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Spray Characterization and Herbicide Efficacy as Influenced by Pulse-Width Modulation Sprayers

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SPRAY CHARACTERIZATION AND HERBICIDE EFFICACY AS INFLUENCED BY PULSE-WIDTH MODULATION SPRAYERS

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Pesticide applications are a heavily scrutinized facet of today's agricultural industry, and a concerted effort to optimize each application needs to be implemented. More precise and efficient pesticide applications are necessary to meet regulatory demands and increase economic efficiency through reduced pesticide inputs. Current pesticide application methods using precision technologies, including pulse-width modulation (PWM) sprayers, can assist with these goals. However, vast advancements in pesticide formulations, adjuvants, and nozzles, as well as the increasing popularity of PWM systems, have only increased the need for applied PWM and weed science research. Additionally, efforts have been placed on increasing spray droplet size to reduce particle drift, but this practice has led to reduced herbicide efficacy. Therefore, identifying an optimum herbicide droplet size which can reduce particle drift while simultaneously maintaining efficacy is a necessity.

The objectives of this research were to: (1) identify the influence of application parameters on droplet size, droplet exit velocity, nozzle tip pressure, and spray pattern uniformity from a PWM sprayer, (2) create best use PWM recommendations to optimize pesticide applications from these sprayers, (3) investigate the effect of spray droplet size

and carrier volume on the efficacy of multiple herbicide solutions, (4) establish novel weed management recommendations based on an optimum droplet size, and (5) determine the plausibility of using PWM sprayers in site-specific weed management strategies.

The results of this research have led to more precise PWM sprayer operation through clear and concise best use recommendations. The capability of PWM sprayers to make precise and uniform applications can assist with the reduction of spray particle drift and increase the overall application effectiveness. Additionally, site-specific weed management strategies were effectively established and optimum herbicide droplet sizes were estimated across a wide range of geographies and weed species. Although, convoluted interactions were identified between droplet size, carrier volume, and other application parameters in regards to their effect on herbicide efficacy. As a result of this research, applicators can more effectively utilize PWM sprayers, reduce herbicide inputs, mitigate spray particle drift, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

For my family,

Your love and support made all of this possible.

"No other human occupation opens so wide a field for the profitable and agreeable combination of labor with cultivated thought as agriculture."

- Abraham Lincoln

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CHAPTER 1

LITERATURE REVIEW

Application Technology Introduction

A majority of US agriculture row crop production hectares have pesticides applied to them during the growing season. In 2015, 72.5 million hectares (95% of the total planted hectares) of corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr], and cotton (*Gossypium hirsutum* L.) received a minimum of one herbicide application (USDA-NASS, 2015). These herbicide applications are critical to maintaining high levels of production as weed interference in corn and soybean reduced annual yields by 50% and 52%, respectively, across North America (Soltani et al., 2017, 2016). The aforementioned yield losses resulted in annual farm revenue losses for corn and soybean crops of $26.7 billion and $17.2 billion, respectively. As pesticide applications are a heavily scrutinized facet of today's agricultural industry, a concerted effort to optimize each application needs to be implemented. However, previous survey results highlighted only 20-30% of applicators were applying pesticides within 5% of their intended application rate (Grisso et al., 1989; Ozkan, 1987). Furthermore, a 2016 survey from Missouri identified greater than 62% of applicators changed nozzles less than 50% of the time when switching herbicide products, and on average, only 45% of applicators inspected sprayer parts prior to each application (Bish and Bradley, 2017). As a result, improper applications may occur due to undetected issues such as nozzle wear (Ozkan et al., 1992a, 1992b), incorrect sprayer setup (Forney et al., 2017), and incorrect nozzle selection (Klein and Kruger, 2011). In today's production agricultural systems, this is unacceptable. More precise and efficient pesticide applications are necessary to meet regulatory demands and increase economic efficiency through reduced pesticide inputs.

In broadcast agricultural applications (both aerial and ground), spray solution is almost exclusively applied using hydraulic nozzles (Matthews et al., 2014). These nozzles meter the flow and atomize the spray solution by applying pressure and forcing the solution through a small orifice. As a result, a heterogeneous mixture of droplet sizes are emitted (Young, 1990). The nozzle exit orifice design coupled with the spray pressure, sheet thickness, surface tension, density, and viscosity creates the resulting spray pattern (Dombrowski et al., 1960).

Pesticide applications are complex processes that require great detail to optimize effectively (Ebert et al., 1999). As this complexity was realized, a focus on application technology research was established to fully comprehend the entirety of pesticide applications. In 1990, the US Environmental Protection Agency (US EPA) established a collaborative research project with 40 agricultural chemical companies. This collaboration, termed the Spray Drift Task Force (SDTF), developed large databases containing droplet size distribution and field drift deposition data for a wide range of spray application parameters to evaluate the application technology impact on pesticide applications and spray drift. Since the development of the SDTF, vast advancements in pesticide formulations, adjuvants, nozzles, and spray delivery methods have only increased the need for application technology research. In particular, efforts have been placed on optimizing applications to reduce spray drift and simultaneously maximize spray impaction and retention to increase pesticide efficacy.

Spray Pattern and Drift

A holistic comprehension of droplet dynamics within a spray cloud (size, velocity, trajectory, etc.) is critical to understand pesticide transport and the final spray destination (Giles et al., 2002). The spray pattern is critical for maintaining optimum coverage to maximize efficacy throughout an application. Drift reduction adjuvants (Ozkan et al., 1993) and spray formulations (Mun et al., 1999) have been shown to impact spray pattern uniformity by forcing a greater volume of spray toward the center of the nozzle. This spray pattern collapse with the resulting increase of spray volume centered under the nozzle may lead to improper overlap between nozzles and thereby underapply chemical between each nozzle. Underapplication may lead to decreased efficacy and hasten the evolution of pesticide resistance (Gressel, 2011; Manalil et al., 2011; Neve and Powles, 2005). Reductions in sprayer speed and tire pressure were also identified as methods to enhance spray pattern uniformity (Langenakens et al., 1995).

Spray drift is a critical concern for pesticide applications as previous research determined severe crop injury could occur up to 200 m downwind when synthetic auxin herbicides were applied in a light wind (Byass and Lake, 1977). Multiple application factors, including droplet velocity (Zhu et al., 1994), droplet trajectory (Miller and Hadfield, 1989), boom height (Hobson et al., 1993), distance to susceptible vegetation (Smith et al., 2000), air temperature and relative humidity (Zhu et al., 1994), and wind speed (Hobson et al., 1993; Smith et al., 2000; Zhu et al., 1994), influence spray drift and have been previously used in drift prediction models.

Several application parameters were observed to have convoluted interactions between spray pattern and drift. Nozzle factors such as tip material (Wang et al., 1995), orifice wear (Ozkan et al., 1992a), lateral angle, spacing, pitch angle, and incorrect selection (Forney et al., 2017) were identified as sources of pattern deformities. Additionally, it was previously noted that venturi nozzles have greater variability in spray pattern distribution, especially at low application pressures, compared to non-venturi nozzles (Ayers et al., 1990; Etheridge et al., 1999), but venturi nozzles remain commercially popular due to reduced spray drift and injury to downwind susceptible vegetation (Bueno et al., 2017; Johnson et al., 2006). An increase in boom height and pressure reduced CV values, thus producing more uniform spray patterns (Azimi et al., 1985); however, increases in boom height and pressure resulted in greater downwind spray drift (Nordby and Skuterud, 1974). Narrow nozzle spacing (< 51 cm) reduced CV values and buffered the negative effects of reduced boom heights and pressures on pattern uniformity, thereby indirectly assisting with drift mitigation efforts. Crosswinds increased pattern CV values (Krishnan et al., 1988) and spray particle drift (Farooq et al., 2001) compared to headwinds of the same velocity, especially at increased pressures, indicating the important role wind speed and direction plays in pesticide applications. The array of aforementioned factors influencing spray patterns and drift illustrates the complexity of optimizing application safety and uniformity.

Spray Droplet Size

Numerous application factors influencing spray drift were previously discussed; however, the largest focus for spray drift reduction practices has been placed on increasing spray droplet size. This is likely due to spray droplet size being one of the most manageable factors influencing pesticide applications, specifically particle drift and pesticide efficacy (Hewitt, 1997; Vieira et al., 2018). A wide array of application parameters have been studied for their effect on droplet size generation.

Physical spray characteristics, such as surface tension, viscosity, and specific gravity, influence spray droplet size and delivery (Miller and Tuck, 2005); however, wide ranges of droplet sizes have been atomized from liquid materials with similar physical properties (Bouse et al., 1990) and the physical properties were deemed as poor predictors within droplet size models (Chapple et al., 1993). Nonetheless, adjuvants (Butler Ellis et al., 1997), pesticide formulations (Miller and Butler Ellis, 2000), and convoluted interactions between spray solution chemistry and nozzle (Butler Ellis and Tuck, 2000) have been shown to affect spray droplet size. Additional application parameters such as nozzle spray angle during aerial applications (Hoffmann et al., 2014), nozzle orifice size (Creech et al., 2015), nozzle orifice wear (Ozkan et al., 1992b), pressure (Nuyttens et al., 2007), and air and solution temperatures (Hoffmann et al., 2011; Miller and Tuck, 2005) have impacted droplet size distributions. Nozzle design or type has been shown to influence the emitted droplet size in both aerial (Bouse, 1994) and ground applications (Nuyttens et al., 2007), and was identified as the variable with the greatest influence over droplet size (Creech et al., 2015).

Significant innovations in nozzle designs to increase spray droplet size have taken place such as: (1) the entrainment of air into spray solution, termed air inclusions, within a nozzle tip (venturi nozzles) (Briffa and Dombrowski, 1966), (2) the development of pre-orifices to utilize the Bernoulli principle (Barnett and Matthews, 1992), and (3) the manipulation of flow path and exit trajectory (Matthews et al., 2014). Previous research identified droplet size was mainly influenced by the ratio between a pre- and exit-orifice, and only minimally impacted by air inclusions from a venturi nozzle which led to the conclusion that increasing droplet size, not droplet density, was more critical for drift reduction practices (Butler Ellis et al., 2002). Further efforts must be made to fully characterize droplet dynamics within spray clouds from the abundant nozzle designs now commercially available as complex interactions between droplet size and velocity can affect particle drift potential (Farooq et al., 2001; Nuyttens et al., 2009). Additionally, current nozzle technologies have demonstrated variable uniformity and consistency from their emitted droplet size distributions leading to the conclusion that not all nozzles are created equal and no single nozzle would be appropriate for all applications (Ferguson et al., 2015). Based on this premise, the American Society of Agricultural and Biological Engineers (ASABE) created a standard to classify spray droplet sizes across a wide arena of testing facilities and assist nozzle users with general information regarding spray drift potential (ASABE, 2009).

An increase in spray droplet size reduces the likelihood of off-target movement of spray particles (Hewitt, 1997). This basic assumption has been validated through drift modelling efforts (Hobson et al., 1993; Zhu et al., 1994) and in-field deposition measurements (Bueno et al., 2017; Vieira et al., 2018). However, increasing spray droplet size to reduce drift potential has limitations, specifically in regards to target coverage and final biological efficacy.

Herbicide Efficacy

Agricultural pesticide research has evaluated an abundance of factors that influence pesticide efficacy, especially in regards to herbicides. Herbicide performance has been previously linked with biotic (e.g. weed species and weed size) and abiotic (e.g. soil texture, light, temperature, humidity, time of application, precipitation, and wind) factors (Kudsk, 2017). However, an often overlooked aspect affecting the success of herbicide applications includes the application equipment and process such as sprayer travel speed (C.J. Meyer et al., 2016), nozzle selection (Jensen et al., 2001; Klein and Johnson, 2002), pressure (Ferguson et al., 2016), and spray pattern distribution (Etheridge et al., 2001). Novel herbicide delivery methods and application technologies, specifically the growing popularity of venturi nozzles, have significantly changed the application process and require additional research to fully comprehend herbicide impaction, retention, and the resulting biological efficacy. Therefore, research and education efforts for applicators must include information regarding the application process to integrate these technologies into the marketplace and successfully reduce drift while simultaneously maximize herbicide efficacy (Wolf, 2002).

Although coarser droplets decrease spray drift, there is a convoluted interaction between increasing droplet size and droplet impaction and retention, and the resulting biological efficacy. May and Clifford, (1967) identified droplet impaction efficiency increased when droplet impaction distances were minimized; therefore, finer droplets and reduced droplet velocities would have greater impaction efficiencies. Further research with external horizontal winds resulted in greater impaction/retention efficiency on vertical leaf surfaces with finer droplets (Lake, 1977); however, coarser droplets had greater impaction/retention efficiency on horizontal leaf surfaces (Spillman, 1984). Therefore, plant architecture and leaf surface composition influence droplet impaction/retention and thereby herbicidal efficacy (Massinon et al., 2017; Nairn et al., 2013). Although droplet impaction/retention increased on horizontal leaf surfaces with coarser droplets, adhesion was reduced with increasing droplet size as droplets bounced or shattered upon impact (Forster et al., 2005). Additionally, models indicated decreasing droplet size increased spray penetration into a plant canopy (Bache, 1985), and this result was field validated as smaller droplet sizes emitted from single exit orifice nozzles resulted in greater soybean canopy penetration (Wolf and Daggupati, 2009). However, increasing spray carrier volume may buffer the impact of increasing droplet size on spray coverage and penetration (Bretthauer et al., 2008). These results help to explain reductions in herbicide efficacy when coarser droplets at a fixed carrier volume were used across multiple herbicides and weed species (Ennis and Williamson, 1963; Knoche, 1994; Lake, 1977; Lake and Taylor, 1974; McKinlay et al., 1972; Meyer et al., 2016).

As droplet diameter increases, the volume of solution contained within individual droplets increases; if an application carrier volume is held constant and the droplet diameter doubled, the number of droplets available for plant surface impaction and retention is reduced by a ratio of 8:1. Typically, this is used as justification for the following guideline: reduced droplet sizes are necessary for contact herbicides to maximize efficacy, while systemic herbicide efficacy is less sensitive to droplet size changes. Glyphosate, a systemic herbicide, had greater absorption and translocation with Coarse droplets (Feng et al., 2009); however, this guideline was not consistent across systemic herbicides as translocation of 2,4-D (systemic herbicide) increased as droplet size decreased, indicating droplet size plays a role in 2,4-D efficacy (Wolf et al., 1992) as well as several other systemic herbicides (Prasad and Cadogan, 1992). Additionally, no losses in herbicide efficacy as droplet size increased were observed for several contact herbicides (Ramsdale and Messersmith, 2001a; Shaw et al., 2000). Droplet size impacts on herbicide efficacy are convoluted, and each herbicide and weed species interaction requires a tailored approached to maximize efficacy (Creech et al., 2016).

In addition to droplet size, carrier volume plays a crucial role in herbicide coverage and efficacy. Generally, across herbicides, efficacy decreased as carrier volume decreased (Knoche, 1994). This result is expected as a reduced volume should result in decreased coverage of the target weed species. Field research validated this assumption as an increase in carrier volume ($\geq$ 94 L ha^{-1}) resulted in greater spray coverage and penetration, while changing nozzle type (droplet size) had no effect on the overall spray coverage or penetration (Barbosa et al., 2009; Legleiter and Johnson, 2016). However, similar to the complex interactions observed with droplet size, carrier volume has shown mixed effects on herbicide efficacy. Etheridge et al., (2001) and Ramsdale and Messersmith, (2001b) showed minimal to no efficacy reduction from a decrease in carrier volume across multiple contact herbicides. In contrast, a reduction in dicamba efficacy (systemic herbicide) when large droplet sizes were applied was observed as carrier volume was reduced (C J Meyer et al., 2016). Further complications developed from previous research in which reduced droplet sizes and carrier volumes (more concentrated droplets) increased efficacy with both contact and systemic herbicides (McKinlay et al., 1974; Merritt and Taylor, 1977). Homogenization of the droplet sizes represented within a spray pattern through unique pesticide delivery methods and carrier volumes tailored for specific herbicides and weed species could result in greater droplet adhesion to leaf surfaces and increase biological efficacy, while limiting drift potential (De Cock et al., 2017).

Pulse-Width Modulation Sprayers

The objective of pesticide applications is to precisely and accurately deliver the minimum amount of active ingredient to the target to achieve the desired biological effect with safety and economy (Matthews et al., 2014). Current pesticide application methods using precision technologies, such as electronic controllers, can assist with these goals (Rietz et al., 1997). Pulse-width modulation (PWM) sprayers optimize applications through precision electronic techniques such as automatic boom and individual nozzle control (Luck et al., 2010a, 2010b), overlap efficiency, and flow rate turn compensation across the boom to improve the reliability of desired flow rates and droplet sizes (Giles et al., 2003; Needham et al., 2012). Flow is controlled by pulsing an electronically-actuated solenoid valve on a fixed frequency (typically 10 Hz) that is placed directly upstream of the nozzle (Giles and Comino, 1989) and an alternating electrical signal timing for adjacent nozzles is used across the boom (Blended Pulse®) to mitigate application overlap errors (Capstan Ag Systems Inc., 2006). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003) and PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Application pressure based variable rate flow control devices have been shown to have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). Previous PWM research illustrated little to no effect from duty cycle on spray droplet size (Giles et al., 1996; Giles and Comino, 1990); however, only non-venturi and pre-orifice lacking nozzles were evaluated. Furthermore, PWM sprayers have the capability of producing up to a 10:1 turndown ratio in flow rate with no pressure or nozzle based changes, thus creating more flexible options for pesticide applicators (Giles et al., 1996; GopalaPillai et al., 1999). Additional PWM benefits include: increased spray coverage uniformity when used in conjunction with capacitive accelerometers to compensate for horizontal boom movements (Lebeau et al., 2004), precision in-season nitrogen applications through the use of high-resolution prescription maps (Han et al., 2001), and maintained spray integrity when using larger orifice size nozzles (larger droplet sizes) paired with low carrier volumes such as with aerial applications (Giles et al., 1995).

Previous PWM research illustrated droplet velocity decreased as duty cycle decreased (Giles et al., 2002), which could be problematic due to increased drift potential (Farooq et al., 2001) and reduced canopy penetration, specifically in vertically oriented plant canopies such as corn (*Zea mays* L.) (Creech et al., 2018). However, the decrease in droplet velocity from a change in duty cycle is smaller than the decrease in droplet velocity from a change in application pressure across equivalent flow rates (Giles et al., 2003). Furthermore, compared to pressure-based flow rate adjustments, increasing nozzle orifice size and operating at a lower duty cycle will increase droplet velocities and spray kinetic energies (Giles, 2001). Spray kinetic energies from PWM sprayers were minimally affected by duty cycle and were more stable than spray kinetic energies obtained from pressure-based alterations to obtain equivalent flow rates (Giles et al., 2002; Giles and Ben-Salem, 1992). In brief, PWM sprayers could reduce drift potential, increase canopy penetration, and increase impaction compared to sprayers using pressure-based alterations to obtain equivalent flow rates. These hypotheses were field validated as pulsing dual nozzle configurations increased coverage of Palmer amaranth (*Amaranthus palmeri* S. Wats.) while simultaneously minimized the drift potential of small droplets (Womac et al., 2017, 2016).

Although numerous benefits have been presented for PWM application systems, there have been drawbacks identified. Currently, nozzle selection is limited because venturi nozzles are not recommended (Capstan Ag Systems Inc., 2013). Previous research also demonstrated as PWM duty cycle decreased, spray pattern uniformity decreased for hollow-cone, solid-cone, and, to a lesser extent, non-venturi flat fan nozzles, because more spray was concentrated directly underneath the nozzle (Giles and Comino, 1990). Mangus et al., (2017) expanded on this concept and identified that although the correct flow rate was emitted per pulse regardless of duty cycle, spray coverage uniformity decreased as duty cycle decreased suggesting that areas of under- and over-application may occur. On-ground application coverage estimates were ±10% of the desired target 67 and 38% of the time for 40 and 20% duty cycles, respectively, indicating a severe penalty for operating the PWM sprayer below a 40% duty cycle (Mangus et al., 2017). Additional research regarding spray deposition parallel with the sprayer path identified 80° fan angle nozzles should not be operated with a 25% duty cycle at sprayer speeds greater than 11 km h^{-1} as the CV increased above 15% (Tian and Zheng, 2000). However, no such limitation was detected for 110° fan angle nozzles with sprayer speeds up to 16 km hr^{-1}. In further research, the 25% duty cycle paired with an 80° fan angle nozzle resulted in an extremely non-uniform spray pattern parallel to the sprayer direction of travel (65% CV) and losses in weed control of up to 35% were noted (Pierce and Ayers, 2001). Therefore, proper nozzle selection (specifically, fan angle and orifice size) paired with appropriate sprayer speeds (to maintain an appropriate duty cycle) is critical to achieving an optimized PWM sprayer application. Overall, PWM sprayers provide an opportunity for increased application precision; however best use practices need to be identified for applicators to effectively utilize the technology.

Objectives

The optimization of pesticide applications is necessary in today's agricultural setting to reduce environmental contamination potential and increase efficacy on the intended target. PWM sprayers allow for several confounding application factors, such as pressure and flow rate, to become independent from sprayer speed, thereby providing a more homogenous spray cloud and increasing application precision compared to a conventional sprayer. The increasing popularity of PWM sprayers and the continual development of new application technologies has led to the need for the identification of best use PWM practices. Therefore, the laboratory objectives of this research were: (1) to identify the influence of current nozzle technology (venturi vs. non-venturi nozzles), application pressure, and PWM duty cycle on droplet size, droplet exit velocity, nozzle tip pressure, and spray pattern uniformity, and (2) to create best use PWM recommendations to optimize pesticide applications from these sprayers.

Additionally, an increasing need for site-specific weed management has been established (Tian et al., 1999; Wilkerson et al., 2004), and PWM sprayers could provide a unique opportunity for use in site-specific management scenarios by mitigating droplet size variation within an application (GopalaPillai et al., 1999). The need for field studies to evaluate droplet size efficacy was also previously noted as discrepancies between laboratory and field results were observed (Ebert et al., 1999). Utilizing the best use PWM practices previously identified in the laboratory objectives, the field research objectives included: (1) investigating the effect of spray droplet size and carrier volume on the efficacy of dicamba and glufosinate herbicides, (2) investigate the spray droplet size effect on 2,4-D choline plus glyphosate pre-mixture and dicamba plus glyphosate tank-mixture herbicide solutions, (3) determine the plausibility of using PWM sprayers in site-specific weed management strategies, and (4) create new weed management recommendations based on an optimum droplet size to achieve a high level of weed control while simultaneously mitigating particle drift potential. As a result of this research, applicators will more effectively utilize drift reduction technologies and PWM sprayers, reduce herbicide inputs, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

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CHAPTER 2

DROPLET SIZE AND NOZZLE TIP PRESSURE FROM A PULSE-WIDTH MODULATION SPRAYER

Abstract

Pulse-width modulation (PWM) sprayers can improve application accuracy through flow control, turn compensation, and high-resolution overlap control by pulsing an electronically-actuated solenoid valve and controlling the relative proportion of time each solenoid valve is open (duty cycle). The objective of this experiment was to identify the droplet size distribution and nozzle tip pressure when influenced by PWM duty cycle, nozzle technology, and gauge pressure to provide PWM guidelines. The experiment was conducted in a low-speed wind tunnel at the Pesticide Application Technology Laboratory using a SharpShooter® PWM system. In general, for non-venturi nozzles, as duty cycle decreased, droplet size slightly increased between 40% to 100% duty cycles. Conversely, venturi nozzles did not always follow this trend. The lowest duty cycle evaluated (20%) negatively impacted droplet size and caused inconsistencies for all nozzle by pressure combinations. The addition of a solenoid valve lowered nozzle tip pressure while gauge pressure remained constant indicating a restriction is present within the solenoid valve. Greater orifice sizes increased the pressure loss observed. Duty cycle minimally impacted nozzle tip pressure trends which were similar to the electrical square wave PWM signals. However, venturi nozzles deviated from this trend, specifically twin-fan, single pre-orifice venturi nozzles. In conclusion, venturi nozzles are not

recommended for PWM systems as they may lead to inconsistent applications, specifically in regards to droplet size generation and nozzle tip pressures. Spray pressures of 276 kPa or greater and PWM duty cycles of 40% or greater are recommended to ensure proper PWM operation.

Introduction

Pesticide input costs have increased in the U.S. by $5.35 billion over the past decade with weed management comprising the largest portion of these applications as greater than 92% of corn, soybean, and cotton hectares were treated for weeds in 2015 (USDA-NASS, 2015). The complexity of pesticide applications (Ebert et al., 1999) has led to reports of inaccurate and inefficient sprayer performance (Bish and Bradley, 2017; Grisso et al., 1989; Ozkan, 1987). In current production agricultural systems, this is unacceptable. More precise and efficacious pesticide applications are necessary to meet regulatory demands, increase crop yield potential, and reduce the selection pressure for the evolution of herbicide resistance.

Agricultural pesticides are typically applied in a spray solution atomized by hydraulic nozzles creating a heterogeneous mixture of droplet sizes within the spray pattern (Matthews et al., 2014). The resulting spray droplet sizes are determined by numerous factors and the complex interactions between them such as spray solution chemistry (Bouse et al., 1990; Butler Ellis et al., 1997; Chapple et al., 1993), nozzle orifice size (Barnett and Matthews, 1992; Nuyttens et al., 2009, 2007), nozzle design technology (Bouse, 1994; Butler Ellis et al., 2002; Nuyttens et al., 2009, 2007), and application pressure (Barnett and Matthews, 1992; Bouse, 1994; Nuyttens et al., 2007;

Young, 1990). Creech et al., (2015) determined nozzle design and application pressure caused the greatest changes in spray droplet size. Previous research highlighted the importance of droplet size on drift mitigation (Bueno et al., 2017; Hewitt, 1997; Johnson et al., 2006) and herbicide efficacy (Etheridge et al., 1999; Knoche, 1994; Meyer et al., 2016). Furthermore, homogenization of the droplet sizes represented within a spray pattern coupled with reduced droplet velocities could result in greater droplet adhesion to leaf surfaces and increase biological efficacy, while limiting drift potential (De Cock et al., 2017).

Pulse-width modulation (PWM) sprayers allow for several factors, including application pressure and spray droplet size, to be standardized across a range of sprayer speeds while variably controlling flow to increase application precision. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003) and PWM solenoid valves buffer some negative impacts, such as spray boom velocity variation during turning movements and flow on/off latency of automatic boom shutoffs, observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Application pressure based variable rate flow control devices have been shown to have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). Previous PWM research illustrated little to no effect from duty cycle on spray droplet size

(Giles et al., 1996; Giles and Comino, 1990); however, only non-venturi nozzles and nozzles lacking a pre-orifice were evaluated.

PWM sprayers provide the possibility for more precise applications through automatic boom and individual nozzle shut off controls (Luck et al., 2010a, 2010b) and minimizing changes in droplet trajectory and velocity (Butts et al., 2017; Giles, 2001; Giles and Ben-Salem, 1992). Furthermore, pulsing dual nozzle configurations increased coverage of Palmer amaranth (*Amaranthus palmeri* S. Wats.) while simultaneously minimizing the drift potential of small droplets (Womac et al., 2017, 2016). One drawback to PWM application systems has been the inability to create wide ranges of droplet distributions because venturi nozzles are not recommended (Capstan Ag Systems Inc., 2013). However, previous research demonstrated there are commercially available, non-venturi nozzles that can produce the range of droplet size distributions needed to reduce drift potential (Butts et al., 2015).

Current nozzle technologies and application parameters must be evaluated on PWM sprayers to determine best use practices for the equipment. The objective of this experiment was to identify the droplet size distribution and pressure at the nozzle tip as influenced by PWM duty cycle, current nozzle technology (venturi versus non-venturi), and gauge application pressure, and provide guidelines for optimal PWM use.

Materials and Methods

EXPERIMENTAL DESIGN

Research was conducted in the spring and summer of 2016 to evaluate the effect of nozzle type, PWM duty cycle, and gauge application pressure on droplet size distribution and nozzle tip pressure. The experiment was conducted using the low-speed wind tunnel at the Pesticide Application Technology Laboratory located at the West Central Research and Extension Center in North Platte, NE. Creech et al., (2015) and Henry et al., (2014) provide further details regarding the low-speed wind tunnel framework and operation. The wind tunnel was equipped with a SharpShooter® PWM system (Capstan Ag Systems, Inc., Topeka, KS) to select the specific duty cycle for each treatment.

The experiment was a 12 x 6 x 3 x 2 factorial cumulating in a total of 432 treatments, and each treatment was replicated three times (three separate nozzle traverses across the laser). The treatments consisted of 12 nozzle types, 6 PWM duty cycles, 3 gauge application pressures (pressure before the solenoid valve), and 2 spray solutions (Table 2.1). Droplet size and nozzle tip pressure of water were also measured for the 12 nozzle types at the 3 gauge application pressures in a standard nozzle body configuration (no solenoid valve). Glyphosate (Roundup PowerMAX®, Monsanto Co., St. Louis, MO 63167) plus ammonium sulfate (AMS) solution was applied at a carrier volume of 94 L ha^{-1} to assess whether an active ingredient within the spray solution would affect droplet size and nozzle tip pressure trends when pulsed compared to water alone. Reference nozzles were used to determine spray classifications (ASABE, 2009) and allow for comparisons between testing laboratories (Fritz et al., 2014b). Air temperature, solution temperature, and relative humidity were also recorded during the time periods the experiment was conducted.

DROPLET SIZE DISTRIBUTION COLLECTION

The droplet size distribution for each treatment was measured using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany). The laser was linked with WINDOX 5.7.0.0 software (Sympatec Inc.) operated on a computer adjacent to the laser. The R7 lens measures droplets in a dynamic size range from 18 to 3,500 µm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser, and a receiver housing containing the lens and detector element (Figure 2.1). The two laser housings are separated (1.2 m) on each side of the wind tunnel and mounted on an aluminum optical bench rail that was connected underneath the wind tunnel to maintain proper laser alignment. The laser was beamed through two 10-cm holes bored into the Plexiglass wind tunnel side wall. The spray plume was oriented perpendicular to the laser and traversed at 0.2 m s^{-1} using a mechanical linear actuator. The distance from the nozzle tip to the laser was 30 cm. The wind tunnel generated a 24 km h^{-1} airspeed in which measurements were recorded (Fritz et al., 2014a). The laser diffraction system provided multiple categories to compare the spray droplet distributions of each treatment. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet diameters such that 10, 50, and 90% of the spray volume was contained in droplets of smaller diameter, respectively. Furthermore, the percent of spray volume with droplets ≤ 150 µm (referred to as driftable fines throughout) were recorded for each treatment.

NOZZLE TIP PRESSURE DETERMINATION

The gauge application pressures of 207, 276, and 414 kPa were verified by a PX309, 5V, 0 – 689 kPa range pressure transducer (Omega Engineering, Inc., Stamford, CT) located 40 cm upstream from the solenoid valve and connected to a display monitor. The nozzle tip pressure was measured using a similar pressure transducer installed inline between the PWM solenoid valve and nozzle (Figure 2.2). The nozzle tip pressure transducer was powered by an 80W switching mode DC power supply (Extech Instruments, Nashua, NH) which was set to output 10V. These specific pressure transducers have a silicon sensor protected by a fluid filled stainless steel diaphragm that converts pressure to an analog electrical signal. The analog electrical signals were sampled at a 100 Hz rate for five seconds using an Arduino Mega 2560 board (open-source prototyping platform, Arduino.cc). The Arduino board converted the analog signals to digital and sent them to a serial monitor on a connected computer where the signals were transformed to pressure measurements (kPa).

STATISTICAL ANALYSES

Regression analysis was conducted on $D_{v0.5}$ values to allow for droplet size predictions as impacted by duty cycle within nozzle type and gauge application pressure and evaluate the variability across nozzle types when pulsed. Seventy different linear, nonlinear, and polynomial models were evaluated to determine best fit using CurveExpert Professional© (v. 2.6.5, Hyams Development). Droplet size parameters, driftable fines, and average nozzle tip pressure data were subjected to analysis of variance (ANOVA) using a mixed effect model in SAS (SAS v9.4, SAS Institute Inc., Cary, NC). Nozzle type, PWM duty cycle, gauge application pressure, and spray solution were treated as fixed effects. Means were separated using Fisher's Protected LSD Test with the Tukey adjustment to correct for multiplicity. A gamma distribution was used for analysis of droplet size parameters and nozzle tip pressures as data were bound between zero and positive infinity, and a beta distribution was used for analysis of driftable fines as data were bound between zero and one (Stroup, 2013). Backtransformed data are presented for clarity.

Results and Discussion

The environmental conditions within the Pesticide Application Technology Laboratory were maintained to be relatively constant. The average air temperature and relative humidity throughout the duration of this study was 25 C and 47%, respectively. The average solution temperature across treatments was 21 C. Previous literature suggested less than 5 C difference between air and solution temperatures to minimize variance in droplet size measurements (Hoffmann et al., 2011; Miller and Tuck, 2005).

The $D_{v0.5}$ regression over duty cycle analysis revealed that a polynomial regression model (Equation 2.1) was among the top fitting models across pressures and nozzles; therefore it was fit to all data. The degree of polynomial (first through fourth degrees) for each treatment was selected based on both the AICC and an F-test at α = 0.01.

$$D_{v0.5} = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_2 x^2 + a_1 x + a_0 \qquad [2.1]$$

Where:

$D_{v0.5}$ = droplet diameter such that 50% of the spray volume was contained in droplets of smaller diameter,

a_0 = y-intercept,

a_n = constant coefficients, and

x = duty cycle.

Across response variables, ANOVA resulted in a nozzle*duty cycle*gauge application pressure*solution interaction ($P < 0.0001$). Therefore, comparisons were reduced to strictly observe the effect of PWM duty cycle on droplet size ($D_{v0.1}$, $D_{v0.5}$, $D_{v0.9}$, and driftable fines) within a nozzle, gauge application pressure, and solution. Moreover, for nozzle tip pressure measurements, comparisons were reduced to specifically observe the effect of nozzle type within a solution, gauge application pressure, and PWM duty cycle. Relative trends across analyses were similar for the water and glyphosate plus AMS solutions; therefore, the water solution is strictly discussed within this manuscript, but glyphosate plus AMS data can be found in APPENDIX (A).

DROPLET SIZE

Venturi Nozzles

Polynomial regressions established for venturi nozzles (AITTJ-6011004, AM11002, AM11004, AMDF11004, AMDF11008, GAT11004, and TTI11004) to predict the effect of duty cycle on the $D_{v0.5}$ for each gauge pressure are presented in Figures 2.3 and 2.4. The 20% duty cycle caused severe deviations from observed droplet size trends across other duty cycle treatments (Figures 2.3 and 2.4) resulting in curved tails to the fit models. This duty cycle was determined as the cause of the required polynomial regression as opposed to linear models previously used in PWM droplet size research (Giles and Comino, 1990). It is highly recommended that applicators operate a PWM sprayer at 40% duty cycles or greater. The resulting model parameters and coefficient of determination (r^2) values are presented in Table 2.2. Generally, as duty cycle decreased, the droplet size increased across venturi nozzles within each gauge pressure. On average, as duty cycle decreased from 100 to 40%, models predicted an increase in droplet size of 0.90, 0.64, and 0.48 µm for every 1% duty cycle decrease for the 207, 276, and 414 kPa gauge pressures, respectively, across venturi nozzles. Although the r^2 values tended to decrease as gauge pressure increased, these results indicate increasing the operating pressure on PWM sprayers can buffer the effect of pulsing on droplet size.

The droplet size distributions and driftable fines of venturi nozzles as affected by pulsing are presented in Tables 2.3 through 2.6. Across duty cycles, the droplet size distributions from venturi nozzles followed the pattern (from smallest to greatest): AM11002 < GAT11004 < AMDF11004 < AM11004 < AMDF11008 < AITTJ-6011004 < TTI11004 (Tables 2.3 – 2.5). Driftable fines emitted from venturi nozzles were inversely proportional across duty cycles (Table 2.6). These droplet size patterns were expected according to the nozzle manufacturer’s catalogs. For reference, the spray classifications were Coarse, Coarse, Very Coarse, Very Coarse, Very Coarse, Extremely Coarse, and Ultra Coarse for the AM11002, GAT11004, AMDF11004, AM11004, AMDF11008, AITTJ-6011004, and TTI11004 nozzles, respectively, at 276 kPa.

The addition of the solenoid valve to the spray system had variable effects on the droplet size distributions from venturi nozzles. The AITTJ-6011004, AMDF11008, and TTI11004 had greater droplet sizes and reduced or equal driftable fines across gauge pressures when the solenoid valve was operated at a 100% duty cycle compared to the standard configuration (no solenoid valve equipped). This is likely due to an additional restriction or elongated flow path within dual-fan and deflector-type venturi nozzles compared to other nozzles resulting in reduced pressure at the nozzle exit. Previous research corroborates this theory as reductions in droplet velocity from these nozzles were observed when a solenoid valve was equipped and operated at a 100% duty cycle (Butts et al., 2017).

The $D_{v0.1}$, $D_{v0.9}$, and driftable fines from venturi nozzles followed similar trends as model predictions of the $D_{v0.5}$ previously discussed. Typically, as duty cycle decreased, the $D_{v0.1}$ and $D_{v0.9}$ increased, and the driftable fines decreased across venturi nozzles and within gauge pressures. The average increase in $D_{v0.1}$ and $D_{v0.9}$ was 5.6% and 6.7%, respectively, across venturi nozzles and within gauge pressures when duty cycle was decreased from 100% to 40%. The effect of pulsing caused complex fluctuations in the droplet diameters across gauge pressures and venturi nozzles as the $D_{v0.9}$ ranged from a decrease of 10.2% to an increase of 24.0% when duty cycle was reduced from 100% to 40%. The general trend would indicate particle drift potential would decrease slightly from a pulsing PWM sprayer operated with venturi nozzles; however, due to the extreme fluctuations of the droplet size distributions and driftable fines emitted from venturi nozzles across a range of duty cycles and gauge pressures, this conclusion cannot be drawn with any certainty. Greater variability within venturi nozzle droplet size distribution measurements compared to non-venturi nozzles was also noted in previous research (Etheridge et al., 1999; Miller and Butler Ellis, 2000). The variability resulted in negative effects on spray pattern (Ayers et al., 1990) and decreased weed control

(Etheridge et al., 2001). The unpredictable nature of droplet size distributions when affected by pulsing venturi nozzles is simply unacceptable for the optimization and homogenization of PWM sprays.

Non-venturi Nozzles

Polynomial regressions established for non-venturi nozzles (DR11004, ER11004, MR11004, SR11004, and UR11004) to predict the effect of duty cycle on the $D_{v0.5}$ for each gauge pressure are presented in Figure 2.4. The resulting model parameters and r^2 values are presented in Table 2.2. Similar to venturi nozzles, as duty cycle decreased, droplet size increased across non-venturi nozzles (Figure 2.4). The non-venturi nozzles required polynomial regressions, similar to the venturi nozzles, which may be an indication that more complex models are needed to appropriately fit droplet size data as affected by pulsing with current nozzle technologies, such as pre-orifice and venturi type nozzles, in contrast to conclusions from previous research using only non-venturi nozzles with no pre-orifice (Giles and Comino, 1990). On average, non-venturi models predicted an increase in $D_{v0.5}$ as duty cycle decreased from 100 to 40% with estimated increases in $D_{v0.5}$ of 0.68, 0.62, and 0.34 µm for every 1% decrease in duty cycle for 207, 276, and 414 kPa gauge pressures, respectively. These increases in droplet size were smaller than those caused by pulsing venturi nozzles; therefore, non-venturi nozzles stabilized the droplet size distributions more than venturi nozzles across a range of duty cycles and would be the preferred nozzle on PWM sprayers. Similar to venturi nozzles, although r^2 values decreased as gauge pressure increased, the increase in gauge pressure buffered the pulsing effect on droplet size, further validating PWM sprayers should be operated at greater gauge pressures (≥ 276 kPa) as much as drift mitigation efforts allow.

The $D_{v0.1}$, $D_{v0.5}$, $D_{0.9}$, and driftable fines emitted from non-venturi nozzles as affected by PWM duty cycle are presented in Tables 2.3 through 2.6. Across duty cycles, the droplet size distributions from non-venturi nozzles followed the pattern (from smallest to greatest): ER11004 < SR11004 < MR11004 < DR11004 < UR11004 (Tables 2.3 – 2.5). Driftable fines emitted from non-venturi nozzles followed the inverse pattern across duty cycles (Table 2.6). These trends were expected according to the nozzle manufacturer's catalog. For reference, the spray classifications were Medium, Medium, Coarse, Extremely Coarse, and Extremely Coarse for the ER11004, SR11004, MR11004, DR11004, and UR11004 nozzles, respectively, at 276 kPa. In previous PWM literature, only non-venturi nozzles with no pre-orifice were evaluated (Giles et al., 1996; Giles and Comino, 1990). For the non-venturi nozzles evaluated in this research, four out of five (SR11004, MR11004, DR11004, and UR11004) had pre-orifices, and little to no difference was observed in the droplet size trends when pulsed between the non-venturi nozzles with pre-orifices and the non-venturi nozzle without a pre-orifice (ER11004).

The addition of an inline solenoid valve caused a decrease in droplet size when operated at a 100% duty cycle compared to the standard configuration (no solenoid valve equipped) within gauge pressures and across most non-venturi nozzles. This result was peculiar as the nozzle tip pressure data, discussed in detail later in this manuscript, identified a decrease in pressure across the solenoid valve. Flow rates of non-venturi nozzles across gauge pressures were measured to determine if flow rates were increasing through a solenoid valve to explain the droplet size decrease (data not shown). The addition of a solenoid valve operated at a 100% duty cycle decreased flow rate by approximately 5% compared to the standard configuration, matching the nozzle tip pressure reductions observed from the addition of a solenoid valve (Table 2.7). Therefore, this does not explain the decrease in droplet size from non-venturi nozzles operated at a 100% duty cycle compared to a standard configuration and further research should be conducted to identify the underlying cause. Overall, the decrease in droplet size indicates PWM sprayers operating with non-venturi nozzles at high duty cycles increase spray drift potential slightly compared to conventional sprayers. However, this increase in spray drift potential is minimal, especially when compared to the drift potential increases observed from conventional sprayers implementing similar flow rate changes (Giles et al., 2003).

