500 µm may drift up to 5 meters downwind if the droplets have slow initial exit velocity values and are applied in high wind speeds. This effect may explain the increases in spray deposition and airborne spray flux, as well as the collection larger spray droplets 3 meters downwind, for the TDXL11004 nozzle compared to the AIXR11004 when operated at a wind speed of 21 km hr$^{-1}$. 

Conclusions

The results of this study indicated that increasing spray droplet size may not necessarily result in reduced spray particle drift potential. The TDXL11004 nozzle, despite producing a coarser spray and fewer driftable fines, resulted in more airborne drift of Enlist Duo herbicide, as well as larger spray particles moving further downwind, when compared to the AIXR11004 at a wind speed of 21 km hr$^{-1}$. This may be explained by the interaction of wind speed and initial exit velocity, as the TDXL produced droplets with a lower initial exit velocity than the AIXR nozzle.
despite producing significantly larger spray droplets. With Enlist Duo being applied through both nozzles under identical experimental conditions and at a constant pressure, the differences in drift and droplet initial exit velocity observed are due to differences in nozzle design: The TDXL11004 nozzle consists of a flow-metering 0.4 orifice and a 0.8 distribution orifice compared to the 0.4 pre-orifice and exit orifice of the AIXR11004.

Though it is generally accepted that increasing spray droplet size results in reduced spray particle drift potential, this research indicates that droplet initial exit velocity also has an impact on spray particle drift potential. Knowledge of initial exit velocity profiles of sprays produced by agricultural nozzles, as well as application parameters that impact them, is important when assessing the performance of drift reduction nozzles, as nozzles designed to increase droplet size may tend to do so through decreased spray pressures at the exit orifice which reduces initial fluid exit velocities. Understanding the relationship between droplet size and initial exit velocity may be especially important for new products containing 2,4-D or dicamba such as Enlist Duo and Xtendimax herbicides, as minimizing spray particle drift of these products is critical to ensure that both weed management systems remain viable weed control options for years to come.

While wind tunnel studies improve environmental control and reduce measurement uncertainty, they ignore the physical aspects of a field environment (Walklate and Miller 2000). Therefore, the measurement of spray drift droplet size and deposition in a wind tunnel is a relative measure meant for closer examination in a field setting.
Literature Cited


de Snoo GF and de Wit PJ. (1998). Buffer zones for reducing pesticide drift to ditches and risk to aquatic organisms. Ecotoxicology and Environmental Safety 41:112-118


Table 2.1. Droplet size distribution of selected nozzles applying Enlist Duo herbicide at 276 kPa. Herbicide solution was mixed at a rate of 2.9% v v⁻¹ with a carrier volume of 140 L ha⁻¹. Droplet data is reported as the $D_{v0.1}$ and $D_{v0.5}$, which represent droplet sizes such that 10 and 50% of the spray volume is contained in droplets smaller than that diameter. Numbers followed by the same letter in the same column are not different using the Tukey test (P≤0.05).

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>$D_{v0.1}$</th>
<th>$D_{v0.5}$</th>
<th>$D_{v0.9}$</th>
<th>Vol&lt;141</th>
<th>RS⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μm</td>
<td></td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>AIXR11004</td>
<td>250</td>
<td>B</td>
<td>463</td>
<td>B</td>
<td>1.7</td>
</tr>
<tr>
<td>TDXL11004</td>
<td>290</td>
<td>A</td>
<td>543</td>
<td>A</td>
<td>0.9</td>
</tr>
</tbody>
</table>

⁴ Relative span is a dimensionless parameter used to indicate the uniformity of the droplet size distribution.
Table 2.2. Droplet size of spray particle drift from application of Enlist Duo herbicide at 276 kPa though two nozzle types averaged across all downwind distances. Herbicide solution was mixed at a rate of 2.9% v v$^{-1}$ with a carrier volume of 140 L ha$^{-1}$. Data is reported as the D$_{0.5}$ value, which represent a droplet size such that 50% of the spray volume is in droplets smaller than that diameter. Numbers followed by the same letter in the same row/column are not different using the Tukey test (P≤0.05).

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>D$_{0.5}$</th>
<th>km hr$^{-1}$</th>
<th>μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIXR11004</td>
<td>141 A</td>
<td>190 B</td>
<td>226 BC</td>
</tr>
<tr>
<td>TDXL11004</td>
<td>155 A</td>
<td>166 AB</td>
<td>261 C</td>
</tr>
</tbody>
</table>
Table 2.3. Measured droplet size data from water sensitive papers for Enlist Duo herbicide applied at 276 kPa across both nozzle types. The herbicide solution was mixed at a rate of 2.9% v v\(^{-1}\) with a carrier volume of 140 L ha\(^{-1}\). Data is reported as the \(D_{v0.5}\) value, which represent a droplet size such that 50% of the spray volume is in droplets smaller than that diameter. Numbers followed by the same letter in the same row/column are not different using the Tukey test (\(P\leq0.05\)).

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>(D_{v0.5}) (μm)</th>
<th>8 km hr(^{-1})</th>
<th>16 km hr(^{-1})</th>
<th>21 km hr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>206 CBD</td>
<td>258 BC</td>
<td>391 A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>155 FED</td>
<td>186 CEFD</td>
<td>273 B</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>116 F</td>
<td>141 FED</td>
<td>202 BCD</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>141 FED</td>
<td>167 FED</td>
<td>193 CED</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>117 FE</td>
<td>140 FED</td>
<td>159 FED</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.4. Deposition rate (μg cm⁻²) as measured on horizontal mylar cards at five downwind distances in the low-speed wind tunnel at the Pesticide Application Laboratory (PAT LAB) North Platte, NE. Enlist Duo was applied at a rate of 2.9 %v v⁻¹ and carrier volume of 140 L ha⁻¹. The tracer dye was mixed at a rate of 0.6 mg ml⁻¹. Deposition rate (μg cm⁻²) is the amount of PTSA dye deposited divided by the area of the sampler. Both the AIXR and TDXL nozzles had a 110º spray angle and flow rate of 1.5 L/min at 276 kPa. Values followed by the same letter in the same row/column are not different using Tukey’s test (P≤0.05).

<table>
<thead>
<tr>
<th>Distance</th>
<th>Deposition (μg cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km hr⁻¹</td>
</tr>
<tr>
<td>m</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
</tr>
<tr>
<td>9</td>
<td>0.10</td>
</tr>
<tr>
<td>12</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Table 2.5. Deposition rate (μg cm\(^{-2}\)) of airborne spray flux from application of Enlist Duo herbicide at 276 kPa though two nozzle types averaged across all downwind distances. Herbicide solution was mixed at a rate of 2.9% v v\(^{-1}\) with a carrier volume of 140 L ha\(^{-1}\). The tracer dye was mixed at a rate of 0.6 mg ml\(^{-1}\). Deposition rate (μg cm\(^{-2}\)) is the amount of PTSA dye deposited divided by the area of the sampler. Numbers followed by the same letter in the same row/column are not different using the Tukey test (P≤0.05).