The $D_{v0.1}$ and $D_{0.9}$ generally increased as duty cycle decreased across non-venturi nozzles and gauge pressures similar to the model predictions for the $D_{v0.5}$. The $D_{v0.1}$ and $D_{v0.9}$ increased by an average of 6.0% and 9.6%, respectively, within gauge pressures and across non-venturi nozzles when the duty cycle was reduced from 100% to 40%. The non-venturi nozzle droplet size distributions fluctuated when pulsed, but not as great as the venturi nozzles, as the $D_{v0.9}$ values ranged from a decrease of 3.1% to an increase of 23.6% when the duty cycle was reduced from 100% to 40%. The driftable fines were reduced by 0.0 – 3.2 percentage points across non-venturi nozzles and within gauge pressures as the duty cycle decreased from 100% to 40% indicating the pulsing of PWM sprayers can reduce particle drift potential. Overall, droplet size distributions from non-venturi nozzles were more stable and homogenous when pulsed compared to venturi nozzles, and the addition of a pre-orifice had little to no impact on the droplet size trends observed across PWM duty cycles. Therefore, non-venturi nozzles with or without pre-orifices are recommended for use on PWM sprayers to stabilize droplet size distributions across a range of duty cycles, and a 40% duty cycle or greater should be utilized to optimize and homogenize PWM pesticide applications, especially for site-specific pest management strategies requiring an explicit droplet size.

NOZZLE TIP PRESSURE

Visual assessments of nozzle tip pressure patterns across duty cycles revealed minimal deviations from the square wave PWM electrical signal pattern due to gauge pressure changes. Nozzle tip pressure measurements over time at the 276 kPa gauge pressure are presented in Figures 2.5 and 2.6. They illustrate PWM duty cycles operating at the 10 Hz frequency and that nozzle tip pressures do not follow the square wave electrical signal pattern explicitly, especially across nozzle types (Figures 2.5 and 2.6). Some of the pressure measurement variability can be attributed to the single nozzle/spray solution supply line used for testing (Figure 2.1). Commercial systems buffer this effect by placing multiple solenoid valves, operating on alternate frequencies, on a similar supply line or boom section (Mangus et al., 2017). Nozzle tip pressure peaks and valleys emerged for venturi nozzles, excluding the AMDF11008 and TTI11004, compared to non-venturi nozzles. Additionally, the AITTJ-6011004 and GAT11004 venturi nozzles had severe deformities in nozzle tip pressure measurement patterns when pulsed. This is likely due to the nozzle design of each. The AITTJ-6011004 and GAT11004 have a single pre-orifice with dual fan exit orifices which is unique compared to other nozzles tested. Although these pressure fluctuation deformities did not influence droplet size to a great extent, spray pattern could be highly affected, and should be evaluated in future research.

The average nozzle tip pressure measurement trends across duty cycle were unaffected by gauge pressure (Table 2.7). Nozzle design and orifice size impacted the nozzle tip pressure measurements across gauge pressures and duty cycles. When the PWM duty cycle was reduced from 100% to a specific duty cycle, the average nozzle tip pressure reduction should have been equivalent to the duty cycle reduction (i.e. if the duty cycle were reduced from 100% to 50%, the average nozzle tip pressure at the 50% duty cycle should be half of the nozzle tip pressure at the 100% duty cycle). When nozzle orifice size decreased (AM11002), the percent change in average nozzle tip pressure was less than expected (54%) across gauge pressures if duty cycle was reduced by 60%. In contrast, when nozzle orifice size increased (AMDF11008), the percent change in average nozzle tip pressure was greater than expected (64%) across gauge pressures if duty cycle was reduced by 60%. The AITTJ-6011004 and GAT11004 nozzles again had larger disturbances in their nozzle tip pressure patterns compared to other nozzles. The percent change in average nozzle tip pressure for the AITTJ-6011004 and GAT11004 was greater than expected, 66% for both nozzles across gauge pressures, if duty cycle was reduced by 60%. Other nozzles tested had a percent change in average nozzle tip pressure of 60% across gauge pressures if duty cycle was reduced 60%.

Measurements further revealed a reduction in nozzle tip pressure as orifice size increased and when the dual fan, single pre-orifice venturi nozzles (AITTJ-6011004 and GAT11004) were equipped and operated at a 100% duty cycle compared to a standard configuration with no solenoid valve equipped (Figure 2.7). The AITTJ-6011004, AMDF11008, and GAT11004 had the lowest average nozzle tip pressures and the AM11002 had the greatest average nozzle tip pressure compared to other nozzles across gauge pressures when a solenoid valve was equipped. The greatest pressure reduction observed was for the AMDF11008 which had a loss in pressure of nearly 75 kPa. These pressure losses are likely created due to a restriction within the solenoid valve; therefore, maximum flow is restricted especially with greater orifice sizes (flow rates), and a low pressure area is created on the exit side of the solenoid. Commercial PWM systems adjust for this pressure loss with an increase in calculated duty cycle to maintain the appropriate output. However, applicators should make note of this pressure loss, as several negative impacts may arise from this finding: (1) the reduced pressure at the nozzle increases droplet size compared to what would be expected from the input gauge pressure, and reductions in biological efficacy may occur, especially in droplet size oriented site-specific pest management strategies; (2) if PWM sprayers were operated at low gauge pressures, the pressure loss may result in nozzles being operated below nozzle manufacturer's recommended pressure ranges; and (3) the reduced nozzle pressure may lead to incomplete pattern formation, especially when pulsed, resulting in reduced efficacy and inefficient applications.

Conclusions

The effectiveness of site-specific pest management strategies relies on two factors, (1) maximizing the biological effect, and (2) minimizing environmental contamination through off-target spray movement. Spray droplet size is a critical component to influence these two factors simultaneously. If spray droplet size is to be optimized and homogenized across a PWM application, the following best use practices should be followed:

1. PWM sprayers should be operated at or above a 40% duty cycle. Droplet size was severely affected and the pattern of change was inconsistent when pulsed at the 20% duty cycle tested in this research.
2. PWM sprayers should be operated at or above 276 kPa gauge pressure. This practice buffers the pulsing impact on droplet size and remains above nozzle manufacturers' recommended pressures due to the pressure loss across the solenoid valve.
3. Only non-venturi nozzles should be equipped and operated on PWM sprayers. These nozzle types, with and without pre-orifices, minimize variation in droplet size and nozzle tip pressure across duty cycles compared with venturi nozzles.

Applicators using a PWM sprayer should also acknowledge the pressure loss across the solenoid valve. The decreased pressure, especially for greater orifice size nozzles, could affect spray pattern and create coarser droplet sizes than desired for biological control. Further, as PWM duty cycle decreases, spray droplet size increases, thereby potentially impacting spray coverage and the resulting biological efficacy. Across non-venturi nozzles and gauge pressures, droplet size ($D_{v0.5}$) increased by approximately 0.55 µm for every 1% decrease in duty cycle. Spray solution changed the overall droplet sizes observed; however, the effect of pulsing had little to no impact on the droplet size trends observed across duty cycles for the solutions tested. Through these practices, applicators can increase the efficiency of PWM pesticide applications and reduce the risks of off-target spray particle movement by better understanding the complexities of spray applications.

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Tables

Table 2.1. Nozzles (12), pulse-width modulation duty cycles (7), gauge application pressures (3), and spray solutions (2) evaluated in a factorial arrangement of treatments in this research.

Broadcast nozzles			Duty cycle	Gauge pressure	Spray solution
Abbreviation	Name	Design			
			%	kPa	
AITTJ-6011004[a]	Air Induction Turbo TwinJet	Venturi	Standard[e]	207	Water Alone
AM11002[b]	Airmix	Venturi	100	276	Glyphosate (Roundup PowerMAX®) plus ammonium sulfate (AMS)
AM11004[b]	Airmix	Venturi	80	414	
AMDF11004[b]	Airmix DualFan	Venturi	60		
AMDF11008[b]	Airmix DualFan	Venturi	50		
GAT11004[c]	GuardianAIR Twin	Venturi	40		
TTI11004[a]	Turbo TeeJet Induction	Venturi	20		
DR11004[d]	Combo-Jet Drift Control	Non-Venturi			
ER11004[d]	Combo-Jet Extended Range	Non-Venturi			
MR11004[d]	Combo-Jet Mid Range	Non-Venturi			
SR11004[d]	Combo-Jet Small Reduction	Non-Venturi			
UR11004[d]	Combo-Jet Ultra Drift Control	Non-Venturi			

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Pentair Hypro SHURflo plc., Minneapolis, MN
[d] Wilger Industries Ltd., Lexington, TN
[e] Standard duty cycle indicates no solenoid valve is equipped.

Table 2.2. Polynomial regression parameters (*a*, *b*, *c*, *d*, *e*) and coefficient of determination (r^2) for droplet size ($D_{v0.5}$) regressed over duty cycle of water for each nozzle*pressure combination.

Nozzle	Gauge pressure	*a*	*b*	*c*	*d*	*e*	Coefficient of determination
	kPa			μm			r^2
AITTJ-6011004[a]	207	612.06	3.85	-0.06	2.11 E -04	–	0.96
AM11002[b]	207	552.89	-0.63	-0.03	2.07 E -04	–	0.99
AM11004[b]	207	803.43	-22.31	0.56	-5.47 E -03	1.85 E -05	0.86
AMDF11004[b]	207	777.85	-21.41	0.57	-5.81 E -03	2.02 E -05	0.94
AMDF11008[b]	207	506.68	7.70	-0.18	1.70 E -03	6.06 E -06	0.99
GAT11004[d]	207	608.88	-6.74	0.22	-2.66 E -03	1.05 E -05	0.97
TTI11004[a]	207	595.66	7.51	-0.05	–	–	0.94
DR11004[c]	207	446.70	11.17	-0.17	7.33 E -04	–	0.97
ER11004[c]	207	448.53	-9.13	0.21	-2.11 E -03	7.65 E -06	0.98
MR11004[c]	207	767.14	-21.60	0.56	-5.87 E -03	2.11 E -05	0.91
SR11004[c]	207	540.98	-9.65	0.24	-2.57 E -03	9.84 E -06	0.99
UR11004[c]	207	422.63	17.85	-0.23	9.12 E -04	–	0.86
AITTJ-6011004[a]	276	563.95	3.35	-0.05	2.18 E -04	–	0.97
AM11002[b]	276	503.11	-4.46	0.09	-8.49 E -04	3.00 E -06	0.99
AM11004[b]	276	747.43	-18.38	0.49	-5.06 E -03	1.77 E -05	0.89
AMDF11004[b]	276	665.57	-15.31	0.40	-4.07 E -03	1.39 E -05	0.96
AMDF11008[b]	276	522.78	2.55	-0.02	–	–	0.97
GAT11004[d]	276	476.70	2.41	-0.05	2.13 E -04	–	0.99
TTI11004[a]	276	642.98	15.78	-0.40	4.37 E -03	-1.74 E -05	0.98
DR11004[c]	276	624.47	-4.10	0.15	-1.96 E -03	7.96 E -06	0.94
ER11004[c]	276	475.18	-13.43	0.34	-3.50 E -03	1.26 E -05	0.89
MR11004[c]	276	715.79	-18.31	0.46	-4.65 E -03	1.62 E -05	0.96
SR11004[c]	276	487.27	-8.52	0.20	-2.03 E -03	7.46 E -06	0.97
UR11004[c]	276	550.55	15.30	-0.32	2.60 E -03	-7.28 E -06	0.96
AITTJ-6011004[a]	414	479.36	2.94	-0.05	2.07 E -04	–	0.99
AM11002[b]	414	419.10	-1.30	0.04	–	–	0.89
AM11004[b]	414	546.59	-9.56	0.23	-2.29 E -03	7.86 E -06	0.82
AMDF11004[b]	414	536.24	-10.51	0.26	-2.64 E -03	9.00 E -06	0.89
AMDF11008[b]	414	532.04	-2.62	0.04	-2.36 E -04	–	0.98
GAT11004[d]	414	445.16	-6.41	0.19	-2.16 E -03	7.89 E -06	0.90
TTI11004[a]	414	401.07	18.21	-0.40	3.79 E -03	-1.30 E -05	0.95
DR11004[c]	414	654.99	-12.86	0.34	-3.60 E -03	1.32 E -05	0.74
ER11004[c]	414	321.09	-5.54	0.14	-1.48 E -03	5.45 E -06	0.89
MR11004[c]	414	516.55	-8.66	0.22	-2.36 E -03	8.83 E -06	0.89
SR11004[c]	414	385.76	-6.06	0.15	-1.61 E -03	5.93 E -06	0.88
UR11004[c]	414	759.89	-2.48	0.01	–	–	0.25

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN

Table 2.3. Droplet size data such that 10% of the spray volume is contained in droplets of lesser diameter ($D_{v0.1}$) for water impacted by duty cycle for nozzle and pressure combinations.

		$D_{v0.1}$						
	Gauge	Duty cycle (%)[e]						
Nozzle	pressure	20	40	50	60	80	100	Standard
	kPa	μm						
AITTJ-6011004[a]	207	360 a	359 a	356 a	359 a	340 b	325 c	313 d
AM11002[b]	207	244 a	240 b	234 c	224 d	212 f	203 g	217 e
AM11004[b]	207	261 b	248 e	245 f	258 c	264 a	251 d	263 ab
AMDF11004[b]	207	260 a	248 cd	256 b	259 a	256 b	246 d	249 c
AMDF11008[b]	207	305 b	308 a	306 b	302 c	299 d	289 e	275 f
GAT11004[d]	207	268 a	271 a	270 a	268 a	260 b	234 d	244 c
TTI11004[a]	207	397 e	442 c	439 c	459 a	452 b	449 b	427 d
DR11004[c]	207	309 c	331 a	330 a	329 a	323 b	309 c	330 a
ER11004[c]	207	138 a	128 c	127 c	126 cd	124 d	119 e	132 b
MR11004[c]	207	241 b	230 d	233 cd	236 c	234 c	215 e	247 a
SR11004[c]	207	185 a	174 b	174 b	169 c	166 d	158 e	186 a
UR11004[c]	207	374 f	427 c	446 a	427 c	435 b	419 e	422 d
AITTJ-6011004[a]	276	315 b	318 a	313 b	311 b	297 c	287 d	277 e
AM11002[b]	276	205 a	200 b	197 c	196 d	192 e	187 f	191 e
AM11004[b]	276	255 a	241 d	247 c	250 b	241 d	236 e	230 f
AMDF11004[b]	276	232 a	225 d	226 cd	229 ab	229 bc	218 e	217 e
AMDF11008[b]	276	282 b	280 b	289 a	284 b	280 b	266 c	241 d
GAT11004[d]	276	253 a	253 a	250 b	247 b	233 c	214 d	213 d
TTI11004[a]	276	432 c	443 a	438 b	440 ab	441 ab	429 c	371 d
DR11004[c]	276	297 ab	292 bc	298 a	293 abc	289 c	278 d	293 abc
ER11004[c]	276	129 a	120 b	116 c	128 a	116 c	111 d	120 b
MR11004[c]	276	236 a	220 b	220 b	222 b	215 c	205 e	212 d
SR11004[c]	276	164 a	156 b	152 c	153 c	148 d	143 e	162 a
UR11004[c]	276	397 c	407 a	400 b	392 d	386 e	377 f	387 e
AITTJ-6011004[a]	414	259 a	258 a	258 a	253 b	241 c	231 d	225 e
AM11002[b]	414	168 a	160 c	165 b	160 cd	155 e	150 f	159 d
AM11004[b]	414	194 a	185 cd	184 d	185 cd	188 bc	182 d	191 ab
AMDF11004[b]	414	190 a	183 b	182 bc	180 cd	181 bc	172 e	177 d
AMDF11008[b]	414	231 a	220 b	217 c	216 c	214 c	208 d	198 e
GAT11004[d]	414	178 d	186 b	190 a	193 a	185 b	182 c	174 e
TTI11004[a]	414	310 d	326 a	322 ab	316 cd	319 bc	314 cd	303 e
DR11004[c]	414	243 b	233 d	237 c	234 d	236 c	228 e	259 a
ER11004[c]	414	101 b	97 de	100 bc	98 cd	97 de	96 e	104 a
MR11004[c]	414	188 a	179 b	178 b	176 c	174 c	167 d	189 a
SR11004[c]	414	130 b	127 bc	127 bc	128 bc	125 cd	122 d	137 a
UR11004[c]	414	350 b	361 a	320 f	318 f	335 d	326 e	342 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 2.4. Droplet size data such that 50% of the spray volume is contained in droplets of lesser diameter ($D_{v0.5}$) for water impacted by duty cycle for nozzle and pressure combinations.

		$D_{v0.5}$						
	Gauge	Duty cycle (%)[e]						
Nozzle	pressure	20	40	50	60	80	100	Standard
	kPa	μm						
AITTJ-6011004[a]	207	669 c	688 a	679 b	689 a	661 d	627 e	609 f
AM11002[b]	207	531 a	494 b	478 c	455 d	427 e	409 g	423 f
AM11004[b]	207	538 a	505 f	498 g	529 c	535 b	509 e	512 d
AMDF11004[b]	207	533 b	499 d	525 c	538 a	527 c	499 d	489 e
AMDF11008[b]	207	601 d	623 a	619 b	610 c	602 d	579 e	536 f
GAT11004[d]	207	540 ab	543 a	541 ab	534 b	517 c	465 d	465 d
TTI11004[a]	207	719 f	838 d	837 d	892 a	882 b	868 c	819 e
DR11004[c]	207	608 f	677 a	673 a	667 b	646 c	615 e	636 d
ER11004[c]	207	334 a	300 b	296 bc	294 c	280 d	268 e	283 d
MR11004[c]	207	515 a	484 cd	480 d	495 b	490 bc	450 e	478 d
SR11004[c]	207	423 a	394 b	390 c	383 d	369 e	351 f	384 d
UR11004[c]	207	691 g	822 c	883 a	814 d	838 b	801 e	792 f
AITTJ-6011004[a]	276	611 c	626 a	615 bc	620 b	591 d	567 e	551 f
AM11002[b]	276	442 a	419 b	410 c	406 d	396 e	383 f	384 f
AM11004[b]	276	538 a	499 d	526 b	538 a	504 c	482 e	462 f
AMDF11004[b]	276	489 a	464 c	480 b	488 a	481 b	454 d	437 e
AMDF11008[b]	276	567 c	584 b	595 a	582 b	579 b	546 d	484 e
GAT11004[d]	276	507 a	505 a	496 b	490 c	460 d	426 e	413 f
TTI11004[a]	276	829 d	877 a	864 b	862 b	882 a	851 c	732 e
DR11004[c]	276	588 bc	583 cd	605 a	599 ab	589 bc	561 e	574 de
ER11004[c]	276	315 a	286 c	274 d	296 b	268 e	251 g	262 f
MR11004[c]	276	498 a	460 c	458 c	477 b	457 c	431 d	428 d
SR11004[c]	276	380 a	353 b	344 c	343 c	335 d	321 e	344 c
UR11004[c]	276	746 e	800 a	787 b	772 c	755 d	732 g	739 f
AITTJ-6011004[a]	414	520 b	530 a	527 a	520 b	502 c	479 d	470 e
AM11002[b]	414	394 a	365 c	381 b	357 d	340 e	326 g	331 f
AM11004[b]	414	431 a	408 c	414 b	406 c	416 b	396 d	399 d
AMDF11004[b]	414	411 a	393 c	395 bc	391 c	400 b	371 d	366 d
AMDF11008[b]	414	494 a	482 b	474 c	474 c	473 c	453 d	415 e
GAT11004[d]	414	378 bc	377 c	383 b	396 a	377 c	361 d	352 e
TTI11004[a]	414	631 d	696 a	689 ab	684 b	683 b	666 c	620 e
DR11004[c]	414	506 b	485 d	501 c	487 d	501 c	480 e	518 a
ER11004[c]	414	255 a	240 c	244 b	237 d	236 d	224 e	235 d
MR11004[c]	414	413 a	391 c	397 b	383 d	384 d	364 e	389 c
SR11004[c]	414	313 a	298 b	299 b	298 b	292 c	284 d	297 bc
UR11004[c]	414	703 b	747 a	633 e	627 e	681 c	658 d	666 d

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 2.5. Droplet size data such that 90% of the spray volume is contained in droplets of lesser diameter ($D_{v0.9}$) for water impacted by duty cycle for nozzle and pressure combinations.

Nozzle	Gauge pressure	$D_{v0.9}$ Duty cycle (%)[e] 20	40	50	60	80	100	Standard
	kPa	µm						
AITTJ-6011004[a]	207	948 d	997 bc	989 c	1033 a	1003 b	952 d	931 e
AM11002[b]	207	855 a	789 b	734 c	699 d	645 e	600 f	631 e
AM11004[b]	207	808 b	764 d	754 e	832 a	831 a	802 b	788 c
AMDF11004[b]	207	821 d	744 g	841 c	898 a	861 b	796 e	781 f
AMDF11008[b]	207	841 f	983 a	975 b	962 c	949 d	889 e	818 g
GAT11004[d]	207	828 b	852 a	853 a	831 b	829 b	713 c	704 c
TTI11004[a]	207	968 e	1168 d	1164 d	1312 a	1306 a	1287 b	1199 c
DR11004[c]	207	865 e	1043 a	1044 a	1032 a	988 b	945 d	967 c
ER11004[c]	207	631 a	562 b	550 b	536 c	470 d	452 e	466 d
MR11004[c]	207	819 a	746 cd	762 bc	789 ab	790 ab	707 e	726 de
SR11004[c]	207	718 a	665 b	667 b	639 c	588 e	561 f	616 d
UR11004[c]	207	954 g	1172 d	1356 a	1151 e	1254 b	1195 c	1136 f
AITTJ-6011004[a]	276	895 d	937 b	919 c	972 a	933 b	880 e	852 f
AM11002[b]	276	712 a	691 b	672 c	659 d	620 e	590 f	588 f
AM11004[b]	276	857 b	779 d	850 b	931 a	821 c	750 e	713 f
AMDF11004[b]	276	798 c	743 d	788 c	835 a	817 b	747 d	708 e
AMDF11008[b]	276	852 d	954 b	956 b	937 c	978 a	861 d	781 e
GAT11004[d]	276	808 a	823 a	805 a	806 a	737 b	672 c	659 c
TTI11004[a]	276	1233 d	1303 b	1285 c	1276 c	1344 a	1281 c	1099 e
DR11004[c]	276	887 b	887 b	960 a	971 a	943 a	864 b	876 b
ER11004[c]	276	612 a	554 b	503 c	551 b	466 d	423 f	438 e
MR11004[c]	276	810 a	724 c	737 bc	793 a	755 b	689 d	670 e
SR11004[c]	276	667 a	595 b	580 c	573 d	557 f	531 g	563 e
UR11004[c]	276	1084 e	1203 a	1176 b	1149 c	1112 d	1082 e	1084 e
AITTJ-6011004[a]	414	790 d	842 a	838 ab	832 bc	823 c	775 e	778 e
AM11002[b]	414	688 b	645 c	715 a	605 d	559 e	527 f	525 f
AM11004[b]	414	718 a	682 bc	695 b	671 c	712 a	653 d	646 d
AMDF11004[b]	414	685 a	649 bc	658 b	638 c	698 a	585 e	605 d
AMDF11008[b]	414	803 b	821 a	800 b	801 b	795 b	760 c	683 d
GAT11004[d]	414	614 b	597 c	598 c	668 a	618 b	578 d	571 d
TTI11004[a]	414	939 c	1089 a	1066 a	1063 a	1067 a	1018 b	997 b
DR11004[c]	414	801 b	752 d	803 b	773 c	829 a	775 c	816 ab
ER11004[c]	414	505 a	457 b	502 a	445 c	421 d	398 e	407 e
MR11004[c]	414	689 a	655 bc	666 b	630 d	639 cd	584 e	625 d
SR11004[c]	414	571 a	524 b	538 b	536 b	501 c	475 d	482 d
UR11004[c]	414	992 c	1176 a	924 d	911 d	1046 b	1007 c	1006 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 2.6. Percent of spray volume less than 150 µm (driftable fines) for water as impacted by duty cycle for each nozzle and pressure combination.

		Driftable fines						
	Gauge	Duty cycle (%)[e]						
Nozzle	pressure	20	40	50	60	80	100	Standard
	kPa	%						
AITTJ-6011004[a]	207	0.09 c	0.54 b	0.56 b	0.55 b	0.63 b	0.71 ab	0.87 a
AM11002[b]	207	2.90 d	2.62 f	2.78 e	3.33 c	3.97 b	4.46 a	3.23 c
AM11004[b]	207	2.27 b	2.55 a	2.60 a	2.16 c	1.97 d	2.33 b	1.79 e
AMDF11004[b]	207	2.12 b	2.32 ab	2.17 b	2.11 b	2.15 b	2.52 a	2.13 b
AMDF11008[b]	207	1.34 c	1.18 e	1.21 e	1.27 d	1.31 cd	1.43 b	1.48 a
GAT11004[d]	207	1.66 c	1.80 c	1.74 c	1.79 c	1.94 bc	2.91 a	2.16 b
TTI11004[a]	207	0.15 b	0.33 ab	0.34 a	0.23 ab	0.24 ab	0.25 ab	0.27 ab
DR11004[c]	207	1.45 a	1.11 c	1.07 c	1.06 c	1.13 c	1.31 b	0.77 d
ER11004[c]	207	11.78 e	14.03 cd	14.36 c	14.45 bc	15.17 b	16.60 a	13.56 d
MR11004[c]	207	3.16 bc	3.44 b	2.98 c	3.12 bc	3.27 bc	4.11 a	2.24 d
SR11004[c]	207	6.18 e	7.14 d	7.01 d	7.55 c	7.92 b	8.90 a	5.60 f
UR11004[c]	207	0.73 a	0.52 b	0.37 d	0.50 b	0.39 d	0.45 c	0.30 e
AITTJ-6011004[a]	276	0.74 f	0.86 e	0.92 de	0.97 d	1.12 c	1.21 b	1.36 a
AM11002[b]	276	4.49 d	4.51 d	4.72 c	4.77 c	5.03 b	5.52 a	5.08 b
AM11004[b]	276	2.09 e	2.61 d	2.70 cd	2.61 d	2.78 bc	2.88 ab	2.92 a
AMDF11004[b]	276	2.90 e	3.12 d	3.32 bc	3.18 cd	3.20 cd	3.72 a	3.39 b
AMDF11008[b]	276	1.45 d	1.73 c	1.53 d	1.63 c	1.70 c	1.97 b	2.36 a
GAT11004[d]	276	1.94 f	2.08 e	2.15 de	2.21 d	2.60 c	3.79 a	3.49 b
TTI11004[a]	276	0.01 d	0.25 c	0.25 c	0.25 c	0.25 c	0.29 b	0.48 a
DR11004[c]	276	1.32 d	1.51 c	1.52 c	1.61 b	1.65 b	1.81 a	1.28 d
ER11004[c]	276	13.67 d	16.09 c	17.32 b	14.26 d	17.28 b	19.32 a	16.90 bc
MR11004[c]	276	2.90 e	3.49 d	3.47 d	3.78 c	4.14 b	4.65 a	3.90 c
SR11004[c]	276	8.11 e	9.09 d	9.63 c	9.58 c	10.21 b	11.05 a	8.15 e
UR11004[c]	276	0.01 f	0.49 d	0.52 c	0.55 b	0.57 b	0.64 a	0.44 e
AITTJ-6011004[a]	414	1.66 f	1.90 e	1.91 e	2.04 d	2.34 c	2.71 b	3.03 a
AM11002[b]	414	7.62 e	8.48 c	7.89 d	8.52 c	9.14 b	9.93 a	8.50 c
AM11004[b]	414	5.07 c	5.86 ab	6.14 a	5.90 ab	5.72 b	6.18 a	5.22 c
AMDF11004[b]	414	5.35 d	5.89 c	6.10 bc	6.40 b	6.33 bc	7.03 a	6.43 b
AMDF11008[b]	414	3.18 f	3.75 e	3.92 de	3.95 cd	4.13 c	4.38 b	4.75 a
GAT11004[d]	414	6.45 a	5.31 c	4.97 d	4.96 d	5.54 bc	5.78 b	6.55 a
TTI11004[a]	414	0.81 c	0.92 bc	0.95 abc	0.95 abc	0.94 abc	1.04 ab	1.08 a
DR11004[c]	414	2.64 d	2.94 c	3.08 b	2.98 bc	3.09 b	3.41 a	1.95 e
ER11004[c]	414	21.72 d	23.82 b	22.93 c	23.86 b	24.25 b	25.58 a	22.22 d
MR11004[c]	414	5.75 d	6.52 c	6.71 c	6.79 bc	7.02 b	7.76 a	5.34 e
SR11004[c]	414	13.35 bc	14.15 b	14.26 ab	13.93 b	14.58 ab	15.42 a	12.17 c
UR11004[c]	414	1.06 ab	0.86 bc	1.05 ab	1.05 ab	1.04 ab	1.14 a	0.70 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 2.7. Average nozzle tip pressure over five seconds for water as impacted by nozzle for each gauge pressure and duty cycle combination.

		Average nozzle tip pressure						
	Gauge	Duty cycle (%)[e]						
Nozzle	pressure	20	40	50	60	80	100	Standard
		kPa						
AITTJ-6011004[a]	207	36 bc	67 bc	83 bc	95 cd	137 d	194 i	210 b
AM11002[b]	207	58 a	106 a	127 a	148 a	196 a	216 a	213 a
AM11004[b]	207	39 b	78 ab	99 ab	118 abc	172 bc	202 f	204 g
AMDF11004[b]	207	39 b	77 b	95 b	114 bc	152 cd	199 g	207 e
AMDF11008[b]	207	27 c	55 c	70 c	86 d	117 e	164 j	197 i
GAT11004[d]	207	35 bc	70 bc	86 bc	103 bcd	157 bc	196 h	209 c
TTI11004[a]	207	41 ab	81 ab	100 ab	118 abc	160 bc	203 f	208 d
DR11004[c]	207	41 ab	80 ab	98 ab	116 abc	161 bc	205 d	207 e
ER11004[c]	207	41 ab	80 ab	97 ab	122 ab	175 ab	206 c	205 f
MR11004[c]	207	42 ab	81 ab	98 ab	121 ab	166 bc	207 b	208 d
SR11004[c]	207	40 b	77 b	96 b	119 abc	157 bc	204 e	203 h
UR11004[c]	207	40 b	79 ab	98 ab	115 bc	163 b	204 e	208 d
AITTJ-6011004[a]	276	47 bcd	88 bc	107 bcd	138 bcd	197 bc	260 g	279 b
AM11002[b]	276	66 a	121 a	149 a	178 a	235 a	276 a	277 c
AM11004[b]	276	56 abc	103 abc	130 abc	147 abc	202 b	256 i	274 f
AMDF11004[b]	276	65 ab	110 ab	137 ab	164 ab	222 ab	273 b	279 b
AMDF11008[b]	276	39 d	78 c	94 d	111 d	153 d	208 j	268 g
GAT11004[d]	276	46 cd	85 bc	104 cd	122 cd	175 c	258 h	277 c
TTI11004[a]	276	57 abc	108 ab	134 abc	160 ab	220 ab	265 d	276 de
DR11004[c]	276	55 abc	104 abc	128 abc	158 ab	209 ab	266 c	283 a
ER11004[c]	276	55 abc	107 ab	134 abc	162 ab	222 ab	261 f	275 ef
MR11004[c]	276	55 abc	107 ab	133 abc	159 ab	222 ab	266 c	283 a
SR11004[c]	276	51 abcd	104 abc	130 abc	156 ab	206 b	265 d	276 d
UR11004[c]	276	54 abcd	106 ab	129 abc	151 abc	211 ab	264 e	278 b
AITTJ-6011004[a]	414	69 bc	132 b	160 bc	202 bc	293 b	392 i	409 f
AM11002[b]	414	105 a	189 a	231 a	278 a	368 a	427 a	418 b
AM11004[b]	414	81 ab	158 ab	196 ab	235 abc	315 ab	400 f	419 a
AMDF11004[b]	414	81 ab	158 ab	196 ab	236 abc	317 ab	399 g	419 a
AMDF11008[b]	414	55 c	121 b	143 c	184 c	246 c	337 j	409 f
GAT11004[d]	414	63 bc	127 b	160 bc	201 bc	292 b	400 fg	409 f
TTI11004[a]	414	81 ab	160 ab	199 ab	240 abc	319 ab	404 d	418 b
DR11004[c]	414	82 ab	161 ab	199 ab	240 abc	320 ab	405 c	416 c
ER11004[c]	414	80 abc	158 ab	196 ab	234 abc	311 b	402 e	411 e
MR11004[c]	414	84 ab	162 ab	203 ab	242 ab	326 ab	410 b	418 b
SR11004[c]	414	79 abc	156 ab	192 abc	232 abc	309 b	398 h	413 d
UR11004[c]	414	82 ab	161 ab	199 ab	236 abc	323 ab	405 c	416 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and duty cycle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Figures

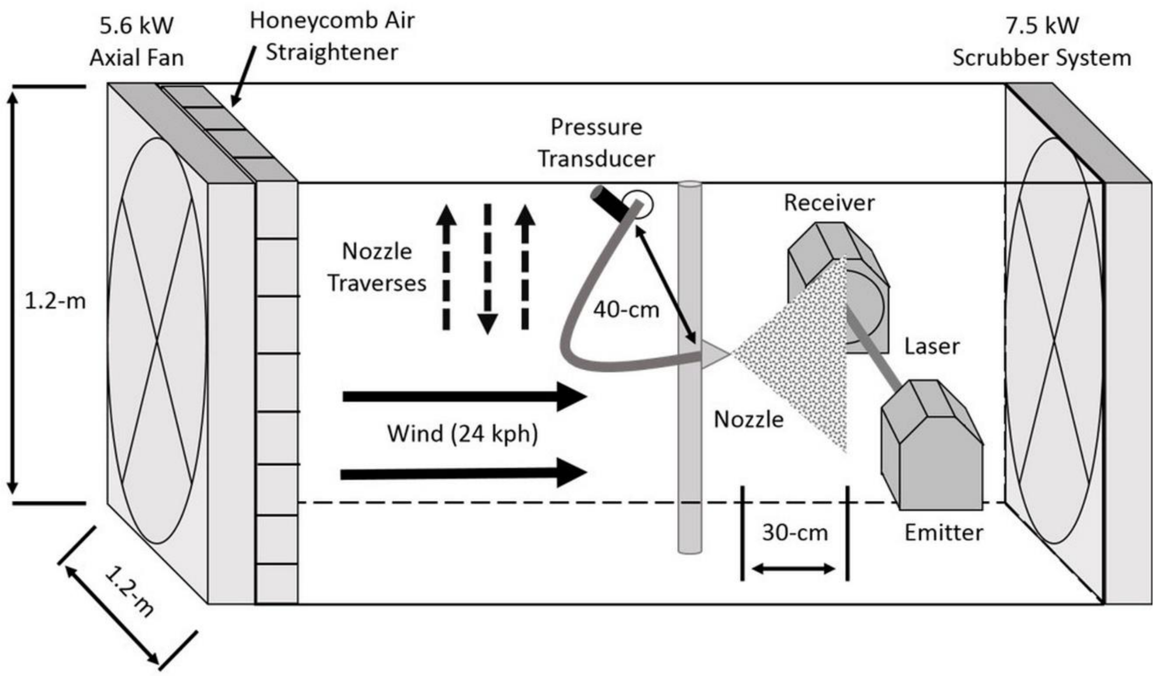

Figure 2.1. Illustration of the low-speed wind tunnel and laser diffraction system used for droplet spectrum analysis at the University of Nebraska-Lincoln Pesticide Application Technology Laboratory located in North Platte, NE.

Figure 2.2. Nozzle body and pressure transducer assembly used to measure nozzle tip pressures after the pulse-width modulation solenoid valve. Another pressure transducer was connected inline 40-cm upstream from this assembly to provide gauge application pressure.

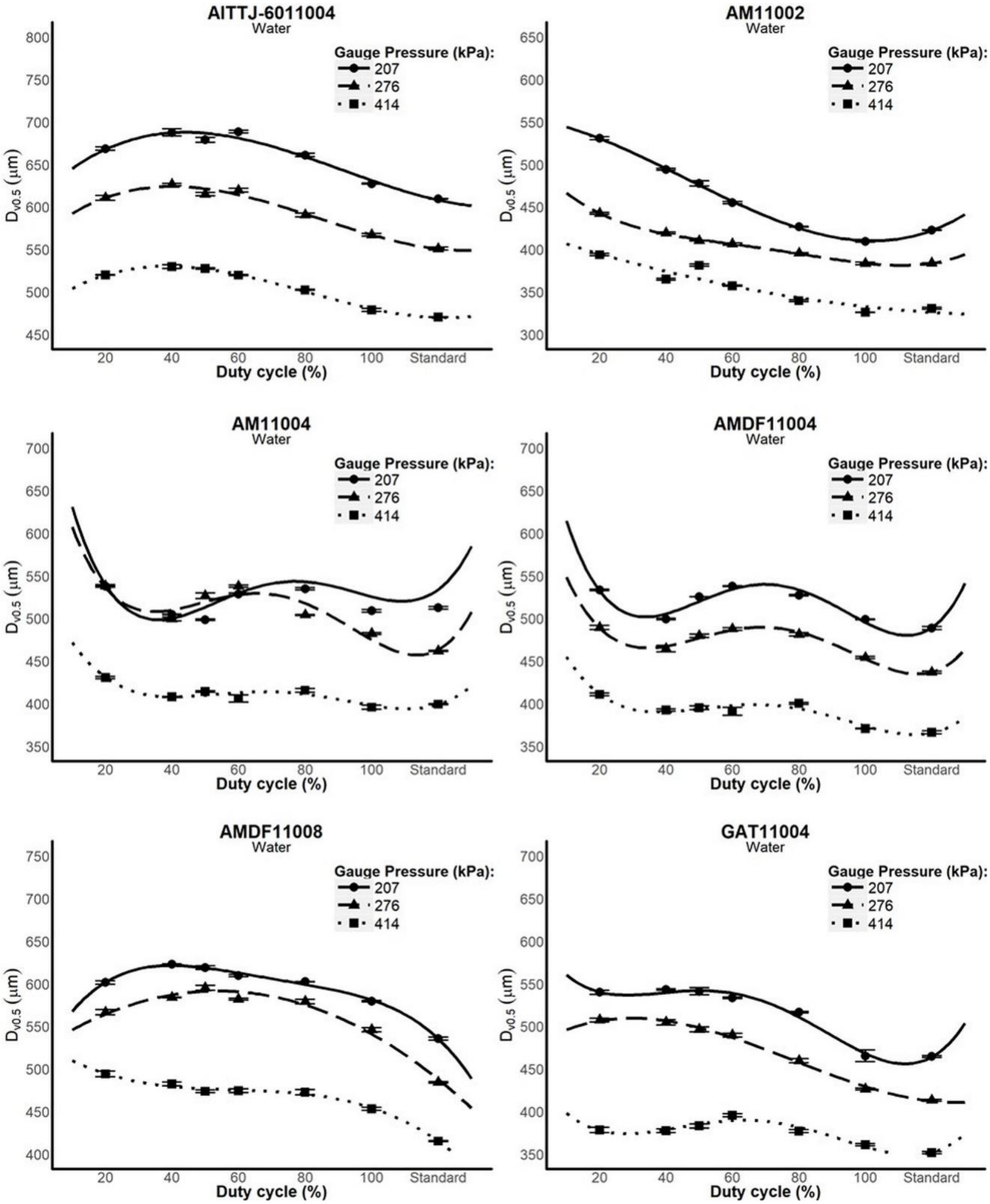

Figure 2.3. Polynomial regressions of droplet size data ($D_{v0.5}$) of water as influenced by duty cycle for the AITTJ-6011004 (top left), AM11002 (top right), AM11004 (middle left), AMDF11004 (middle right), AMDF11008 (bottom left), and GAT11004 (bottom right) nozzles.