<table>
<thead>
<tr>
<th>Nozzle(^a)</th>
<th>Deposition</th>
<th>km hr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>AIXR11004</td>
<td>1.0 C</td>
<td>2.4 BC</td>
</tr>
<tr>
<td>TDXL11004</td>
<td>1.0 C</td>
<td>2.1 BC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>μg cm(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIXR11004</td>
<td>1.0 C</td>
<td>2.4 BC 4.6 B</td>
</tr>
<tr>
<td>TDXL11004</td>
<td>1.0 C</td>
<td>2.1 BC 7.2 A</td>
</tr>
</tbody>
</table>

\(^a\) Numbers followed by the same letter in the same row/column are not different using the Tukey test (P≤0.05).
Table 2.6. Airborne spray flux deposits (μg cm\(^{-2}\)) measured on suspended monofilament lines at five downwind distances in the low-speed wind tunnel at the Pesticide Application Laboratory (PAT LAB) North Platte, NE. Enlist Duo was applied at a rate of 2.9 %v v\(^{-1}\) and carrier volume of 140 L ha\(^{-1}\). The tracer dye was mixed at a rate of 0.6 mg ml\(^{-1}\). Deposition rate (μg cm\(^{-2}\)) is the amount of PTSA dye deposited divided by the area of the sampler. Both the AIXR and TDXL nozzles had a 110º spray angle and flow rate of 1.5 L/min at 276 kPa. Values followed by the same letter in the same row/column are not different using Tukey’s test (P≤0.05).

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Deposition (μg cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.6 CD 6.3 CB 15.6 A</td>
</tr>
<tr>
<td>3</td>
<td>1.4 D 2.6 CD 7.2 B</td>
</tr>
<tr>
<td>6</td>
<td>0.6 D 1.0 D 3.2 BCD</td>
</tr>
<tr>
<td>9</td>
<td>0.4 D 0.6 D 2.0 D</td>
</tr>
<tr>
<td>12</td>
<td>0.2 D 0.4 D 1.5 D</td>
</tr>
</tbody>
</table>
Table 2.7. Sensitive crop percent biomass reduction resulting from application of Enlist Duo herbicide in a low-speed wind tunnel averaged across wind speed and nozzle type. The herbicide solution was applied at a rate of 2.9 % v⁻¹ and a carrier volume of 140 L ha⁻¹. Percent dried biomass reduction for treated crop species was calculated using dry weights compared to the average dried biomass from non-treated control plants. Both the AIXR and TDXL nozzles had a 110° spray angle and flow rate of 1.5 L/min at 276 kPa. Values followed by the same letter in the same row/column are not different using Tukey’s test (P≤0.05).

<table>
<thead>
<tr>
<th>Distance</th>
<th>Soybean</th>
<th>Cotton</th>
<th>Tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>57 A</td>
<td>70 A</td>
<td>53 A</td>
</tr>
<tr>
<td>3</td>
<td>43 B</td>
<td>53 AB</td>
<td>40 B</td>
</tr>
<tr>
<td>6</td>
<td>31 C</td>
<td>34 BC</td>
<td>24 CD</td>
</tr>
<tr>
<td>9</td>
<td>23 CD</td>
<td>20 CD</td>
<td>9 E</td>
</tr>
<tr>
<td>12</td>
<td>17 CD</td>
<td>20 CD</td>
<td>2 E</td>
</tr>
</tbody>
</table>
Table 2.8. Initial exit velocity profiles (m s\(^{-1}\)) by droplet diameter (µm) for the AIXR11004 and TDXL11004 nozzles operated at 276 kPa. Measurements were made in the low-speed wind tunnel at the Aerial Application Technology Research Unit (AAT) Laboratory in College Station, TX. Images were taken directly under the nozzle orifice at a distance of 15.24 cm, and the wind tunnel was operated at a wind speed of 3.6 km hr\(^{-1}\). Enlist Duo herbicide was mixed at a 2.9 % v v\(^{-1}\) concentration with a carrier volume of 140 L ha\(^{-1}\). Values followed by the same letter in the same row are not different using Tukey’s test (P ≤ 0.05).

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>AIXR11004</th>
<th>TDXL11004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>7.5</td>
<td>A 6.6</td>
</tr>
<tr>
<td>300</td>
<td>9.4</td>
<td>A 8.5</td>
</tr>
<tr>
<td>400</td>
<td>10.6</td>
<td>A 9.4</td>
</tr>
<tr>
<td>500</td>
<td>10.9</td>
<td>A 9.8</td>
</tr>
<tr>
<td>600</td>
<td>11.1</td>
<td>A 9.7</td>
</tr>
<tr>
<td>700</td>
<td>11.4</td>
<td>A 10.1</td>
</tr>
<tr>
<td>800</td>
<td>12.4</td>
<td>A 10.4</td>
</tr>
<tr>
<td>900</td>
<td>11.7</td>
<td>A 9.6</td>
</tr>
</tbody>
</table>
Figure 2.1. Photograph of Sympatec HELOS/KR laser diffraction instrument at the PAT Laboratory in North Platte, NE.
Figure 2.2. The low-speed wind tunnel at the Pesticide Application Technology Laboratory in North Platte, NE.

Figure 2.3. Diagram of experiment setup in low-speed wind tunnel for collection of spray particle drift.
Figure 2.4. Estimated soybean visual injury in low-speed wind tunnel from application of Enlist Duo herbicide. Values are averaged across all downwind distances (1.5, 3, 6, 9, 12 m). Herbicide solution was mixed at a rate of 2.9% v v\(^{-1}\) with a carrier volume of 140 L ha\(^{-1}\). Letters indicate significant differences between nozzle type across three wind speeds.
Figure 2.5. From top to bottom: Tomato (*Solanum lycopersicum*), soybean (*Glycine max*), and cotton (*Gossypium hirsutum*) plants sprayed in the low-speed wind tunnel with the TDXL11004 nozzle at 276 kPa and a wind speed of 21 km hr\(^{-1}\). The Enlist Duo solution was mixed at a 2.9 % v v\(^{-1}\) concentration with a carrier volume of 140 L ha\(^{-1}\). From left to right, the plants were untreated, 1.5, 3.0, 6.0, 9.0, and 12.0 meters downwind of the nozzle.
Figure 2.6. From top to bottom: Tomato (*Solanum lycopersicum*), soybean (*Glycine max*), and cotton (*Gossypium hirsutum*) plants sprayed in the low-speed wind tunnel with the AIXR11004 nozzle at 276 kPa and a wind speed of 21 km hr\(^{-1}\). The Enlist Duo solution was mixed at a 2.9 % v v\(^{-1}\) concentration with a carrier volume of 140 L ha\(^{-1}\). From left to right, the plants were untreated, 1.5, 3.0, 6.0, 9.0, and 12.0 meters downwind of the nozzle.
Figure 2.7. Droplet exit velocity (m s\(^{-1}\)) by droplet diameter (µm) for the AIXR11004 and TDXL11004 nozzles operated at 276 kPa. Enlist Duo herbicide was mixed at a 2.9 % v v\(^{-1}\) concentration with a carrier volume of 140 L ha\(^{-1}\).
CHAPTER 3

Evaluation of Drift from a Field Application of Enlist Duo

Abstract

Increased reliance on chemical weed control in agricultural systems has led to the evolution of herbicide resistance in various weed species, thus prompting the development of new weed management systems to address these concerns. These systems require careful management to ensure herbicide off-target movement is minimized, as herbicide drift from pre-mixtures such as 2,4-D and glyphosate (Enlist Duo) may pose a threat to sensitive non-tolerant crops. The objective of this study was to determine the influence of nozzle type on the drift potential of a field application of Enlist Duo herbicide. Enlist Duo was applied to a corn-fallow field with a tractor mounted sprayer at a rate of 2.9% v v$^{-1}$ and carrier volume of 140 L ha$^{-1}$. PTSA tracer dye was added to the tank at 0.6 mg ml$^{-1}$. The solution was applied through the AIXR11004 and TDXL11004 nozzles at a spray pressure of 276 kPa. Mylar cards were used to collect spray deposition, and water sensitive paper was used to collect droplet size data. Data was also analyzed using a mass-balance transfer analysis and the computer program AGDISP to generate drift models. The results of this study indicated that following label application requirements, including using nozzles that produce a very coarse to extremely coarse spray quality, can sufficiently minimize drift potential. While no difference in spray deposition was observed between nozzles for the field drift evaluation, models generated with AGDISP indicated more drift deposition at further downwind distances for the AIXR11004 compared to the TDXL11004. The observed contrasts in deposition between field data and AGDISP models
indicates factors besides droplet size distribution influenced the drift potential of Enlist Duo herbicide applied through two drift reduction type nozzles.

Introduction

Much like the process of applying herbicides, attempting to define spray particle drift is a complex endeavor. The US Environmental Protection Agency (EPA) defines spray drift as the “physical movement of a pesticide droplet through the air at the time of application or soon thereafter, to any site other than the one intended for application” (EPA 1999). Herbicide can move off-target as spray particle drift or vapor drift. Spray particle drift has been defined as “drift that occurs when wind causes spray droplets to be displaced from their intended flight path into non-target areas” (Wolf et al. 1993). Herbicide vapor drift occurs when a volatile herbicide changes from either a solid or liquid state to a gaseous state, and subsequently moves from the target area (Dexter 1995). Henceforth, references to drift will refer to the physical movement of spray droplets from the site of application following their generation during ground application.

Agricultural systems in the US rely heavily on pesticides to control pests and maximize profit. More than 230 million kilograms of pesticide was applied in the US in 2008, with 22% stemming from herbicide use in soybean alone (USDA ERS 2014). Agricultural producers pay a price for their reliance on pesticides, as nearly $12 billion was spent on pesticides in 2008. Pesticide use incurs additional costs as well, as the unsafe and improper use of pesticides is associated with detrimental human and environmental health effects including acute and chronic poisoning in both humans and animals, pesticide residues in food products, the destruction of natural predators and parasites, crop damage and losses, and ground/surface water contamination (Pimentel 2005). Continued usage of pesticides has also resulted in the development of pesticide
resistance in both insect and weed species (Pimentel 1992; Jutsum 1998). The introduction of crop cultivars tolerant to dicamba and 2,4-D place renewed emphasis on the consequences of herbicide drift. The nonselective nature of these herbicides, combined with the high sensitivity of many fruits, vegetables, and broadleaf crops to these herbicides, increases the potential for drift to damage non-target susceptible plants. Dicamba injury to soybean has been observed up to 60 DAT at 1/100th of the recommended use rate (Al-Khatib and Peterson 1999), and substantial injury to wine grapes from simulated drift of 2,4-D (29% visual injury) and dicamba (36% visual injury) was observed 42 DAT at 1/100th of their respective use rates (Mosheni-Moghadam et al. 2016).

Spray particle drift is likely to occur when fine spray droplets are generated during application; when compared to coarse droplets, small droplets settle in the air more slowly and thus can be carried further by wind (Spillman 1984). While application efficiency may be increased with small droplets, the percentage of spray solution that consists of small droplets is an important factor in determining the degree of drift hazard (Whisenant et al. 1993). There are many other factors that increase the drift propensity of an application: Environmental factors: wind speed and direction, temperature, and humidity; Application factors: nozzle type, nozzle orifice size, operating pressure, spray angle, ground speed, and boom height; Spray solution: formulation, active ingredient, and adjuvants (Bouse et al. 1990; Carlsen et al. 2006; Combellack et al. 1996; Holterman 2003; Nordby and Skuterud 1974).

Early application research was typically focused on increasing the efficiency of pesticide application, thus little attention was focused on the consequences of pesticide drift (Felsot 2005). The principles, measurement, and ramifications of spray drift were first reviewed and published in 1964 (Akesson and Yates 1964). From that point on, various studies have been conducted
with the intent of measuring herbicide drift in field settings. Early examination of drift was focused on the drift potential of various 2,4-D formulations (Grover et al. 1972; Renne and Wolf 1979), the amount of drift produced by aerial and ground applications (Yates et al. 1966; Salyani and Cromwell 1992) and the impact of application factors such as boom height, herbicide solution, nozzle type, operating pressure, and carrier volume (Nordby and Skuterud 1974; Bode et al. 1976; Wolf et al. 1993). This early drift research demonstrated that measuring herbicide drift is a complex task, and that methods such as lowering spray boom height, increasing droplet size, and reducing operating pressure all contribute to reducing spray drift potential. The impact of environmental factors on both drift potential and measuring herbicide drift has been examined as well (Byass and Lake 1977; Maybank and Yoshida 1978; Grover et al. 1985; Goering and Butler 1975), concluding that high wind speeds, high air temperature, and low relative humidity may contribute to increased herbicide drift potential.

The total amount of herbicide lost to drift during an application has been the focus of many studies as well. Quantifying the amount of drift both deposited and lost to evaporation is challenging, especially as the downwind distance increases. Meteorological conditions are highly important at such distances, as they impact small droplet drift, deposition, and evaporation (Renne and Wolf 1979). Byass and Lake (1977) concluded that drift behavior up to 100 meters can be predicted, but the task of measuring drift further downwind becomes more challenging. Estimates of herbicide lost as spray particle drift from the site of application range from as low as 0.2% (Grover et al. 1985) to between 1 and 8% (Maybank et al. 1978) depending upon environmental and application factors. Further research examining spray particle drift near field borders noted that drift deposition was greatest within 0-20 meters downwind from the site of
application (Marrs et al. 1989; de Snoo and De Witt 1998; Longley et al. 1996; Carlsen et al. 2006).

Data from studies such as these, along with droplet size data, have contributed to the creation of drift models for both aerial (Teske et al. 2002) and ground application (Baetens et al. 2009). The Spray Drift Task Force (STDF) was formed in 1990 with the goal of creating a herbicide drift study database to aid in the development of models to predict drift and provide a basis for the evaluation of risk mitigation strategies (Hewitt et al. 2002). AgDRIFT is a spray drift modeling tool powered by the AGDISP aerial spray application model (Bilanin et al. 1989; Hewitt et al. 2002; Teske et al. 2002). This modeling software calculates the downwind deposition by modeling droplet trajectories for a range of droplet sizes and subsequently summarizes their fate, recovers the mean deposition within the treated area, and accounts for all spray material released including the fraction lost to evaporation (Teske et al. 2003). While AGDISP was originally developed to estimate in-swath deposition, and later off-target movement, for aerial applications (Bilanin et al. 1989), a model for ground boom sprayers has been developed (Teske et al. 2009). The performance of this model has been validated in a number of studies for both aerial application (Fritz et al. 2010; Teske et al. 2002) and ground application (Teske et al. 2009; Nsibande et al. 2015). In general, AGDISP is a useful tool for the evaluation of drift potential under specified atmospheric and operating conditions (Bilanin et al. 1989) and minimizes the need for expensive and time-consuming field drift trials.

The imminent release of dicamba and 2,4-D-tolerant cotton, corn, and soybean will lead to increased use of these growth regulator herbicides in the US, thus increasing the importance of evaluating the drift potential from application of these products. Various methods of deposition measurement have been used, but deposition is typically quantified as the amount of active
ingredient or fluorescent tracer dye deposited both in the spray swath and downwind of the application site. Collection materials used to measure deposition have included mylar sheets, glass plates, filter paper, silica gel plates, and pans of water in addition to potted plants, and airborne spray flux is typically measured using monofilament line located ~10 meters above the ground (Felsot 2005). Measuring droplet size of drifting spray particles in field settings has typically consisted of collecting droplets on magnesium-oxide (Hewitt 1997) or kaolin (Byass and Lake 1977) coated slides. This technique is affected the collection efficiency of the sampler and the size of drifting spray droplets, and a spread factor is needed to interpret droplet size data accurately (Hewitt 1997). Newer methods include the use of water sensitive paper to record spray droplet statistics and deposition (Cunha et al. 2013; Wolf et al. 1999).