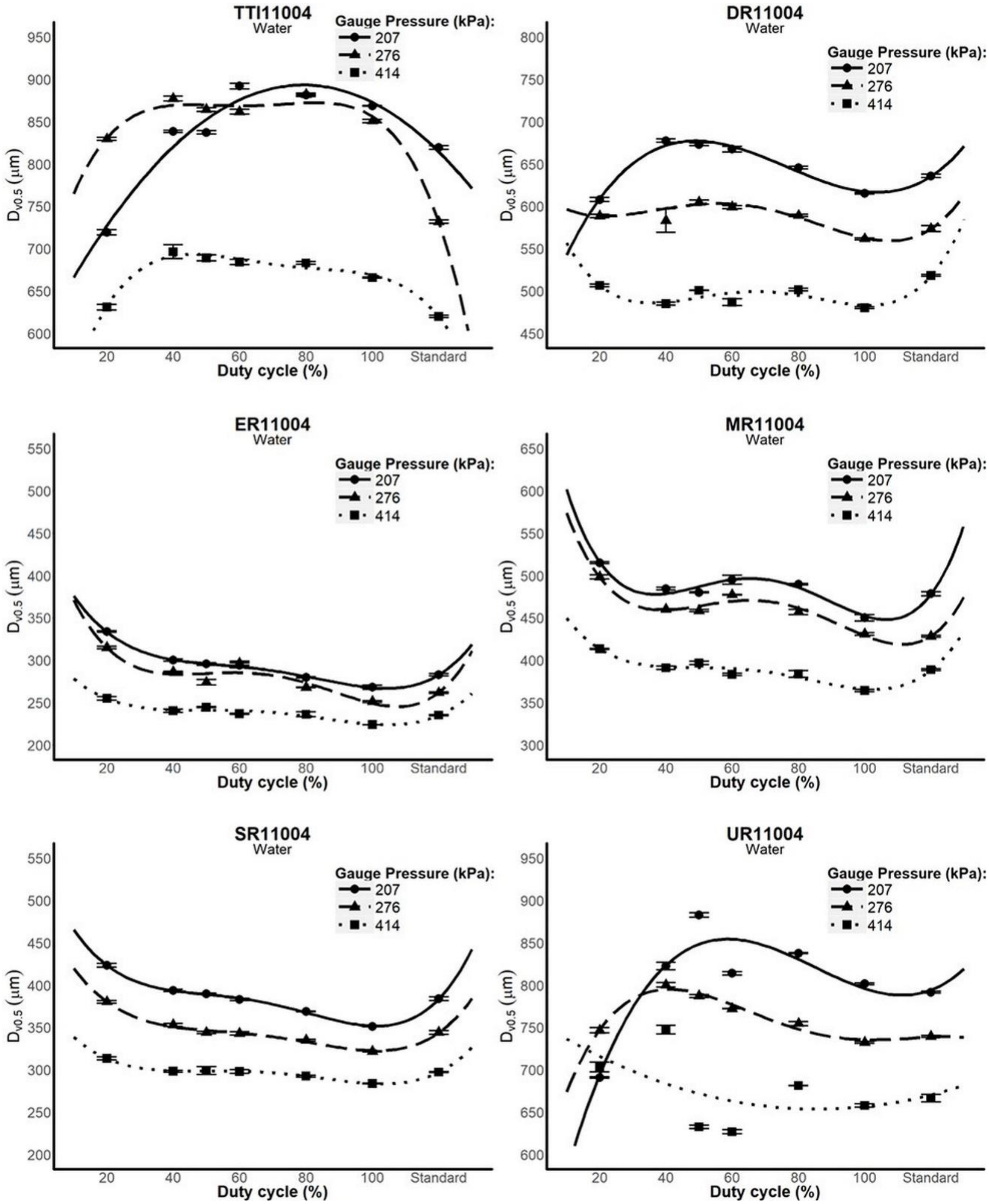

Figure 2.4. Polynomial regressions of droplet size data ($D_{v0.5}$) of water as influenced by duty cycle for the TTI11004 (top left), DR11004 (top right), ER11004 (middle left), MR11004 (middle right), SR11004 (bottom left), and UR11004 (bottom right) nozzles.

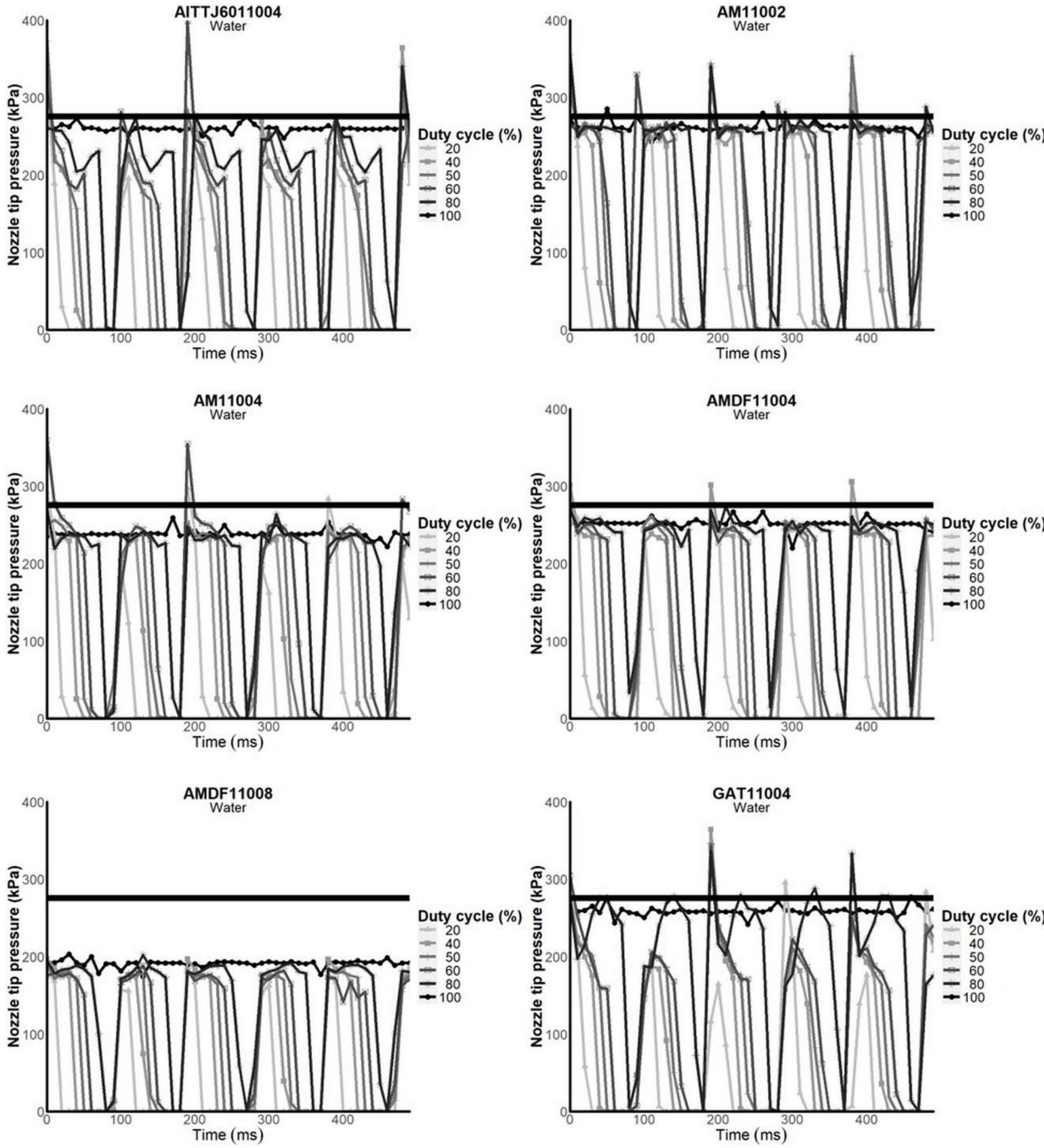

Figure 2.5. Fluctuations in nozzle tip pressure (kPa) over 0.5 s for a gauge pressure of 276 kPa with water spray solution as influenced by duty cycle for the AITTJ-6011004 (top left), AM11002 (top right), AM11004 (middle left), AMDF11004 (middle right), AMDF11008 (bottom left), and GAT11004 (bottom right) nozzles. The solid black bar indicates the 276 kPa gauge pressure.

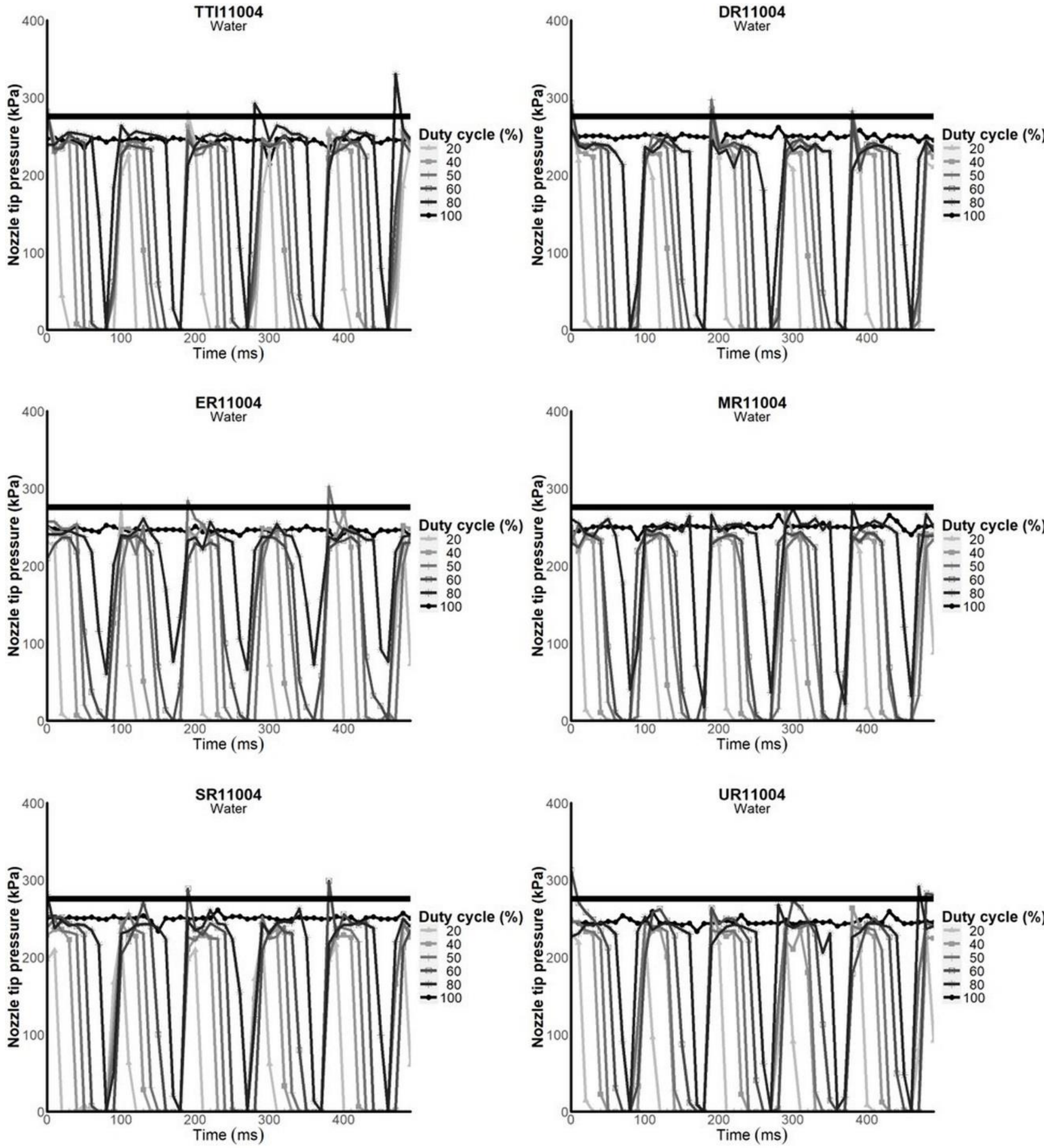

Figure 2.6. Fluctuations in nozzle tip pressure (kPa) over 0.5 s for a gauge pressure of 276 kPa with water spray solution as influenced by duty cycle for the TTI11004 (top left), DR11004 (top right), ER11004 (middle left), MR11004 (middle right), SR11004 (bottom left), and UR11004 (bottom right) nozzles. The solid black bar indicates the 276 kPa gauge pressure.

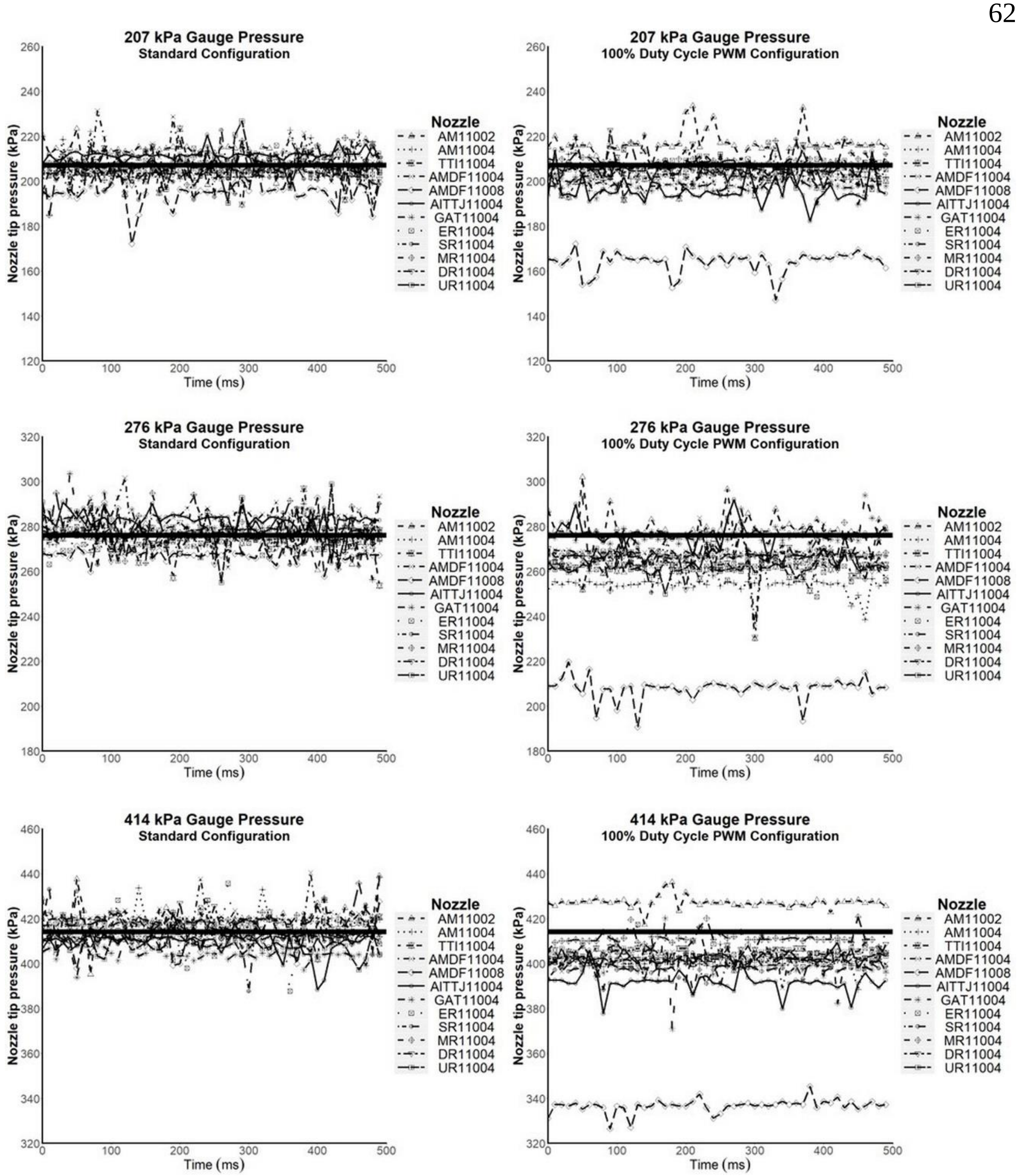

Figure 2.7. Nozzle tip pressure of 12 nozzles when spraying water in a standard nozzle body configuration (no solenoid valve) at 207 kPa (top left), 276 kPa (middle left), and 414 kPa (bottom left) and at a 100% duty cycle in a pulsing nozzle body configuration (with solenoid valve) at 207 kPa (top right), 276 kPa (middle right), and 414 kPa (bottom right). The solid black bar indicates the respective gauge pressure.

APPENDIX (A)

Table A.1. Polynomial regression parameters (*a*, *b*, *c*, *d*, *e*) and coefficient of determination (r^2) for droplet size ($D_{v0.5}$) regressed over duty cycle of the glyphosate (Roundup PowerMAX®) plus AMS solution for each nozzle*pressure combination.

Nozzle	Gauge pressure	*a*	*b*	*c*	*d*	*e*	Coefficient of determination
	kPa			µm			r^2
AITTJ-6011004[a]	207	416.82	14.62	-0.24	1.15 E -03	–	0.96
AM11002[b]	207	585.58	-4.10	0.02	–	–	0.98
AM11004[b]	207	877.48	-32.10	0.89	-1.01 E -02	3.90 E -05	0.98
AMDF11004[b]	207	506.50	2.48	-0.05	1.79 E -04	–	0.99
AMDF11008[b]	207	760.91	-6.13	0.08	-3.64 E -04	–	0.99
GAT11004[d]	207	491.53	2.30	-0.03	–	–	0.96
TTI11004[a]	207	578.95	8.41	-0.06	–	–	0.74
DR11004[c]	207	338.16	20.62	-0.55	6.10 E -03	-2.40 E -05	0.97
ER11004[c]	207	425.88	-10.06	0.24	-2.44 E -03	9.00 E -06	0.99
MR11004[c]	207	434.12	5.29	-0.26	3.99 E -03	-1.92 E -05	0.98
SR11004[c]	207	440.92	-4.17	0.05	-2.51 E -04	–	0.99
UR11004[c]	207	389.70	23.13	-0.52	4.73 E -03	-1.55 E -05	0.98
AITTJ-6011004[a]	276	680.34	-9.95	0.41	-5.52 E -03	2.34 E -05	0.97
AM11002[b]	276	626.12	-11.52	0.26	-2.70 E -03	9.99 E -06	0.99
AM11004[b]	276	852.33	-32.39	0.93	-1.10 E -02	4.65 E -05	0.95
AMDF11004[b]	276	582.06	-9.28	0.28	-3.31 E -03	1.31 E -05	0.97
AMDF11008[b]	276	652.42	-5.47	0.10	-5.67 E -04	–	0.91
GAT11004[d]	276	632.45	-14.44	0.44	-5.48 E -03	2.32 E -05	0.97
TTI11004[a]	276	776.39	2.83	-0.02	–	–	0.62
DR11004[c]	276	582.41	-1.40	0.03	-2.37 E -04	–	0.95
ER11004[c]	276	364.82	-4.96	0.07	-3.42 E -04	–	0.99
MR11004[c]	276	454.31	1.20	-0.12	1.97 E -03	-9.72 E -06	0.98
SR11004[c]	276	408.60	-3.77	0.05	-2.13 E -04	–	0.99
UR11004[c]	276	343.11	29.39	-0.72	7.22 E -03	-2.61 E -05	0.98
AITTJ-6011004[a]	414	212.05	28.84	-0.73	7.65 E -03	-2.88 E -05	0.98
AM11002[b]	414	501.28	-11.15	0.31	-3.72 E -03	1.56 E -05	0.98
AM11004[b]	414	551.35	-10.66	0.27	-2.78 E -03	1.00 E -05	0.97
AMDF11004[b]	414	489.93	-4.16	0.06	-3.31 E -04	–	0.90
AMDF11008[b]	414	285.65	22.39	-0.77	9.73 E -03	-4.16 E -05	0.95
GAT11004[d]	414	615.35	-19.84	0.54	-6.06 E -03	2.35 E -05	0.98
TTI11004[a]	414	211.02	39.29	-1.08	1.23 E -02	-4.95 E -05	0.95
DR11004[c]	414	678.47	-17.24	0.47	-5.19 E -03	1.96 E -05	0.96
ER11004[c]	414	287.38	-3.28	0.05	-2.27 E -04	–	0.99
MR11004[c]	414	450.38	-3.69	0.05	-2.83 E -04	–	0.96
SR11004[c]	414	326.86	-0.94	2.21 E -03	–	–	0.99
UR11004[c]	414	-298.75	82.97	-2.48	2.92 E -02	-1.18 E -04	0.92

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN

Table A.2. Droplet size data such that 10% of the spray volume is contained in droplets of lesser diameter ($D_{v0.1}$) for glyphosate (Roundup PowerMAX®) plus AMS impacted by duty cycle for nozzle and pressure combinations.

Nozzle	Gauge pressure	$D_{v0.1}$ Duty cycle (%)[e] 20	40	50	60	80	100
	kPa	µm					
AITTJ6011004[a]	207	311 d	332 a	323 b	319 c	303 e	298 f
AM11002[b]	207	226 a	204 b	199 c	187 d	177 e	178 e
AM11004[b]	207	239 a	223 c	225 b	227 b	219 d	209 e
AMDF11004[b]	207	253 a	247 b	242 c	240 d	228 e	216 f
AMDF11008[b]	207	309 a	289 b	283 c	279 d	273 e	262 f
GAT11004[d]	207	250 a	253 a	252 a	251 a	232 b	215 c
TTI11004[a]	207	382 f	417 c	434 a	410 d	423 b	404 e
DR11004[c]	207	281 c	288 a	285 b	281 c	280 c	271 d
ER11004[c]	207	120 a	111 b	109 c	109 c	106 d	103 e
MR11004[c]	207	215 a	200 b	195 d	196 cd	197 c	187 e
SR11004[c]	207	159 a	147 b	144 c	142 d	141 d	135 e
UR11004[c]	207	364 d	378 a	376 ab	374 b	368 c	362 d
AITTJ6011004[a]	276	302 c	310 b	316 a	314 ab	299 c	282 d
AM11002[b]	276	223 a	211 b	208 c	205 d	200 e	192 f
AM11004[b]	276	227 b	214 c	214 c	214 c	210 d	241 a
AMDF11004[b]	276	220 a	212 c	214 b	215 b	209 d	200 e
AMDF11008[b]	276	262 a	244 c	238 d	251 b	240 cd	227 e
GAT11004[d]	276	218 a	207 b	207 b	202 c	187 d	178 e
TTI11004[a]	276	411 c	414 bc	411 bc	425 a	415 b	400 d
DR11004[c]	276	276 a	271 b	264 c	264 c	257 d	244 e
ER11004[c]	276	115 a	105 b	103 c	103 c	100 d	96 e
MR11004[c]	276	204 a	191 b	188 c	184 d	182 e	176 f
SR11004[c]	276	148 a	137 b	134 c	132 d	129 e	127 f
UR11004[c]	276	359 c	376 a	371 ab	368 b	355 c	342 d
AITTJ6011004[a]	414	264 c	277 a	273 b	270 b	260 c	252 d
AM11002[b]	414	155 a	147 b	146 c	142 d	133 e	128 f
AM11004[b]	414	191 a	182 b	180 bc	178 c	174 d	169 e
AMDF11004[b]	414	196 a	186 b	183 c	182 c	179 d	172 e
AMDF11008[b]	414	220 a	208 b	198 c	195 d	192 e	182 f
GAT11004[d]	414	165 a	152 b	152 b	150 b	142 c	135 d
TTI11004[a]	414	319 c	330 a	328 ab	326 b	326 b	319 c
DR11004[c]	414	227 a	218 b	218 b	219 b	216 c	210 d
ER11004[c]	414	90 a	85 b	84 b	82 c	82 c	78 d
MR11004[c]	414	172 a	163 b	162 bc	159 bc	157 c	148 d
SR11004[c]	414	127 a	121 b	119 c	116 d	110 e	106 f
UR11004[c]	414	281 c	290 b	266 e	265 e	277 d	294 a

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$).

Table A.3. Droplet size data such that 50% of the spray volume is contained in droplets of lesser diameter ($D_{v0.5}$) for glyphosate (Roundup PowerMAX®) plus AMS as impacted by duty cycle for each nozzle and pressure combination.

		$D_{v0.5}$					
	Gauge	Duty cycle (%)[e]					
Nozzle	pressure	20	40	50	60	80	100
	kPa	μm					
AITTJ6011004[a]	207	621 d	698 a	681 b	675 b	636 c	619 d
AM11002[b]	207	510 a	456 b	439 c	409 d	385 e	383 e
AM11004[b]	207	519 a	479 d	495 c	501 b	479 d	451 e
AMDF11004[b]	207	539 b	544 a	535 c	528 d	499 e	468 f
AMDF11008[b]	207	666 a	616 b	602 c	594 d	580 e	559 f
GAT11004[d]	207	528 b	540 a	540 a	543 a	504 c	464 d
TTI11004[a]	207	711 e	830 c	899 a	819 d	865 b	831 c
DR11004[c]	207	574 e	607 a	596 b	590 c	583 d	561 f
ER11004[c]	207	301 a	269 b	263 c	264 c	252 d	241 e
MR11004[c]	207	464 a	432 b	419 c	419 c	430 b	401 d
SR11004[c]	207	377 a	343 b	336 c	330 d	322 e	311 f
UR11004[c]	207	680 f	750 a	742 b	735 c	712 d	707 e
AITTJ6011004[a]	276	605 c	641 b	668 a	664 a	636 b	596 d
AM11002[b]	276	480 a	436 b	430 c	422 d	405 e	388 f
AM11004[b]	276	494 a	456 c	454 c	469 b	445 d	493 a
AMDF11004[b]	276	484 b	477 d	487 a	481 c	466 e	441 f
AMDF11008[b]	276	577 a	550 c	538 d	558 b	530 e	495 f
GAT11004[d]	276	478 a	462 b	463 b	455 b	418 c	399 d
TTI11004[a]	276	828 e	854 c	840 d	882 a	864 b	831 e
DR11004[c]	276	564 a	564 a	551 c	558 b	542 d	507 e
ER11004[c]	276	291 a	255 b	248 c	246 c	238 d	225 e
MR11004[c]	276	445 a	412 b	403 c	395 d	398 d	380 e
SR11004[c]	276	350 a	319 b	311 c	306 d	299 e	290 f
UR11004[c]	276	696 c	761 a	752 a	747 a	720 b	688 c
AITTJ6011004[a]	414	553 e	612 a	599 b	589 c	572 d	547 e
AM11002[b]	414	374 a	346 c	350 b	332 d	309 e	295 f
AM11004[b]	414	424 a	399 b	402 b	400 b	393 c	375 d
AMDF11004[b]	414	429 a	405 b	404 b	392 c	399 b	380 d
AMDF11008[b]	414	497 a	472 b	434 c	433 c	439 c	416 d
GAT11004[d]	414	390 a	357 c	365 b	363 bc	343 d	318 e
TTI11004[a]	414	656 d	716 ab	709 b	698 c	719 a	698 c
DR11004[c]	414	485 a	464 d	475 c	481 b	474 c	456 e
ER11004[c]	414	238 a	214 b	211 c	207 d	203 e	192 f
MR11004[c]	414	396 a	371 b	369 b	360 c	359 c	341 d
SR11004[c]	414	310 a	291 b	285 c	278 d	267 e	254 f
UR11004[c]	414	582 d	626 a	546 e	542 e	587 c	615 b

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$).

Table A.4. Droplet size data such that 90% of the spray volume is contained in droplets of lesser diameter ($D_{v0.9}$) for glyphosate (Roundup PowerMAX®) plus AMS as impacted by duty cycle for each nozzle and pressure combination.

Nozzle	Gauge pressure	$D_{v0.9}$ Duty cycle (%)[e] 20	40	50	60	80	100
	kPa	μm					
AITTJ6011004[a]	207	914 d	1089 a	1049 b	1053 b	1005 c	993 c
AM11002[b]	207	853 a	776 b	742 c	671 d	602 e	590 e
AM11004[b]	207	837 b	755 d	813 c	883 a	816 c	748 d
AMDF11004[b]	207	852 c	948 a	931 b	920 b	837 d	777 e
AMDF11008[b]	207	1059 a	998 b	977 c	963 d	939 e	909 f
GAT11004[d]	207	827 d	864 b	859 bc	930 a	841 cd	763 e
TTI11004[a]	207	954 e	1190 d	1380 a	1182 d	1319 b	1287 c
DR11004[c]	207	844 f	993 a	973 b	962 c	947 d	903 e
ER11004[c]	207	603 a	522 b	498 d	511 c	476 e	438 f
MR11004[c]	207	743 a	708 b	681 c	688 c	743 a	662 d
SR11004[c]	207	688 a	599 b	588 c	572 d	553 e	535 f
UR11004[c]	207	939 e	1118 a	1102 bc	1096 c	1063 d	1108 b
AITTJ6011004[a]	276	881 d	970 c	1045 a	1048 a	1005 b	973 c
AM11002[b]	276	840 a	710 b	704 bc	693 c	630 d	588 e
AM11004[b]	276	833 a	734 cd	739 c	801 b	716 d	793 b
AMDF11004[b]	276	807 d	811 cd	867 a	845 b	817 c	748 e
AMDF11008[b]	276	966 b	928 c	933 c	998 a	927 c	822 d
GAT11004[d]	276	781 ab	770 b	796 a	781 ab	707 c	683 d
TTI11004[a]	276	1222 f	1294 d	1279 e	1405 a	1360 b	1312 c
DR11004[c]	276	873 c	876 bc	851 d	930 a	891 b	816 e
ER11004[c]	276	592 a	503 b	485 c	486 c	458 d	411 e
MR11004[c]	276	748 a	693 b	677 bc	664 c	686 b	639 d
SR11004[c]	276	633 a	566 b	547 c	533 d	523 e	492 f
UR11004[c]	276	1009 b	1162 a	1143 a	1167 a	1106 a	1039 b
AITTJ6011004[a]	414	851 e	1004 a	988 b	969 c	961 c	918 d
AM11002[b]	414	689 a	639 c	676 b	596 d	532 e	497 f
AM11004[b]	414	706 a	671 d	689 bc	684 c	698 ab	647 e
AMDF11004[b]	414	717 a	692 ab	683 bc	660 cd	707 ab	658 d
AMDF11008[b]	414	832 a	842 a	712 c	729 c	776 b	725 c
GAT11004[d]	414	696 a	638 b	693 a	695 a	646 b	571 c
TTI11004[a]	414	941 e	1142 c	1129 c	1103 d	1190 a	1165 b
DR11004[c]	414	779 b	748 d	779 b	808 a	805 a	767 c
ER11004[c]	414	521 a	450 b	452 b	423 c	408 c	372 d
MR11004[c]	414	688 a	624 b	618 b	591 c	599 c	567 d
SR11004[c]	414	560 a	524 b	504 c	492 d	483 e	454 f
UR11004[c]	414	899 c	1029 a	838 d	831 d	971 b	975 b

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$).

Table A.5. Percent of spray volume less than 150 µm (driftable fines) for glyphosate (Roundup PowerMAX®) plus AMS as impacted by duty cycle for each nozzle and gauge pressure combination.

		Driftable fines					
	Gauge	Duty cycle (%)[e]					
Nozzle	pressure	20	40	50	60	80	100
	kPa	%					
AITTJ6011004[a]	207	0.89 e	0.92 e	0.99 d	1.04 c	1.21 b	1.27 a
AM11002[b]	207	3.26 e	4.38 d	4.68 c	5.63 b	6.61 a	6.48 a
AM11004[b]	207	2.78 e	3.29 d	3.44 c	3.36 cd	3.78 b	4.26 a
AMDF11004[b]	207	2.22 f	2.74 e	2.84 d	2.92 c	3.30 b	3.93 a
AMDF11008[b]	207	1.44 e	1.72 d	1.81 c	1.87 c	1.98 b	2.25 a
GAT11004[d]	207	2.27 c	2.36 c	2.37 c	2.41 c	3.07 b	3.82 a
TTI11004[a]	207	0.49 a	0.43 ab	0.28 d	0.42 b	0.33 c	0.38 b
DR11004[c]	207	1.51 ab	1.36 b	1.40 b	1.47 ab	1.46 ab	1.59 a
ER11004[c]	207	16.00 e	18.87 d	19.66 c	19.63 c	21.05 b	22.33 a
MR11004[c]	207	3.57 e	4.55 d	4.98 b	4.75 cd	4.84 bc	5.53 a
SR11004[c]	207	8.76 f	10.39 e	10.88 d	11.26 c	11.50 b	12.60 a
UR11004[c]	207	0.58 a	0.49 b	0.47 b	0.44 b	0.47 b	0.50 b
AITTJ6011004[a]	276	1.01 e	1.12 c	1.06 d	1.09 cd	1.29 b	1.48 a
AM11002[b]	276	3.24 e	3.79 d	3.91 d	4.06 c	4.43 b	4.91 a
AM11004[b]	276	3.23 d	3.70 c	3.68 c	4.00 a	3.84 b	2.77 e
AMDF11004[b]	276	3.58 e	4.22 bc	4.10 cd	4.03 d	4.33 b	4.76 a
AMDF11008[b]	276	2.34 d	3.02 bc	3.12 b	2.72 c	3.02 b	3.56 a
GAT11004[d]	276	3.54 e	4.34 d	4.40 d	4.72 c	5.73 b	6.57 a
TTI11004[a]	276	0.37 a	0.34 b	0.36 ab	0.31 c	0.35 ab	0.37 a
DR11004[c]	276	1.54 e	1.84 d	1.99 c	1.95 c	2.10 b	2.36 a
ER11004[c]	276	17.49 e	21.23 d	22.15 c	22.34 c	23.67 b	25.87 a
MR11004[c]	276	4.26 f	5.12 e	5.37 d	5.62 c	6.03 b	6.56 a
SR11004[c]	276	10.26 f	12.12 e	12.85 d	13.23 c	13.86 b	14.55 a
UR11004[c]	276	0.28 e	0.53 d	0.56 cd	0.57 c	0.65 b	0.69 a
AITTJ6011004[a]	414	1.68 d	1.68 d	1.76 cd	1.82 c	2.01 b	2.19 a
AM11002[b]	414	9.20 e	10.37 d	10.57 d	11.27 c	12.85 b	14.16 a
AM11004[b]	414	5.23 e	6.12 d	6.42 c	6.56 c	6.93 b	7.40 a
AMDF11004[b]	414	4.82 e	5.63 d	6.09 c	5.90 cd	6.43 b	7.03 a
AMDF11008[b]	414	3.91 f	4.54 e	4.80 d	5.12 c	5.54 b	6.39 a
GAT11004[d]	414	7.86 d	9.65 c	9.68 c	9.94 c	11.19 b	12.60 a
TTI11004[a]	414	1.03 a	0.83 d	0.89 c	0.87 c	0.88 c	0.93 b
DR11004[c]	414	3.19 e	3.52 d	3.83 bc	3.80 c	3.94 b	4.25 a
ER11004[c]	414	26.19 f	30.20 e	30.69 d	31.62 c	32.47 b	34.97 a
MR11004[c]	414	7.19 c	8.17 b	8.30 b	8.70 b	8.90 b	10.36 a
SR11004[c]	414	13.96 e	15.56 d	16.08 d	16.97 c	18.74 b	20.42 a
UR11004[c]	414	1.35 c	1.39 c	1.58 ab	1.61 a	1.55 b	1.38 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$).

Table A.6. Average nozzle tip pressure over five seconds for glyphosate (Roundup PowerMAX®) plus AMS as impacted by nozzle for each gauge pressure and duty cycle combination.

		Average nozzle tip pressure					
	Gauge	Duty cycle (%)[e]					
Nozzle	pressure	20	40	50	60	80	100
		kPa					
AITTJ6011004[a]	207	37 bc	70 bc	87 bc	105 bc	144 c	202 ef
AM11002[b]	207	61 a	109 a	141 a	172 a	208 a	217 a
AM11004[b]	207	42 b	81 ab	100 b	120 b	161 bc	205 c
AMDF11004[b]	207	42 b	80 abc	99 b	119 b	163 bc	202 f
AMDF11008[b]	207	28 c	60 c	74 c	91 c	122 d	165 h
GAT11004[d]	207	34 bc	63 bc	82 bc	97 bc	158 bc	191 g
TTI11004[a]	207	43 b	82 ab	101 b	121 b	162 bc	205 c
DR11004[c]	207	44 ab	84 ab	102 b	122 b	163 b	204 d
ER11004[c]	207	42 b	80 abc	100 b	119 b	160 bc	203 e
MR11004[c]	207	44 ab	83 ab	102 b	123 b	164 b	206 b
SR11004[c]	207	42 b	80 bc	99 b	120 b	158 bc	203 d
UR11004[c]	207	46 ab	85 ab	103 b	123 b	169 b	202 f
AITTJ6011004[a]	276	49 bc	90 bc	112 b	139 bc	188 de	257 e
AM11002[b]	276	76 a	127 a	157 a	191 a	254 a	280 a
AM11004[b]	276	58 abc	108 abc	131 ab	159 ab	211 bc	259 d
AMDF11004[b]	276	64 ab	118 ab	151 a	156 abc	212 b	255 f
AMDF11008[b]	276	45 c	85 c	109 b	126 c	177 e	213 g
GAT11004[d]	276	48 bc	89 c	110 b	137 bc	189 cde	257 e
TTI11004[a]	276	60 abc	111 abc	134 ab	159 b	219 b	261 c
DR11004[c]	276	59 abc	109 abc	137 ab	163 ab	218 b	264 b
ER11004[c]	276	57 abc	108 abc	133 ab	157 abc	217 b	264 b
MR11004[c]	276	59 abc	110 abc	137 ab	162 ab	218 b	263 b
SR11004[c]	276	56 abc	106 abc	130 ab	157 abc	210 bcd	257 e
UR11004[c]	276	58 abc	111 abc	136 ab	164 ab	216 b	264 b
AITTJ6011004[a]	414	71 bc	135 b	168 b	206 b	289 b	388 h
AM11002[b]	414	106 a	188 a	227 a	272 a	370 a	421 a
AM11004[b]	414	81 ab	159 ab	196 ab	234 ab	309 b	398 f
AMDF11004[b]	414	82 ab	159 ab	197 ab	235 ab	313 ab	399 f
AMDF11008[b]	414	55 c	119 b	151 b	184 b	242 c	335 i
GAT11004[d]	414	76 abc	144 ab	178 ab	216 ab	293 b	399 f
TTI11004[a]	414	83 ab	161 ab	199 ab	239 ab	317 ab	403 c
DR11004[c]	414	82 ab	160 ab	199 ab	238 ab	315 ab	401 e
ER11004[c]	414	80 ab	156 ab	193 ab	232 ab	305 b	399 f
MR11004[c]	414	83 ab	160 ab	198 ab	237 ab	312 ab	406 b
SR11004[c]	414	77 abc	153 ab	191 ab	232 ab	304 b	397 g
UR11004[c]	414	83 ab	162 ab	200 ab	239 ab	318 ab	402 d

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and duty cycle with the same letter are not significantly different ($P \leq 0.05$).

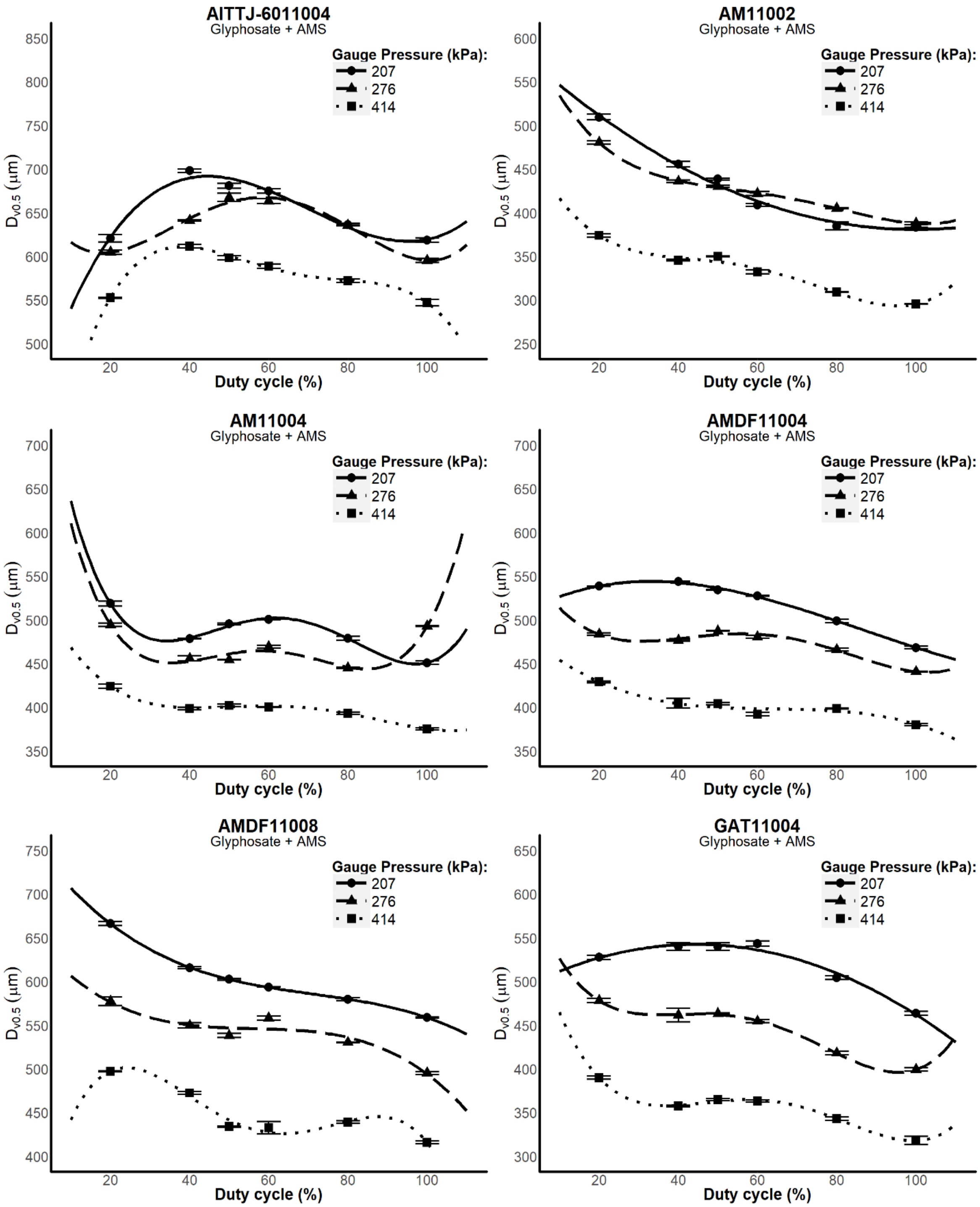

Figure A.1. Polynomial regressions of droplet size data ($D_{v0.5}$) of glyphosate (Roundup PowerMAX®) plus AMS as influenced by duty cycle for the AITTJ6011004 (top left), AM11002 (top right), AM11004 (middle left), AMDF11004 (middle right), AMDF11008 (bottom left), and GAT11004 (bottom right) nozzles.