The objectives of this study were to evaluate an application of Enlist Duo herbicide to determine the size of drifting spray particles, drift deposition, and airborne drift in a field setting. The specific application requirements listed on the herbicide label and the amount of drift resulting from an on-label application of Enlist Duo were also examined.

**Materials and Methods**

This experiment was conducted at the Pesticide Application Technology Laboratory (PAT Lab) and the UNL Dryland Research Farm in North Platte, NE. Droplet sizing work was conducted in a low speed wind tunnel (PAT Lab) measuring 1.2 m wide, 1.2 m tall, and 12 m long. Materials and methods for droplet sizing measurements were consistent with those used for the wind tunnel drift evaluation. Field drift studies were conducted during the summer of 2016 in a 6.5-acre corn-fallow field.
Field Drift Measurement

A field drift study was conducted during the summer of 2016 at the West Central Research and Extension Center in North Platte. The intention of this study was to measure the resulting spray particle drift from an on-application ground application of Enlist Duo herbicide. Two separate runs of this study were conducted resulting in 9 total replications.

The design of this study is consistent with ASABE Standard S561.1: Procedure for Measuring Drift Deposits from Ground, Orchard, and Aerial Sprayers (ASABE 2009) and with past research conducted by Fritz et al. (2011). Applications were consistent with the specific requirements listed on the product label. The herbicide solution was applied with a tractor-mounted ground sprayer (Wilmar 642 Three-Point Wheel Boom Broadcast Sprayer, Wilmar Fabrication LLC., Wilmar, MN) with a 9.1 m boom traveling at 15.6 km hr\(^{-1}\). This setup allowed for the utilization of 18 110° fan angle nozzles aligned 50.8 cm apart. The Teejet Air Induction Extended Range Flat Spray Tip (AIXR) (Spraying Systems Co. Wheaton, IL) and the Greenleaf TurboDrop® XL Flat Spray Tip (TDXL) (Greenleaf Technologies, Covington, LA) were used, both at the 04 orifice size selected to meet the required application rate of 1.5 L min\(^{-1}\). The spray operating pressure was 276 kPa and boom height was kept at ~100 cm above the ground.

Enlist Duo herbicide (Dow AgroSciences, Indianapolis, IN) was used at a rate of 4.01 L ha\(^{-1}\) (592 g acid equivalent ha\(^{-1}\) glyphosate, 557 g acid equivalent ha\(^{-1}\) 2,4-D) and a carrier volume of 140 L ha\(^{-1}\). The spray solution consisted of the herbicide, tap water, and a PTSA fluorescent tracer dye (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) (Spectra Colors Corp., Kearny, NJ) added at 0.6 mg ml\(^{-1}\). PTSA is an extremely water-soluble, stable tracer dye that is
highly detectible by fluorometry (Hoffman et al. 2014). Prior to spraying, a tank sample was collected to ensure the water, herbicide, and tracer dye were thoroughly mixed in the spray tank.

A 122 m driveline was established on field edges for both runs, with a heading of due east for the first run and a heading of due north for the second run. Two collection lines 15 m apart were set up perpendicular to these drivelines with collection distances of 1, 2, 4, 8, 16, 32, and 64 m (Figure 3.1). These distances were measured from the last nozzle on the sprayer boom. Two petri dishes per line were placed in the sprayer swath, and an additional petri dish was located upwind of the boom. Downwind collection stations consisted of Mylar cards (10 cm x 10 cm, 20 cm x 20 cm) (Grafix Platics, Cleveland, OH) to record deposition and water sensitive paper (5 cm x 8 cm) (Spraying Systems, Wheaton, IL, 60189) to record suspended spray droplet size. Larger 20 x 20 cm cards were used to collect deposition at 32 and 64 meter distances. Mylar cards were horizontally attached on the collection stations 30 cm above the ground, and water sensitive paper was positioned 50 cm above the ground. Monofilament line (Berkley®, Spirit Lake, IA) was used to collect airborne spray flux. Lines 11 m in length and 0.5 mm in diameter were horizontally strung ~6 m above the ground between the collection stations for all distances excluding the 64 m.

The study consisted of nine total replications, with each rep consisting of one pass with both nozzle types. These replications were carried out over two runs. Before spraying each replicate, the collection stations were set up and the wind speed/direction checked to ensure it was perpendicular to the driveline. Weather conditions were monitored with a weather station. Additionally, the wind speed/direction were monitored at boom height with a WeatherFlow™ wind meter (WeatherFlow Inc., Scotts Valley, CA). After each replicate five minutes was allowed before material collection to allow droplets to reach the furthest sampled distance. Mylar
cards and monofilament line were placed into pre-labeled plastic bags and stored in a dark storage bin to minimize photodegradation potential (Hoffman et al. 2014). Water sensitive papers were placed in pre-labeled bags and stored in a freezer to prevent moisture contamination.

Tracer dye was extracted from Mylar cards and monofilament line in a manner similar to techniques described by Fritz et al. (2011) and Roten et al. (2014). A 10:90 isopropyl alcohol: distilled water solution was added to each plastic bag using a bottle top dispenser (LabSciences Inc., 60000-BTR, Reno, NV). Mylar cards and monofilament line were each washed with 40 and 25 ml of solution, respectively. Samples were then shaken to release the tracer dye from the samplers. Upon the suspension of dye in the washing solution, a 1.5 ml aliquot from each bag was drawn and placed in a glass cuvette. Each cuvette was then placed into a PTSA module inside a fluorimeter (Turner Designs, Trilogy 7200.000, Sunnyvale, CA), and fluorescence values were recorded. Fluorescence values were then converted into dye concentrations and the amount of spray deposited. These calculations were made assuming a linear response between fluorescence and dye concentration, which was made possible by selecting a PTSA use rate that results in dye deposits falling within the accepted concentration range (Fritz et al. 2011).

The deposition data was adjusted for dye recovery rate during the wash procedure using methods similar to those used by Henry RS (2016). This was done by spiking a 10 µl sample from representative tank-mixtures onto six mylar cards. These cards were washed as described above and fluorescence values where then compared to a separate 10 µl sample. The recovery rates for the mylar cards and the solution used in this study was 90%. Additionally, dye degradation was calculated, as dye may be quenched at increased concentration and/or affected by the composition of the spray solution (Hoffman et al. 2014). This was accomplished by adding a 10 µl to a known volume of water: alcohol solution every hour for 6 hours and
comparing the results to the value of a similar solution taken shortly after mixing. Degradation analysis for the Enlist Duo: PTSA solution showed minimal degradation over the measured period.

Water sensitive papers were analyzed with the software program DropletScan™ version 2.5 (WRK of Arkansas LLC., Lonoke, AR) to determine the droplet size of drifting spray particles. This program captures and processes images of exposed cards and returns estimates of spray coverage, deposition rate, and spray droplet size. Papers were paced onto a scanner (Epson V600 Photo Scanner, Epson Shinjuku, Tokyo, Japan), scanned and analyzed, and droplet statistics recorded. Droplet size was reported as the $D_{v0.5}$, which represents a droplet size such that 50% of the spray volume is contained in droplets smaller than that diameter. WSP’s are coated with a yellow surface which is stained blue by impacting water droplets; therefore, programs such as DropletScan™ measure droplet stain diameter instead of actual droplet diameter. To determine the diameter of collected spray droplets, a spread factor, which varies by the spray solution, must be applied.

The spread factor for the Enlist Duo and water solution used was calculated by depositing individual droplets from a micro-syringe onto WSP paper. A video-based optical contact angle measuring system (Model #OAC 15EC, DataPhysics Instruments, Fildenstadt, Germany) was used to generate the spray droplets. This system has the capability of generating volume-controlled, individual droplets. As each droplet was generated, a video of the droplet was captured and processed to determine the droplet diameter for each individual droplet. Targeted droplet diameters were chosen (50–1000 µm), and six droplets were deposited on labeled water-sensitive paper (WSP). Each paper was then analyzed with DropletScan™ using the method
described above and the diameter recorded. The plot of droplet diameter vs stain diameter and the resulting curve fit are shown in in Figure 3.2.

Droplet data generated in this experiment was analyzed using SAS v9.4 (SAS, Cary, NC, USA). The PROC GLIMMIX procedure was used to analyze droplet data from selected nozzles. Tukey’s means separation was used to determine statistical significance with $\alpha=0.05$. The spray characteristics analyzed included the percent of the spray volume < 141 µm, $D_{v0.5}$ and the $D_{v0.1}$ value. Statistical analysis of drift study data was conducted using both SAS v9.4 and AGDISP™. The PROC GLIMMIX procedure was used to analyze deposition and droplet size data, with data separated by nozzle type. Nozzle, distance downwind, and wind classification were analyzed as well. Reps were grouped into one of three different wind classes based on the average wind speed during treatment, with reps having wind speeds between 5-11 km hr$^{-1}$, 11-18 km hr$^{-1}$, and 18-24 km hr$^{-1}$ being classified as ‘low’, ‘medium’, and ‘high’, respectively. Deposition rate, nozzle type, collection distance, and their interaction were considered fixed effects, and replicate was considered a random effect. Tukey’s mean separation was used to determine statistical significance with $\alpha=0.05$.

Additionally, a mass-balance transfer analysis of deposition data was conducted. The first step was determining the amount of dye deposited in a defined in-swath area. A 10 cm x 9.1-meter area (9144 cm$^2$) was used as the in-swath area, with the width representing the diameter of the petri dishes used as collectors. The total amount of dye deposited (10071 µg) in this area was then calculated using the nominal flow rate of the selected nozzles (1.5 L min$^{-1}$), ground speed (12.75 km hr$^{-1}$), and the PTSA tracer mix rate (793 µg ml$^{-1}$). The deposition rate processed from in-swath was then averaged across the collection lines for each replication and multiplied by total in-swath collection area to give the percent fraction of dye deposited in the treatment area. The
percent fraction of dye deposited downwind was then calculated. Sample integration area values were created by subtracting the distance between sequential downwind collection distances and multiplying it by the 10 cm collector diameter. The deposition rates collected from mylar cards were then multiplied by this area to give the total dye deposited in each integration area. Dividing the total dye deposited by the dye deposited in the in-swath area then produced the percent fraction of the total spray deposited at downwind distances.

Finally, previously collected droplet size distribution data for the AIXR11004 and TDXL11004 was used in AGDISP v8.26 to model the dispersion and deposition of spray particles moving downwind. Additionally, a “worst-case” scenario was modeled using the droplet size data from the AIXR11003 at 276 kPa ($D_{v0.5} = 405 \mu m$, $RS = 0.91$). While this nozzle is listed on the product label, a spray pressure of 276 kPa constitutes an off-label application. The simulation was run at wind speeds of 8, 16, and 21 km hr$^{-1}$ for both one spray pass and twenty spray passes, as the program is designed to be a multi-pass model. The following settings (Figure 3.3) were used for each model iteration:

Application Method: Ground, air injection nozzle, 276 kPa, 1-meter discharge height, 1(20) spray line(s)

Application Technique: Liquid product (Enlist Duo), DSD from user data, 18 nozzles, 9.1-meter spray swath

Meteorology: Single height wind speed, -90° wind direction, 30°C, 50% RH, strong solar insolation

Surface: 0° upslope and side slope, no canopy, 0 m swath offset
Results and Discussion

The droplet size distribution data for the two nozzles used in this study are presented in Table 2.1. The spray classification category for the AIXR nozzle was very coarse with the TDXL nozzle being classified as extremely coarse. The percentage of spray volume < 141 µm, $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ values were statistically different for each nozzle ($P \leq 0.05$). These metrics show that between the two nozzle types, the AIXR nozzle produced a smaller droplet size distribution and more driftable fines. Less than 2% of the total spray volume consisted of droplets < 141 µm in diameter for both nozzles. Additionally, both nozzles had the same relative span relative span ($P > 0.3739$).

The two runs conducted on 07/07/2016 and 08/31/2016, and nine total replications of this study were made. The targeted wind velocity was between 8.0 to 24.0 km hr$^{-1}$ with the desired wind direction within 30° of being perpendicular to the spray swath. Meteorological conditions from this study are presented in Table 3.3. Wind speeds are grouped into wind classes due to each individual spray pass occurring at a different wind speed (Table 3.3).

For the droplet size of spray particle drift, ANOVA indicated that only the distance main effect was significant ($P \leq 0.05$) when analyzed by wind class (Table 3.1). No difference in the droplet size of spray particle drift from the AIXR and TDXL nozzles was indicated across all wind speeds. Generally, the size of drifting spray particles decreased as the distance downwind from the spray swath increased. Across nozzle type, the size of spray droplets collected downwind, reported as $D_{v0.5}$ (µm), increased as the wind speed increased and decreased at distances further downwind from the nozzle. The $D_{v0.5}$ of drifting spray droplets collected downwind ranged from about 90 µm to 52 µm in diameter from 1 to 64 meters downwind,
respectively. All droplets collected downwind were smaller than 141 µm in diameter, as these droplets are typically the most susceptible to drift and are typically considered “drivable fines” (Yates 1985).

Analysis of deposition on mylar cards indicated no significant effects for nozzle type and collection distance across all wind classes (Table 3.2). The deposition rate was the same for both nozzles at all distances, regardless of wind speed. Deposition rate (µg cm$^{-2}$) is the amount of PTSA dye deposited divided by the area of the sampler. The deposition rate across nozzle types ranged from .06 µg cm$^{-2}$ to .01 µg cm$^{-2}$ from 1 to 64 meters downwind, respectively. Generally, greater deposition of PTSA tracer dye was observed as wind speed increased, and deposition decreased as the distance from the spray swath increased. Additionally, smaller amounts of deposition were observed beyond 16 meters downwind, an effect that has been reported in previous field drift studies (Henry RS 2016; Fritz et al. 2011).

Mass-balance transfer data showed that the majority of spray solution was accounted for either in-swath or downwind from the site of application (Table 3.4). Initial inspection of the spray collected downwind indicated that ≤ 25% of the total spray solution applied (Table 3.4) was collected downwind; for nine of the 12 replications, the downwind fraction recovered was ≤ 17%. The largest fractions (23, 25, and 53%) recovered downwind occurred when using both nozzle types and in both the high and medium wind classes. Additionally, a wide range of values were observed for the fraction collected in-swath, as the percent fraction recovered in-swath ranged from 21 to 124% (Table 3.5). The mass-balance data indicates in-swath samplers both over and under collected depending upon the location under the spray boom. The collector from line A, which was located under the upwind portion of the boom, reported lower deposition values than the sampler from line B, which was positioned under the downwind portion of the
spray boom. This over-collection of spray by the downwind in-swath sampler is likely due to spray swath displacement, which was visually observed by the authors during the duration of the field study. The effects of this displacement was observed for the repetition with the largest percent fraction recovered downwind. The mass-balance transfer analysis showed 53% of the spray was recovered downwind for repetition seven. However, grouping the deposition rate of dye collected at one-meter downwind with the deposition values collected in-swath would reduce the fraction of spray recovered downwind by 20%.