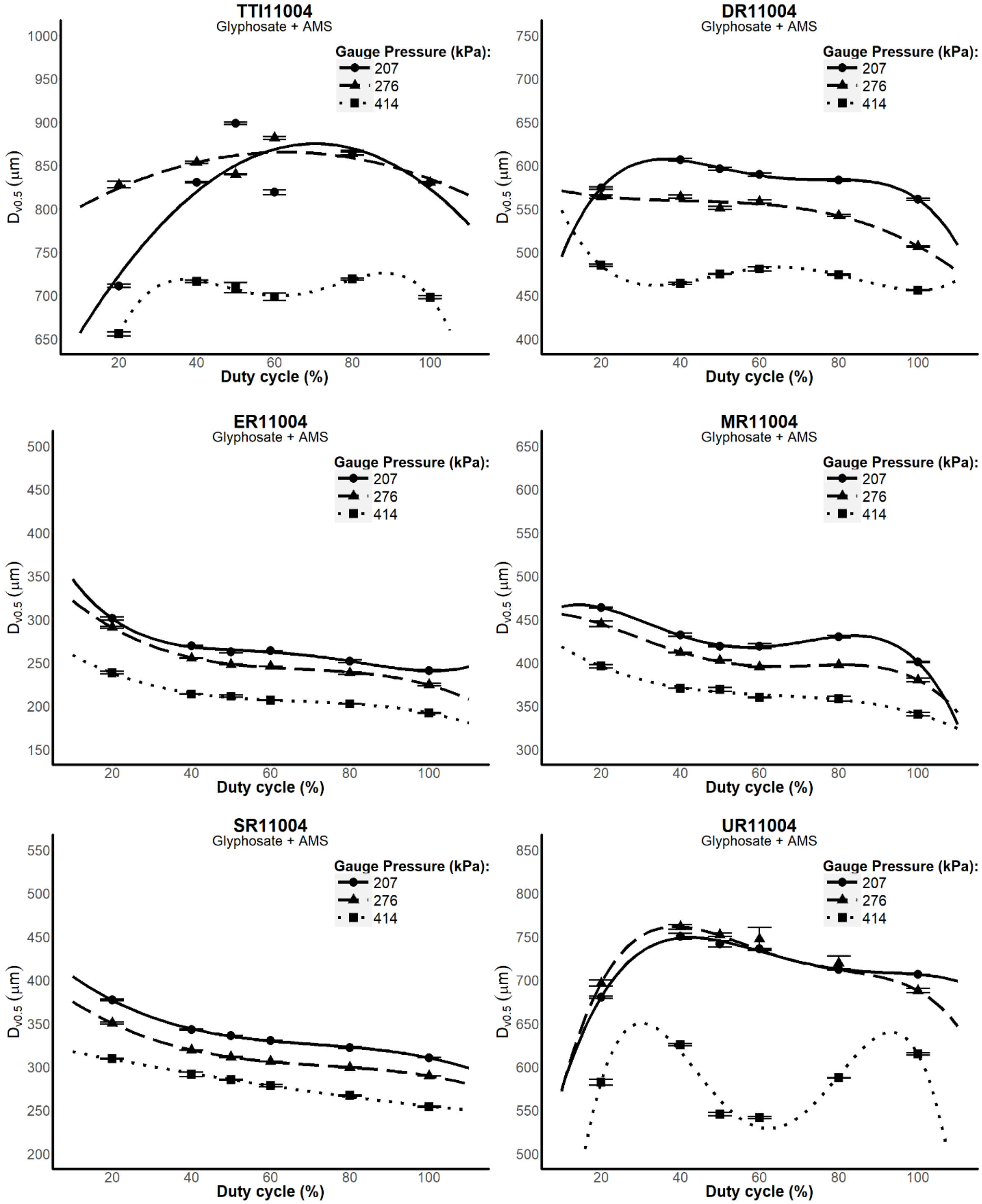

Figure A.2. Polynomial regressions of droplet size data ($D_{v0.5}$) of glyphosate (Roundup PowerMAX®) plus AMS as influenced by duty cycle for the TTI11004 (top left), DR11004 (top right), ER11004 (middle left), MR11004 (middle right), SR11004 (bottom left), and UR11004 (bottom right) nozzles.

CHAPTER 3

DROPLET VELOCITY FROM BROADCAST AGRICULTURAL NOZZLES AS INFLUENCED BY PULSE-WIDTH MODULATION

Abstract

The recognition of agricultural pesticide application complexity has increased in recent years due to pesticide drift concerns and increasingly difficult to control pests. Spray application optimization is necessary to maximize pesticide efficacy while reducing environmental impact. Pulse width modulation (PWM) spray application systems can be a vital precision agricultural tool by providing quick and accurate variable rate application changes and creating an opportunity for a site specific pest management strategy. Research was conducted to identify the impact of PWM duty cycle, nozzle type, application pressure, and spray solution on spray droplet velocity to develop potential PWM optimization practices. Spray droplet velocity increased as pressure and duty cycle increased across nozzles. Greater variability in droplet velocities was observed across nozzles when pulsed at a 20% duty cycle. Venturi nozzles created greater reductions in droplet velocity as duty cycle decreased and had greater variability in droplet velocity measurements than non venturi nozzles. Based on present research, if PWM sprayers are to be used in site specific pest management strategies, it is recommended that non venturi nozzles coupled with greater than 40% duty cycle be used to reduce spray droplet velocity variability, mitigate changes in drift potential, and assist pesticide applicators in optimizing site specific pest management strategies.

Introduction

Pesticide applications are a heavily scrutinized facet of the agricultural industry requiring a concerted effort to optimize each application. Spray particle drift (Byass and Lake, 1977; Hobson et al., 1993; Smith et al., 2000; Zhu et al., 1994b) and pesticide resistance (CropLife International, 2017a, 2017b; Heap, 2017) have further stimulated the need for maximizing pesticide efficacy while minimizing environmental contamination. However, the optimization of pesticide applications is difficult due to the complexity of the application process (Ebert et al., 1999) and the lack of appropriate sprayer preparation (Grisso et al., 1989).

Pulse-width modulation (PWM) sprayer systems provide a unique opportunity for site-specific pest management practices as they standardize numerous factors while variably controlling flow. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003). Application pressure based variable rate flow control devices have been shown to have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989) and droplet velocity (Giles et al., 2002). The variation in droplet size and velocity can negatively impact herbicide efficacy and off-target movement of spray particles. PWM sprayers further provide the possibility for more precise applications through automatic boom and individual nozzle shut off controls (Luck et al., 2010a, 2010b). One initial drawback to PWM application systems was the inability to create coarser droplet distributions because venturi nozzles are not recommended (Capstan Ag Systems Inc., 2013). Venturi nozzles were designed to create coarser droplets by entraining air within the spray solution in the nozzle body (Briffa and Dombrowski, 1966). However, there are commercially available, non-venturi nozzles using a pre-orifice design that can produce the range of droplet distributions needed to reduce drift potential (Butts et al., 2015).

More precise pesticide applications can be achieved by understanding the effect pulsing spray has on droplet velocity from current nozzle technologies. Droplet velocity is a critical spray characteristic affecting numerous aspects of pesticide applications, one of which includes spray particle drift. Spray drift is a major concern in pesticide applications, specifically herbicides, as it has been previously shown that severe crop injury can occur up to 200 m downwind in a 4 m s^{-1} wind speed (Byass and Lake, 1977; Nordby and Skuterud, 1974). Several models have been established to estimate spray drift (Hobson et al., 1993; Miller and Hadfield, 1989; Zhu et al., 1994b, 1994a). The aforementioned models include droplet velocity as a critical parameter affecting spray particle drift. To reduce particle drift utilizing spray droplet velocity, vertical droplet velocity must be increased and horizontal velocity minimized (Farooq et al., 2001).

In addition to affecting spray particle drift, droplet velocity can influence pesticide efficacy. May and Clifford, (1967) found impaction efficiency of sprays were maximized when the stopping distance of a droplet was approximately twice the amount of the width of the target. Greater exit velocities and droplet sizes increase these stopping distances, and further models and research validated the result that smaller droplets with lower terminal velocities resulted in greater leaf adhesion (Forster et al., 2005; Spillman, 1984). Lake, (1977) field tested model estimates and determined the models accurately predicted that smaller droplets (100 µm diameter) with a lower terminal velocity were less likely to bounce and had greater deposition on vertical plant surfaces. Therefore, droplets with lower terminal velocity had greater leaf retention and were the most efficacious compared to droplets with higher terminal velocity on barley (*Hordeum vulgare* L.) and wild oat (*Avena fatua* L.) (Lake, 1977).

These observed drift, canopy penetration, and leaf impaction effects from spray droplet velocity are closely correlated with spray droplet size. Typically, current nozzle technologies have been designed to increase spray droplet size to minimize drift potential, but simultaneously reduce droplet velocity, thereby limiting the potential of droplets to bounce or shatter. Because of the complex interaction between droplet size and velocity, distinguishing which factor specifically influences the resulting spray deposition and transport characteristics can be difficult. PWM sprayers cause further complications as duty cycle slightly influences the resulting droplet size distributions (Butts et al., 2017). Despite these complications, it is vital to understand how individual spray characteristics, such as droplet velocity, are influenced by application technologies to begin optimizing each application.

Previous research with PWM spray application systems illustrated that a decrease in duty cycle will decrease droplet exit velocity (Giles et al., 2002). This could be problematic due to increased drift potential and reduced canopy penetration, specifically, in a site-specific management situation in which an optimum droplet velocity is trying to be ascertained. However, the decrease in droplet velocity from a change in duty cycle is smaller than the decrease in droplet velocity from a change in application pressure across equivalent flow rates (Giles et al., 2003). Furthermore, compared to pressure-based flow rate adjustments, increasing nozzle orifice size and operating at a lower duty cycle will increase droplet velocities and spray kinetic energies (Giles, 2001). Spray kinetic energies from PWM sprayers were minimally affected by duty cycle and were more stable than spray kinetic energies obtained from pressure-based alterations to obtain equivalent flow rates (Giles et al., 2002; Giles and Ben-Salem, 1992). In brief, PWM sprayers could reduce drift potential, increase canopy penetration, and increase impaction compared to sprayers using pressure-based alterations to obtain equivalent flow rates.

Previous PWM droplet velocity research illustrated numerous patterns and advantages compared to alternative sprayers. However, only non-venturi and pre-orifice lacking nozzles were used. In this research, the PWM spray application system was tested as if it were to be used in a site-specific management scenario in which the nozzle and pressure were fixed (to generate a specific or optimum droplet size), but duty cycle was allowed to fluctuate to maintain flow rate. The objective of this experiment was to specifically investigate changes in droplet exit velocity and the droplet size in which 50 and 75% of the maximum velocity was achieved as affected by PWM duty cycle across 11 current nozzle technologies (non-venturi versus venturi nozzle types), three gauge application pressures, and two spray solutions.

Materials and Methods

Research was conducted in January of 2017 to evaluate the effect of nozzle type, gauge application pressure, and PWM duty cycle on spray droplet exit velocity. The experiment was conducted using the low-speed wind tunnel at the Aerial Application

Technology Laboratory located at the United States Department of Agriculture Southern Plains Agricultural Research Center in College Station, TX. Wind tunnel construction and operation is illustrated in previous literature (Fritz et al., 2014; Hoffmann et al., 2014). The wind tunnel was equipped with one nozzle and a SharpShooter® PWM system (Capstan Ag Systems, Inc., Topeka, KS) to select the specific duty cycle for each treatment. The solenoid valve was operated at a 10 Hz frequency across treatments. A 1.0 m s^{-1} wind speed was created to allow for one directional droplet movement, but not influence droplets' exit velocities. The average air temperature and relative humidity during the time of the experiment was 22 C and 71%, respectively.

The experiment was a completely randomized design with an 11 x 6 x 3 x 2 factorial treatment structure for a total of 396 treatments. The treatments consisted of 11 nozzle types, six pulsing configurations (five PWM duty cycles plus a standard configuration excluding the PWM solenoid valve), three gauge application pressures (pressure before the solenoid valve), and two spray solutions (Table 3.1). The glyphosate (Roundup PowerMAX®) plus ammonium sulfate (AMS) solution was applied at a carrier volume of 94 L ha^{-1}.

A LaVision SprayMaster (LaVision Inc., Ypsilanti, MI) droplet imaging system was set to Shadowography mode and used to simultaneously measure droplet size and velocity. The Shadowography mode uses a pulsed laser to backlight images, and paired images are recorded 10 μs apart. Droplet size and velocities were recorded 15 cm from the nozzle over a 19 x 19 cm area with an approximate depth of field of 3 mm and a droplet size measurement range between 60 and 2000 μm. Measurements were taken in close proximity to the nozzle exit orifice to investigate the specific impact of PWM duty cycle on exit droplet velocities. Each treatment was continuously sprayed for 68 seconds which allowed for 300 paired images to be collected. The nozzle was traversed for two complete revolutions which allowed for four samples of the entire spray plume within the 300 paired images. These sampling techniques were chosen to provide a minimum of 250 paired droplets post-processing to be measured for every treatment. DaVis Software (Version 7.2, LaVision Inc., Ypsilanti, MI) processed the images and returned a listing of each droplet detected and measured. Droplet velocity was calculated using the process described in previous literature (Hoffmann et al., 2014).

Droplet size and velocity paired measurements for each treatment were modeled using the dose response package in R statistical software (V 3.3.1). Three parameter log-logistic models were fit to the data using Equation 3.1:

$$Y = d / 1 + \exp[b(\log x - \log e)] \qquad [3.1]$$

where:

Y = droplet exit velocity (m s^{-1})

b = relative slope around e

d = upper limit

e = inflection point

x = droplet size (μm).

The DS_{50} and DS_{75} were determined from the fitted models to estimate the droplet size in which 50 and 75% of the maximum velocity was attained, respectively. Droplet velocity data were also subjected to ANOVA using a mixed effect model in SAS (SAS v9.4, SAS Institute Inc., Cary, NC) to compare overall average spray velocities. Means were separated using Fisher's Protected LSD Test with the Tukey adjustment to correct for multiplicity.

Results and Discussion

A significant interaction ($P < 0.0001$) between solution, nozzle type, gauge application pressure, and PWM duty cycle was observed. Similar trends were observed between the glyphosate plus AMS and water solutions; therefore, the water solution is strictly discussed within this manuscript. Tables and figures pertaining to the glyphosate plus AMS solution can be found in APPENDIX (B).

Gauge application pressure and orifice size impacted droplet velocity from a PWM sprayer similar to previous literature using a conventional (non-pulsing) sprayer (Farooq et al., 2001; Hoffmann et al., 2014; Nuyttens et al., 2009, 2007). Across nozzles and duty cycles, as gauge application pressure increased, average spray velocity increased (Table 3.2). Similarly, as nozzle orifice size increased, average spray velocity increased within a similar nozzle type. Due to these similar results, comparisons between treatments were reduced to specifically observe the impact of PWM duty cycle on droplet exit velocity within nozzle type, gauge application pressure, and solution.

NON-VENTURI NOZZLES

Average spray velocities from non-venturi nozzles (DR11004, ER11004, MR11004, SR11004, and UR11004) followed similar single-asymptotic patterns across pressures and duty cycles tested (Figures 3.1-3.3). As droplet size increased, droplet velocity increased until reaching a maximum plateau. Deviations from this asymptotic pattern for the ER11004 and SR11004 nozzles at 414 kPa can be explained due to the resulting fine droplets produced and the low resolution of our measurement system to detect that size of droplets. Similar asymptotic models were established in previous literature to model the relationship between PWM duty cycle and droplet velocity (Giles et al., 2002; Giles and Ben-Salem, 1992). It is interesting to note previous research tested non-venturi nozzles with no pre-orifice. Four of the five non-venturi nozzles evaluated in this research (DR11004, MR11004, SR11004, and UR11004) contain a pre-orifice which implements Bernoulli's principle to cause a pressure reduction within the nozzle to increase spray droplet size. It can be concluded the addition of a pre-orifice to a nozzle does not change the pattern observed for spray droplet velocity as affected by PWM duty cycle.

The addition of a pre-orifice does change the maximum spray droplet velocities achieved by different nozzle types (Nuyttens et al., 2007). Across pressures and duty cycles, the average spray droplet velocity for the non-venturi nozzles from highest to lowest followed the pattern: ER11004 > SR11004 > MR11004 > DR11004 > UR11004 (Table 3.2). This is intriguing as average droplet size emitted from these nozzles follows an inverse pattern (Butts et al., 2017). Furthermore, across non-venturi nozzles and pressures, the average spray droplet velocity either remained the same or increased slightly (excluding the MR11004 at 276 kPa) when a solenoid valve was operated at a 100% duty cycle compared with the standard configuration without a solenoid valve. This illustrates the addition of an inline solenoid valve does not reduce the average spray velocity compared to a conventional sprayer, thereby maintaining similar spray deposition and transport characteristics.

As duty cycle decreased, average spray velocities decreased across non-venturi nozzles. The 80% and 60% duty cycles reduced spray droplet velocities 2-9% and 9-21%, respectively, compared to the 100% duty cycle across non-venturi nozzles and pressures. The 40% and 20% duty cycles further reduced average droplet velocities, though the reductions were not consistent across nozzle types and pressures, as shown by the DR11004 nozzle. At 276 kPa, the 20% duty cycle reduced spray droplet velocity by 12% compared to the 40% duty cycle, but at 207 and 414 kPa, the average spray droplet velocity was similar between the 40% and 20% duty cycles. Because of this velocity reduction, particle drift potential slightly increases when spray is pulsed. However, previous research demonstrated that this slight increase in drift potential from a PWM sprayer is less than that from a similar change in flow rate using only pressure-based changes (Giles, 2001; Giles et al., 2002).

Predictions for the DS_{50} (Table 3.3) and DS_{75} (Table 3.4) resulted in no apparent correlation with PWM duty cycle when non-venturi nozzles were operated. This is further illustrated by Figures 3.1-3.3. The slopes of the spray droplet velocity models for each PWM duty cycle slightly decrease as duty cycle decreased within a nozzle and pressure. This leads to the similar DS_{50} and DS_{75} values observed for each duty cycle model within a nozzle and pressure although the maximum velocities are different. Results also indicate the ER11004 nozzle achieves maximum spray droplet velocity with smaller droplets compared to the other non-venturi nozzles tested. The smaller droplets of the ER11004 nozzle coupled with higher initial velocities (but lower terminal velocities) could result in greater overall target surface impaction, specifically on vertical plant surfaces, compared with all other non-venturi nozzles (Lake, 1977; Matthews et al., 2014; Spillman, 1984). However, due to the complex interaction between droplet size and velocity, the larger droplets emitted from the UR11004 nozzle coupled with the reduced velocity to minimize droplet bounce and shatter could result in similar impaction efficiency, especially on horizontal leaf surfaces. The 20% duty cycle had greater standard errors and more variability within their DS_{50} and DS_{75} values compared to the other duty cycles, similar to the average spray droplet velocity results. These results indicate if PWM systems are used for site-specific pest management practices, it is highly advisable to remain above a 40% duty cycle with non-venturi nozzles to maintain consistency with the application and minimize the reduction in droplet velocity which could lead to increased drift potential.

VENTURI NOZZLES

Droplet velocity models established for venturi nozzles (AITTJ6011004, AM11002, AM11004, AMDF11004, AMDF11008, and TTI11004) across duty cycles and pressures evaluated in this research were similar to asymptotic models for the non-venturi nozzles (Figures 3.4-3.6). Few differences in spray droplet velocity patterns were observed between dual-fan venturi nozzles (AITTJ6011004, AMDF11004, and AMDF11008) and single-fan venturi nozzles (AM11002, AM11004, and TTI11004). However, as can be seen for the AITTJ6011004, AMDF11008, and TTI11004 nozzles at all pressures, the droplet velocities for spray particles less than 200 µm (driftable fines) are reduced for the 100% duty cycle compared to the standard configuration excluding a solenoid valve. Therefore, operating these venturi nozzles on a PWM sprayer causes an increase in drift potential simply with the inclusion of the inline solenoid valve.

Compared to the non-venturi nozzles, average droplet velocity patterns of venturi nozzles were less discernable (Table 3.2). When the PWM system was operated at a 100% duty cycle, the AITTJ6011004, AM11002, and AM11004 nozzles average spray droplet velocities increased or remained equal to a standard configuration with no inline solenoid valve. In contrast, the average spray droplet velocities for the AMDF11004, AMDF11008, and TTI11004 nozzles operated at a 100% duty cycle decreased or remained equal compared to a standard configuration. Across pressures and duty cycles, the average spray droplet velocity from highest to lowest for venturi nozzles followed the pattern: AM11004 > AMDF11008 > AM11002 > AMDF11004 > AITTJ6011004 > TTI11004. In contrast, the average droplet size for these nozzles followed the pattern: TTI11004 > AITTJ6011004 > AMDF11008 > AM11004 > AMDF11004 > AM11002 (Butts et al., 2017). The duty cycle impact on average droplet velocities for venturi nozzles was similar to, but more severe than the impact from non-venturi nozzles. Venturi nozzles operated at an 80% and 60% duty cycle reduced average droplet velocities by 3-16% and 7-27%, respectively, across pressures compared to the 100% duty cycle. The 40% and 20% duty cycles caused significant reductions (up to 50%) in average droplet velocities for venturi nozzles compared to the 100% duty cycle. Due to the increased reductions in droplet velocities caused by the use of venturi nozzles on a PWM sprayer and the inconsistent correlation between droplet size and velocity compared to non-venturi nozzles, there is merit to current recommendations of avoiding the use of venturi nozzles on PWM sprayers.

Similar to the non-venturi nozzles, the DS_{50} (Table 3.3) and DS_{75} (Table 3.4) of the venturi nozzles resulted in no apparent correlation with PWM duty cycle. Once again, this can be explained due to a decreased slope and maximum velocity of the models as duty cycle decreased within a nozzle and pressure observed in Figures 3.4-3.6. The DS_{50} and DS_{75} estimates and standard errors for the venturi nozzles were greater compared to the non-venturi nozzles across pressures. Therefore, the droplet velocities from venturi nozzles are less consistent and have a wider range of velocities within the spray pattern compared to the non-venturi counterparts demonstrating potential for problems if venturi nozzles are used in conjunction with a PWM sprayer. Similar to the non-venturi nozzles, the 20% duty cycle caused significant increases in standard errors of the DS_{50} and DS_{75} venturi nozzle estimates.

Conclusions

Spray droplet velocities were influenced by pressure, nozzle type, orifice size, and PWM duty cycle, but minimally impacted by spray solution. Similar trends were observed across spray solutions for the effect pressure, nozzle type, orifice size, and PWM duty cycle had on spray droplet velocity. Spray droplet velocities increased as pressure and orifice size increased across duty cycles, and decreased as PWM duty cycle decreased across nozzles and pressures. The 20% duty cycle resulted in greater variability in the resulting spray droplet velocities across nozzles. Venturi nozzles resulted in greater variability and reductions in spray droplet velocity than non-venturi nozzles when used in conjunction with a PWM system. The increased variability and reduction in spray droplet velocity could increase spray drift potential and reduce canopy penetration; future research will investigate the PWM effect on these spray characteristics. Based on present research, if PWM sprayers are to be used in site-specific pest management strategies, it is recommended that non-venturi nozzles coupled with greater than 40% duty cycle be used to reduce spray droplet velocity variability and mitigate changes in drift potential.

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Tables

Table 3.1. Nozzles (11), pulse-width modulation duty cycles (6), gauge application pressures (3), and spray solutions (2) used as treatments in this experiment.

Nozzle abbreviation	Nozzle name	Nozzle design	Duty cycle	Gauge pressure	Spray solution
			%	kPa	
AITTJ6011004[a]	Air Induction Turbo TwinJet	Venturi	Standard[d]	207	Water Alone
AM11002[b]	Airmix	Venturi	100	276	Glyphosate (Roundup PowerMAX®) plus ammonium sulfate (AMS)
AM11004[b]	Airmix	Venturi	80	414	
AMDF11004[b]	Airmix DualFan	Venturi	60		
AMDF11008[b]	Airmix DualFan	Venturi	40		
TTI11004[a]	Turbo TeeJet Induction	Venturi	20		
DR11004[c]	Combo-Jet Drift Control	Non-Venturi			
ER11004[c]	Combo-Jet Extended Range	Non-Venturi			
MR11004[c]	Combo-Jet Mid Range	Non-Venturi			
SR11004[c]	Combo-Jet Small Reduction	Non-Venturi			
UR11004[c]	Combo-Jet Ultra Drift Control	Non-Venturi			

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Standard duty cycle indicates no solenoid valve is equipped.

Table 3.2. Average spray droplet velocity of water influenced by nozzle type, gauge pressure, and duty cycle.

Nozzle	Gauge pressure	Average droplet velocity[d]					
		Duty cycle (%)					
		20	40	60	80	100	Standard[e]
	kPa	$m\ s^{-1}$					
AITTJ6011004[a]	207	3.6 e	4.0 de	4.3 cd	4.6 bc	4.9 a	4.7 b
AITTJ6011004[a]	276	4.9 bc	4.8 c	5.3 b	5.3 b	5.7 a	5.2 b
AITTJ6011004[a]	414	6.1 cd	6.3 cd	6.5 bc	6.8 b	7.1 a	6.0 d
AM11002[b]	207	5.5 c	5.6 c	5.8 c	6.1 b	6.5 a	6.4 a
AM11002[b]	276	5.8 d	6.7 bc	6.6 c	6.9 b	7.6 a	7.5 a
AM11002[b]	414	8.1 e	8.5 d	8.7 cd	9.0 b	9.5 a	8.8 bc
AM11004[b]	207	5.1 e	5.6 d	6.3 c	6.9 b	7.5 a	7.4 a
AM11004[b]	276	5.8 d	7.1 c	7.0 c	8.0 b	8.3 a	8.4 a
AM11004[b]	414	8.2 d	8.4 d	9.2 c	9.9 b	10.8 a	10.7 a
AMDF11004[b]	207	4.0 cd	3.9 d	4.5 c	5.2 b	5.9 a	5.9 a
AMDF11004[b]	276	3.9 e	4.3 e	4.9 d	5.6 c	6.3 b	6.8 a
AMDF11004[b]	414	5.2 e	5.7 e	6.2 d	6.9 c	7.5 b	8.2 a
AMDF11008[b]	207	3.7 f	4.5 e	5.4 d	6.6 c	7.4 b	8.1 a
AMDF11008[b]	276	4.9 e	5.5 e	6.2 d	7.2 c	8.3 b	9.2 a
AMDF11008[b]	414	6.2 f	7.2 e	8.1 d	8.7 c	10.3 b	11.6 a
TTI11004[a]	207	3.0 c	3.2 c	3.5 b	4.0 a	4.1 a	4.0 a
TTI11004[a]	276	3.5 d	3.5 d	4.0 c	4.1 c	4.3 b	4.7 a
TTI11004[a]	414	4.1 d	4.1 d	4.7 c	4.8 c	5.1 b	5.4 a
DR11004[c]	207	4.9 c	5.0 c	5.1 c	5.9 b	6.2 a	6.2 a
DR11004[c]	276	5.2 e	5.9 d	6.4 c	6.7 b	7.0 a	7.0 a
DR11004[c]	414	7.2 d	7.3 d	7.1 d	7.8 c	8.2 a	8.0 b
ER11004[c]	207	8.5 e	8.9 d	10.0 c	11.2 b	11.8 a	11.8 a
ER11004[c]	276	11.5 d	11.7 d	12.1 c	12.8 b	13.8 a	13.8 a
ER11004[c]	414	14.6 e	14.1 f	15.0 d	15.7 c	16.9 a	16.6 b
MR11004[c]	207	5.4 e	6.1 d	6.7 c	7.6 b	8.3 a	7.8 b
MR11004[c]	276	7.4 f	8.2 e	8.5 d	8.7 c	8.9 b	9.4 a
MR11004[c]	414	9.7 d	9.6 d	10.4 c	10.9 b	11.4 a	10.8 b
SR11004[c]	207	7.8 d	7.9 d	8.4 c	9.8 b	10.6 a	10.6 a
SR11004[c]	276	9.0 f	9.6 e	10.7 d	11.6 c	12.3 a	12.2 b
SR11004[c]	414	10.9 e	12.8 d	13.8 c	14.2 b	15.5 a	15.4 a
UR11004[c]	207	4.0 d	4.4 c	4.5 c	5.2 b	5.4 a	5.3 b
UR11004[c]	276	5.0 d	5.5 c	5.1 d	5.7 bc	5.8 ab	5.9 a
UR11004[c]	414	5.6 d	5.9 c	6.2 b	6.7 a	6.9 a	6.8 a

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Means within a nozzle and gauge pressure with the same letter are not significantly different ($P \leq 0.05$).
[e] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

Table 3.3. Estimated droplet size of water that has 50% of the maximum velocity (DS_{50}) and standard errors influenced by nozzle type, gauge pressure, and duty cycle.

Nozzle	Gauge pressure	DS_{50} (SE)					
		Duty cycle (%)					
		20	40	60	80	100	Standard[d]
	kPa	µm					
AITTJ6011004[a]	207	229 (15)	229 (12)	222 (6)	228 (7)	219 (5)	205 (6)
AITTJ6011004[a]	276	279 (64)	227 (22)	223 (9)	228 (7)	216 (5)	214 (6)
AITTJ6011004[a]	414	244 (42)	246 (26)	224 (8)	219 (9)	235 (12)	233 (9)
AM11002[b]	207	174 (4)	153 (3)	153 (3)	149 (2)	149 (2)	149 (2)
AM11002[b]	276	176 (6)	161 (3)	165 (4)	161 (3)	148 (4)	147 (2)
AM11002[b]	414	159 (4)	146 (4)	153 (4)	144 (4)	147 (4)	155 (3)
AM11004[b]	207	182 (10)	161 (5)	150 (3)	156 (2)	145 (3)	155 (3)
AM11004[b]	276	190 (7)	161 (4)	172 (5)	156 (3)	162 (4)	159 (4)
AM11004[b]	414	168 (5)	162 (4)	161 (7)	156 (6)	154 (8)	168 (9)
AMDF11004[b]	207	175 (15)	178 (18)	160 (10)	158 (8)	148 (5)	156 (5)
AMDF11004[b]	276	187 (12)	177 (7)	164 (5)	163 (4)	150 (4)	156 (4)
AMDF11004[b]	414	163 (11)	181 (8)	161 (5)	157 (5)	154 (4)	147 (5)
AMDF11008[b]	207	166 (19)	144 (12)	138 (8)	133 (6)	136 (4)	136 (3)
AMDF11008[b]	276	163 (21)	153 (29)	125 (7)	135 (3)	133 (4)	129 (3)
AMDF11008[b]	414	170 (15)	151 (6)	135 (4)	130 (4)	128 (4)	137 (6)
TTI11004[a]	207	232 (48)	266 (43)	238 (12)	216 (5)	246 (7)	209 (7)
TTI11004[a]	276	239 (10)	221 (6)	197 (4)	203 (3)	210 (3)	200 (4)
TTI11004[a]	414	214 (6)	209 (4)	200 (3)	202 (3)	193 (2)	204 (4)
DR11004[c]	207	132 (7)	124 (5)	129 (4)	118 (3)	116 (3)	117 (3)
DR11004[c]	276	163 (23)	128 (4)	128 (3)	123 (3)	109 (3)	117 (3)
DR11004[c]	414	134 (4)	131 (3)	131 (3)	111 (3)	122 (2)	118 (2)
ER11004[c]	207	110 (4)	100 (4)	96 (3)	81 (3)	79 (2)	96 (4)
ER11004[c]	276	90 (4)	91 (4)	72 (4)	79 (3)	72 (17)	119 (12)
ER11004[c]	414	98 (4)	83 (14)	88 (4)	240 (158)	321 (NA)	267 (119)
MR11004[c]	207	125 (9)	117 (4)	123 (3)	113 (3)	100 (2)	130 (2)
MR11004[c]	276	137 (4)	120 (4)	112 (3)	117 (2)	114 (3)	127 (2)
MR11004[c]	414	129 (4)	120 (3)	116 (3)	106 (3)	113 (9)	117 (3)
SR11004[c]	207	124 (4)	103 (4)	98 (4)	92 (3)	84 (3)	102 (2)
SR11004[c]	276	127 (4)	100 (5)	98 (3)	78 (4)	87 (4)	113 (6)
SR11004[c]	414	128 (3)	110 (3)	96 (3)	95 (8)	363 (1106)	335 (110)
UR11004[c]	207	101 (13)	188 (NA)	106 (6)	101 (5)	104 (4)	120 (3)
UR11004[c]	276	132 (6)	118 (5)	104 (6)	110 (5)	128 (3)	115 (3)
UR11004[c]	414	139 (6)	126 (5)	124 (4)	117 (3)	123 (3)	111 (3)

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

Table 3.4. Estimated droplet size of water that has 75% of the maximum velocity (DS_{75}) and standard errors influenced by nozzle type, gauge pressure, and duty cycle.

		DS_{75} (SE)					
		Duty cycle (%)					
Nozzle	Gauge pressure	20	40	60	80	100	Standard[d]
	kPa	μm					
AITTJ6011004[a]	207	351 (40)	361 (34)	312 (14)	370 (22)	343 (15)	364 (22)
AITTJ6011004[a]	276	623 (261)	457 (91)	368 (30)	375 (23)	347 (17)	361 (18)
AITTJ6011004[a]	414	498 (166)	492 (100)	368 (29)	383 (35)	430 (47)	418 (29)
AM11002[b]	207	242 (11)	219 (9)	237 (11)	211 (6)	219 (6)	224 (7)
AM11002[b]	276	244 (15)	233 (10)	253 (12)	241 (8)	260 (16)	226 (8)
AM11002[b]	414	245 (14)	235 (15)	245 (14)	243 (15)	257 (16)	252 (12)
AM11004[b]	207	298 (32)	247 (14)	234 (10)	243 (8)	243 (9)	258 (10)
AM11004[b]	276	287 (22)	249 (11)	284 (16)	253 (10)	290 (16)	284 (14)
AM11004[b]	414	268 (17)	257 (15)	304 (28)	304 (24)	344 (40)	373 (41)
AMDF11004[b]	207	278 (42)	323 (59)	270 (33)	266 (25)	226 (14)	252 (16)
AMDF11004[b]	276	283 (30)	252 (16)	244 (13)	248 (13)	238 (11)	256 (14)
AMDF11004[b]	414	258 (32)	282 (22)	242 (12)	253 (14)	256 (14)	262 (19)
AMDF11008[b]	207	310 (65)	264 (42)	262 (28)	260 (24)	235 (12)	227 (9)
AMDF11008[b]	276	329 (81)	395 (146)	242 (24)	215 (9)	254 (16)	228 (11)
AMDF11008[b]	414	305 (50)	243 (19)	216 (12)	223 (13)	246 (16)	308 (31)
TTI11004[a]	207	598 (226)	685 (203)	432 (44)	355 (17)	443 (27)	384 (24)
TTI11004[a]	276	378 (28)	344 (19)	298 (11)	299 (8)	324 (9)	337 (14)
TTI11004[a]	414	317 (15)	313 (12)	307 (10)	309 (8)	291 (6)	350 (14)
DR11004[c]	207	236 (23)	182 (7)	204 (9)	195 (7)	197 (6)	194 (6)
DR11004[c]	276	405 (124)	208 (10)	206 (7)	205 (7)	199 (8)	203 (7)
DR11004[c]	414	210 (11)	203 (8)	203 (7)	203 (9)	209 (7)	206 (7)
ER11004[c]	207	159 (5)	143 (4)	144 (3)	165 (11)	172 (15)	234 (31)
ER11004[c]	276	175 (16)	138 (4)	161 (18)	183 (23)	324 (212)	326 (71)
ER11004[c]	414	139 (4)	247 (125)	191 (25)	1203 (1213)	2199 (NA)	1022 (670)
MR11004[c]	207	234 (28)	190 (9)	192 (6)	195 (7)	184 (7)	201 (5)
MR11004[c]	276	218 (11)	206 (11)	184 (7)	185 (5)	235 (18)	221 (9)
MR11004[c]	414	204 (10)	205 (11)	188 (7)	187 (7)	325 (64)	247 (20)
SR11004[c]	207	193 (11)	155 (5)	166 (7)	176 (8)	210 (22)	215 (14)
SR11004[c]	276	194 (11)	180 (11)	163 (5)	224 (46)	234 (39)	285 (41)
SR11004[c]	414	188 (8)	177 (8)	165 (7)	276 (65)	2829 (12478)	2081 (990)
UR11004[c]	207	193 (26)	8246 (NA)	169 (8)	162 (5)	172 (6)	184 (5)
UR11004[c]	276	210 (14)	195 (9)	223 (20)	208 (12)	200 (5)	182 (5)
UR11004[c]	414	200 (9)	184 (7)	203 (8)	192 (7)	201 (6)	200 (8)

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

Figures

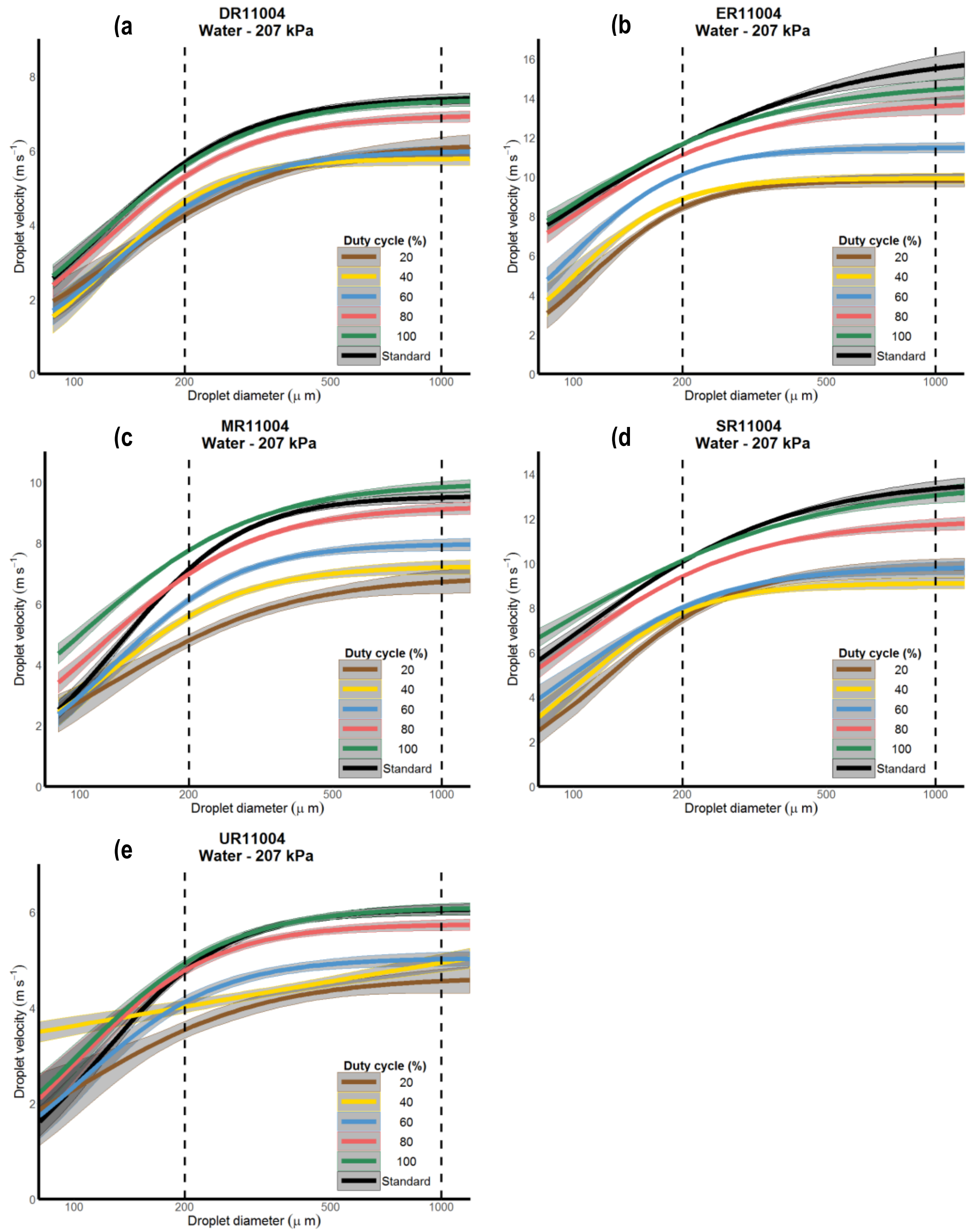

Figure 3.1. Droplet velocity predictions of water at 207 kPa as influenced by duty cycle for the (a) DR11004, (b) ER11004, (c) MR11004, (d) SR11004, and (e) UR11004 non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