Observations pertaining to the design, execution, and evaluation of the field drift study lead the authors to present several recommendations for future studies examining spray drift in a field setting. While additional collection lines or in-swath samplers may make field drift measurements more arduous, additional collection sites may assist the experimenter in seeing a more complete picture of the herbicide application and drift process. In-swath sampling is particularly important, as target site deposition is crucial understand the quantity of spray moving off-target. The authors recommend using a line of in-swath collectors across the width of the spray boom to assist in determining on-target deposition. Additionally, careful handling and processing of collection materials is crucial to prevent sample contamination.

The AGDISP drift models constructed with field drift study parameters and wind tunnel droplet size data showed minimal differences in downwind deposition between the three nozzle types (Table 3.6). Similar to deposition data collected in the field, greater spray drift was observed as wind speed increased. The addition of 20 spray pass models is more representative of a field application scenario than the single pass model, and the decrease in downwind deposition values expressed as a fraction of the total applied material was expected due to the size of the spray block and corresponding increase in material applied. The downwind deposition
values observed ranged from 0-3.1% due to the relatively large droplet size distribution produced by all three nozzles. It should be noted there are various issues associated with using the AGDISP ground model. Initial comparisons of field data to AGDISP models showed that spray deposition was over predicted close to the site of application, and under predicted at further downwind distances (Teske et al. 2009; Woodward et al. 2008). However, later versions (8.20 and higher) have been shown to incorporate the ground model more accurately (Teske et al. 2009).

The models generated by AGDISP show minimal differences in drift potential between the two nozzles, as 1.4% downwind deposition was reported for the TDXL11004 at a wind speed of 21 km hr\(^{-1}\) compared to 3.1% downwind deposition for the AIXR11004. This matches the deposition data collected in the field drift examination conducted by the authors, as no difference in spray deposition was observed between nozzle types. Measuring meaningful differences in deposition in field drift experiments is difficult due to the large degree of variability and error associated with drift studies, including variability from meteorological conditions, application equipment, and sampling methods (Fritz et al. 2011). While the highest amount of deposition was noted for the “worst-case scenario” (AIXR11003 at 276 kPa), the magnitude of difference is small (< 1.5%). The AIXR and TDXL are air-induction nozzles designed to generate coarse droplets and minimize the amount of spray comprised of small, “drift-able” droplets, and have been approved for ground application of Enlist Duo due to the coarse spray quality they generate. The combination of these factors make discerning a difference in drift potential between nozzles incredibly difficult. The addition of a flat-fan type nozzle, though off-label, would assist in demonstrating the reduction in drift potential achieved by using drift-reduction type nozzles.
While drift of Enlist Duo herbicide applied through the AIXR11004 and TDXL11004 was evaluated in a low-speed wind tunnel, a direct comparison of field and wind tunnel deposition data is not feasible due to differences in experimental and meteorological conditions. The amount of drift deposited downwind in the low-speed wind tunnel was several magnitudes higher than that observed in the field, which can be attributed to the contained flow of spray in the wind tunnel which prevents the dispersion and settling of droplets as would occur in atmospheric conditions. The minimal amount of 2,4-D injury to soybeans seen at these elevated deposition levels, combined with the reduced damage to tomato and cotton at further downwind distances in the wind tunnel was encouraging as the drift deposition data in the tunnel was much higher than would be observed at equivalent distances under field conditions. The percent biomass reduction across all wind speeds and nozzle types evaluated in the wind tunnel were -8, 20, and 2 percent at 12 meters downwind for soybean, cotton, and tomato, respectively. A typical deposition rate recovered at this distance for the 21 km hr\(^{-1}\) wind speed was \(\sim 0.13 \mu g*cm^{-2}\). The highest deposition rate observed in the field, 0.12 \(\mu g \text{ cm}^2\), was collected at 1 meter downwind, and the deposition rate at a comparable distance in the field (16 meters downwind) was between 0.04 and 0.06 \(\mu g \text{ cm}^2\).

**Conclusions**

The objective of this study was to determine transport and the ultimate fate from ground spray application of Enlist Duo herbicide applied through two air-inclusion nozzles. Field tracing of spray movement resulted in minimal downwind deposition of tracer dye, with little to no dye being recovered beyond 16 meters downwind. The deposition rates collected in the field likely correspond to little or no damage to susceptible crops such as soybean based on previous wind tunnel drift screening.
Field drift deposition data suggests no difference in drift potential between the AIXR11004 and TDXL11004, regardless of wind speed and distance from the site of application, which is not surprising as both nozzles produce coarse sprays. While differences in deposition between the two nozzle types was observed when using droplet size distribution data in AGDISP to model downwind deposition, the magnitude of the difference between nozzles was small. The model distinguishes differences where field data does not both as a result of inherent variability in field data resulting from meteorological difference and sampling variability as well as the potential impact resulting from differences in initial exit velocity, which has been shown to affect drift potential (Miller and Butler Ellis 2000; Ozkan 1998). While air-induction nozzles tend to produce larger spray droplets, the sprays generated by these nozzles tend to exit the final orifice at lower velocities as compared to non-air-induction type nozzles (Dorr et al. 2013), thus increasing the potential for the generated spray to quickly lose initial exit velocity and be affected by ambient wind conditions resulting in off-target movement.

Based on these results, an applicator can minimize drift to levels well below those that would damage susceptible crops when applying Enlist Duo by following all product label application requirements and by using nozzles that produce very coarse to extremely coarse spray qualities.


de Snoo GF and de Wit PJ. (1998). Buffer zones for reducing pesticide drift to ditches and risk to aquatic organisms. Ecotoxicology and Environmental Safety 41: 112-118


Jutsum AR, Heaney SP, Perrin BM, Wege PJ. Pesticide resistance: assessment of risk and the development and implementation of effective management strategies.


Mohseni-Moghadam M, Wolfe S, Dami I, Doohan D. (2016). Response of wine grape cultivars to simulated drift rates of 2,4-D, dicamba, and glyphosate, and 2,4-D or dicamba plus glyphosate. Weed Technology 30: 807-814


Renne DS, Wolf MA. (1979). Experimental studies of 2,4-D herbicide drift characteristics. Agricultural Meteorology 20: 7-24


Spillman, JJ. Spray impaction, retention, and adhesion: an introduction to basic characteristics. Pesticide Science 15:97-106


Table 3.1. ANOVA table of fixed effects and interactions for the dependent variable suspended spray droplet size ($D_{v0.5}$). The $D_{v0.5}$ (μm) represents a droplet size where 50% of the spray volume consists of droplets smaller or larger than that diameter. Type III fixed were examined using PROC GLIMMIX in SAS to determine significance (P≤0.05).

<table>
<thead>
<tr>
<th>Effect</th>
<th>df&lt;sup&gt;a&lt;/sup&gt;</th>
<th>F Value</th>
<th>Pr &gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>1</td>
<td>0.02</td>
<td>0.9610</td>
</tr>
<tr>
<td>Distance</td>
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<td>42.21</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>WindClass</td>
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<td>1.57</td>
<td>0.2118</td>
</tr>
<tr>
<td>Nozzle*Distance</td>
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<td>0.14</td>
<td>0.9905</td>
</tr>
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<td>0.3276</td>
</tr>
<tr>
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<td>0.2346</td>
</tr>
<tr>
<td>Nozzle<em>Distance</em>WindClass</td>
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<td>0.45</td>
<td>0.9410</td>
</tr>
</tbody>
</table>

<sup>a</sup>- degrees of freedom
Table 3.2. ANOVA table of fixed effects and interactions for the dependent variable spray deposition rate. Deposition rate (μg cm⁻²) is the amount of PTSA dye deposited divided by the area of the sampler. Type III fixed were examined using PROC GLIMMIX in SAS to determine significance (P≤0.05).