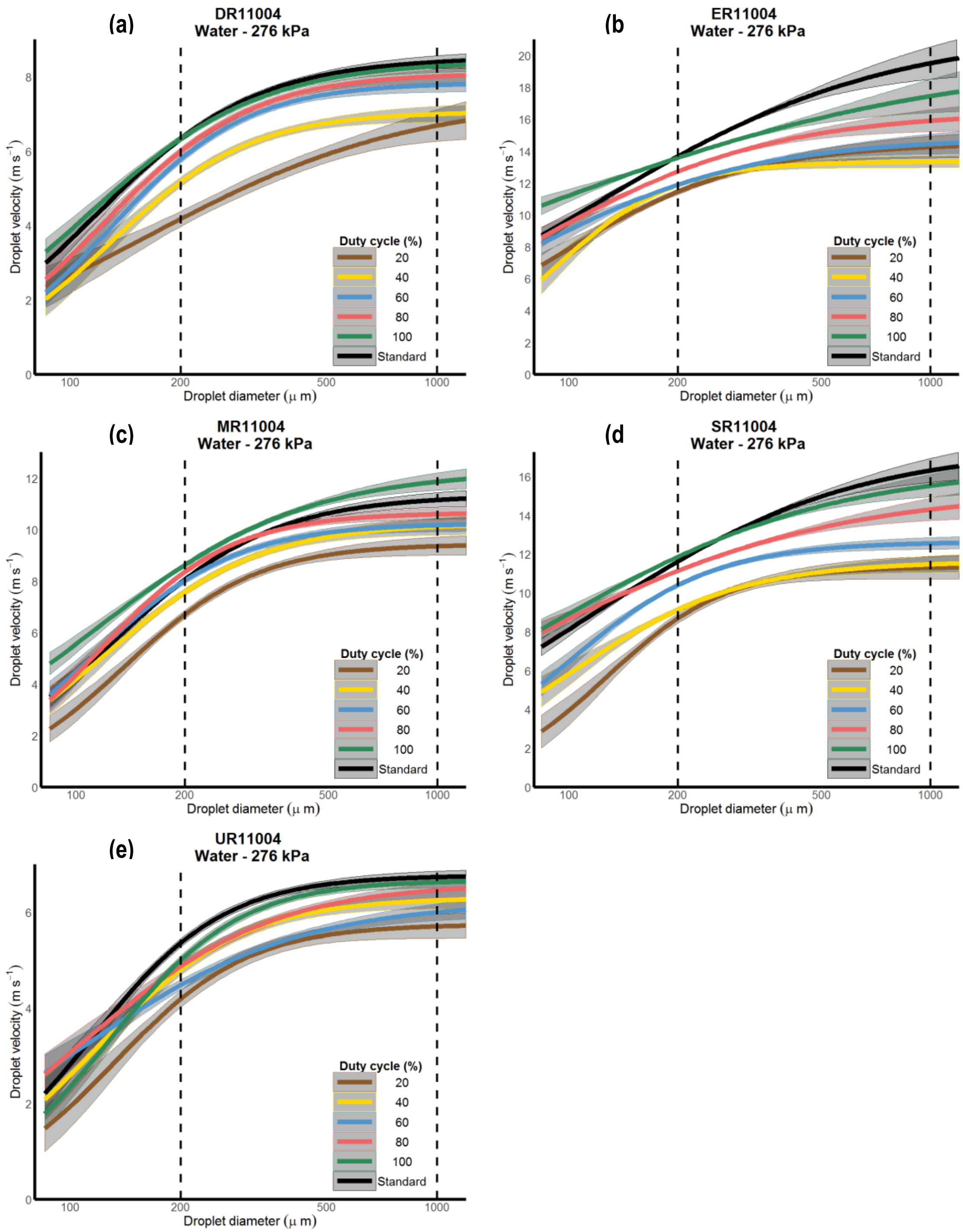

Figure 3.2. Droplet velocity predictions of water at 276 kPa as influenced by duty cycle for the (a) DR11004, (b) ER11004, (c) MR11004, (d) SR11004, and (e) UR11004 non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

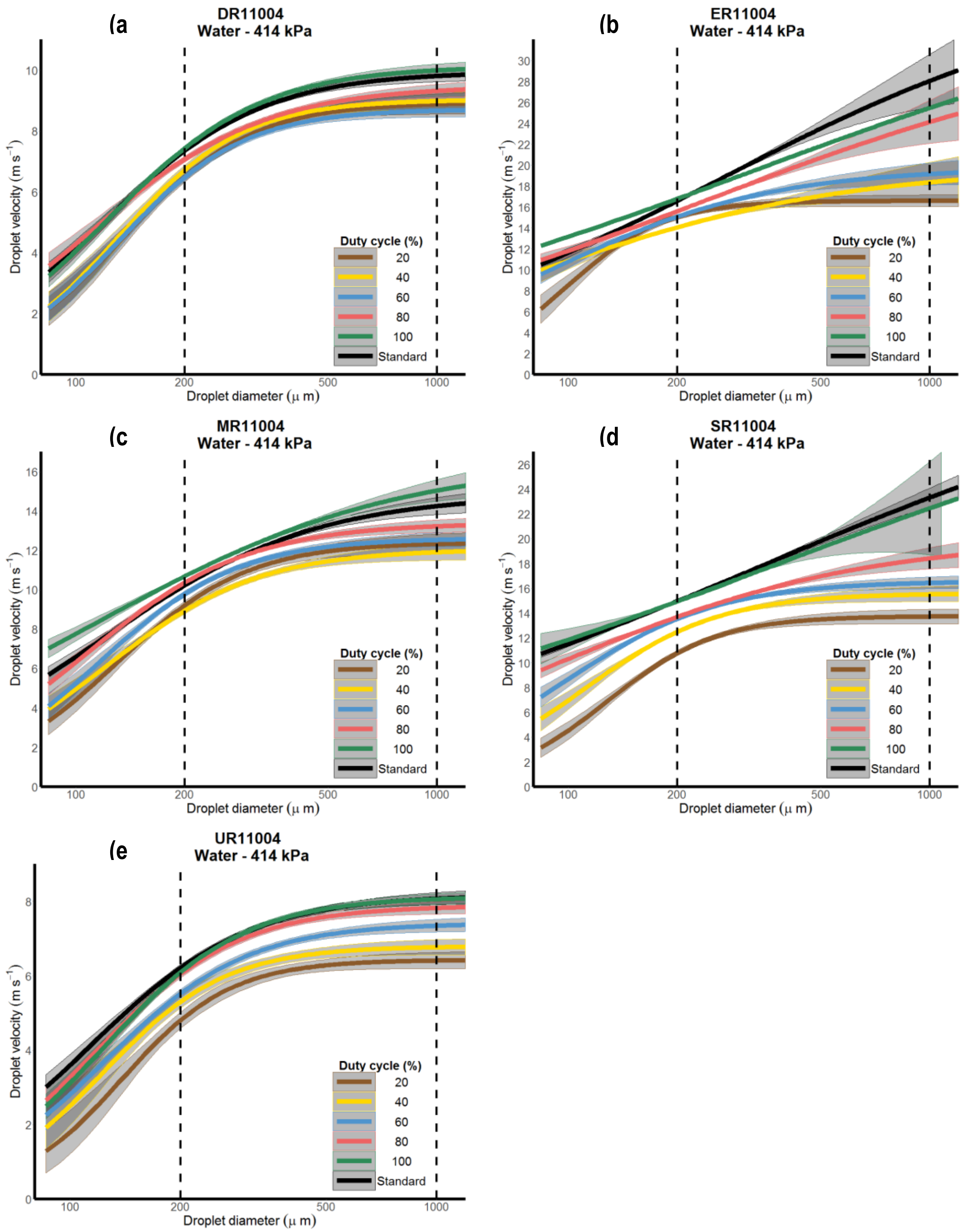

Figure 3.3. Droplet velocity predictions of water at 414 kPa as influenced by duty cycle for the (a) DR11004, (b) ER11004, (c) MR11004, (d) SR11004, and (e) UR11004 non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

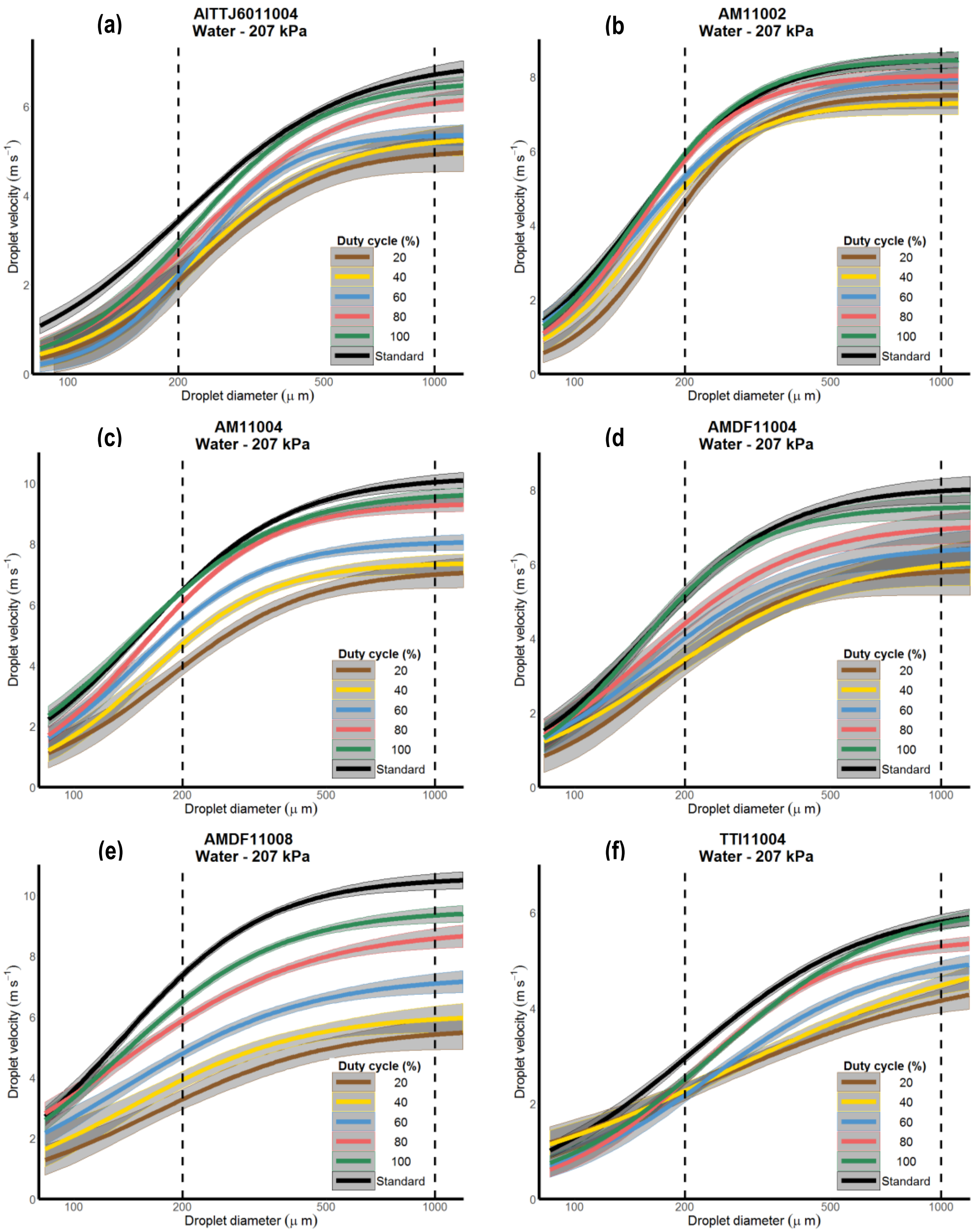

Figure 3.4. Droplet velocity predictions of water at 207 kPa as influenced by duty cycle for the (a) AITTJ6011004, (b) AM11002, (c) AM11004, (d) AMDF11004, (e) AMDF11008, and (f) TTI11004 venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

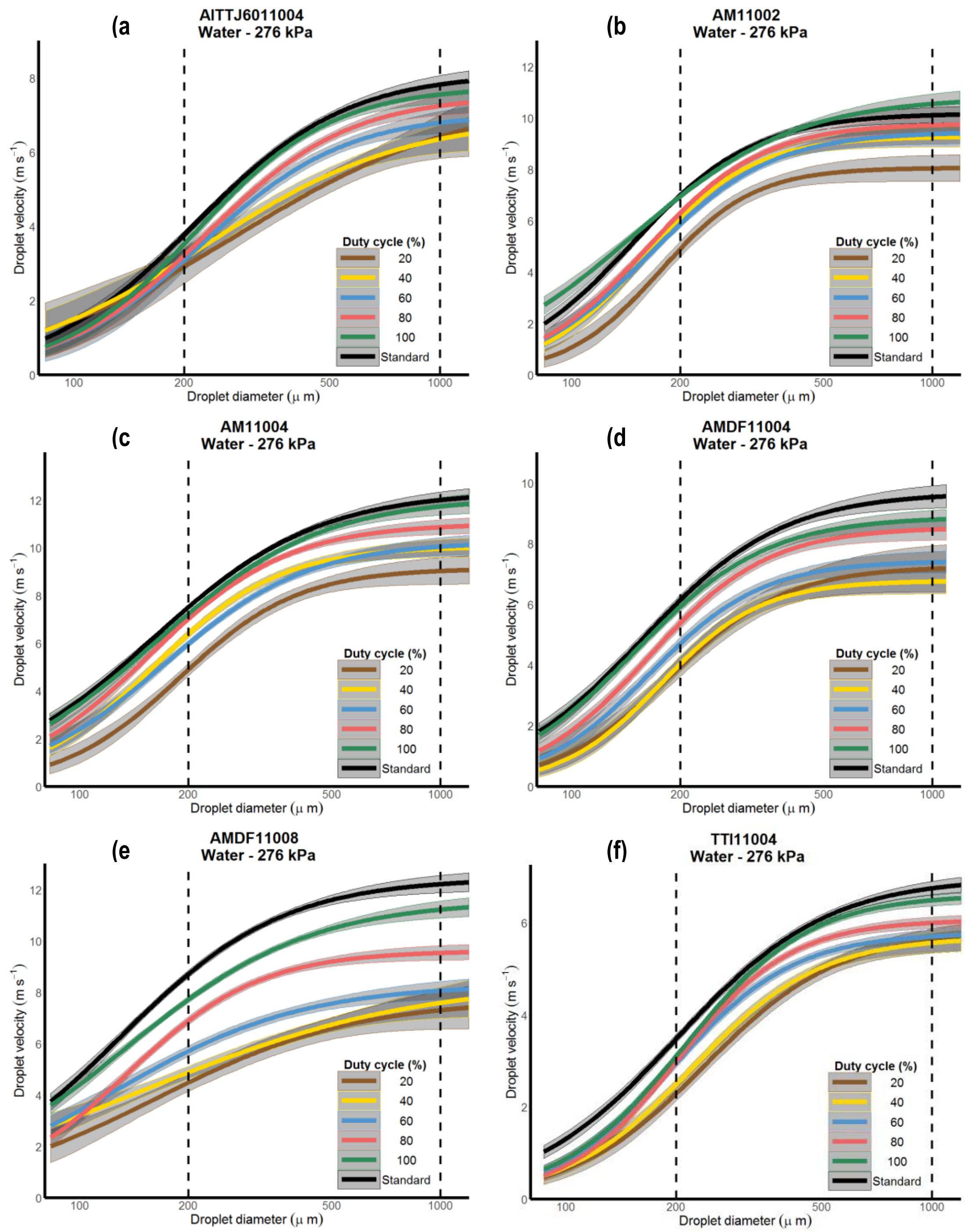

Figure 3.5. Droplet velocity predictions of water at 276 kPa as influenced by duty cycle for the (a) AITTJ6011004, (b) AM11002, (c) AM11004, (d) AMDF11004, (e) AMDF11008, and (f) TTI11004 venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

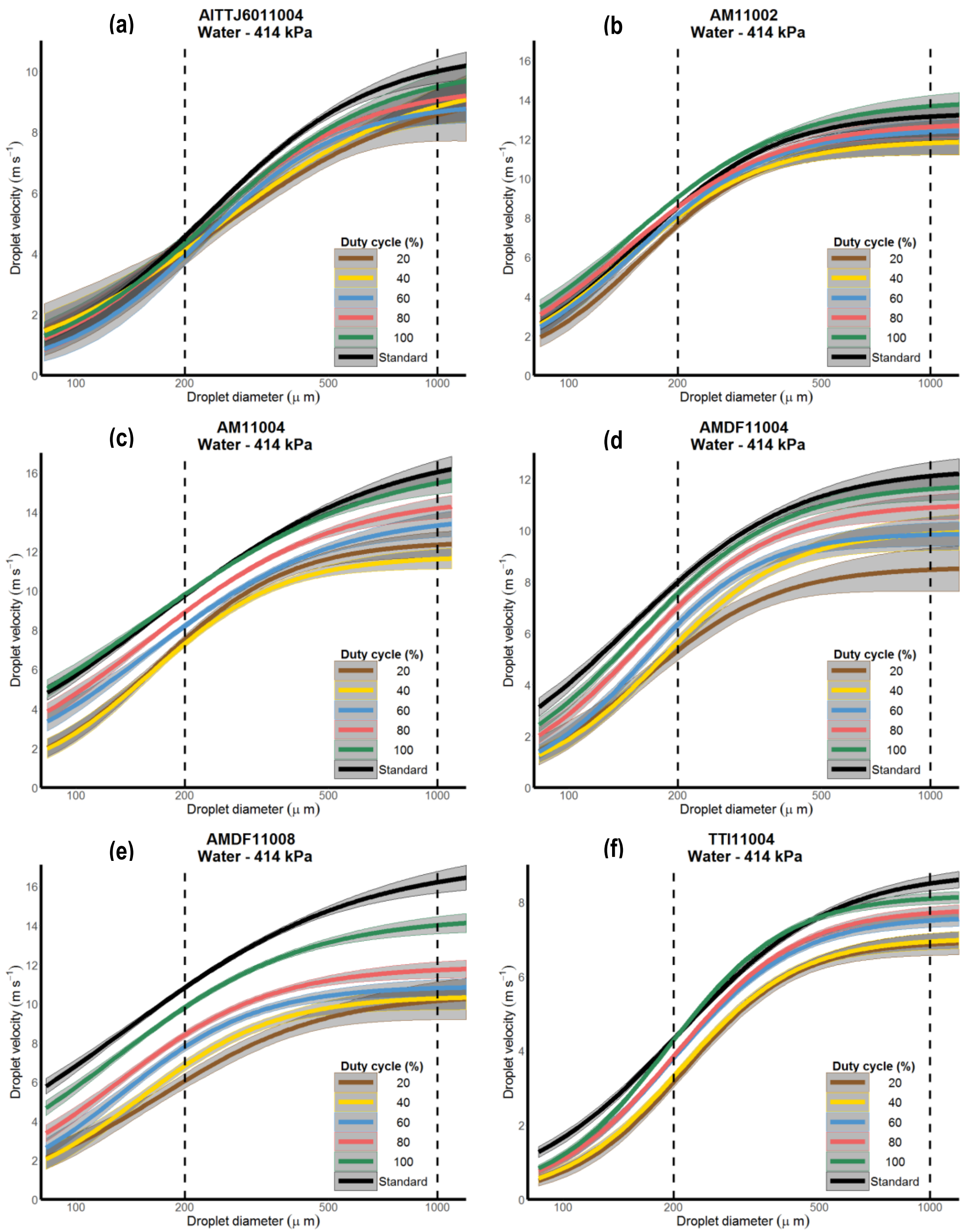

Figure 3.6. Droplet velocity predictions of water at 414 kPa as influenced by duty cycle for the (a) AITTJ6011004, (b) AM11002, (c) AM11004, (d) AMDF11004, (e) AMDF11008, and (f) TTI11004 venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

APPENDIX (B)

Table B.1. Average spray droplet velocity of glyphosate plus AMS solution influenced by nozzle type, gauge pressure, and duty cycle.

Nozzle	Gauge pressure	Average droplet velocity[d]					
		Duty cycle (%)					
		20	40	60	80	100	Standard[e]
	kPa	m s^{-1}					
AITTJ6011004[a]	207	3.9 b	4.0 b	4.1 b	4.5 a	4.7 a	4.7 a
AITTJ6011004[a]	276	4.8 bc	4.7 c	4.9 bc	5.1 b	5.3 a	5.1 b
AITTJ6011004[a]	414	5.4 d	5.6 d	5.9 c	6.1 bc	6.4 a	6.3 ab
AM11002[b]	207	5.1 d	5.2 d	5.5 c	5.8 b	6.1 a	5.6 bc
AM11002[b]	276	6.2 d	6.6 cd	6.8 bc	7.0 b	7.2 a	6.8 bc
AM11002[b]	414	7.4 e	8.2 d	8.5 cd	8.9 b	9.5 a	8.7 bc
AM11004[b]	207	5.2 d	5.3 d	5.8 c	6.6 b	7.0 a	6.9 ab
AM11004[b]	276	6.4 d	6.4 d	7.1 c	7.6 b	8.0 a	7.9 a
AM11004[b]	414	7.5 d	8.4 c	8.2 c	9.7 b	10.5 a	9.7 b
AMDF11004[b]	207	4.2 c	4.6 c	5.2 b	5.6 b	6.0 a	5.5 b
AMDF11004[b]	276	5.4 cd	5.3 d	5.8 c	6.4 b	6.9 a	6.4 b
AMDF11004[b]	414	6.3 e	6.9 d	7.7 c	8.3 b	9.0 a	7.8 c
AMDF11008[b]	207	3.6 f	4.2 e	5.0 d	5.9 c	7.0 b	7.8 a
AMDF11008[b]	276	4.6 f	5.2 e	6.0 d	6.9 c	7.8 b	8.9 a
AMDF11008[b]	414	6.7 e	7.4 d	8.0 c	8.7 b	10.0 a	10.2 a
TTI11004[a]	207	3.0 e	3.0 e	3.4 d	3.7 c	3.8 b	4.5 a
TTI11004[a]	276	3.9 c	4.0 c	4.3 b	4.7 a	4.9 a	4.8 a
TTI11004[a]	414	5.1 bc	5.1 c	4.8 c	5.1 c	5.5 ab	5.6 a
DR11004[c]	207	4.7 e	5.0 d	5.6 c	5.9 b	6.1 a	6.0 b
DR11004[c]	276	5.6 e	5.9 d	6.1 c	6.4 b	6.7 a	6.4 b
DR11004[c]	414	6.3 d	6.8 c	6.9 c	7.4 b	7.7 a	7.7 a
ER11004[c]	207	8.2 e	8.6 d	9.5 c	10.4 b	11.1 a	11.2 a
ER11004[c]	276	9.8 d	9.8 d	11.0 c	11.7 b	12.7 a	12.8 a
ER11004[c]	414	11.7 e	12.9 d	13.5 c	15.8 b	16.6 a	15.6 b
MR11004[c]	207	6.0 f	6.3 e	7.0 d	7.7 c	8.0 b	8.4 a
MR11004[c]	276	7.3 f	7.7 e	8.2 d	8.8 c	9.2 b	9.5 a
MR11004[c]	414	9.1 e	9.4 d	9.9 c	10.5 b	11.1 a	11.0 a
SR11004[c]	207	7.5 e	7.8 d	8.5 c	9.4 b	10.1 a	10.0 a
SR11004[c]	276	8.7 e	8.9 e	9.8 d	10.9 c	11.3 b	11.8 a
SR11004[c]	414	11.5 f	11.9 e	12.6 d	13.5 c	14.4 b	14.7 a
UR11004[c]	207	4.0 e	4.2 e	4.4 d	4.9 c	5.3 b	5.5 a
UR11004[c]	276	5.2 cd	5.0 d	5.1 d	5.3 c	5.7 b	5.9 a
UR11004[c]	414	5.1 e	5.8 d	6.1 c	6.4 b	6.6 a	6.7 a

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Means within a nozzle and gauge pressure with the same letter are not significantly different ($P \leq 0.05$).
[e] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

Table B.2. Estimated droplet size of glyphosate plus AMS solution that has 50% of the maximum velocity (DS_{50}) and standard errors influenced by nozzle type, gauge pressure, and duty cycle.

Nozzle	Gauge pressure	DS_{50} (SE)					
		Duty cycle (%)					
		20	40	60	80	100	Standard[d]
	kPa	µm					
AITTJ6011004[a]	207	216 (14)	206 (13)	215 (8)	214 (7)	227 (6)	201 (7)
AITTJ6011004[a]	276	207 (13)	201 (9)	205 (8)	214 (6)	219 (5)	219 (10)
AITTJ6011004[a]	414	222 (14)	217 (9)	199 (7)	217 (8)	236 (9)	242 (19)
AM11002[b]	207	152 (4)	152 (4)	148 (3)	142 (2)	141 (2)	159 (4)
AM11002[b]	276	157 (5)	144 (3)	145 (4)	136 (3)	135 (3)	160 (6)
AM11002[b]	414	148 (3)	133 (3)	132 (3)	133 (3)	127 (4)	147 (6)
AM11004[b]	207	155 (6)	147 (4)	156 (3)	141 (3)	138 (3)	160 (7)
AM11004[b]	276	192 (12)	167 (4)	151 (3)	153 (3)	147 (3)	170 (10)
AM11004[b]	414	165 (6)	150 (5)	130 (4)	150 (6)	157 (13)	186 (19)
AMDF11004[b]	207	95 (15)	125 (16)	153 (33)	186 (36)	131 (9)	163 (7)
AMDF11004[b]	276	149 (22)	158 (12)	154 (7)	149 (8)	131 (7)	148 (6)
AMDF11004[b]	414	193 (30)	130 (8)	161 (12)	133 (10)	128 (9)	159 (9)
AMDF11008[b]	207	156 (11)	132 (8)	120 (5)	125 (4)	116 (3)	137 (5)
AMDF11008[b]	276	165 (16)	125 (5)	122 (4)	123 (3)	119 (3)	131 (5)
AMDF11008[b]	414	144 (20)	144 (12)	141 (8)	126 (4)	138 (13)	174 (18)
TTI11004[a]	207	219 (10)	219 (7)	196 (5)	205 (4)	196 (3)	180 (5)
TTI11004[a]	276	231 (9)	206 (6)	211 (5)	213 (4)	193 (3)	197 (5)
TTI11004[a]	414	223 (11)	235 (7)	230 (6)	223 (4)	221 (3)	193 (4)
DR11004[c]	207	105 (7)	114 (6)	108 (4)	113 (3)	107 (3)	114 (3)
DR11004[c]	276	117 (6)	122 (4)	118 (3)	108 (3)	109 (3)	116 (4)
DR11004[c]	414	137 (4)	123 (3)	118 (3)	112 (3)	112 (2)	109 (3)
ER11004[c]	207	199 (NA)	86 (4)	83 (4)	67 (3)	57 (4)	69 (3)
ER11004[c]	276	98 (4)	79 (5)	93 (3)	86 (3)	133 (47)	321 (214)
ER11004[c]	414	97 (5)	67 (6)	104 (56)	99 (5)	337 (349)	101 (50)
MR11004[c]	207	119 (4)	107 (5)	108 (3)	103 (3)	99 (3)	93 (2)
MR11004[c]	276	89 (7)	101 (4)	101 (3)	94 (3)	91 (3)	93 (3)
MR11004[c]	414	100 (4)	109 (3)	95 (3)	93 (3)	77 (3)	103 (5)
SR11004[c]	207	112 (6)	101 (4)	94 (3)	89 (3)	77 (3)	85 (3)
SR11004[c]	276	114 (4)	105 (4)	98 (3)	92 (3)	96 (5)	100 (11)
SR11004[c]	414	93 (5)	102 (4)	100 (3)	90 (5)	105 (18)	107 (13)
UR11004[c]	207	745 (NA)	104 (7)	106 (6)	92 (5)	93 (5)	101 (5)
UR11004[c]	276	115 (6)	99 (7)	88 (7)	79 (7)	88 (5)	113 (4)
UR11004[c]	414	124 (6)	100 (6)	105 (4)	103 (3)	101 (3)	101 (3)

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

Table B.3. Estimated droplet size of glyphosate plus AMS solution that has 75% of the maximum velocity (DS_{75}) and standard errors influenced by nozzle type, gauge pressure, and duty cycle.

Nozzle	Gauge pressure	DS_{75} (SE) Duty cycle (%) 20	40	60	80	100	Standard[d]
	kPa	μm					
AITTJ6011004[a]	207	325 (41)	342 (42)	345 (28)	366 (27)	379 (23)	373 (25)
AITTJ6011004[a]	276	356 (53)	325 (26)	347 (27)	356 (22)	359 (19)	434 (36)
AITTJ6011004[a]	414	384 (50)	365 (31)	344 (29)	384 (31)	437 (37)	523 (76)
AM11002[b]	207	213 (9)	245 (14)	224 (8)	218 (8)	216 (7)	250 (13)
AM11002[b]	276	240 (15)	219 (10)	244 (16)	232 (12)	238 (14)	279 (20)
AM11002[b]	414	197 (7)	220 (15)	213 (11)	221 (12)	247 (23)	261 (22)
AM11004[b]	207	249 (18)	239 (15)	241 (10)	243 (11)	245 (12)	305 (25)
AM11004[b]	276	355 (45)	263 (14)	244 (11)	262 (13)	263 (14)	352 (39)
AM11004[b]	414	255 (19)	247 (18)	202 (9)	302 (28)	396 (71)	426 (79)
AMDF11004[b]	207	217 (68)	283 (69)	476 (213)	526 (201)	291 (41)	274 (21)
AMDF11004[b]	276	329 (102)	296 (46)	267 (24)	299 (38)	267 (31)	256 (21)
AMDF11004[b]	414	428 (125)	227 (23)	336 (56)	306 (52)	309 (59)	302 (34)
AMDF11008[b]	207	249 (32)	223 (25)	208 (15)	213 (11)	215 (12)	285 (25)
AMDF11008[b]	276	310 (59)	197 (13)	201 (11)	206 (10)	219 (11)	267 (22)
AMDF11008[b]	414	339 (95)	314 (54)	285 (33)	228 (15)	368 (70)	422 (80)
TTI11004[a]	207	351 (31)	350 (22)	311 (14)	323 (11)	311 (14)	329 (18)
TTI11004[a]	276	356 (29)	307 (15)	316 (12)	328 (11)	292 (8)	341 (15)
TTI11004[a]	414	368 (35)	355 (19)	381 (19)	349 (12)	350 (10)	326 (13)
DR11004[c]	207	156 (8)	179 (8)	160 (4)	174 (4)	171 (4)	192 (8)
DR11004[c]	276	198 (14)	196 (8)	179 (5)	179 (6)	183 (5)	224 (16)
DR11004[c]	414	222 (12)	182 (6)	201 (9)	197 (8)	203 (8)	195 (10)
ER11004[c]	207	2479 (NA)	141 (5)	142 (5)	162 (19)	204 (66)	175 (30)
ER11004[c]	276	139 (5)	152 (13)	160 (8)	190 (22)	560 (366)	2847 (2733)
ER11004[c]	414	151 (9)	143 (20)	490 (530)	215 (30)	2031 (3015)	417 (402)
MR11004[c]	207	184 (8)	192 (12)	172 (5)	166 (4)	182 (7)	154 (5)
MR11004[c]	276	181 (21)	171 (8)	160 (5)	167 (6)	184 (11)	198 (18)
MR11004[c]	414	156 (6)	168 (6)	181 (11)	160 (6)	195 (25)	238 (30)
SR11004[c]	207	222 (27)	162 (6)	147 (4)	192 (15)	210 (31)	181 (15)
SR11004[c]	276	202 (17)	185 (12)	179 (10)	193 (17)	249 (42)	289 (73)
SR11004[c]	414	183 (21)	178 (11)	192 (16)	222 (37)	359 (136)	304 (79)
UR11004[c]	207	59502000 (NA)	157 (7)	155 (6)	135 (4)	135 (3)	167 (7)
UR11004[c]	276	156 (6)	139 (5)	131 (5)	134 (5)	139 (4)	184 (7)
UR11004[c]	414	189 (11)	172 (8)	166 (5)	158 (4)	158 (4)	175 (7)

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

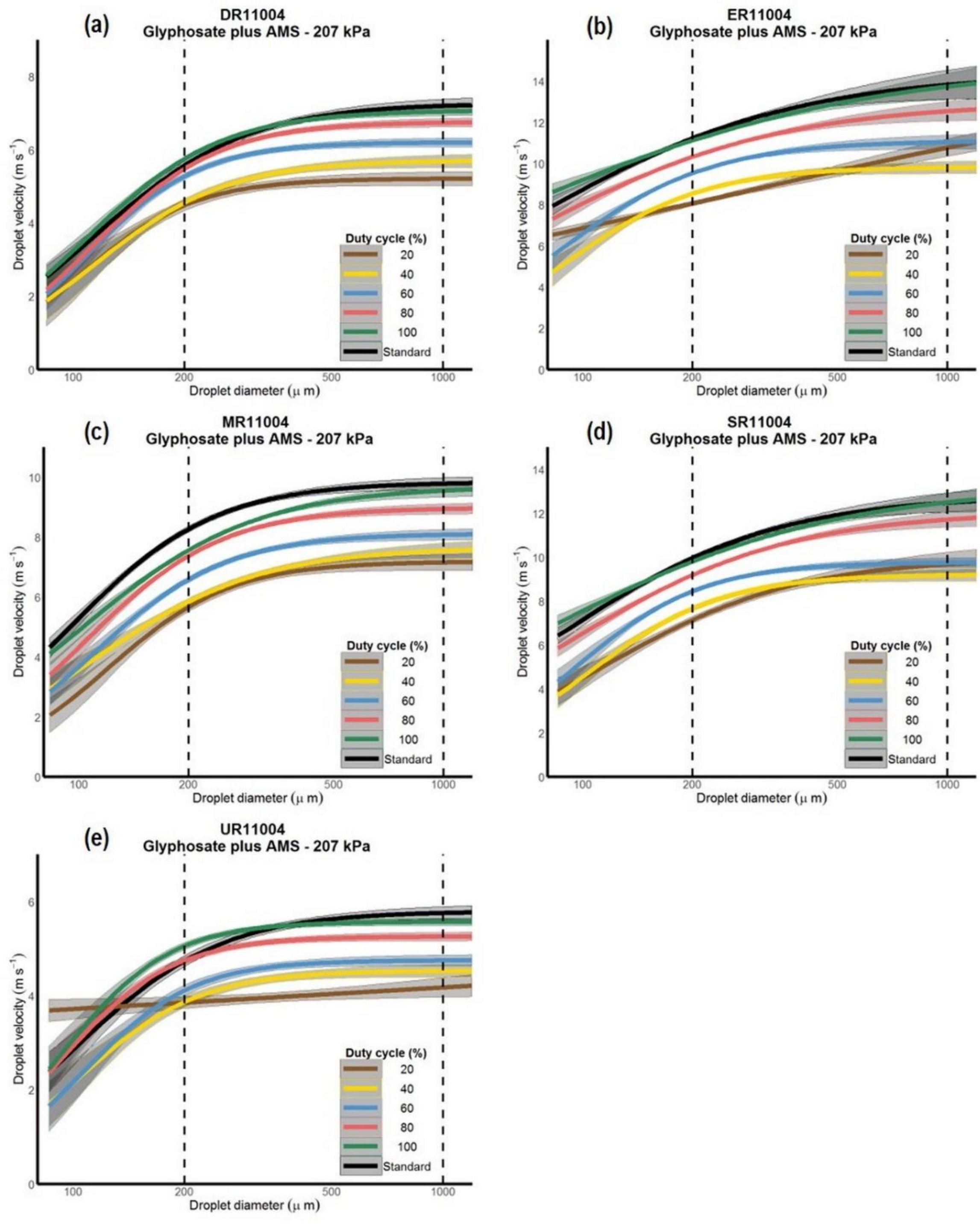

Figure B.1. Droplet velocity predictions of glyphosate plus AMS solution at 207 kPa as influenced by duty cycle for the DR11004 (a), ER11004 (b), MR11004 (c), SR11004 (d), and UR11004 (e) non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

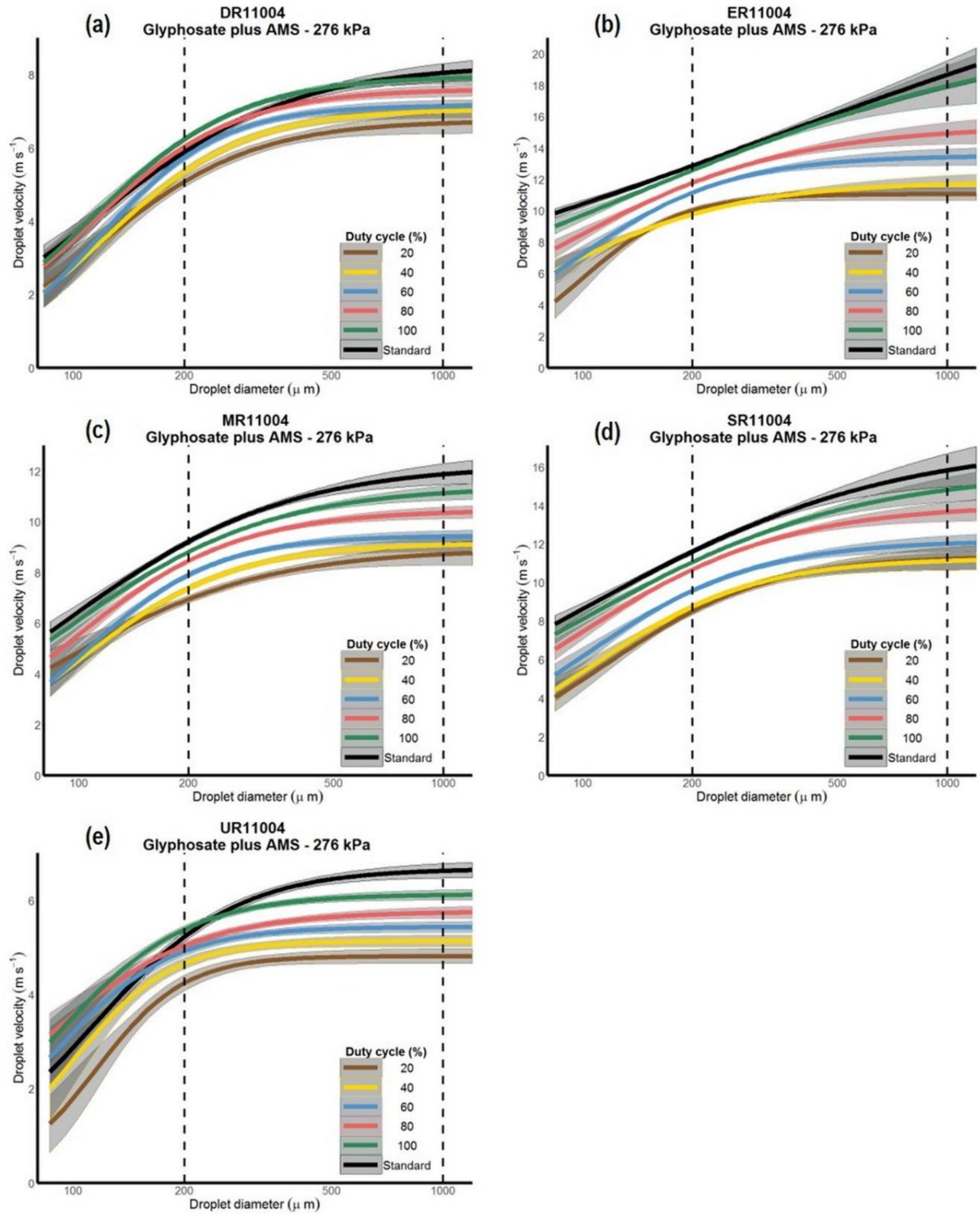

Figure B.2. Droplet velocity predictions of glyphosate plus AMS solution at 276 kPa as influenced by duty cycle for the DR11004 (a), ER11004 (b), MR11004 (c), SR11004 (d), and UR11004 (e) non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

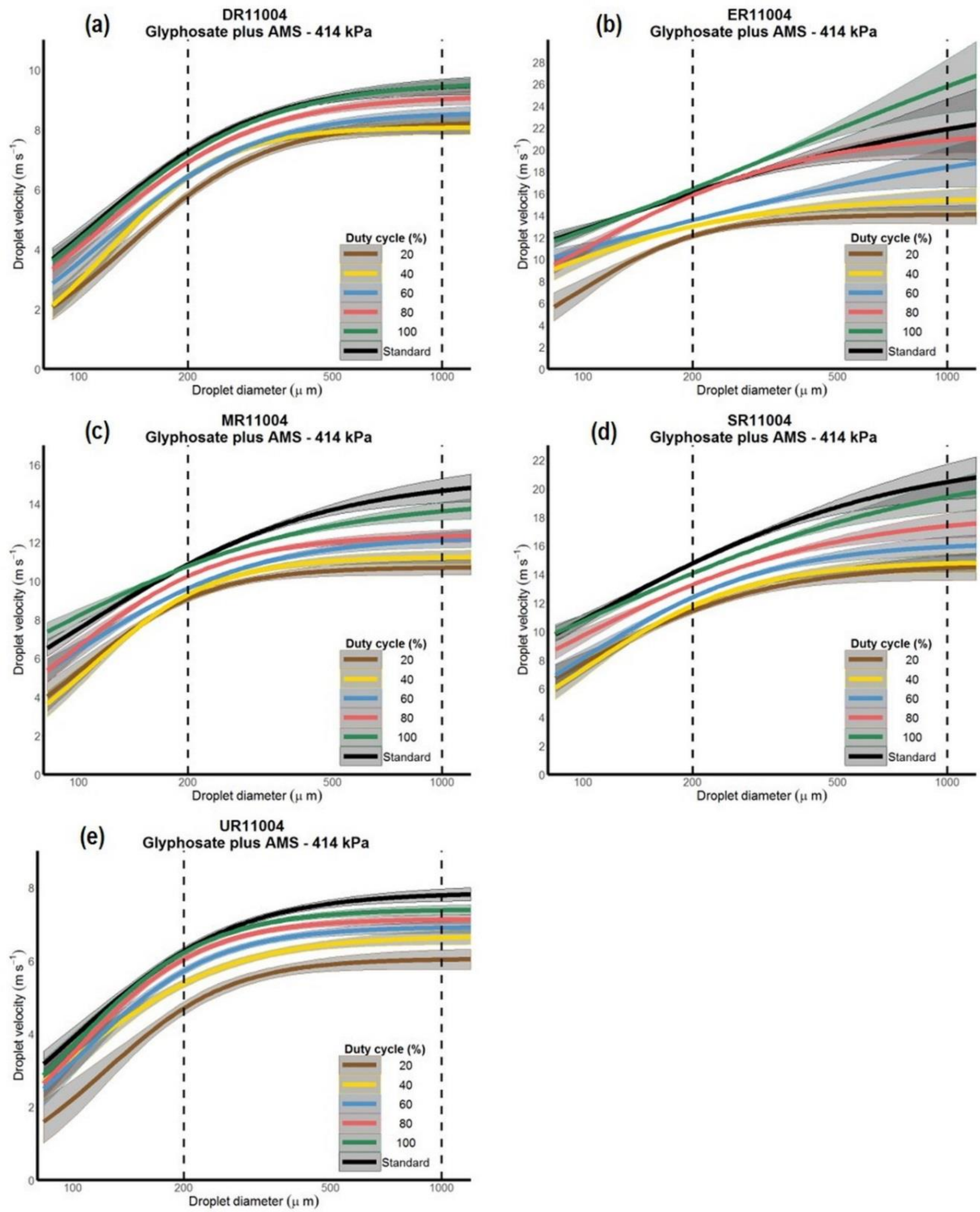

Figure B.3. Droplet velocity predictions of glyphosate plus AMS solution at 414 kPa as influenced by duty cycle for the DR11004 (a), ER11004 (b), MR11004 (c), SR11004 (d), and UR11004 (e) non-venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