<table>
<thead>
<tr>
<th>Effect</th>
<th>dfᵃ</th>
<th>F Value</th>
<th>Pr &gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
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<td>0.03</td>
<td>0.8691</td>
</tr>
<tr>
<td>Distance</td>
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<td>0.1274</td>
</tr>
<tr>
<td>WindClass</td>
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<td>0.8908</td>
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<tr>
<td>Nozzle*WindClass</td>
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<td>Distance*WindClass</td>
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</tr>
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<td>Nozzle<em>Distance</em>WindClass</td>
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<td>0.50</td>
<td>0.9150</td>
</tr>
</tbody>
</table>

dfᵃ- degrees of freedom
Table 3.3. Meteorological conditions for each spray pass. A treatment consisted of two passes of the sprayer; one with the AIXR11004 and one with the TDXL11004. Nine total replications of this study were made over two different runs. The data is presented as an average over the approximately 30 second spray pass.

<table>
<thead>
<tr>
<th>Rep</th>
<th>Nozzle</th>
<th>Air temperature °C</th>
<th>Relative humidity %</th>
<th>Wind speed km hr⁻¹</th>
<th>Wind direction °</th>
<th>Wind class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AIXR</td>
<td>30</td>
<td>43</td>
<td>8.7</td>
<td>354</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>TDXL</td>
<td>31</td>
<td>34</td>
<td>7.1</td>
<td>331</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>AIXR</td>
<td>30</td>
<td>25</td>
<td>6.1</td>
<td>331</td>
<td>Low</td>
</tr>
<tr>
<td>4</td>
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<td>25</td>
<td>9.4</td>
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<tr>
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<tr>
<td>6</td>
<td>TDXL</td>
<td>31</td>
<td>31</td>
<td>7.2</td>
<td>334</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 2</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>7</td>
<td>AIXR</td>
<td>28</td>
<td>68</td>
<td>7.7</td>
<td>96</td>
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</tr>
<tr>
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<td>TDXL</td>
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<tr>
<td>9</td>
<td>TDXL</td>
<td>29</td>
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<td>11.1</td>
<td>83</td>
<td>Low</td>
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<tr>
<td>10</td>
<td>AIXR</td>
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</tr>
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<td>11</td>
<td>AIXR</td>
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<td>64</td>
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</tr>
<tr>
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<td>18.3</td>
<td>79</td>
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</tr>
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<td>TDXL</td>
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<td>66</td>
<td>22.2</td>
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<td>High</td>
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<tr>
<td>14</td>
<td>AIXR</td>
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<td>64</td>
<td>16.7</td>
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<td>Medium</td>
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<tr>
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<td>Medium</td>
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<td>16</td>
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<td>63</td>
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<td>18</td>
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<td>61</td>
<td>15.0</td>
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</table>
3.4. Percent fraction of dye recovered in-swath and downwind from a field drift study conducted in the summer of 2016 at the Pesticide Application Laboratory in North Platte, NE. Enlist Duo was applied at a rate of 2.9 $\%v\ v^{-1}$ and carrier volume of 140 L ha$^{-1}$. The tracer dye was mixed at a rate of 0.6 mg ml$^{-1}$. Petri dishes were used in-swath and mylar cards used at downwind distances, with the collectors positioned 30 cm above the ground.

<table>
<thead>
<tr>
<th>Nozzle$^a$</th>
<th>Rep</th>
<th>Wind class</th>
<th>In-swath</th>
<th>Downwind</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIXR</td>
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<td>Low</td>
<td>33</td>
<td>16</td>
<td>49</td>
</tr>
<tr>
<td>TDXL</td>
<td>8</td>
<td>High</td>
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<td>53</td>
<td>151</td>
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<td>TDXL</td>
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<td>Low</td>
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<td>17</td>
<td>91</td>
</tr>
<tr>
<td>AIXR</td>
<td>10</td>
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<td>76</td>
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$^a$ Selected nozzles evaluated at 110º spray angle and 1.5 L/min flow rate
Table 3.5. Deposition rate from in-swath collectors from a field drift study conducted in the summer of 2016 at the Pesticide Application Laboratory in North Platte, NE. A treatment consisted of two passes of the sprayer, and each individual replication is listed below. Enlist Duo was applied at a rate of 2.9 %v v\(^{-1}\) and carrier volume of 140 L ha\(^{-1}\). The tracer dye was mixed at a rate of 0.6 mg ml\(^{-1}\). Deposition rate (μg cm\(^{-2}\)) is the amount of PTSA dye deposited divided by the area of the sampler.

<table>
<thead>
<tr>
<th>Nozzle(^a)</th>
<th>Rep</th>
<th>Line A(^b)</th>
<th>Line B(^b)</th>
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\(^a\) Selected nozzles evaluated at 110º spray angle and 1.5 L/min flow rate

\(^b\) Line refers to orientation of in-swath collector in treatment area. The collector in Line A was position on the upwind portion of the boom with the Line B collector positioned on the downwind side of the spray boom
Table 3.6. Results of AGDISP calculations for ground application of Enlist Duo herbicide.

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>Spray pass</th>
<th>Wind speed</th>
<th>Application efficiency&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Downwind deposition&lt;sup&gt;b&lt;/sup&gt;</th>
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<tr>
<td></td>
<td></td>
<td>km hr&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>%</td>
<td>%</td>
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<tr>
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</table>

<sup>a</sup> Application efficiency is percentage of active ingredient deposited in the spray swath/block

<sup>b</sup> Downwind deposition is the percentage of active ingredient not deposited in-s swath
Figure 3.1. Diagram of experimental setup for field drift study conducted in the summer of 2016 in North Platte, NE.
Figure 3.2. Spread factor for an Enlist Duo solution mixed at a use rate of 2.9% v v⁻¹. Droplets of a known size were placed on water sensitive paper, and the size of the resulting stain recorded in DropletScan™. This value was then compared to the known size of the deposited droplet.
Figure 3.3. Model parameters used for drift simulation in AGDISPv8.26. Wind speeds of 5, 10, and 15 mph in addition to both 1 and 20 spray lines.
CHAPTER 4

Summary of Experimental Methods

The effect of wind speed and droplet size on spray drift potential from ground applications was examined in this research. While wind speed cannot be controlled by applicators, the droplet size can be through a combination of factors including nozzle type and size, spray pressure, and selection of adjuvants. Therefore, the evaluation of herbicide spray drift in both wind tunnel and field settings first requires an accurate determination of spray droplet size. The droplet sizing methods used by the PAT Laboratory are consistent with the Spray Nozzle Classification by Droplet Spectra Standards (ASABE 2009) and have been further tested, refined and verified to provide for repeatable results in multiple laboratories (Henry 2016 and Fritz et al. 2014). The standardized reference nozzles provide a metric for comparing different labs and measurement methods (ASABE 2009). As with any measurement method, care should be taken to account for all potential sources of error and variability, including nozzle flow rate and pressure, spray solution, and measurement setup. When conducting field trials to compare multiple nozzle types and spray solution, the nozzle type, spray pressure(s) and solution(s) used for droplet size measurements should be consistent with those used in wind tunnel/field drift measurements.

The methods used to measure drift in the low-speed wind tunnel closely followed ISO Standard 22856 (ISO 2008) and other wind tunnel research conducted by Lund (2000), Walklate and Miller (2000), and Derksen et al. (1999). The experimental setup consisted of a single nozzle oriented perpendicular to the direction of the airflow positioned in the furthest upwind section of the wind tunnel. Sampling stations were then positioned at downwind distances of 1.3, 3, 6, 9,
and 12 meters. Additionally, a petri dish was placed in the swath of the single spray nozzle.
Horizontal spray drift deposition was measured using mylar cards, and monofilament line was used to measure airborne spray flux. While deposition is a measurement of the fallout of spray at a predetermined height above the wind tunnel floor, airborne spray flux represents the spray airborne at each sampling distance. Sensitive crop species (tomato, soybean, and cotton) were placed in the wind tunnel at the sampling distances and sprayed as well. Additionally, water sensitive papers were placed adjacent to the monofilament line to measure the droplet size of airborne suspended spray particles. It should be noted that the height of these collectors in relation to each other and to the plants in the wind tunnel must be considered. In this study, deposition was measured using mylar cards positioned near the top of the canopy, not at the base of the plants. Airborne spray flux and the size of suspended spray particles was then measured above the top of the sensitive crop species, as these collection materials are designed to catch spray particles moving downwind, not the spray deposition on horizontal collection surfaces or plants.

Repetitions in the wind tunnel were grouped by wind speed from high to low to ensure identical settings were used for reps at each of the three wind speeds (21, 16, and 8 km hr\(^{-1}\)), as when different levels of wind speed are used as a treatment, randomizing and thereby changing wind speed between each rep may actually introduce more experimental error. An auto-shutoff switch was used to meter total spray volume for each treatment/replication. After spraying plants in the wind tunnel, they were kept outside of the greenhouse to ensure potential vapor drift would not damage nearby plants in the greenhouse. Additionally, while it is important that non-treated plants be exposed wind tunnel conditions, control plants should be kept separate from treated plants for several days to ensure they are not damaged by contact with treated plants.
Treated plants must be handled with great care, as growth regulator herbicides may weaken their stems.

Field drift evaluations were conducted in accordance with ASABE Standard S561.1: Procedure for Measuring Drift Deposits from Ground, Orchard, and Aerial Sprayers (ASABE 2009) and research by Fritz et al. (2011). While some drift studies are designed to purposely create off-target movement, the intent of this drift study was to evaluate drift from an on-label application of Enlist Duo. The spray solution and operational parameters used in the field were consistent with those evaluated in the low-speed win tunnel. A 122-meter long spray line was measured in a fallow corn field with the collectors positioned perpendicular to the middle of the spray swath. The length of this line ensured that the applied spray material traveled to the sampling locations, providing the wind direction remained within +/- 30° of the downwind sampling line direction. The spray solution was applied for the entire length of the swath for each replication. During application, wind speed and direction were monitored using a handheld anemometer to supplement data collected by the weather station. The perpendicular collection lines were positioned 15 meters apart, and each collection station consisted of horizontal mylar cards to record spray deposition and vertical water sensitive papers to record the size of suspended spray droplets. These were located at 1, 2, 4, 8, 16, 32, and 64 meters downwind. One petri dish per-line was placed both upwind from the site of application as well as under the boom in the spray swath.

Sample collection must be done with utmost care when evaluating spray drift. It is important to wait an appropriate amount of time after the spray solution has been applied to ensure the spray has settled prior to sample collection. While the PTSA fluorescent tracer dye (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) used in these studies is extremely stable
(Hoffman et al. 2014), sunlight degrades the concentration of the dye present on samples. Gloves must be warm when removing samples, and should be changed between repetitions. After samples are collected, they should be placed in dark containers to prevent photodegradation. Water sensitive papers can also be contaminated by moisture, as the oil from hands and even humidity can result in unwanted staining. These papers should be marked beforehand and kept in airtight bags either in a freezer or a climate controlled room. Additionally, it is important to keep samples from being contaminated by the treated area, and marking any samples that are contaminated may assist in gathering more accurate data.

When processing mylar cards, petri dishes, and monofilament line to record fluorescence values, samples should be kept until the values have been recorded and checked. Tracer dye is used with the intention of determining the amount of dye recovered in lieu of recovering the active ingredient of the herbicide. Therefore, to accurately interpret the amount recovered on collection materials, the amount of dye in the spray solution must be confirmed from collected tank samples. Tank samples taken during the experiment must be diluted to achieve a readable value from the fluorimeter. This is best accomplished by using a 9:1 alcohol to tank sample dilution, and diluting until the amount of dye in the tank sample dilution is similar to that recorded from washing samples. In this experiment, the tank sample was diluted until RFU values were \( \leq 5,000 \) RFU’s. A rate of dye in micrograms per milliliter (\( \mu g \text{ ml}^{-1} \)) for the tank sample can then be calculated using the total amount of dye added to the tank and the volume of spray solution. The amount of dye present in the final dilution of the tank sample is then calculated, and this value paired with the fluorimeter reading for that final dilution is used to determine dye concentrations. The amount of dye deposited on collection materials can then be calculated from the 1.5 ml aliquot drawn from each sample after being washed with the alcohol
solution. Once the amount of dye deposited (µg) is determined, dividing the amount of dye by the area of the sampler produces the dye deposition rate (µg cm\(^{-2}\)). When evaluating multiple repetitions, the concentration of dye in each tank mix may change and is dependent upon the rate at which dye was added to each tank. Additionally, the deposition rate depends on the surface area of the collection material, and changes depending on the type of collection material (strings vs mylar cards) and the size of the collector. It is important to note that these calculations were made assuming a linear response between fluorescence and dye concentration, which requires the use of dye concentrations that fall within ranges that show a linear response (Fritz et al. 2011). In the future, the creation of a set of standard solutions with known dye concentrations would ensure greater accuracy when analyzing unknown samples, as dye added to spray solution used in field or laboratory studies may be degraded by light and heat or quenched at high concentrations (Hoffman et al. 2014).

When processing water sensitive papers, it should again be noted that while programs such as DropletScan report droplet diameter, the diameter recorded is the diameter of the stain. When using these values for more than screening treatments in a wind tunnel environment, the spread factor of the solution must be calculated to correct for droplet spreading. While plotting known droplet diameter vs stain diameter gives a more accurate reading on the size of suspended spray droplets moving downwind, there are still other issues that make accurate measurement challenging. Smaller droplets that impact water sensitive papers may be masked by large droplets, and multiple small droplets may impact an area already stained by larger spray droplets. Stains that result from moisture in the atmosphere may result in small droplets being recorded that were not actually deposited during application. Additionally, the resolution of the scanner...
determines the size of the droplets captured by droplet scanning programs, meaning that not all drifting spray droplets are able to be recorded.

Measuring drift in the field requires an understanding of the spray deposited in the site of application if the amount of spray leaving the desired treatment zone is to be accurately calculated. The mass-balance transfer analysis conducted by the researchers in this study helped show the fate of the herbicide applied. This was done by determining the amount of dye deposited in the in-swath area using the nominal flow rate of the selected nozzles, ground speed, and the PTSA tracer mix rate. This deposition rate was then averaged across the collection lines for each replication and multiplied by total in-swath collection area to give the percent fraction of dye deposited in the treatment zone. The percent fraction of dye deposited downwind was then calculated and simple integration values created by subtracting the distance between sequential downwind collection distances and multiplying it by collector diameter. Deposition rates from mylar cards were then used to compare the fraction of spray recovered downwind to the fraction recovered in the treatment area. This exercise helps the experimenter examine how much of the solution applied across each individual repetition can be accounted for either in-swath or downwind from the treatment site.

In the case of this particular field study, the mass-balance transfer analysis indicated that a portion of the spray swath was being offset downwind of the spray boom; collectors positioned under the upwind portion of the boom under-collected while collectors positioned under the downwind portion of the boom over-collected. This swath displacement was also observed by the experimenters during the course of the field drift study as well. The authors recommend using additional in-swath collectors to better account for the fate of spray in the treatment zone during application. While the addition of extra collectors or entire collection lines may increase
the workload for the experimenters, understanding where the spray swath ends and drift begins is of critical importance when evaluating spray drift. Additional studies examining the deposition of spray in swath, conducted under similar conditions or on the day of the drift evaluation, may enhance the accuracy of field drift data.
Literature Cited