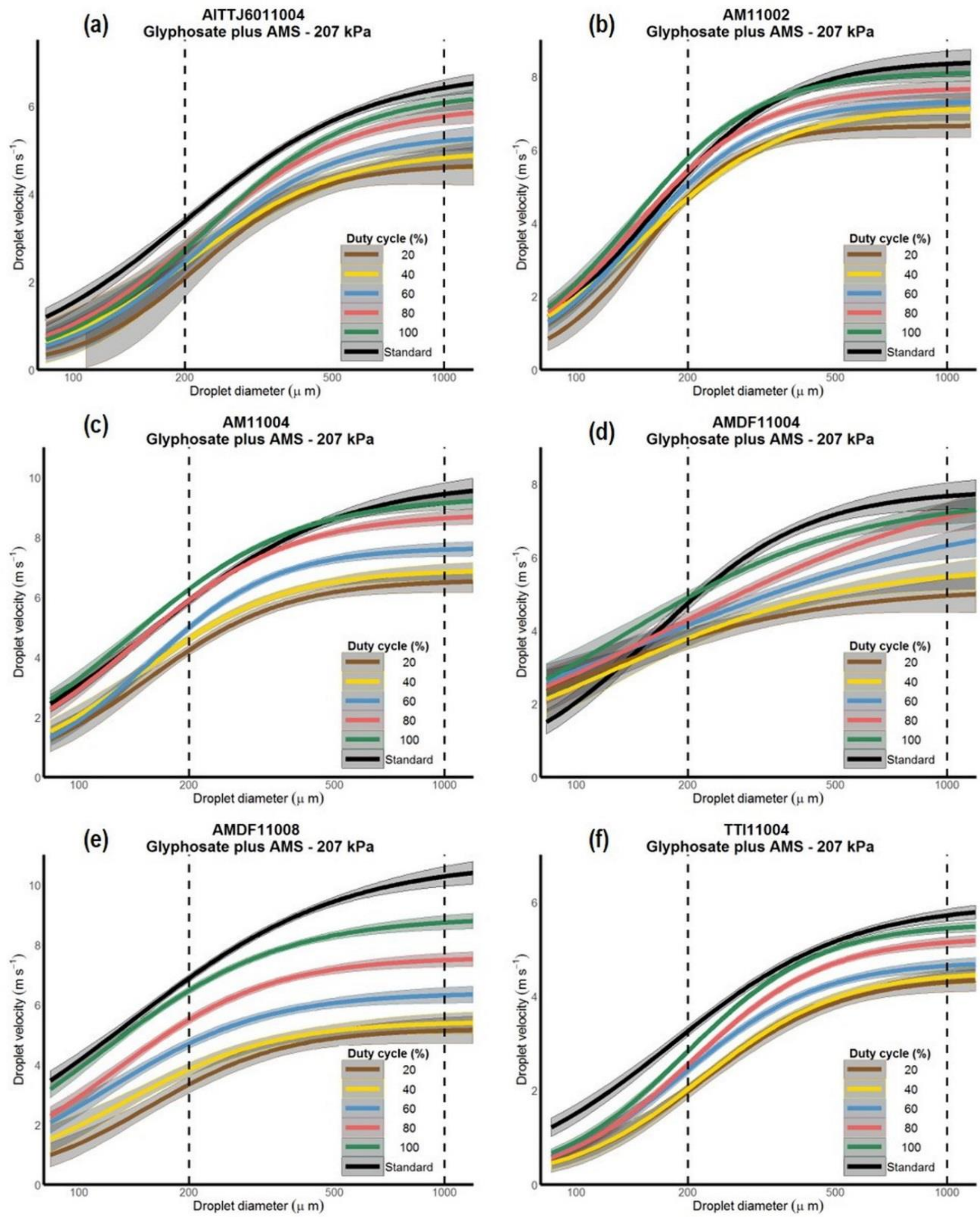

Figure B.4. Droplet velocity predictions of glyphosate plus AMS solution at 207 kPa as influenced by duty cycle for the AITTJ6011004 (a), AM11002 (b), AM11004 (c), AMDF11004 (d), AMDF11008 (e), and TTI11004 (f) venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

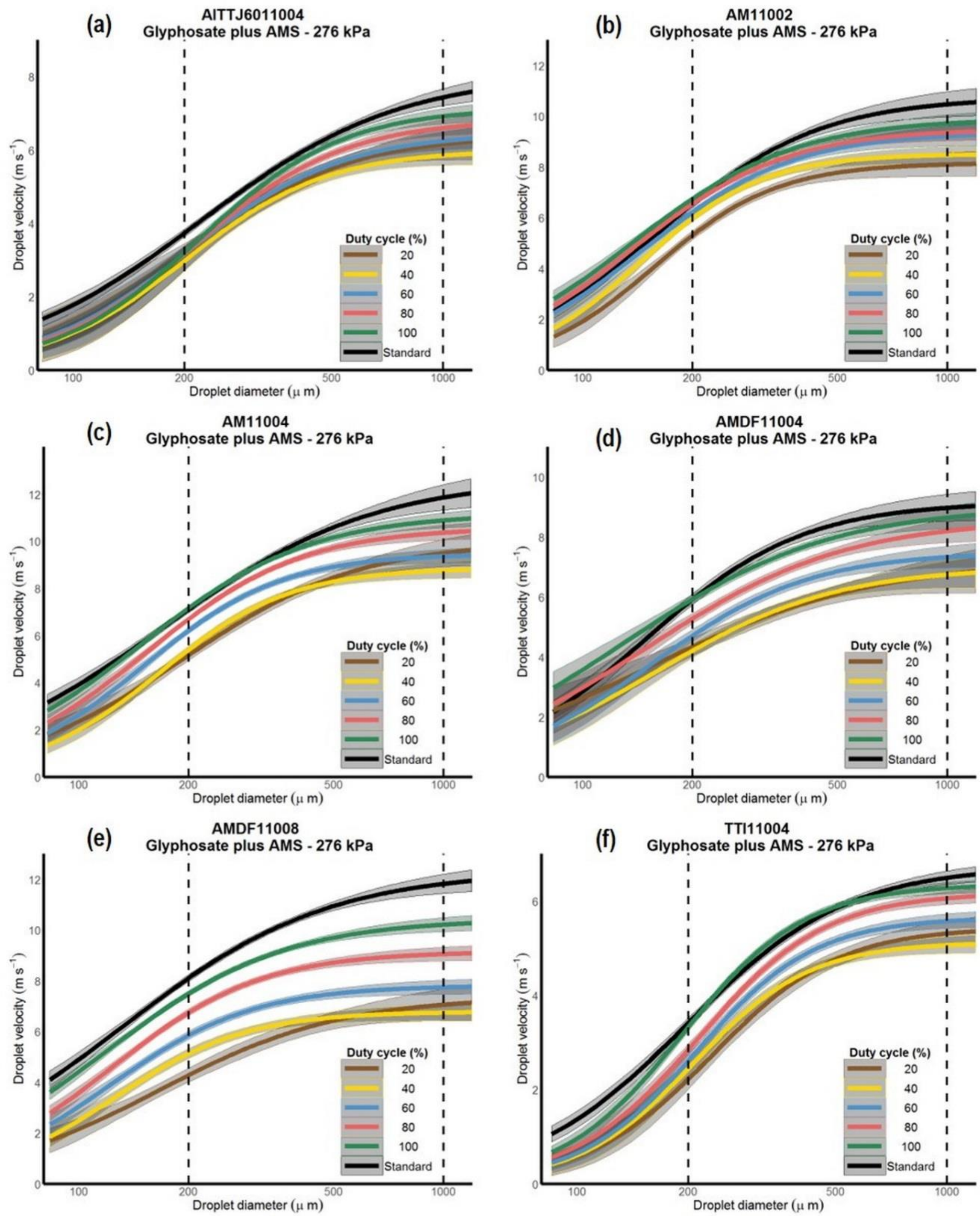

Figure B.5. Droplet velocity predictions of glyphosate plus AMS solution at 276 kPa as influenced by duty cycle for the AITTJ6011004 (a), AM11002 (b), AM11004 (c), AMDF11004 (d), AMDF11008 (e), and TTI11004 (f) venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

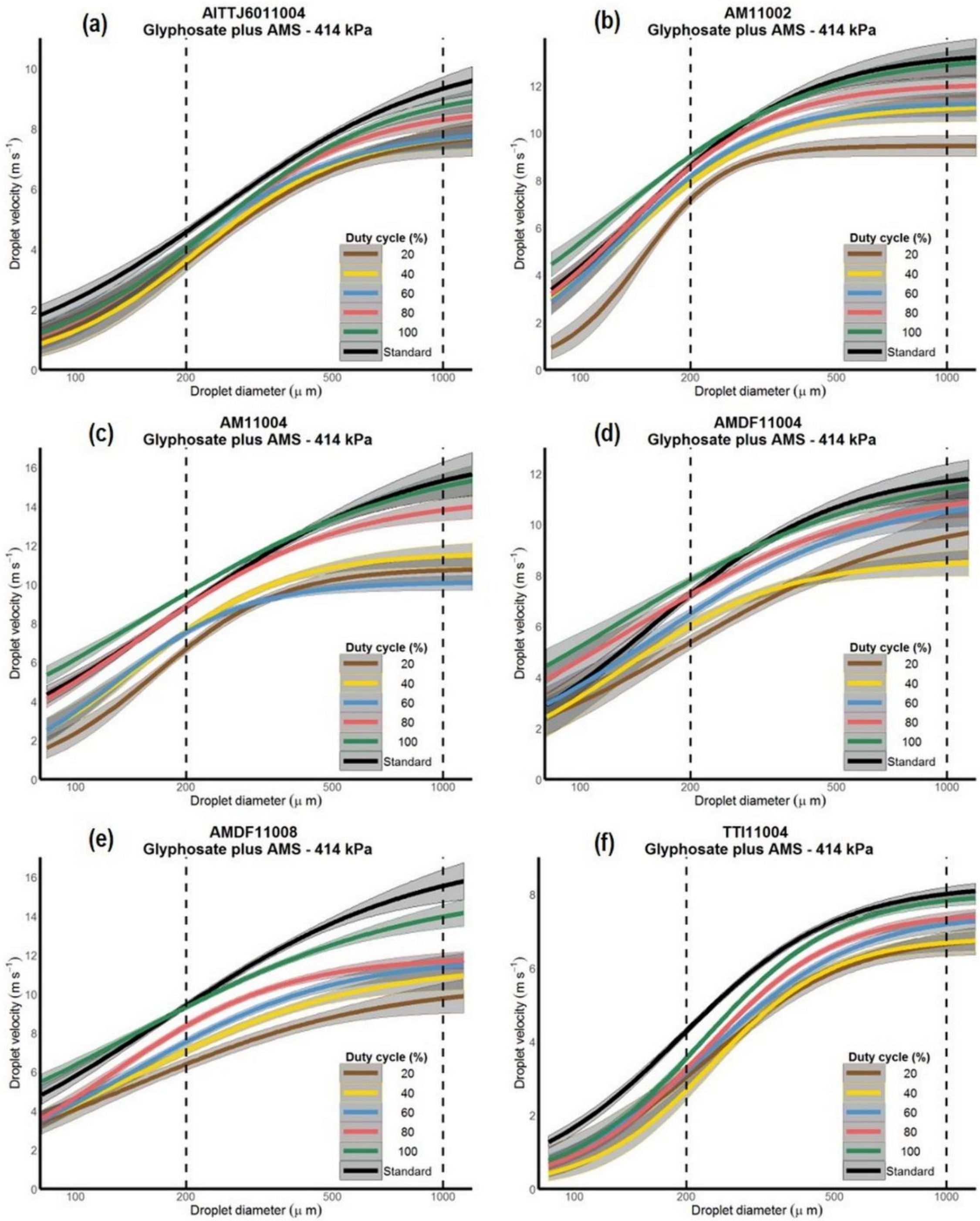

Figure B.6. Droplet velocity predictions of glyphosate plus AMS solution at 414 kPa as influenced by duty cycle for the AITTJ6011004 (a), AM11002 (b), AM11004 (c), AMDF11004 (d), AMDF11008 (e), and TTI11004 (f) venturi nozzles. Standard duty cycle refers to a conventional sprayer with no solenoid valve equipped.

CHAPTER 4

EVALUATION OF SPRAY PATTERN UNIFORMITY USING THREE UNIQUE ANALYSES AS IMPACTED BY NOZZLE, PRESSURE, AND PULSE-WIDTH MODULATION DUTY CYCLE

Abstract

Most agricultural pesticide applications exclusively utilize hydraulic nozzles which form a spray pattern from the breakup of the spray solution liquid sheet. This spray pattern is critical to maintain an accurate overlap of spray to reduce crop injury potential while maximizing coverage on target pests to increase efficacy. The increasing popularity of pulse-width modulation (PWM) sprayers requires that application interaction effects on spray pattern uniformity be completely understood to maximize sprayer efficiency. The objective of this research was to determine the impacts of nozzle type (venturi vs. non-venturi), gauge application pressure, and PWM duty cycle on spray pattern uniformity. Research was conducted using an indoor spray patternator with automated data collection located at the University of Nebraska-Lincoln in Lincoln, NE USA. Coefficient of variation (CV), root mean square error (RMSE), and average percent error (APE) were used to characterize the spray pattern uniformity. Generally, across nozzles and pressures, duty cycle had minimal impact on the CV of spray patterns. However, across nozzles and duty cycles, increasing pressure decreased CV values resulting in more uniform spray patterns. The RMSE values typically increased as pressure and duty cycle increased across nozzles. This may be the result of a correlation between RMSE

values and flow rate as RMSE values also increased as nozzle orifice size increased. Generally, APE increased as duty cycle decreased across nozzles and pressures with significant increases (40%) caused by the 20% duty cycle. Within non-venturi nozzles, increasing pressure reduced APE across duty cycles, while venturi nozzles followed no such trend. Overall, results suggest PWM duty cycles at or above 40% minimally impact spray pattern uniformity. Further, increased application pressures and the use of non-venturi nozzles on PWM sprayers increase the precision and uniformity of spray applications.

Introduction

Pesticide applications are complex processes that require great detail to optimize effectively. Previous survey results highlighted only 20 – 30% of applicators were applying pesticides within 5% of their intended application rate (Grisso et al., 1989; Ozkan, 1987). Furthermore, only 38% and 51% of commercial and noncommercial applicators, respectively, inspected sprayer parts prior to each use to detect potential issues that may affect spray pattern uniformity (Bish and Bradley, 2017). The spray pattern is critical for maintaining optimum coverage to maximize efficacy throughout an application as agricultural pesticides are almost exclusively applied using hydraulic nozzles (Matthews et al., 2014). These nozzles meter the flow and atomize the spray solution through breakup of the liquid sheet which creates the resulting spray pattern.

Current nozzle technologies, specifically venturi nozzles, were designed to create coarser droplets by entraining air within the spray solution in the nozzle body (Briffa and Dombrowski, 1966). These designs were created because Fine droplets, specifically droplets < 200 µm, have a higher probability of drifting off-target than coarser droplets (Byass and Lake, 1977; Hewitt, 1997). However, it was previously noted that venturi nozzles have greater variability in spray pattern distribution, especially at low application pressures, compared to non-venturi nozzles which in turn contributes to a loss in weed control (Ayers et al., 1990; Etheridge et al., 1999). Additionally, a multitude of nozzle factors were observed to influence spray pattern uniformity including tip material (Wang et al., 1995), orifice wear (Ozkan et al., 1992), lateral angle, spacing, pitch angle, and incorrect selection (Forney et al., 2017).

Drift reduction adjuvants (Ozkan et al., 1993) and spray formulations (Mun et al., 1999) have been shown to impact spray pattern uniformity by forcing a greater volume of spray toward the center of the nozzle. This spray pattern collapse with the resulting increase of spray volume centered under the nozzle may lead to improper overlap between nozzles and thereby underapply chemical between each nozzle. This underapplication may lead to decreased efficacy and hasten the evolution of pesticide resistance (Gressel, 2011; Manalil et al., 2011; Neve and Powles, 2005).

Azimi et al. (1985) investigated the influence of boom height, application pressure, and nozzle spacing on spray pattern uniformity. Results indicated increasing boom height and pressure reduced CV values, thus producing more uniform spray patterns. Narrow nozzle spacing (< 51 cm) reduced CV values and buffered the negative effects of reduced boom heights and pressures on pattern uniformity. However, improper sprayer setup, specifically in regards to nozzle selection and placement, may be the greater cause of spray pattern deformities in current pesticide applications (Forney et al., 2017). Krishnan et al. (1988) showed crosswinds increased pattern CV values compared to headwinds of the same velocity, especially at increased pressures. Reductions in sprayer speed and tire pressure were also identified as methods to enhance spray pattern uniformity (Langenakens et al., 1995). The array of aforementioned factors influencing spray patterns illustrates the complexity of optimizing application uniformity and the need for alternative technologies to reduce confounding effects within an application.

Pulse-width modulation (PWM) sprayers allow for several factors, including application pressure and sprayer speed, to become independent from flow rate to increase application precision. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003). PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Pressure based variable rate flow control devices were shown to have slow response time and affect nozzle performance (Giles & Comino, 1989).

PWM sprayers provide the possibility for more precise applications through automatic boom and individual nozzle shut off controls (Luck et al., 2010a, 2010b) and minimizing changes in droplet trajectory and velocity (Butts et al., 2017b; Giles, 2001; Giles and Ben-Salem, 1992). PWM sprayers also provide the opportunity to maintain an optimum droplet size throughout an application as duty cycle minimally impacts droplet size emitted from non-venturi nozzles (Butts et al., 2017a; Giles et al., 1996). Additionally, pulsing dual non-venturi nozzle configurations increased coverage on

Palmer amaranth (*Amaranthus palmeri* S. Wats.) while simultaneously minimizing the drift potential of small droplets (Womac et al., 2017, 2016). Although PWM sprayers have numerous benefits, previous research demonstrated that as PWM duty cycle decreased, spray pattern uniformity decreased for hollow-cone, solid-cone, and, to a lesser extent, non-venturi flat fan nozzles, because more spray was concentrated directly underneath the nozzle (Giles and Comino, 1990). Mangus et al. (2017) expanded on this concept and identified that although the correct flow rate was emitted per pulse regardless of duty cycle, spray coverage uniformity decreased as duty cycle decreased suggesting that areas of under- and over-application may occur.

Spray pattern uniformity is critical for an optimum pesticide application to reduce the likelihood of crop injury, maximize coverage, and increase pesticide efficacy. The increasing popularity of PWM sprayers requires that current nozzle technologies, pressure, and duty cycle interactions be completely understood to maximize sprayer efficiency. The objectives of this research were: (1) to determine the impacts of nozzle type (venturi vs. non-venturi), gauge application pressure, and PWM duty cycle on spray pattern uniformity, and (2) compare three unique analyses and identify potential benefits and drawbacks for each to provide a more holistic spray pattern uniformity evaluation.

Materials and Methods

SPRAY PATTERN TESTING

Research was conducted using an indoor spray patternator (Figure 4.1) at the University of Nebraska-Lincoln in Lincoln, NE USA to evaluate how nozzle type, gauge pressure, and PWM duty cycle influenced spray pattern uniformity. Patternator construction (Luck et al., 2016) and operation (Forney et al., 2017) were described in detail in previous literature. In short, the patternator measured the amount of time needed to fill fixed-volume (166 mL) individual collection tubes spaced 2.5 cm apart. Each collection tube was equipped with a liquid-level sensor (102101, Honeywell Inc., Morris Plains, NJ) connected directly to an adjacent computer and triggered a virtual instrument in LabVIEW software (National Instruments Corporation, Austin, TX) to automatically record time measurements.

Pattern testing was conducted applying water with three nozzles spaced 51 cm apart and a 51 cm boom height to meet nozzle manufacturer recommendations for correct overlap. A SharpShooter® PWM system (Capstan Ag Systems, Inc., Topeka, KS) was equipped to select the specific duty cycle treatments and was operated at a 10 Hz frequency with the nozzles on an alternate timing (Blended Pulse®) (Capstan Ag Systems Inc., 2006). Spray pattern data were collected in two 51 cm sets to the left and right of the center nozzle. The two sets were then combined into one 102 cm dataset. Three replicates of the 102 cm data collection width were collected for each treatment.

The experimental design of this research was a completely randomized design with a factorial arrangement of treatments. Treatments consisted of 12 nozzles, six PWM duty cycles, and three gauge application pressures for a total of 216 treatments (Table 4.1). Gauge application pressures were determined by measuring the pressure prior to the solenoid valve as previous research demonstrated PWM solenoid valves contain an internal restriction which causes a pressure loss at the nozzle (Butts et al., 2017a).

After the raw spray pattern data were collected, time measurements were converted to flow rates (mL min^{-1}) for further analysis. The standard method of characterizing spray pattern uniformity is by calculating the coefficient of variation (CV) (Equation 4.1). The CV is a standardized measure of data point dispersion and provides a relative estimate of the extent of variability in relation to the average flow rate across the spray pattern. Greater CV values indicate greater dispersion and variability within the spray pattern. A CV below 10% indicates a desirable spray pattern uniformity, while a CV greater than 15% is unacceptable for an application (Forney et al., 2017; Krishnan et al., 1988; Ozkan et al., 1992; Siebe and Luck, 2016).

$$CV(proportion) = \frac{\sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n-1}}}{\frac{\sum_i^n x_i}{n}} \quad [4.1]$$

where:

x_i = flow rate (mL min^{-1}) of the i^{th} sample across spray pattern width,

$\bar{x}$ = mean flow rate (mL min^{-1}) to fill collection tubes across 102 cm pattern width,

n = number of collection tubes.

In addition to CV, alternative methods of evaluating spray pattern uniformity were tested as previous hypotheses have indicated CV may not be a good representation of the entire spray pattern variation present (Forney et al., 2017; Ozkan, 1987). The root mean square error (RMSE) and average percent error (APE) were calculated using predicted flow rate data based on an assumption of an ideal uniform spray pattern across the collection width using the capacity of one nozzle. The predicted flow rate data were calculated for each treatment across collection tubes using Equation 4.2.

$$PFR = \left(\frac{\frac{(flow_1 * \sqrt{kPa_2})}{\sqrt{276}}}{20^*} \right) * DC \quad [4.2]$$

where:

PFR = predicted flow rate (ml min^{-1} $tube^{-1}$),

$flow_1$= theoretical flow rate (ml min^{-1}) of respective nozzle treatment at 276 kPa,

$\sqrt{kPa_2}$= square root of gauge application pressure,

20* = number of collection tubes a 110° fan angle nozzle at a 51 cm boom height would span,

DC = duty cycle (proportion).

The RMSE estimates how concentrated the individual collection tube flow rate data is around the *PFR* and was calculated using Equation 4.3. Greater RMSE values indicate greater disparity between the calculated and measured data points, thus less uniform spray patterns.

$$RMSE = \sqrt{\frac{\sum_i^n((AFR_i - PFR)^2)}{n}} \quad [4.3]$$

where:

RMSE = root mean square error (mL min^{-1}),

AFR_i = actual flow rate measured (mL min^{-1}) for the i^{th} collection tube,

PFR = predicted flow rate (mL min^{-1}),

n = number of collection tubes.

The APE is a measurement of the discrepancy between measured and predicted values and provides an estimation of the data precision. It was calculated for each individual collection tube, and then averaged across collection tubes for one average error data point per treatment replicate (Equation 4.4). Greater APE values indicate greater discrepancy between measured and predicted values, thus lower precision and less uniform spray patterns.

$$APE\ (\%) = \frac{\sum_i^n \left(\frac{AFR_i - PFR}{PFR} * 100\right)}{n} \qquad [4.4]$$

STATISTICAL ANALYSES

Spray pattern CV, RMSE, and APE data were subjected to analysis of variance (ANOVA) using a mixed effect model in SAS (SAS v9.4, SAS Institute Inc., Cary, NC). Nozzle type, PWM duty cycle, and gauge application pressure were treated as fixed effects. Means were separated using Fisher's Protected LSD Test at $\alpha = 0.05$. A gamma distribution was used for analysis of RMSE values as data were bound between zero and positive infinity, and a beta distribution was used for analysis of CV proportion values as data were bound between zero and one (Stroup, 2013). A beta distribution was initially used for analysis of APE data; however, the models became overdispersed, so a Gaussian distribution was used for simplicity. Backtransformed data are presented for clarity.

Results and Discussion

CV DATA

CV data had a significant duty cycle*nozzle*pressure interaction ($P < 0.0001$). Due to the complexity of the three-way interaction and the abundance of treatments, the results are discussed generally as overall observed trends, but the importance of the three-way interaction should not be dismissed as it demonstrates the complexity of the application process. Further, the mean separations provided in Table 4.2 are presented to specifically evaluate the influence of PWM duty cycle on spray pattern CV values.

No discernable trend in CV data emerged for the effect of duty cycle (Table 4.2). Across nozzles and pressures, CV values at the 100% duty cycle increased, decreased, or remained the same compared to the standard setup (no solenoid valve equipped) 19, 11, and 70% of the time, respectively. This indicates the addition of a solenoid valve to the system did not consistently influence spray pattern uniformity similar to droplet size or velocity findings in previous research (Butts et al., 2017a, 2017b).

The AITTJ-6011004, AMDF11008, and GAT11004 nozzles (dual fan venturi nozzles) had CV values greater than 10% occur 89, 56, and 72% of the time across pressures and duty cycles, which was a greater percentage of occurrences than other nozzles tested, excluding the SR11004 non-venturi nozzle. This research suggests that the design of these dual fan venturi nozzles creates less uniform spray patterns and thus less precise applications as a CV below 10% indicates a desirable spray pattern uniformity (Forney et al., 2017; Krishnan et al., 1988; Ozkan et al., 1992; Siebe and Luck, 2016). Other venturi nozzles (AM11002, AM11004, AMDF11004, and TTI11004) had acceptable spray pattern uniformity CV values and were relatively unaffected by duty cycle or pressure. In contrast, increasing application pressure reduced CV values from non-venturi nozzles (DR11004, ER11004, MR11004, SR11004, and UR11004) especially at lower duty cycles. Despite increasing application pressure up to 414 kPa, the SR11004 non-venturi nozzle never had a CV value less than 10% across duty cycles, thus never produced an acceptable spray pattern. Current PWM best use practices have recommended the use of only non-venturi nozzles on these systems (Butts et al., 2017a; Capstan Ag Systems Inc., 2013). Based on CV data, increasing application pressure would benefit the spray pattern uniformity emitted from the recommended non-venturi nozzles similar to conclusions from previous research (Siebe and Luck, 2016). Overall, CV data would suggest pulsing, regardless of nozzle, has minimal impact on spray pattern uniformity, especially when operated at greater gauge application pressures.

RMSE DATA

RMSE data had a significant duty cycle*nozzle*pressure interaction (P = 0.0004). Similarly to CV data, due to the complexity of the three-way interaction and the abundance of treatments, the RMSE results are discussed generally as overall observed trends. Further, the mean separations provided in Table 4.3 are presented to specifically evaluate the influence of PWM duty cycle on spray pattern RMSE values.

Generally, across nozzles and pressures, duty cycle impacted RMSE spray pattern data similarly (Table 4.3). As duty cycle decreased from 100% to 80%, RMSE values typically increased which indicates the 80% duty cycle resulted in less uniform spray patterns as there was greater disparity between measured and predicted flow rate data. However, the 60% duty cycle RMSE values were typically less than or equal to the 100% duty cycle RMSE values and further decreases in duty cycle resulted in even lower RMSE values. These results indicate lower duty cycles, specifically below 80%, result in similar or more uniform spray patterns across nozzles and pressures when measured using RMSE. Across nozzles and pressures, RMSE values at the 100% duty cycle increased, decreased, or remained the same compared to the standard setup (no solenoid valve equipped) 19, 3, and 78% of the time, respectively. Similar to the CV values, the addition of a solenoid valve did not influence the spray pattern uniformity as measured using RMSE.

Generally, across duty cycles and nozzles, as gauge application pressure increased, RMSE values increased indicating less uniform spray patterns. The UR11004 non-venturi nozzle was the main exception to this general trend as increasing pressure decreased the RMSE values across duty cycles. Venturi nozzles were much more sensitive to this pressure effect than non-venturi nozzles as greater ranges in RMSE values across pressures were observed for the venturi nozzles. For example, the largest range of RMSE values for a venturi nozzle was from 38.9 mL min^{-1} at 207 kPa to 87.1 mL min^{-1} at 414 kPa for the AMDF11008 nozzle at a standard configuration. The largest range of RMSE values for a non-venturi nozzle was from 5.0 mL min^{-1} at 207 kPa to 14.0 mL min^{-1} at 414 kPa for the MR11004 nozzle at an 80% duty cycle. On average, across pressures and duty cycles, venturi nozzles had slightly greater RMSE values compared to the non-venturi nozzles. One interesting note on the use of RMSE values as a spray pattern uniformity measurement is the possible bias of flow rate. The increase of pressure and duty cycle both increase flow rate and had observed increases of RMSE values to some extent. Further, as orifice size increased (thereby flow rate increased), RMSE values increased significantly, as can be seen when comparing the AM11002, AM11004, AMDF11004, and AMDF11008 nozzles. Additionally, future research should identify a critical value for RMSE that creates a limit to identify acceptable spray pattern uniformity similar to the 10% CV value guideline. Based on RMSE values, non-venturi nozzles would provide a wider range of pressure options compared to venturi nozzles for applicators to optimize their spray pattern uniformities on a PWM sprayer.

APE DATA

The APE data did not have a significant duty cycle*nozzle*pressure interaction (P = 0.9729), but the two-way interactions of nozzle*duty cycle, pressure*duty cycle, and pressure*nozzle were statistically significant (P < 0.0001).

The nozzle*duty cycle interaction impacting APE is illustrated in Figure 4.2. Averaged across gauge pressures, as duty cycle decreased, the APE increased among non-venturi nozzles (Figure 4.2). The only exception was within the UR11004 nozzle as the 80% duty cycle had a slightly greater APE than the 60% duty cycle. The 100% duty cycle slightly increased APE compared to the standard configuration for non-venturi nozzles indicating the addition of the inline solenoid valve increased the discrepancy between measured and predicted flow rates, but the increase was minimal as no differences were greater than 10%. The 40 – 80% duty cycles resulted in relatively similar APE near 20%, while the 20% duty cycle increased APE to greater than 40% across non-venturi nozzles. A 40% APE indicates the average of the measured flow rates across the width of the measured spray pattern (102 cm) were 40% greater than the expected theoretical flow rates. This is unacceptable spray pattern uniformity for current pesticide application methods. The AMDF11008 venturi nozzle had the smallest range of APE, but did not follow a consistent trend across duty cycles and spray pattern uniformity was therefore unpredictable when pulsed. The remaining venturi nozzles' APE generally increased as duty cycle decreased and reached similar APE to that of the non-venturi nozzles. However, the venturi nozzle APE trends across duty cycles were unpredictable and less consistent than for the non-venturi nozzles. These results suggest venturi nozzles should not be equipped and operated on a PWM sprayer as spray pattern uniformity is reduced.

When averaged across nozzles, similar trends in APE were observed for each gauge pressure across duty cycles (Figure 4.3). The 100% duty cycle and standard configuration were similar in APE values and were minimally impacted by gauge pressure. Furthermore, duty cycles between 40 and 80% had APE values between 20 and 25%, while the 20% duty cycle had APE values between 34 and 48%, indicating a severe penalty in spray pattern uniformity for operating below a 40% duty cycle. As duty cycle decreased below 80%, the 414 kPa gauge pressure decreased the APE compared to the 207 and 276 kPa gauge pressures. Therefore, the operation of PWM sprayers at increased pressures (> 276 kPa) increased the spray pattern uniformity when nozzles were pulsed, especially at reduced duty cycles.

The APE as affected by the gauge pressure*nozzle interaction is presented in Figure 4.4. Almost exclusively, as gauge pressure increased, the APE decreased across the non-venturi nozzles (Figure 4.4). In contrast, venturi nozzles had no trend or consistency across pressures and the resulting APE. The GAT11004 venturi nozzle at 207 kPa had the greatest APE value. These overall spray pattern uniformity results corroborate previous PWM research in which recommendations were created to operate PWM sprayers with only non-venturi nozzles, greater than or equal to a 276 kPa gauge pressure, and greater than or equal to a 40% duty cycle (Butts et al., 2017a, 2017b). Previous research also identified as-applied application results for on-ground application coverage was ±10% of the desired target 67% of the time when operated at a 40% duty cycle. However, when duty cycle was reduced to 20%, the application was only within ±10% of the desired target 38% of the time indicating a severe penalty for operating the PWM sprayer below a 40% duty cycle (Mangus et al., 2017). Results from APE data indicated gauge pressure minimally impacted spray pattern uniformity compared to certain nozzles and PWM duty cycle. The largest margins of difference in APE were 15, 25, and 55% for pressure, nozzle, and duty cycle factors, respectively. Therefore, if concerned with spray pattern uniformity, applicators should first focus their efforts on operating PWM sprayers at duty cycles within an acceptable range (> 40%). A non-venturi nozzle and gauge application pressure for a PWM sprayer should then be selected based on drift mitigation and pesticide coverage needs rather than spray pattern uniformity concerns.

COMPARISON OF SPRAY PATTERN ANALYSES

The three spray pattern analyses used in this research provided unique measurements of uniformity across nozzles, pressures, and PWM duty cycles. Some of the variability across analyses can be explained through observing the individual collection tube flow rate data. As an example, the AITTJ-6011004 venturi nozzle CV values remained relatively equal across pressures tested; however, the RMSE and APE generally increased as pressure increased. When observing the spray pattern across the collected width (Figure 4.5), these results are rationalized. Across the three pressures, the spray pattern trend or shape is relatively similar which resulted in similar CV values as the average of the standard deviations from the mean for each pressure were approximately the same. However, as pressure increased, the *AFR* deviation from the respective *PFR* increased, thereby increasing the RMSE and APE values. Conversely, the CV values for the UR11004 non-venturi nozzle decreased as pressure increased, while the RMSE and APE values remained relatively similar between 207 and 276 kPa, but decreased at 414 kPa. Similar to the AITTJ-6011004 nozzle, the spray pattern across the collected width provides insight into these results for the UR11004 (Figure 4.6). As pressure increased, the spray pattern trend or shape flattened and became less variable, resulting in the lower CV values. Further, the 207 and 276 kPa *AFR* measurements remained approximately the same distance from their respective *PFR*, while the 414 kPa *AFR* measurements were much closer to their respective *PFR* resulting in the lower RMSE and APE values, and indicating greater spray pattern uniformity at 414 kPa.

The PWM duty cycle effect on the CV, RMSE, and APE spray analyses can also be explained through the individual collection tube flow rate data using the AITTJ-6011004 and UR11004 as representative nozzles. Duty cycle impacted both the AITTJ-6011004 venturi nozzle (Figure 4.7) and the UR11004 non-venturi nozzle (Figure 4.8) similarly. The spray pattern trend or shape for the collection width remained relatively constant regardless of duty cycle, thus no discernable trend emerged in CV values as impacted by PWM duty cycle. The 80% duty cycle *AFR* values had the greatest deviation from its respective *PFR* values corresponding to the previously noted increase in RMSE. As duty cycle decreased, the actual difference between *AFR* and *PFR* values slightly decreased, resulting in the decreased RMSE values. However, the percent difference between the *AFR* and *PFR* values actually increased as duty cycle decreased which corresponded to the increase in APE as duty cycle decreased. Upon review of the three methods of spray pattern analysis used in this research, the APE analysis seems a logical choice for future spray pattern analysis as it factors both pattern uniformity and flow rate accuracy in its measurement.

Conclusions

Spray pattern uniformity is critical for avoiding areas of under- and over-application to achieve maximum pest control while minimizing crop injury potential. PWM sprayers continue to increase in popularity and optimizing applications, specifically PWM spray pattern uniformity, would lead to increased pesticide stewardship and efficacy. CV results indicated pulsing, regardless of nozzle, minimally impacted the spray pattern uniformity. Conversely, increasing gauge pressure paired with non-venturi nozzles decreased CV values thereby creating more uniform spray patterns. Dual fan venturi nozzles had the greatest CV values across pressures and duty cycles tested excluding the SR11004.

Across nozzles and pressures, RMSE values typically increased (less uniform spray patterns) when duty cycle decreased from 100 to 80%. However, as duty cycle decreased further, RMSE values decreased resulting in more uniform spray patterns. Venturi nozzles were more sensitive to changes in pressure than non-venturi nozzles as greater ranges in RMSE values across pressures were observed for the venturi nozzles. Furthermore, results suggested RMSE values may be biased by flow rate as increasing flow rate almost exclusively increased the RMSE values.

Duty cycle impacted APE more than any other factor. As duty cycle decreased, APE increased (except with the AMDF11008 nozzle) and the 20% duty cycle caused severe losses in spray pattern uniformity compared to other duty cycles. Further, non-venturi nozzles with the 414 kPa gauge pressure reduced APE and maintained consistency across duty cycles compared to venturi nozzles with reduced gauge pressures, thereby resulting in more uniform spray patterns when pulsed.

Overall, PWM spray patterns can be optimized, regardless of the evaluation method used, if operated with non-venturi nozzles, at gauge pressures greater than or equal to 276 kPa, and at duty cycles greater than or equal to 40%. The three evaluation methods for spray pattern uniformity in this research each provided unique observations into spray pattern characteristics. The APE spray pattern analysis may provide the best guidance for determining optimum sprayer setup as it takes into account both uniformity and flow rate accuracy; however future research should fully evaluate all analyses for their specific benefits and drawbacks.

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Tables

Table 4.1. Nozzles (12), pulse-width modulation duty cycles (6), and gauge application pressures (3) used in a factorial arrangement of treatments in this research.

Nozzles			Duty cycle	Gauge pressure
Abbreviation	Name	Design		
			%	kPa
AITTJ-6011004[a]	Air Induction Turbo TwinJet	Venturi	Standard[e]	207
AM11002[b]	Airmix	Venturi	100	276
AM11004[b]	Airmix	Venturi	80	414
AMDF11004[b]	Airmix DualFan	Venturi	60	
AMDF11008[b]	Airmix DualFan	Venturi	40	
GAT11004[c]	GuardianAIR Twin	Venturi	20	
TTI11004[a]	Turbo TeeJet Induction	Venturi		
DR11004[d]	Combo-Jet Drift Control	Non-Venturi		
ER11004[d]	Combo-Jet Extended Range	Non-Venturi		
MR11004[d]	Combo-Jet Mid Range	Non-Venturi		
SR11004[d]	Combo-Jet Small Reduction	Non-Venturi		
UR11004[d]	Combo-Jet Ultra Drift Control	Non-Venturi		

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Pentair Hypro SHURflo plc., Minneapolis, MN
[d] Wilger Industries Ltd., Lexington, TN
[e] Standard duty cycle indicates no solenoid valve is equipped.

Table 4.2. Spray pattern coefficient of variation (CV) (102 cm collection width) of water impacted by pulse-width modulation duty cycle for 12 nozzle and three pressure combinations.

		CV					
	Gauge	Duty cycle (%) [e]					
Nozzle	pressure	20	40	60	80	100	Standard
	kPa	%					
AITTJ-6011004[a]	207	11.6 a	11.7 a	11.9 a	11.5 a	10.1 a	10.0 a
AM11002[b]	207	5.6 a	5.8 a	6.2 a	5.5 a	6.0 a	6.6 a
AM11004[b]	207	9.5 bc	11.8 a	7.9 c	9.4 bc	10.8 ab	9.7 abc
AMDF11004[b]	207	6.2 a	6.2 a	6.4 a	7.1 a	7.4 a	9.5 a
AMDF11008[b]	207	7.5 c	7.8 c	9.7 bc	10.5 b	15.1 a	12.0 b
GAT11004[d]	207	16.8 a	10.5 b	9.7 b	12.0 ab	10.4 b	9.4 b
TTI11004[a]	207	9.3 ab	7.0 bc	6.2 c	7.1 abc	8.9 ab	9.6 a
DR11004[c]	207	10.6 a	9.4 a	9.0 a	10.5 a	9.7 a	8.3 a
ER11004[c]	207	10.8 a	10.5 a	11.4 a	12.0 a	11.8 a	10.5 a
MR11004[c]	207	10.2 a	9.9 ab	8.3 abc	7.2 c	7.7 bc	9.7 ab
SR11004[c]	207	17.2 b	17.4 b	18.3 ab	19.9 a	20.1 a	14.4 c
UR11004[c]	207	11.1 bc	13.3 ab	10.1 c	11.7 abc	11.0 bc	14.1 a
AITTJ-6011004[a]	276	10.2 b	10.2 b	13.0 a	11.2 ab	13.4 a	10.1 b
AM11002[b]	276	8.1 a	6.3 a	7.5 a	6.2 a	7.1 a	6.9 a
AM11004[b]	276	12.0 a	8.7 a	13.3 a	13.5 a	9.3 a	7.6 a
AMDF11004[b]	276	7.6 b	7.5 b	8.2 ab	8.4 ab	9.2 a	9.1 a
AMDF11008[b]	276	8.3 d	8.5 d	9.3 d	11.1 c	13.2 b	15.5 a
GAT11004[d]	276	14.8 a	11.2 b	10.7 b	10.2 b	10.6 b	7.5 c
TTI11004[a]	276	9.9 bc	9.0 bc	8.4 c	9.0 bc	11.7 ab	13.2 a
DR11004[c]	276	10.6 a	10.9 a	9.7 a	9.7 a	7.4 b	7.1 b
ER11004[c]	276	9.6 b	10.4 ab	10.7 ab	12.0 a	10.8 ab	9.7 b
MR11004[c]	276	11.0 a	10.6 a	8.8 ab	11.1 a	7.3 b	10.5 a
SR11004[c]	276	14.4 bc	14.4 bc	15.8 abc	16.5 ab	17.5 a	14.3 c
UR11004[c]	276	13.3 a	10.6 b	8.3 c	9.0 bc	8.4 c	9.8 bc
AITTJ-6011004[a]	414	8.8 c	9.1 bc	10.1 abc	11.1 ab	11.2 a	11.9 a
AM11002[b]	414	7.5 a	6.3 a	6.0 a	6.5 a	7.0 a	7.1 a
AM11004[b]	414	8.5 a	9.1 a	8.9 a	8.6 a	10.0 a	8.0 a
AMDF11004[b]	414	8.4 d	9.3 cd	10.6 bc	10.5 bc	11.2 ab	12.5 a
AMDF11008[b]	414	9.6 d	9.3 d	11.5 cd	12.8 bc	14.0 b	17.3 a
GAT11004[d]	414	14.8 a	9.0 c	10.1 bc	9.9 bc	10.4 bc	11.6 b
TTI11004[a]	414	8.1 ab	6.6 b	6.4 b	9.4 a	9.0 a	9.1 a
DR11004[c]	414	9.6 a	9.3 a	9.2 a	9.8 a	8.9 a	7.0 b
ER11004[c]	414	8.2 ab	9.9 a	7.5 b	7.9 ab	8.5 ab	9.3 ab
MR11004[c]	414	9.3 ab	6.5 c	8.0 bc	7.6 bc	10.6 a	8.9 ab
SR11004[c]	414	13.1 bc	12.6 c	14.0 bc	15.1 b	17.8 a	13.4 bc
UR11004[c]	414	8.1 a	7.5 a	5.3 b	7.5 a	6.7 ab	5.1 b

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Table 4.3. Spray pattern root mean square error (RMSE) (102 cm collection width) of water impacted by pulse-width modulation duty cycle for 12 nozzle and three pressure combinations.

		RMSE					
	Gauge	Duty cycle (%) [e]					
Nozzle	pressure	20	40	60	80	100	Standard
	kPa	mL min^{-1}					
AITTJ-6011004[a]	207	5.1 c	6.2 bc	9.3 a	9.8 a	7.7 ab	7.1 abc
AM11002[b]	207	3.4 a	2.9 b	2.7 c	2.5 c	2.0 e	2.3 d
AM11004[b]	207	6.6 c	9.4 bc	10.7 ab	16.4 a	8.6 bc	8.3 bc
AMDF11004[b]	207	5.2 bc	4.7 c	5.4 bc	8.5 a	6.1 b	6.0 b
AMDF11008[b]	207	7.1 d	9.3 cd	15.1 bc	24.8 ab	32.7 a	38.9 a
GAT11004[d]	207	10.4 a	10.6 a	14.6 a	20.2 a	13.0 a	10.7 a
TTI11004[a]	207	5.3 bc	3.1 d	3.7 cd	3.7 cd	6.5 ab	8.7 a
DR11004[c]	207	7.0 c	8.5 bc	10.5 abc	12.8 ab	15.1 a	9.0 bc
ER11004[c]	207	6.3 b	6.4 b	9.2 ab	9.7 a	8.1 ab	7.7 ab
MR11004[c]	207	5.7 a	6.1 a	6.5 a	5.0 a	5.4 a	6.6 a
SR11004[c]	207	7.5 b	10.0 b	15.4 a	16.5 a	16.5 a	10.0 b
UR11004[c]	207	7.7 b	11.6 ab	10.9 ab	17.3 a	13.1 a	13.7 a
AITTJ-6011004[a]	276	5.7 d	8.7 cd	13.6 bc	23.2 a	17.7 ab	11.4 bc
AM11002[b]	276	3.3 a	3.4 a	3.3 a	3.0 ab	2.8 b	2.7 b
AM11004[b]	276	7.0 d	9.9 cd	17.8 ab	26.3 a	12.8 bc	5.6 d
AMDF11004[b]	276	6.0 b	6.0 b	7.2 ab	7.8 a	7.8 a	8.7 a
AMDF11008[b]	276	6.9 d	7.4 d	13.6 c	27.4 b	30.8 ab	50.8 a
GAT11004[d]	276	8.8 b	8.2 b	11.2 ab	15.8 a	11.8 ab	8.3 b
TTI11004[a]	276	5.7 c	6.0 c	9.3 bc	20.1 a	13.9 ab	13.3 ab
DR11004[c]	276	7.3 b	9.6 ab	9.2 ab	12.7 a	9.0 ab	5.9 b
ER11004[c]	276	6.4 c	8.8 b	8.3 bc	13.6 a	12.7 a	7.8 bc
MR11004[c]	276	5.9 c	7.6 b	8.2 b	12.6 a	8.2 b	9.1 b
SR11004[c]	276	8.0 d	10.6 cd	14.2 abc	18.4 a	16.5 ab	12.1 bc
UR11004[c]	276	8.9 c	11.3 bc	14.3 ab	19.2 a	10.6 bc	10.4 bc
AITTJ-6011004[a]	414	6.5 c	7.5 c	11.5 bc	21.8 a	14.5 ab	22.0 a
AM11002[b]	414	3.7 ab	3.7 ab	3.4 b	4.3 a	3.5 b	3.5 b
AM11004[b]	414	6.6 c	8.0 bc	12.5 ab	20.2 a	19.1 a	11.2 abc
AMDF11004[b]	414	5.8 c	7.1 c	11.0 b	14.3 ab	11.4 ab	16.5 a
AMDF11008[b]	414	6.4 d	9.6 d	21.4 c	37.6 b	56.8 ab	87.1 a
GAT11004[d]	414	7.7 b	12.1 ab	15.7 a	20.2 a	13.2 ab	14.9 a
TTI11004[a]	414	4.1 b	4.7 b	4.7 b	14.2 a	12.0 a	10.9 a
DR11004[c]	414	8.9 b	11.9 a	12.9 a	12.0 a	8.9 b	7.4 c
ER11004[c]	414	6.9 b	8.6 ab	7.9 ab	9.4 ab	10.9 a	11.5 a
MR11004[c]	414	5.4 c	5.2 c	9.0 ab	14.0 a	11.8 ab	8.9 b
SR11004[c]	414	9.0 c	10.9 bc	14.1 b	21.0 a	23.6 a	12.7 b
UR11004[c]	414	6.8 bc	8.7 ab	6.6 bc	11.9 a	9.2 ab	5.4 c

[a] TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL
[b] Greenleaf Technologies, Covington, LA
[c] Wilger Industries Ltd., Lexington, TN
[d] Pentair Hypro SHURflo plc., Minneapolis, MN
[e] Means within a gauge pressure and nozzle with the same letter are not significantly different ($P \leq 0.05$). Standard duty cycle refers to a sprayer configuration with no solenoid valve equipped.

Figures

Figure 4.1. Spray patternator table with automated collection system used in this research located at the University of Nebraska-Lincoln in Lincoln, NE.

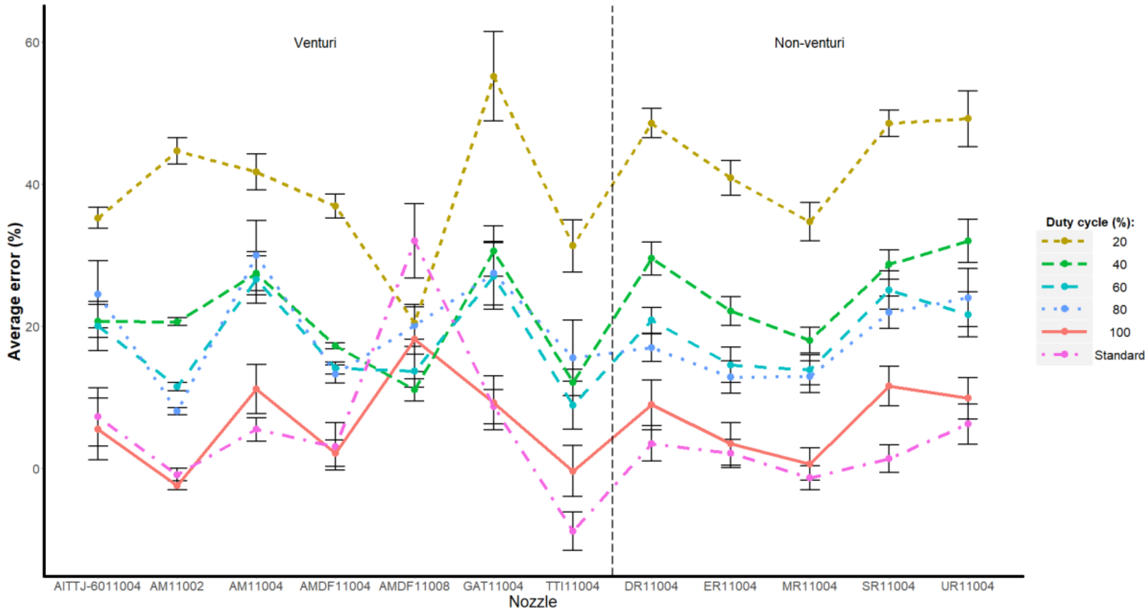

Figure 4.2. Average percent error (APE) of spray pattern measurements (102 cm collection width) as affected by a nozzle*duty cycle interaction.

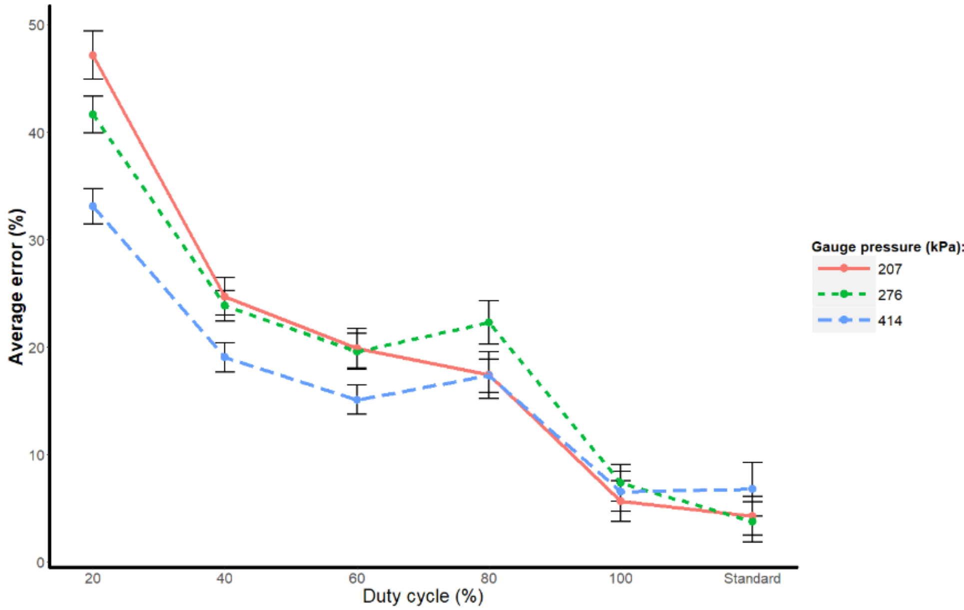

Figure 4.3. Average percent error (APE) of spray pattern measurements (102 cm collection width) as affected by a gauge pressure*duty cycle interaction.

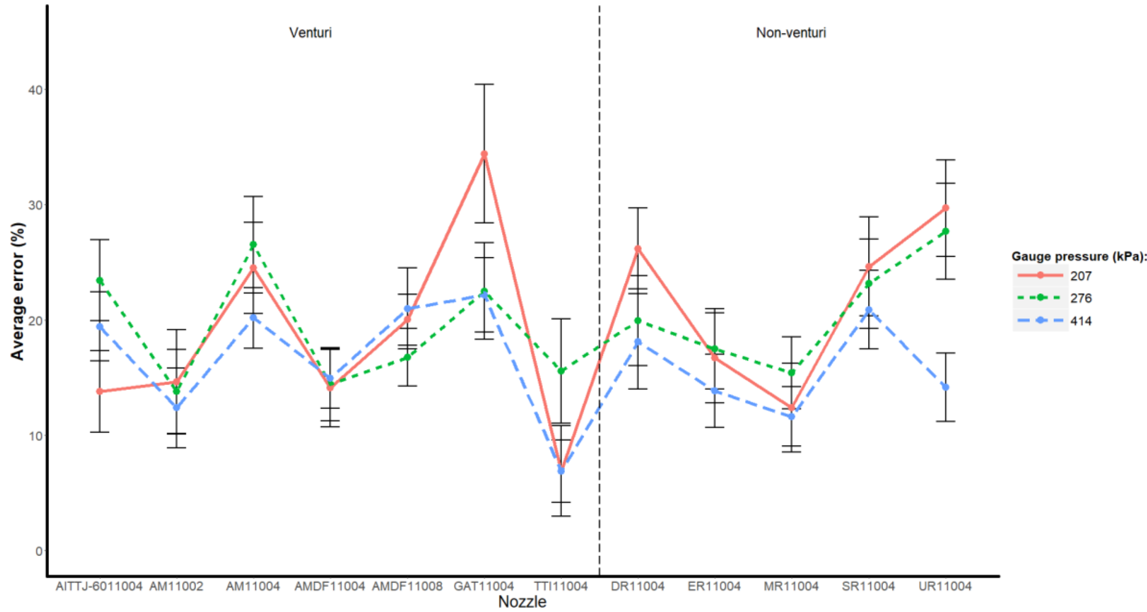

Figure 4.4. Average percent error (APE) of spray pattern measurements (102 cm collection width) as affected by a gauge pressure*nozzle interaction.

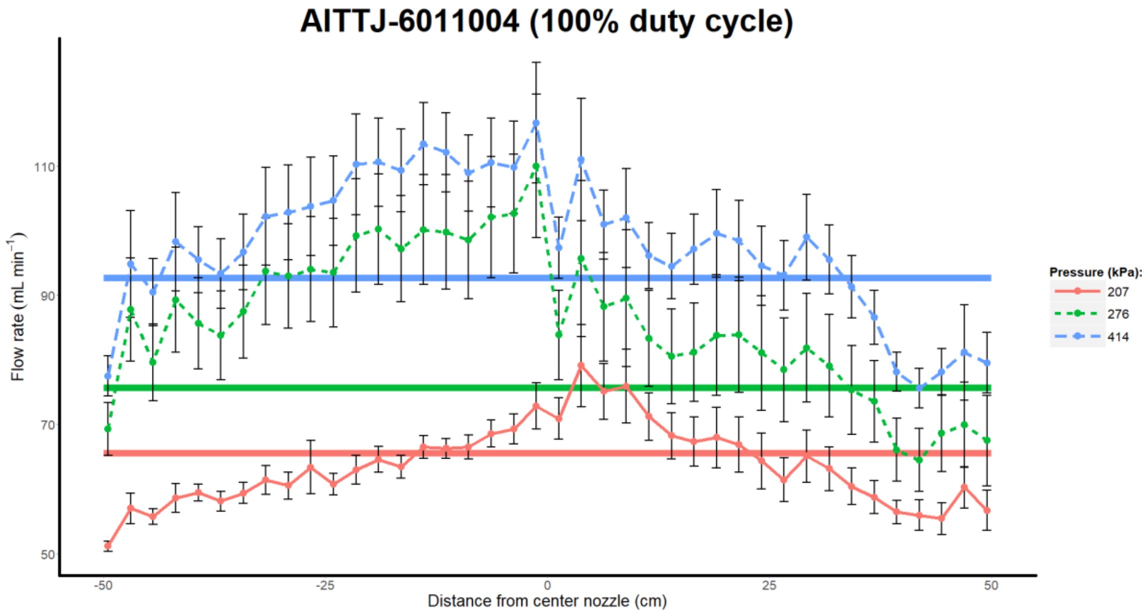

Figure 4.5. Flow rate (mL min^{-1}) for individual collection tubes across the width of the measured spray pattern (102 cm) of the AITTJ-6011004 venturi nozzle at the 100% duty cycle for three pressures. The solid, horizontal lines are the predicted flow rates (PFR) for each respective pressure.

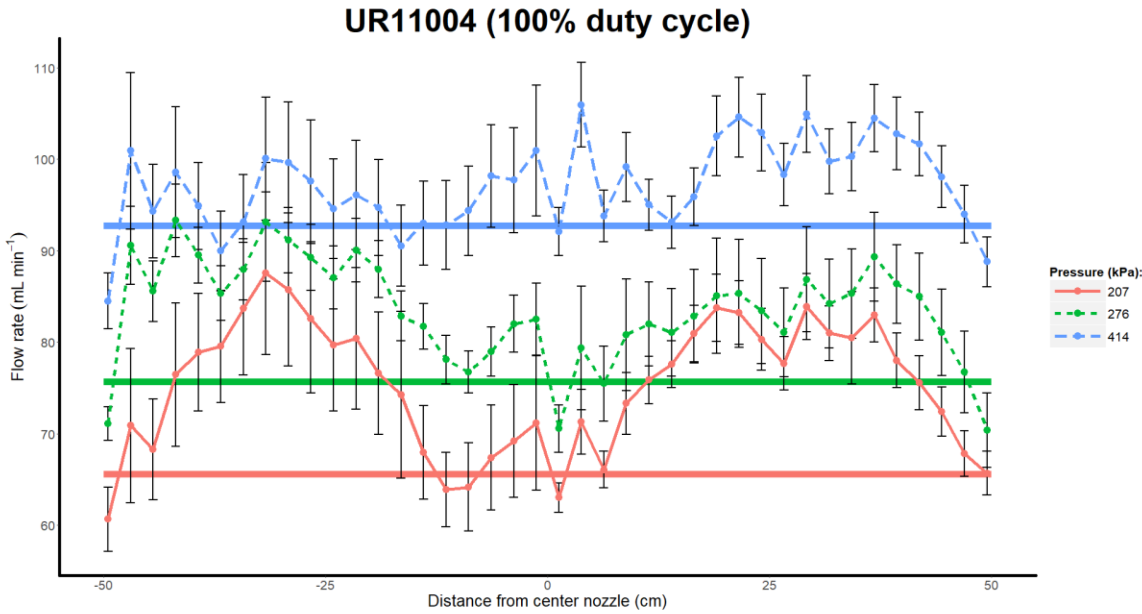

Figure 4.6. Flow rate (mL min^{-1}) for individual collection tubes across the width of the measured spray pattern (102 cm) of the UR11004 non-venturi nozzle at the 100% duty cycle for three pressures. The solid, horizontal lines are the predicted flow rates (PFR) for each respective pressure.

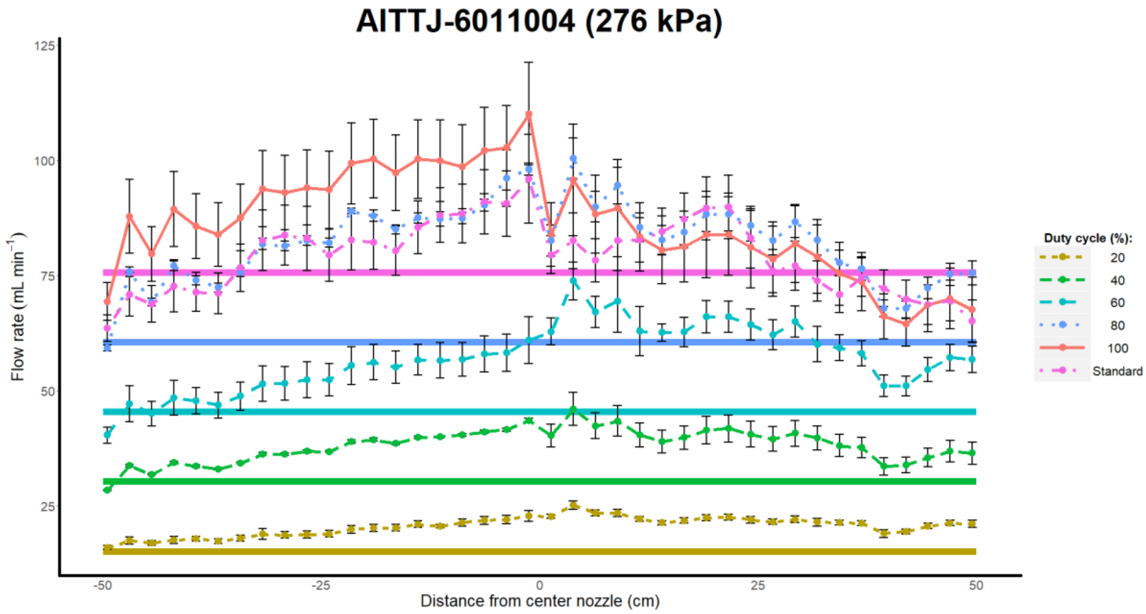

Figure 4.7. Flow rate (mL min^{-1}) for individual collection tubes across the width of the measured spray pattern (102 cm) of the AITTJ-6011004 venturi nozzle at the 276 kPa gauge pressure for six duty cycles. The solid, horizontal lines are the predicted flow rates (PFR) for each respective duty cycle.

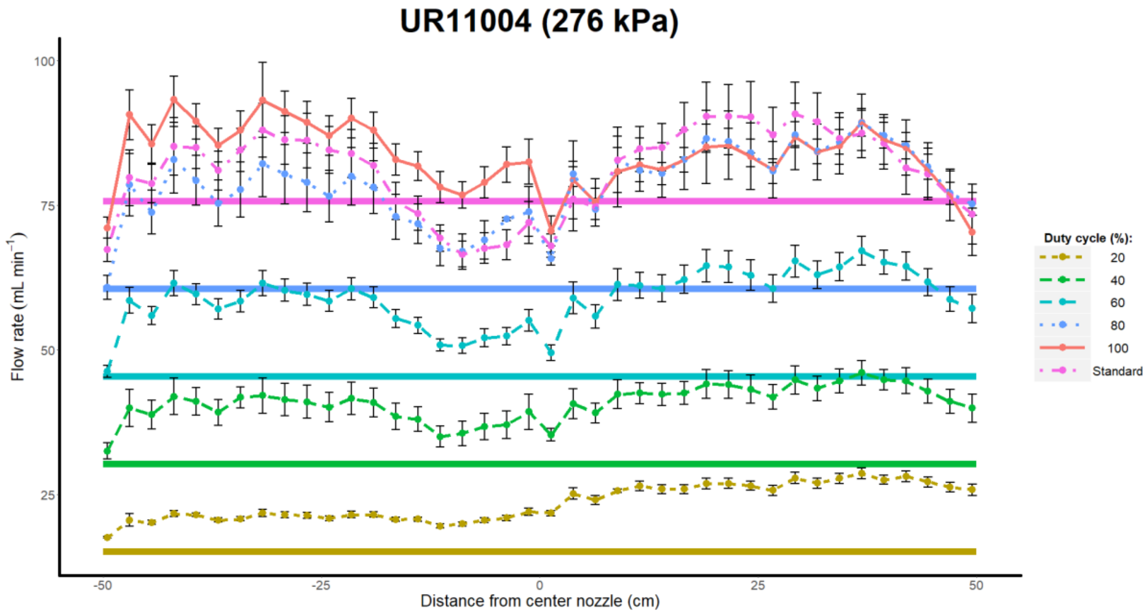

Figure 4.8. Flow rate (mL min^{-1}) for individual collection tubes across the width of the measured spray pattern (102 cm) of the UR11004 non-venturi nozzle at the 276 kPa gauge pressure for six duty cycles. The solid, horizontal lines are the predicted flow rates (PFR) for each respective duty cycle.

CHAPTER 5

SPRAY DROPLET SIZE AND CARRIER VOLUME EFFECT ON DICAMBA AND GLUFOSINATE EFFICACY

Abstract

Pesticide applications using a specific droplet size and carrier volume could maximize herbicide efficacy while mitigating particle drift in a precise and efficient manner. The objectives were to investigate the influence of spray droplet size and carrier volume on dicamba and glufosinate efficacy, and to determine the plausibility of droplet size based site-specific weed management strategies. Generally, across herbicides and carrier volumes, as droplet size increased, weed control decreased. Increased carrier volume (187 L ha^{-1}) buffered this droplet size effect, thus greater droplet sizes could be used to mitigate drift potential while maintaining sufficient levels of weed control. To mitigate drift potential and achieve satisfactory weed control (≥90% of maximum observed control), a 900 µm (Ultra Coarse) droplet size paired with 187 L ha^{-1} carrier volume is recommended for dicamba applications and a 605 µm (Extremely Coarse) droplet size across carrier volumes is recommended for glufosinate applications. Although general droplet size recommendations were created, optimum droplet sizes for weed control varied significantly across site-years. Convoluted interactions occur between droplet size, carrier volume, and other application parameters. Recommendations for optimizing herbicide applications based on droplet size should be based on a site-specific management approach to better account for these interactions.

Introduction

Concern for environmental contamination, pesticide drift, and food security has led to strict regulations on pesticide manufacturers, distributors, and applicators. A survey from Nebraska in the late 1980's found that 72 of 103 herbicide applicators were not applying herbicides within 5% of their intended application rate (Grisso et al., 1989). A 2016 survey from Missouri (Bish and Bradley, 2017) identified greater than 62% of applicators changed nozzles less than 50% of the time when switching herbicide products, potentially leading to inaccurate applications due to increased nozzle orifice wear (Ozkan et al., 1992) and improper nozzle selection (Klein and Kruger, 2011). In today's production agricultural systems, this is unacceptable as more precise and efficient pesticide applications are necessary to meet regulatory demands and increase economic efficiency through reduced pesticide inputs.

Particular interest has been placed on increasing spray droplet size to minimize the particle drift potential of pesticide applications. Even in minimal wind speed conditions, plant injury has been documented up to 200 m downwind from an application with Fine droplets (Byass and Lake, 1977). Multiple factors can increase spray droplet size including adjuvants (Butler Ellis et al., 1997; Chapple et al., 1993), nozzle design (Barnett and Matthews, 1992; Butler Ellis et al., 2002; Etheridge et al., 1999), nozzle orifice size (Nuyttens et al., 2007), and application pressure (Creech et al., 2015a). Multiple spray drift prediction models have been created to estimate downwind drift deposits, all of which include spray droplet size as a crucial parameter (Farooq et al., 2001; Hobson et al., 1993; Miller and Hadfield, 1989; Zhu et al., 1994). These models have been validated through numerous in-field evaluations which identified increases in spray droplet size result in reduced downwind drift deposits (Bueno et al., 2017; Matthews et al., 2014).

Although increasing spray droplet size has enhanced drift mitigation efforts, it has caused negative biological consequences (Wolf, 2002). As droplet diameter increases, the volume of solution contained within individual droplets increases; if an application carrier volume is held constant and the droplet diameter doubled, the number of droplets available for plant surface impaction and retention is reduced by a ratio of 8:1. Typically, this is used as justification for the following guideline: reduced droplet sizes are necessary for contact herbicides to maximize efficacy, while systemic herbicide efficacy is less sensitive to droplet size changes. Previous research demonstrated increased control across multiple herbicides and weed species as droplet size decreased to 100 µm (Ennis and Williamson, 1963; Knoche, 1994; Lake, 1977; Lake and Taylor, 1974; McKinlay et al., 1972). Glyphosate, a systemic herbicide, had greater absorption and translocation with Coarse droplets (Feng et al., 2009); however, this guideline was not consistent across systemic herbicides as translocation of 2,4-D (systemic herbicide) increased as droplet size decreased, indicating droplet size plays a role in 2,4-D efficacy (Wolf et al., 1992). Additionally, no losses in herbicide efficacy as droplet size increased were observed for several contact herbicides (Ramsdale and Messersmith, 2001a; Shaw et al., 2000). Droplet size impacts on herbicide efficacy are convoluted, and each herbicide and weed species interaction requires a tailored approached to maximize efficacy (Creech et al., 2016).

In addition to droplet size, carrier volume plays a crucial role in herbicide coverage and efficacy (Legleiter and Johnson, 2016). Generally, across herbicides, efficacy decreased as carrier volume decreased (Knoche, 1994). This result is expected as a reduced volume should result in decreased coverage of the target weed species. However, similar to the complex interactions observed with droplet size, carrier volume has shown mixed effects on herbicide efficacy. Etheridge et al., (2001) and Ramsdale and Messersmith, (2001b) showed minimal to no efficacy reduction from a decrease in carrier volume across multiple contact herbicides. In contrast, a reduction in dicamba efficacy (systemic herbicide) when large droplet sizes were applied was observed as carrier volume was reduced (Meyer et al., 2016). Therefore, to maximize application efficiency, spray droplet distributions should be homogenized and carrier volumes tailored for specific herbicides and weed species.

Pulse-width modulation (PWM) sprayers allow for several factors, including application pressure and spray droplet size, to be maintained across a range of sprayer speeds while variably controlling flow to provide a more homogenous spray cloud through the duration of an application compared to conventional sprayers. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The flow is changed by controlling the relative proportion of time each solenoid valve is open (duty cycle). This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003) and PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Application pressure based variable rate flow control devices have been shown to have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). In contrast, research has shown PWM duty cycle has little to no effect on droplet size when using non-venturi nozzles (Butts et al., 2017a; Giles et al., 1996). Venturi nozzles are not recommended for use on PWM sprayers (Capstan Ag Systems Inc., 2013) as irregularities with droplet size, nozzle tip pressure, and droplet velocity have been previously observed (Butts et al., 2017a, 2017b). Further, when PWM sprayers were operated at or above a 40% duty cycle, minimal to no negative impacts were observed on spray pattern and coverage (Mangus et al., 2017; Womac et al., 2017, 2016).

An increasing need for site-specific weed management has been established (Tian et al., 1999; Wilkerson et al., 2004), and PWM sprayers could provide a unique opportunity for use in site-specific management scenarios by mitigating droplet size variation within an application (GopalaPillai et al., 1999). In these site-specific management strategies, a PWM sprayer would be equipped and operated with an appropriate nozzle type, orifice size, pressure, and carrier volume to create an optimum droplet size for maximum herbicide efficacy while simultaneously mitigating particle drift potential.

The objectives of our research were to investigate the influence of spray droplet size and carrier volume on the efficacy of dicamba and glufosinate herbicides and to determine the plausibility of using PWM sprayers in the aforementioned site-specific weed management strategy. Recommendations were then established for an optimum droplet size and carrier volume to achieve a high level of weed control while simultaneously mitigating particle drift potential without compromising efficacy. The precise, site-specific application of these herbicides will allow farmers to more effectively utilize drift reduction technologies, reduce herbicide inputs, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

Materials and Methods

EXPERIMENT DESIGN AND ESTABLISHMENT

Field trials were conducted in 2016 and 2017 in a fallow environment across three states (Mississippi, Nebraska, and North Dakota) for a total of six site-years to evaluate the droplet size and carrier volume effect on the efficacy of dicamba and glufosinate (Table 5.1). The trials were randomized complete block experimental designs with factorial arrangements of treatments replicated a minimum of three times. Treatments were arranged in a 2 x 2 x 6 factorial consisting of two herbicides (dicamba and glufosinate), two carrier volumes (47 and 187 L ha^{-1}), and six targeted droplet sizes (150, 300, 450, 600, 750, and 900 µm) determined from the $D_{v0.5}$ of the measured spray solution. The $D_{v0.5}$ parameter represents the droplet diameter such that 50% of the spray volume is contained in droplets of smaller diameter. One nontreated control per site-year was used for comparison which provided a total of 25 treatments. Treatments were applied using a PinPoint® PWM research sprayer (Capstan Ag Systems, Inc., Topeka, KS) (Figure 5.1). Dicamba (Clarity®, 480 g ae L^{-1}, BASF, Research Triangle Park, NC 27709) and glufosinate (Liberty®, 280 g ai L^{-1}, Bayer CropScience LP, Research Triangle Park, NC 27709) were applied postemergence to 15-cm tall or greater weeds at 0.28 kg ae ha^{-1} and 0.45 kg ai ha^{-1}, respectively. No additional adjuvants were tank-mixed into the solution to eliminate confounding effects and evaluation of treatments could occur solely on the herbicide.

Nozzle type, orifice size, and application pressure required to create droplet size treatments for each specific herbicide solution were determined through droplet size measurements made using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) in the low-speed wind tunnel at the Pesticide Application Technology (PAT) Laboratory in North Platte, NE (Table 5.2). Creech et al., (2015) and Henry et al., (2014) provide in-depth details regarding the low-speed wind tunnel at the PAT Laboratory, and Butts et al., (2017a) provides an illustration for further clarification of wind tunnel construction and operation. Only Wilger Industries, Ltd. non-venturi nozzles were used in this research as: (1) only non-venturi nozzles are recommended for use on PWM systems (Butts et al., 2017a; Capstan Ag Systems Inc., 2013) and (2) nozzle designs were similar (flat-fan, non-venturi, straight flow path) to eliminate confounding spray characteristic factors. Spray classifications were assigned in accordance with ASABE S572.1 (ASABE, 2009).

DATA COLLECTION

Each collaborating university collected data from their respective sites. Visual injury estimation proportions were recorded approximately 28 days after treatment (DAT) for entire plots. Further, ten individual weeds per plot were marked at the time of application. At 28 DAT, marked plants were individually evaluated for mortality (alive or dead) and the total number of deceased plants were divided by ten to provide mortality proportion measurements for each plot. The individual weeds were then clipped at the soil surface, harvested, and dried at 55 C to constant mass. The dry plants were pooled into one dry biomass measurement per plot, and were divided by ten for average weed dry shoot biomass per plant measurements.

STATISTICAL ANALYSES

Generalized additive modeling (GAM) analysis was conducted in R 3.4.1 statistical software using the mgcv package to model spray droplet size with each respective response variable to provide an estimate of the optimum spray droplet size for weed control within a carrier volume (Crawley, 2013). Herbicides were analyzed separately. To meet model assumptions, visual injury estimation and mortality proportions were analyzed using a beta distribution as the data were bound between 0 and 1, and weed dry biomass per plant data were subjected to a natural log transformation. Backtransformed data are presented for clarity. Models consisted of one smoothed variable (droplet size) and smoothing parameters were estimated separately for each carrier volume (Equation 5.1).

$$\text{Response variable} \sim s(\text{Target droplet size, by=Carrier volume}) \qquad [5.1]$$

Data within herbicides were pooled across site-years to provide overall droplet size and carrier volume recommendations; however, GAM analysis was also conducted for plant mortality proportion data on individual site-years to assess droplet size and carrier volume efficacy implications in a site-specific weed management scenario. Models were used to predict the droplet size for maximum weed control and the droplet size at which 90% of maximum weed control was attained for drift mitigation recommendations.

Results and Discussion

GPS coordinates, weed species presence, average application weather conditions, and data collected for respective site-years are presented in Table 5.1. When data were pooled, visual injury estimations, mortality, and weed dry biomass per plant response variables consisted of six, four, and five site-years, respectively. Optimum droplet sizes discussed throughout the results and discussion section refer to the $D_{v0.5}$ measurement of the droplet size distribution.

DICAMBA POOLED SITE-YEARS

GAM models established for dicamba across pooled site-years of visual injury estimation proportions, mortality proportions, and weed dry biomass per plant are presented in Figure 5.2. Model smooth term estimated degrees of freedom (edf) and explained deviance are presented in Table 5.3. A smooth term edf of one is equal to a linear model with model fluctuation increasing as the smooth term edf increases. The explained deviance provides an estimate of the discrepancy between model predicted estimates and actual observations with a larger percentage indicating a smaller discrepancy and overall better model fit.

Dicamba GAM models were linear (Figure 5.2) with smooth term edf of one (Table 5.3). The droplet size effect of dicamba on weed control was minimal and inconsistent across response variables. Explained deviance was less than 5% across pooled site-year models indicating 95% of the variability amongst observations must be explained by alternative factors other than droplet size and carrier volume. Geographic region, weather conditions, weed species, and resulting interactions should be investigated in future research to refine the following broad geographic droplet size recommendations for dicamba.

Models for visual injury estimation proportions predicted increases in weed control from dicamba as droplet size increased across carrier volumes leading to recommendations of 900 µm droplets or an Ultra Coarse spray classification to maximize efficacy (Table 5.4). This trend differed for both the mortality proportions and weed dry biomass per plant response variables. Weed control decreased as droplet size increased for the 47 L ha^{-1} carrier volume in respect to both mortality proportions and weed dry biomass per plant resulting in maximum control observed from a 150 µm droplet size (Fine spray classification). Due to the susceptibility of non-target plant species to dicamba, Fine sprays are not recommended for applications as particle drift potential is greater than with coarser sprays. Ninety percent of the maximum weed control within the 47 L ha^{-1} carrier volume could be obtained with predicted droplet sizes of 500 (Very Coarse) and 370 µm (Coarse) for mortality and weed dry biomass per plant, respectively. However, this result shows that even with a systemic, synthetic auxin herbicide there is a critical droplet size at which weed control is lost, especially at low carrier volumes. Previous research had identified decreases in weed control as droplet size increased for other systemic, synthetic auxin herbicides (Ennis and Williamson, 1963; McKinlay et al., 1972), but this trend was not previously observed for dicamba (Creech et al., 2016).

For 187 L ha^{-1}, the droplet size at which maximum weed control was predicted for dicamba was 900 (Ultra Coarse) and 150 µm (Fine) for the mortality proportion and weed dry biomass per plant response variables, respectively. The loss in weed control across the range of droplet sizes for the weed dry biomass per plant response variable was minimal as 90% of maximum weed control was achieved with a 900 µm droplet indicating the greater carrier volume buffered the droplet size effect. From these results, it is recommended across pooled site-years to apply dicamba using a 900 µm droplet size or Ultra Coarse spray classification paired with a carrier volume of 187 L ha^{-1} to maximize weed control and reduce particle drift potential.

The differences observed in predicted droplet sizes for maximum weed control could be attributed to the method in which visual injury estimations are made, especially with synthetic auxin herbicides. When visually assessing plots for dicamba injury, it was not uncommon to see similar plant damage across a range of droplet sizes. However, upon closer inspection of mortality, the plants sprayed with greater droplet sizes often were still alive and producing new biomass leading to decreased weed control as droplet size increased. Care should be taken in future synthetic auxin herbicide research to determine weed mortality as opposed to strictly observing visual injury symptoms to fully evaluate herbicide effectiveness.

GLUFOSINATE POOLED SITE-YEARS

GAM models established for glufosinate across pooled site-years of visual injury estimation proportions, mortality proportions, and weed dry biomass per plant are presented in Figure 5.3. Model smooth term edf and explained deviance are presented in

Table 5.3. When averaged across the three response variables and two carrier volumes, weed control from glufosinate was maximized at 310 µm and decreased as herbicide droplet size increased (Figure 5.3). This result corroborates previous research indicating contact herbicides require smaller droplet sizes to increase coverage and achieve maximum efficacy (Knoche, 1994), and the Medium spray classification this represents supports label recommendations. Conversely, carrier volume did not impact weed control as expected as glufosinate applied in 47 L ha^{-1} achieved equal to better weed control than 187 L ha^{-1} across a wider range of droplet sizes.

Models predicted 47 L ha^{-1} would achieve maximum weed control with 233%, 150%, and 14% greater droplet sizes than 187 L ha^{-1} for the visual injury estimation proportions, mortality proportions, and weed dry biomass per plant, respectively (Table 5.4). This result is likely due to the lack of water conditioning adjuvants added to the spray solution. Label recommendations and previous research for glufosinate suggest the addition of ammonium sulfate or other water conditioners is necessary to overcome the negative effects of hard water (Devkota and Johnson, 2016). As no such adjuvants were used in this research, it is hypothesized the more concentrated droplets within the 47 L ha^{-1} carrier volume compared to 187 L ha^{-1} were able to overcome the antagonistic free cations within the carrier water with greater success resulting in greater weed control. Therefore, when applying glufosinate, if no water conditioning adjuvants are utilized, it may be advantageous to use reduced carrier volumes. Greater overall weed control is often observed with the pairing of water conditioning adjuvants and greater carrier volumes however (Creech et al., 2015b; Devkota and Johnson, 2016).

Although weed control, on average, was maximized with a medium spray classification, model predictions were created to estimate the droplet size at which 90% of the maximum weed control was observed to provide larger droplet size recommendations for enhanced drift mitigation efforts (Table 5.4). When averaged across the three response variables and two carrier volumes, the droplet size which achieved 90% of weed control was elevated to 605 µm, an Extremely Course spray classification. Models predicted 70%, 12%, and 13% greater droplet sizes to achieve 90% of the maximum weed control for 47 L ha^{-1} compared to 187 L ha^{-1} carrier volumes with visual injury estimation proportions, mortality proportions, and weed dry biomass per plant, respectively. Similar to dicamba, the 187 L ha^{-1} carrier volume buffered the penalty from loss of weed control of glufosinate as droplet size increased compared to the 47 L ha^{-1} carrier volume.

Conclusions drawn from this research indicate greater droplet sizes (Extremely Coarse spray classifications) and reduced carrier volumes (if no water conditioning adjuvants are utilized) can be used for applying glufosinate to achieve greater than 90% of maximum control for reduced particle drift potential. However, the model uncertainty should be noted for these broad geographic recommendations. The explained deviance was less than 10% for glufosinate models when site-years were pooled (Table 5.3). Therefore, droplet size and carrier volume only accounted for approximately 10% of the weed control from glufosinate. Similar to dicamba, future glufosinate research is needed to evaluate the interactions between geography, weed species, application weather conditions, and droplet size to account for more variability and provide stronger droplet size recommendations across broad geographic regions and weed spectrums.

SITE-SPECIFIC WEED MANAGEMENT

Prior to field study establishment, it was hypothesized that optimum droplet sizes for weed control with dicamba and glufosinate may be strongly influenced by factors such as geographic region, weed species, and weather conditions. The aforementioned pooled site-year analysis confirmed this theory as models accounted for less than 5% and 10% of the deviance for dicamba and glufosinate, respectively. Therefore, individual site-years were analyzed utilizing GAM models to identify if the explained deviance from droplet size and carrier volume could be improved through a site-specific weed management approach. Mortality proportions were chosen as the response variable for this site-specific approach as they are less subjective than visual injury estimation proportions and more reliable than weed dry biomass per plant when using synthetic auxin (dicamba) herbicides.

The smooth term edf and explained deviance from GAM models for dicamba and glufosinate at each of the four individual site-years with mortality proportion data are presented in Table 5.5. The average deviance explained across the site-specific models was 34 and 31% for dicamba and glufosinate, respectively, which was nearly a seven- and three-fold improvement compared with the pooled site-year models. The 2017 Dundee, MS site-year glufosinate model accounted for nearly 61% of the deviance. The site-specific management approach significantly improved model fit compared to the pooled site-year models. GAM models for the 2016 Beaver City, NE site-year are presented in Figure 5.4 as an example. They provide an illustration as to the benefit of GAM analysis as the irregular fluctuations in the data are able to be modeled accurately.

Further, the 2016 Beaver City, NE site-year models show similar trends as the pooled site-year models. The 187 L ha^{-1} carrier volume buffered weed control losses compared to the 47 L ha^{-1} carrier volume for both dicamba and glufosinate. Severe weed control reductions in the 47 L ha^{-1} carrier volume were observed when droplet size increased greater than 700 µm for dicamba and 300 µm for glufosinate.

Model predictions for droplet sizes to achieve maximum weed control in individual site-years using mortality proportions are presented in Table 5.6. Predicted droplet sizes are unique for each specific site-year, further demonstrating a site-specific approach is necessary when recommending an optimum droplet size and carrier volume to maximize weed control. Across site-years, the predicted droplet sizes for maximum weed control ranged from Fine to Ultra Coarse spray classifications for both dicamba and glufosinate, indicating the application process is extremely complex with multiple variables impacting herbicide efficacy. Despite the complexity, this research showed that site-specific weed management strategies based on optimum droplet sizes and carrier volumes can be effectively implemented using PWM sprayers. Future research needs to identify and evaluate other variables as potential model parameters to create more robust model predictions and droplet size recommendations.

Conclusions

Spray droplet size and carrier volume impacted weed control with both systemic (dicamba) and contact (glufosinate) herbicides. From this research, 900 µm (Ultra Coarse) droplets paired with 187 L ha^{-1} carrier volume is recommended for dicamba applications as this combination provided the greatest weed control with the least particle drift potential across pooled site-years. A 310 µm (Medium) droplet size across carrier volumes is recommended for glufosinate applications across pooled site-years; however, if particle drift concerns exist, glufosinate droplet size can be increased to 605 µm (Extremely Coarse) and 90% of the maximum weed control can still be achieved. Further, if no water conditioning adjuvants are used in conjunction with glufosinate, a lower carrier volume should be utilized as more concentrated droplets are better able to overcome the antagonistic free cations within hard water, but applicators should keep in mind greater weed control is often observed with the combination of water conditioning adjuvants and increased carrier volume.

A site-specific weed management approach provided better model fit with both dicamba and glufosinate herbicides. Although model fits improved, predicted droplet sizes to maximize weed control were highly variable across site-years, leading to the conclusion that factors other than droplet size and carrier volume play a crucial role in determining final herbicide efficacy. Pesticide application and the resulting biological impacts are complex processes that are difficult to effectively manage. This research highlighted an alternative method of application using PWM sprayers to apply optimum droplet sizes in a site-specific weed management approach.

There is a critical droplet size for maintaining satisfactory weed control even with systemic type herbicides such as dicamba. To effectively reduce particle drift potential from future herbicide applications, alternative precautions other than increasing spray droplet size must be identified and implemented to avoid reductions in weed control. Therefore, to optimize spray applications using droplet size, application parameters should be tailored for site-specific weed management approaches to more effectively accommodate the changing application elements such as herbicide, weed species, weather condition, and geographic location to reduce herbicide inputs and reduce selection pressure for the evolution of herbicide-resistant weeds.

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Tables

Table 5.1. Site-year, GPS coordinates, weed species, average application weather conditions, and data collected for this research.

				Application weather conditions					
Year	Location	GPS coordinates	Weed species[a]	Wind speed	Air temperature	Relative humidity	Visual injury estimations	Mortality	Weed dry biomass
				m s^{-1}	°C	%			
2016	Dundee, MS	34.54°N, 90.47°W	AMAPA	1.8	28	81	X[c]	X	X
2016	Beaver City, NE	40.13°N, 99.88°W	AMAPA	1.8	29	45	X	X	X
2016	Prosper, ND	47.00°N, 97.12°W	Multiple[b]	3.1	27	44	X		
2017	Dundee, MS	34.54°N, 90.47°W	AMAPA	1.8	28	81	X	X	X
2017	Hendley, NE	40.12°N, 99.91°W	AMAPA	2.2	27	43	X	X	X
2017	Fargo, ND	46.93°N, 96.86°W	CHEAL	3.6	24	35	X		X

[a] AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; CHEAL, *Chenopodium album* L., common lambsquarters.
[b] Multiple weed species included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.
[c] An "X" indicates the respective response variable data were collected.

Table 5.2. Nozzle type, orifice size, and application pressure combinations for each dicamba and glufosinate droplet size ($D_{v0.5}$) and carrier volume treatment.[a]

Herbicide	Carrier volume	Nozzle[b]	Application pressure	Target droplet size	Actual droplet size	Standard error
	L ha^{-1}		kPa		µm	
dicamba	47	ER110015	414	150	155	1.84
		ER11006	290	300	308	0.29
		SR11006	241	450	447	0.62
		DR11004	234	600	596	1.83
		DR11008	241	750	757	0.47
		UR11006	276	900	893	1.31
	187	ER110015	414	150	153	1.61
		SR11002	207	300	296	0.04
		MR11004	269	450	446	1.63
		DR11005	359	600	600	1.23
		DR11006	262	750	754	1.11
		UR11006	241	900	908	0.97
glufosinate	47	ER110015	414	150	149	1.43
		SR11005	276	300	301	0.36
		DR11004	276	450	451	2.72
		UR11004	241	600	604	2.94
		UR11008	276	750	756	1.18
		UR11010	207	900	902	2.23
	187	ER110015	345	150	153	1.84
		SR11003	207	300	294	0.65
		MR11006	241	450	450	0.45
		DR11008	269	600	599	3.11
		UR11006	228	750	746	1.58
		UR11010	248	900	905	1.53

[a] Target droplet sizes were the designed droplet size treatments used in data analysis. Actual droplet sizes were the experimentally measured droplet sizes from spray solution, nozzle, and application pressure combinations. All actual droplet sizes were within 3.5% of the target droplet sizes.

[b] Flat fan, non-venturi nozzles; Wilger Industries Ltd., Lexington, TN, USA

Table 5.3. Generalized additive model (GAM) smoothing parameters and deviance explained for each response variable, herbicide, and carrier volume combination across pooled site-years.

Response variable	Site-years	Herbicide	Carrier volume	Smooth term edf[a]	Deviance explained
			L ha^{-1}		%
Visual injury estimations	6	Dicamba	47	1.00	4.51
			187	1.00	
		Glufosinate	47	2.75	9.45
			187	1.00	
Mortality	4	Dicamba	47	1.00	0.89
			187	1.00	
		Glufosinate	47	2.70	5.05
			187	1.00	
Weed dry biomass per plant	5	Dicamba	47	1.00	0.73
			187	1.00	
		Glufosinate	47	1.55	2.68
			187	1.56	

[a] Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1 = linear model.

Table 5.4. Generalized additive model (GAM) predicted droplet sizes to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts for each response variable, herbicide, and carrier volume combination across pooled site-years.

				Droplet size			
Response variable	Site-years	Herbicide	Carrier volume	Maximum weed control	Spray classification[a]	90% of maximum weed control	Spray classification[a]
			L ha^{-1}	µm		µm	
Visual injury estimations	6	Dicamba	47	900	UC	900	UC
			187	900	UC	900	UC
		Glufosinate	47	500	VC	740	EC
			187	150	F	435	C
Mortality	4	Dicamba	47	150	F	500	VC
			187	900	UC	900	UC
		Glufosinate	47	375	C	625	EC
			187	150	F	560	EC
Weed dry biomass per plant	5	Dicamba	47	150	F	370	C
			187	150	F	900	UC
		Glufosinate	47	360	M	675	EC
			187	315	M	600	EC

[a] Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

Table 5.5. Mortality proportion generalized additive model (GAM) smoothing parameters and deviance explained for each herbicide and carrier volume combination within individual site-years to investigate the plausibility of site-specific weed management.

Site	Year	Herbicide	Carrier volume	Smooth term edf[a]	Deviance explained
			L ha^{-1}		%
Dundee, MS	2016	Dicamba	47	1.02	29.30
			187	1.00	
		Glufosinate	47	1.32	10.90
			187	1.00	
Dundee, MS	2017	Dicamba	47	1.00	24.70
			187	1.71	
		Glufosinate	47	2.18	60.90
			187	4.76	
Beaver City, NE	2016	Dicamba	47	3.02	50.90
			187	1.17	
		Glufosinate	47	3.79	43.30
			187	1.00	
Hendley, NE	2017	Dicamba	47	1.95	32.70
			187	2.98	
		Glufosinate	47	1.00	9.74
			187	1.00	

[a] Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1 = linear model.

Table 5.6. Mortality proportion generalized additive model (GAM) predicted droplet sizes to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts for each herbicide and carrier volume combination within individual site-years to investigate the plausibility of site-specific weed management.

				Droplet size			
Location	Year	Herbicide	Carrier volume	Maximum weed control	Spray classification[a]	90% of maximum weed control	Spray classification[a]
			L ha^{-1}	µm		µm	
Dundee, MS	2016	Dicamba	47	900	UC	900	UC
			187	900	UC	900	UC
		Glufosinate	47	900	UC	900	UC
			187	150	F	275	M
Dundee, MS	2017	Dicamba	47	150	F	515	VC
			187	150	F	260	M
		Glufosinate	47	600	EC	755	EC
			187	800	UC	865	UC
Beaver City, NE	2016	Dicamba	47	545	VC	685	EC
			187	150	F	710	EC
		Glufosinate	47	300	M	375	C
			187	150	F	900	UC
Hendley, NE	2017	Dicamba	47	900	UC	900	UC
			187	900	UC	900	UC
		Glufosinate	47	900	UC	900	UC
			187	150	F	450	VC

[a] Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

Figures

Figure 5.1. Capstan PinPoint® pulse-width modulation research sprayer at the 2016 Beaver City, Nebraska, field site.

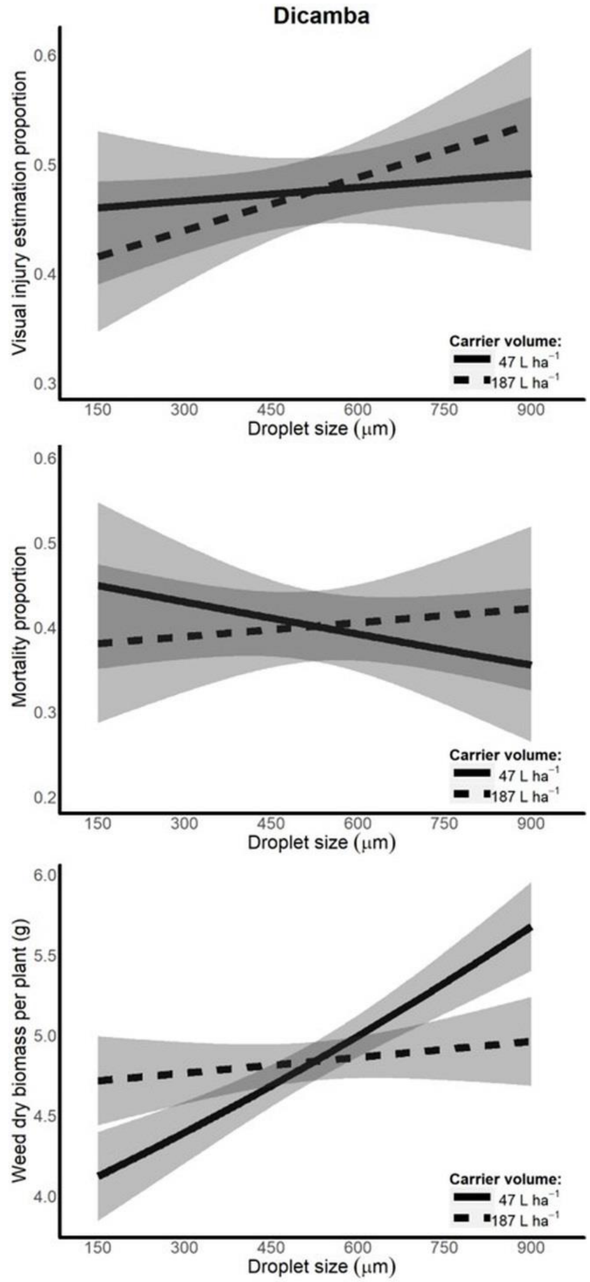

Figure 5.2. Visual injury estimation proportion (top), mortality proportion (middle), and weed dry biomass per plant (bottom) 28 days after treatment as affected by droplet size and carrier volume were pooled across six, four, and five site-years, respectively, and predicted using generalized additive models for dicamba. The grey shaded area indicates the 95% confidence limits.

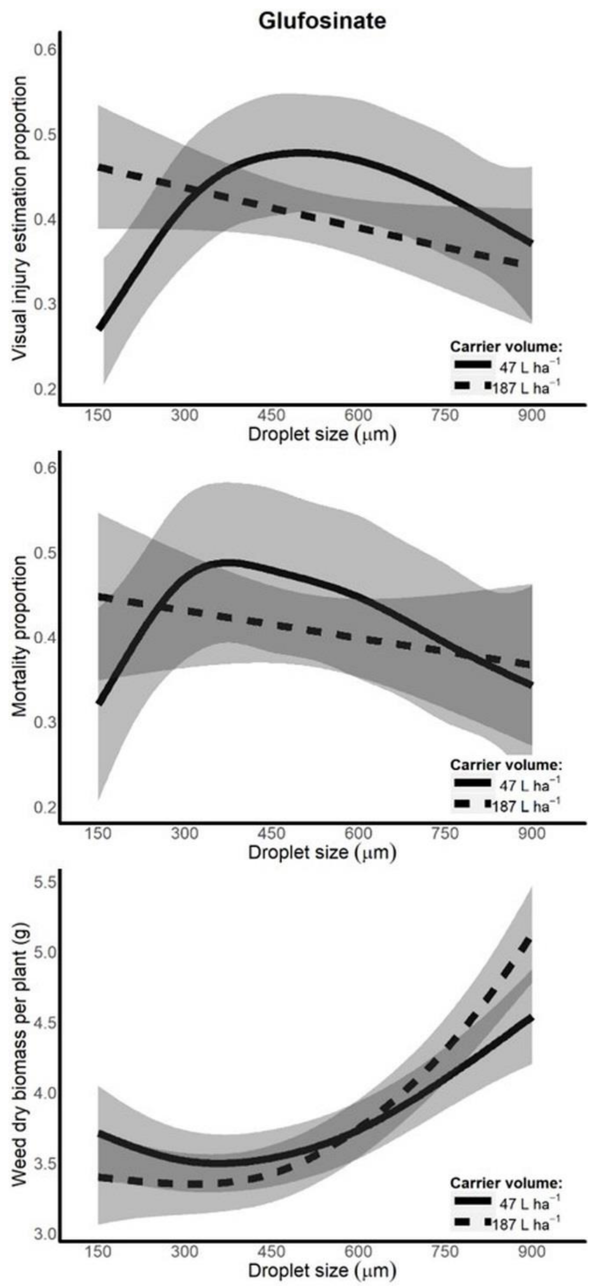

Figure 5.3. Visual injury estimation proportion (top), mortality proportion (middle), and weed dry biomass per plant (bottom) 28 days after treatment as affected by droplet size and carrier volume were pooled across six, four, and five site-years, respectively, and predicted using generalized additive models for glufosinate. The grey shaded area indicates the 95% confidence limits.

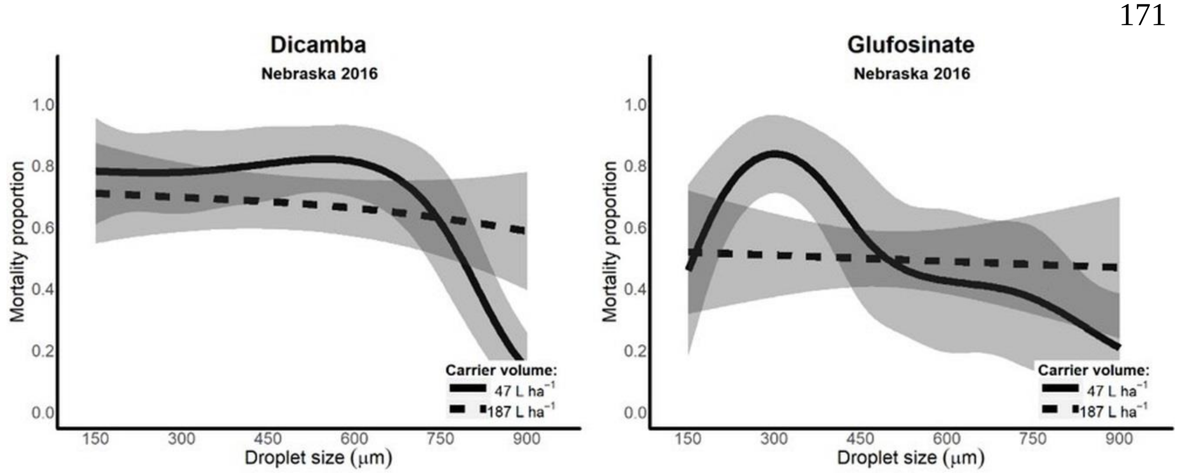

Figure 5.4. Mortality proportion 28 days after treatment as affected by droplet size and carrier volume for the 2016 Beaver City, Nebraska site-year and predicted using generalized additive models for dicamba (left) and glufosinate (right) to assess the plausibility of site-specific weed management strategies. The grey shaded area indicates the 95% confidence limits.

CHAPTER 6

OPTIMUM DROPLET SIZE USING A PULSE-WIDTH MODULATION SPRAYER FOR APPLICATIONS OF 2,4-D CHOLINE PLUS GLYPHOSATE

Abstract

The delivery of an optimum herbicide droplet size using pulse-width modulation (PWM) sprayers can reduce potential environmental contamination, maintain satisfactory efficacy, and provide more flexible options for pesticide applicators. Field research was conducted in 2016, 2017, and 2018 across three locations (Mississippi, Nebraska, and North Dakota) for a total of six site-years. The objectives were to evaluate the efficacy of a range of droplet sizes [150 µm (Fine) to 900 µm (Ultra Coarse)] using a 2,4-D choline plus glyphosate (Enlist Duo®) pre-mixture and create novel weed management recommendations utilizing PWM sprayer technology. Across pooled site-years, a 430 µm (Coarse) droplet size maintained 90% of the maximum weed mortality, thereby reducing the addition of weed seeds to the soil seedbank and mitigating spray particle drift potential. However, model fit was poor, so a site-specific analysis was conducted. Across the Mississippi and North Dakota sites, a 900 µm (Ultra Coarse) droplet size was recommended. In contrast, at the Nebraska sites, droplet sizes between 565 – 690 µm (Extremely Coarse) were almost exclusively required to maintain 90% of the maximum weed control likely due to weed leaf architecture. This research illustrated that PWM sprayers paired with appropriate nozzle*pressure combinations for 2,4-D choline plus glyphosate pre-mixture could be effectively implemented into precision agricultural

practices by generating optimum herbicide droplet sizes for site-specific management plans. To fully optimize spray applications using PWM technology, future research must holistically investigate the influence of weather conditions, time of day, weed species, geographic location, and herbicide droplet size.

Introduction

Weed management is a community problem, and agricultural communities should concern themselves with collaborative and innovative management efforts (Ervin and Frisvold, 2016; Hammonds and Woods, 1938). Weed competition with corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr] was identified to cause 50 and 52% yield loss resulting in annual farm revenue losses of $26.7 billion and $17.2 billion, respectively, across North America (Soltani et al., 2017, 2016). Herbicide applications are a primary component of these integrated management strategies as 95% of corn, soybean, and cotton (*Gossypium hirsutum* L.) hectares were treated for weeds in 2015 (USDA-NASS, 2015). Numerous factors influence each herbicide application, including the often overlooked aspect of application technique and delivery methods (Kudsk, 2017). However, focus should be placed on these factors if applications are to be fully optimized to maximize efficacy while maintaining environmental safety (Matthews et al., 2014).

Pulse-width modulation (PWM) sprayers provide an alternative method to optimize pesticide applications as they allow for several factors, including application pressure and spray droplet size, to be maintained across a range of sprayer speeds while variably controlling flow. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The solenoid valves are typically pulsed on a 10 Hz frequency (10 pulses per second), and the relative proportion of time each valve is open (duty cycle) determines the flow rate. This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003) and PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Furthermore, PWM sprayers have the capability of producing up to a 10:1 turndown ratio in flow rate with no pressure or nozzle based changes, thus creating more flexible options for pesticide applicators (Giles et al., 1996; GopalaPillai et al., 1999). Application pressure based variable rate flow control devices have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). In contrast, research has shown PWM duty cycle has little to no effect on droplet size when using non-venturi nozzles (Butts et al., 2017a; Giles et al., 1996). Additionally, when PWM sprayers were operated at or above a 40% duty cycle, minimal to no negative impacts were observed on spray pattern and coverage (Butts et al., 2018a; Mangus et al., 2017; Womac et al., 2017, 2016). Therefore, it is feasible with a PWM sprayer to sustain an optimum herbicide droplet size and spray pattern throughout an application in which efficacy could be maximized and particle drift minimized.

Spray drift mitigation efforts have primarily focused on increasing spray droplet size as finer droplets have been shown to drift farther downwind (Bueno et al., 2017; Vieira et al., 2018). Numerous application factors have been determined to affect droplet size including: adjuvants (Butler Ellis et al., 1997; Chapple et al., 1993), pesticide formulations (Miller and Butler Ellis, 2000), nozzle design (Barnett and Matthews, 1992;

Butler Ellis et al., 2002; Etheridge et al., 1999), nozzle orifice size (Nuyttens et al., 2007), and application pressure (Creech et al., 2015). Due to the complexity of application parameters' effect on droplet size, a more thorough understanding of the application process is required for sprayer optimization. Furthermore, as a result of increasing spray droplet size to reduce particle drift, noticeable negative biological consequences have occurred (Wolf, 2002).

Previous research demonstrated increased control across multiple herbicides and weed species as droplet size decreased (Ennis and Williamson, 1963; Knoche, 1994; Lake, 1977; McKinlay et al., 1974, 1972). Typically, it has been suggested that systemic herbicides are less sensitive to changes in droplet size. Glyphosate [N-(phosphonomethyl)glycine, isopropylamine salt] had greater absorption and translocation with Coarse droplets (Feng et al., 2009). However, the translocation of 2,4-D (2,4-dichlorophenoxyacetic acid, dimethylamine salt) increased as droplet size decreased, indicating droplet size played a role in 2,4-D efficacy (Wolf et al., 1992). Additionally, several other systemic herbicides (Prasad and Cadogan, 1992) including two forms of dicamba [3,6-dichloro-o-anisic acid, N,N-Bis-(3-aminopropyl)methylamine and dicglycolamine salts] had efficacy reductions when droplet size increased (Butts et al., 2018b; Meyer et al., 2016). Droplet size impacts on systemic herbicide efficacy are convoluted; however, site-specific weed management strategies can assist with more effectively using optimum droplet sizes (Tian et al., 1999; Wilkerson et al., 2004). PWM sprayers provide a unique opportunity for use in site-specific management scenarios by equipping and operating an appropriate nozzle type, orifice size, and pressure previously determined to create an optimum droplet size for maximum herbicide efficacy while simultaneously mitigating particle drift potential. Furthermore, the homogenization of the droplet sizes represented within a spray pattern through unique pesticide delivery methods, such as PWM, could result in greater droplet adhesion to leaf surfaces (De Cock et al., 2017).

The objectives of this research were to evaluate the influence of spray droplet size on the efficacy of a 2,4-D choline (2,4-dichlorophenoxyacetic acid, choline salt) plus glyphosate [N-(phosphonomethyl)glycine, dimethylammonium salt] pre-mixture and to determine the plausibility of using PWM sprayers in a site-specific weed management strategy. Recommendations were then established for an optimum droplet size to mitigate particle drift potential without compromising efficacy. The precise, site-specific application of this herbicide will allow farmers to more effectively utilize drift reduction technologies, reduce herbicide inputs, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

Materials and Methods

EXPERIMENT DESIGN AND ESTABLISHMENT

Field trials were conducted in 2016, 2017, and 2018 in a fallow environment across three states (Mississippi, Nebraska, and North Dakota) for a total of six site-years to evaluate the droplet size effect on the efficacy of 2,4-D choline (2,4-dichlorophenoxyacetic acid, choline salt) plus glyphosate [N-(phosphonomethyl)glycine, dimethylammonium salt] (Table 6.1). The trials were randomized complete block experimental designs replicated a minimum of three times spatially. This research was conducted using similar methods as previous droplet size efficacy research (Butts et al., 2018b). Treatments consisted of six targeted droplet sizes (150, 300, 450, 600, 750, and 900 µm) determined from the $D_{v0.5}$ of the measured droplet size distribution. The $D_{v0.5}$ parameter represents the droplet diameter such that 50% of the spray volume is contained in droplets of smaller diameter. One nontreated control per site-year was used for comparison which provided a total of seven treatments. The herbicide pre-mixture of 2,4-D choline plus glyphosate (Enlist Duo®, 0.19 kg ae L^{-1} 2,4-D, 0.20 kg ae L^{-1} glyphosate, Dow AgroSciences, Indianapolis, IN 46268) was applied postemergence to 15-cm tall or greater weeds at 0.79 kg ae ha^{-1} 2,4-D plus 0.84 kg ae ha^{-1} glyphosate (4.09 L ha^{-1} formulated product) with a carrier volume of 94 L ha^{-1}. No additional adjuvants were tank-mixed into the solution to eliminate confounding effects and evaluation of treatments could occur solely on the herbicide.

Treatments were applied using a PinPoint® PWM research sprayer (Capstan Ag Systems, Inc., Topeka, KS 66609) (Figure 6.1). The benefits of using a PWM sprayer in this research were two-fold. First, PWM allows spray output to become independent from nozzle orifice size, sprayer speed, and application pressure. Therefore, the application process was simplified and standardized for operators across a range of spray environments. Second, as previous research highlighted PWM duty cycle had a minimal effect on droplet characteristics (Butts et al., 2017a, 2017b) and spray pattern (Butts et al., 2018a), a nozzle type, orifice size, and application pressure combination could be selected to provide a consistent droplet size for each treatment while maintaining the appropriate spray output (94 L ha^{-1}) throughout an application.

Nozzle type, orifice size, and application pressure required to create droplet size treatments were determined through droplet size measurements made using a Sympatec

HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) in the low-speed wind tunnel at the Pesticide Application Technology (PAT) Laboratory in North Platte, NE (Table 6.2). Henry et al., (2014) and Creech et al., (2015) provide in-depth details regarding the low-speed wind tunnel at the PAT Laboratory, and Butts et al., (2017a) provides an illustration for further clarification of wind tunnel construction and operation. Only Wilger Industries, Ltd. non-venturi nozzles were used in this research as: (1) only non-venturi nozzles are recommended for use on PWM systems (Butts et al., 2017a; Capstan Ag Systems Inc., 2013) and (2) nozzle designs were similar (flat-fan, non-venturi, straight flow path) to eliminate confounding spray characteristic factors. Spray classifications were assigned in accordance with ASABE S572.1 (ASABE, 2009).

DATA COLLECTION

Each collaborating university collected data from their respective sites. Visual injury estimation proportions were recorded approximately 28 days after treatment (DAT) for entire plots. Furthermore, ten individual weeds per plot were marked at the time of application. At 28 DAT, marked plants were individually evaluated for mortality (alive or dead) and the total number of deceased plants were divided by ten to provide mortality proportion measurements for each plot. The individual weeds were then clipped at the soil surface, harvested, and dried at 55°C to constant mass. The dry plants were pooled into one dry biomass measurement per plot, and were divided by ten for average weed dry shoot biomass per plant measurements.

STATISTICAL ANALYSIS

Generalized additive modeling (GAM) analysis was conducted in R 3.5.0 statistical software using the mgcv package to model spray droplet size with each respective response variable to provide an estimate of the optimum spray droplet size for weed control (Crawley, 2013). To meet model assumptions, visual injury estimation and mortality proportions were analyzed using a beta distribution as the data were bound between 0 and 1, and weed dry biomass per plant data were subjected to a natural log transformation. Backtransformed data are presented for clarity. Models consisted of one smoothed variable (droplet size) (Equation 6.1).

$$\text{Response variable} \sim s(\text{Target droplet size}) \qquad [6.1]$$

Data were pooled across site-years to provide overall droplet size recommendations; however, GAM analysis was also conducted for individual site-years to assess droplet size efficacy implications in a site-specific weed management scenario. Models were used to predict the droplet size for maximum weed control and the droplet size at which 90% of maximum weed control was attained for drift mitigation recommendations.

Results and Discussion

Individual site-year information including GPS coordinates, weed species, weather conditions at the time of application, and data collected are presented in Table 6.1. Visual injury estimation, weed mortality, and weed dry biomass per plant data were collected from six, four, and five site-years, respectively. Additionally, droplet sizes discussed throughout the results and discussion refer to the $D_{v0.5}$ measurement (average droplet size) of the droplet size distribution.

POOLED SITE-YEARS

The GAM models for visual injury estimation proportion, mortality proportion, and dry weed biomass per plant are presented in Figure 6.2. The model smooth term estimated degrees of freedom (edf) and deviance explained for each response variable are presented in Table 6.3. A smooth term edf of one is equal to a linear model with model fluctuation increasing as the smooth term edf increases. The explained deviance provides an estimate of the discrepancy between model predicted estimates and actual observations with a larger percentage indicating a smaller discrepancy and overall better model fit.

Generally, droplet size minimally impacted 2,4-D choline plus glyphosate pre-mixture efficacy across pooled site-years when measured using visual injury estimations or dry weed biomass per plant. Conversely, an increase in droplet size severely reduced the mortality proportion. The smooth term edf for the visual injury estimation, mortality, and weed dry biomass per plant GAM models indicated the herbicide efficacy and droplet size relationship was linear (smooth term edf = 1.000) or nearly linear (smooth term edf = 1.474) when site-years were pooled. Visual injury estimation proportions and dry weed biomass per plant GAM models predicted 90% of maximum herbicidal efficacy was achieved with a 900 µm droplet size (Ultra Coarse) (Table 6.4). The mortality proportion GAM model predicted an optimum droplet size of 150 µm (Fine) for maximum weed control. However, 90% of the maximum weed control could be achieved with a 430 µm droplet size (Coarse). Therefore, across response variables, it is challenging to choose an overall optimum droplet size due to the large discrepancies between evaluation methods. However, at a carrier volume of 94 L ha^{-1}, a 430 µm droplet size (Coarse) for 2,4-D choline plus glyphosate pre-mixture spray applications would maintain 90% of the maximum plant death, thereby reducing the addition of weed seeds to the soil seedbank, while mitigating particle drift potential.

Although general recommendations of an optimum droplet size across a wide range of geographies could be established from the pooled site-year analysis, the deviance explained for each GAM model was low (< 5%) (Table 6.3). These models suggest that across the pooled site-years, a maximum of 4.19% of the herbicide efficacy variability could be attributed to droplet size. Therefore, numerous other factors that influence herbicide efficacy, such as weather conditions, time of day, weed species, and geographic location (Kudsk, 2017), may be larger drivers in final biological efficacy as opposed to droplet size for the pre-mixture of 2,4-D choline plus glyphosate. Future research should investigate the influence of each of these specific application factors on 2,4-D choline plus glyphosate pre-mixture efficacy, and more robust models should be established implementing each factor as a parameter to fully optimize spray applications using this herbicide.

SITE-SPECIFIC WEED MANAGEMENT

Prior to field trial establishment, it was hypothesized that identifying and applying an optimum herbicide droplet size would be more appropriate as a site-specific management strategy. The poor model fit resulting from the pooled site-year analysis validated this assumption. Additionally, the precision agricultural capabilities of PWM sprayers would allow for more precise pesticide applications in site-specific scenarios compared with conventional application equipment. Therefore, each respective site-year was analyzed separately to determine if the deviance explained for each GAM model could be improved and optimum droplet size predictions made more robust.

The GAM models' smooth term edf and deviance explained within individual site-years for each response variable are presented in Table 6.5. Generally, the site-specific management approach increased the deviance explained across models. The average deviance explained across site-years and response variables was 22% indicating nearly 1/4th of the herbicide efficacy variability could be explained on average by the droplet size factor within a site-year. However, the deviance explained was highly variable across site-years and response variables as it ranged from 0.03% to 95.90%. More complex models (greater fluctuation) were required to fit the site-specific data compared to the pooled site-year data as only 50% of the GAM models had linear relationships (smooth term edf = 1.000). Additionally, Figure 6.3 highlights that the three data collection methods, visual injury estimations, weed mortality, and weed dry biomass per plant, provided similar predictive trends of 2,4-D choline plus glyphosate pre-mixture efficacy across treatments. This contradicts previous droplet size research with synthetic auxins (dicamba) in which visual injury estimations provided an unreliable estimation of complete weed control (Butts et al., 2018b).

Maximum weed control across site-years and response variables ranged from an optimum droplet size of 150 µm (Fine) to 900 µm (Ultra Coarse) (Table 6.6). However, across the four Mississippi and North Dakota site-years, 90% of the maximum weed control was achieved with a 900 µm (Ultra Coarse) droplet size, and would be recommended for spray applications of 2,4-D choline plus glyphosate pre-mixture to reduce particle drift potential. In contrast, across the two Nebraska site-years, 90% of the maximum weed control was almost exclusively achieved between droplet sizes of 565 – 690 µm (Extremely Coarse). Severe penalties in weed control were observed as droplet size increased greater than those critical sizes (Figure 6.3). Therefore, alternative particle drift reduction practices must be identified and implemented, otherwise losses in weed control will be observed.

This difference in optimum droplet sizes across sites may be attributed to the weed species evaluated. The primary weed species in Mississippi and North Dakota was Palmer amaranth (*Amaranthus palmeri* S. Wats) and common lambsquarters (*Chenopodium album* L.), respectively. Spillman (1984) identified coarser droplets had greater impaction and retention efficiency on horizontal leaf surfaces. Both Palmer amaranth and common lambsquarters have flat, horizontal leaf surfaces in which coarser droplets may have had increased retention leading to the minimal droplet size effect on herbicidal efficacy. Conversely, the primary weed species in Nebraska was kochia [*Bassia scoparia* (L.) A.J. Scott] and horseweed (*Erigeron canadensis* L.), and they had similar trends in herbicide efficacy across droplet size treatments within the same site-year (Table 6.6) (Figure 6.4). Typically, maximum weed control was achieved with a 150 µm (Fine) droplet size, but 90% of the maximum control was achieved with 565 – 690 µm (Extremely Coarse) droplet sizes. This is likely due to kochia and horseweed having a much smaller and narrower leaf structure paired with relatively vertical plant architecture compared to Palmer amaranth and common lambsquarters. Previous research showed finer droplets paired with horizontal winds resulted in greater impaction and retention efficiency on vertical leaf surfaces (Lake, 1977). Further research observed an effect of plant architecture and leaf surface composition on droplet impaction and retention and thereby herbicidal efficacy (Massinon et al., 2017; Nairn et al., 2013). Therefore, due to the structure of the kochia and horseweed plants, smaller droplet sizes may have been required to achieve the necessary droplet retention and coverage to maximize the efficacy of 2,4-D choline plus glyphosate pre-mixture.

Although the efficacy trends across droplet sizes were similar, there were noteworthy differences in overall weed control levels between the kochia and horseweed species which can be attributed to herbicide resistance. The kochia populations present at the Nebraska field-sites were glyphosate-resistant while the horseweed population was glyphosate-susceptible (unpublished data). As a result, 2,4-D was the only effective mode-of-action for kochia control, and 2,4-D has been shown to have relatively poor control (<70%) on kochia (Knezevic et al., 2017). In contrast, the combination of 2,4-D plus glyphosate has been shown to control glyphosate-susceptible horseweed 90-95%.

The results of the site-specific analysis corroborated previous research in which it was recommended that each herbicide and weed species interaction required a tailored approached to maximize efficacy (Creech et al., 2016). This research provided proof of concept for the use of PWM sprayer technology in site-specific management scenarios and illustrated that PWM sprayers paired with appropriate nozzle*pressure combinations for 2,4-D choline plus glyphosate pre-mixture could be effectively implemented into precision agricultural practices by generating optimum herbicide droplet sizes for site-specific management plans. However, future research should investigate the impact of spray carrier volume on the efficacy of 2,4-D choline plus glyphosate herbicide pre-mixture. Previous research indicated increasing spray carrier volume may buffer the impact of increasing droplet size on spray coverage, penetration, and the resulting biological efficacy (Bretthauer et al., 2008); however, convoluted interactions between droplet size and carrier volume have occurred depending on the active ingredient (Butts et al., 2018b). Additionally, as previously mentioned, future research should holistically investigate the influence of weather conditions, time of day, weed species, and geographic location paired with herbicide droplet size to create more robust models and fully optimize spray applications.

Conclusions

The concern for environmentally safe, efficacious, and more economical herbicide applications is a major concern in today's agricultural industry, and optimizing each application is a must. This research identified across a broad geographic setting and diverse weed spectrum that applications of 2,4-D choline plus glyphosate pre-mixture should utilize a 430 µm (Coarse) droplet size when applying with a carrier volume of 94 L ha^{-1} to maintain weed mortality while simultaneously mitigating particle drift potential.

More precise PWM sprayer applications could be achieved through precision agricultural methods by applying the precise herbicide droplet sizes in a site-specific approach. Across Mississippi and North Dakota sites, a 900 µm (Ultra Coarse) droplet size was recommended, while across Nebraska sites, a droplet size of 565 – 690 µm (Extremely Coarse) was typically needed to maintain 90% of the maximum weed control. These differences in optimum droplet sizes were likely due to weed species plant structure and leaf architecture; however, numerous other factors such as application weather conditions, geographic location, time of day, and herbicide resistance evolution, may have played a significant role in final herbicidal efficacy.

This research highlighted using PWM sprayers to apply optimum droplet sizes in a site-specific weed management approach is both manageable and effective. With the ever increasing droplet size database, appropriate nozzle*pressure combinations to achieve specific droplet sizes for a multitude of herbicide spray solutions may soon be readily available. The use of PWM sprayers paired with appropriate nozzle*pressure combinations could be effectively implemented to optimize an application through precise droplet size control in site-specific management approaches. Finally, to effectively reduce particle drift potential from future herbicide applications, alternative drift reduction strategies other than increasing spray droplet size must be identified and implemented to avoid weed control losses and mitigate the evolution of herbicide-resistant weeds.

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Tables

Table 6.1. Site-year, GPS coordinates, weed species, average application weather conditions, and data collected to understand the impact of droplet size on herbicide efficacy of 2,4-D choline plus glyphosate.

				Application weather conditions					
Year	Location	GPS coordinates	Weed species†	Wind speed	Air temperature	Relative humidity	Visual injury estimations	Mortality	Weed dry biomass
				m s^{-1}	°C	%			
2016	Dundee, MS	34.54°N, 90.47°W	AMAPA	0.5	27	90	X‡	X	X
2016	Prosper, ND	47.00°N, 97.12°W	Multiple§	3.1	27	44	X		
2017	Dundee, MS	34.54°N, 90.47°W	AMAPA	0.9	30	69	X	X	X
2017	Brule, NE	41.16°N, 102.00°W	KCHSC	3.6	36	24	X	X	X
2017	Fargo, ND	46.93°N, 96.86°W	CHEAL	3.6	24	35	X		X
2018	North Platte, NE	41.05°N, 100.75°W	Multiple¶	3.6	32	41	X	X	X

† AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters.
‡ An "X" indicates the respective response variable data were collected from the respective site-year.
§ Multiple weed species at the 2016 Propser, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.
¶ Multiple weed species at the 2018 North Platte, NE site-year included: KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; and ERICA, *Erigeron canadensis* L., horseweed.

Table 6.2. Nozzle type, orifice size, and application pressure combinations for each 2,4-D choline plus glyphosate droplet size ($D_{v0.5}$) treatment.†

Nozzle‡	Application pressure	Target droplet size	Actual droplet size	Standard error	Spray classification§
	kPa	———	µm	———	
ER110015	551	150	168	1.28	F
SR11002	276	300	297	0.13	M
MR11003	207	450	455	1.54	VC
DR11004	207	600	594	0.79	EC
DR11010	413	750	748	2.65	EC
UR11010	324	900	902	2.21	UC

† Target droplet sizes were the designed droplet size treatments used in data analysis. Actual droplet sizes were the experimentally measured droplet sizes from spray solution, nozzle, and application pressure combinations. Actual droplet sizes were within 1.1% of the target droplet sizes with the exception of the 150 µm treatment as 168 µm was the smallest possible droplet size capable of being generated.
‡ Flat fan, non-venturi nozzles; Wilger Industries Ltd., Lexington, TN, USA
§ Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

Table 6.3. Generalized additive model (GAM) smoothing parameters and deviance explained for each response variable across pooled site-years.

Response variable	Site-years	Smooth term edf†	Deviance explained
			%
Visual injury estimations	6	1.474	1.53
Mortality	4	1.000	4.19
Weed dry biomass per plant	5	1.000	0.00

† Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1 = linear model.

Table 6.4. Predicted droplet sizes based on a generalized additive model (GAM) to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts for each response variable across pooled site-years.

		Droplet size			
Response variable	Site-years	Maximum weed control	Spray classification†	90% of maximum weed control	Spray classification†
		µm		µm	
Visual injury estimations	6	490	VC	900	UC
Mortality	4	150	F	430	C
Weed dry biomass per plant	5	900	UC	900	UC

† Spray classifications determined using ASABE S572.1 where F=Fine, C=Coarse, VC=Very Coarse, and UC=Ultra Coarse.

Table 6.5. Generalized additive model (GAM) smoothing parameters and deviance explained within individual site-years for each response variable to investigate the plausibility of site-specific weed management.

Response variable	Site	Year	Weed species†	Smooth term edf‡	Deviance explained
					%
Visual injury estimations	Dundee, MS	2016	AMAPA	1.778	12.50
	Prosper, ND	2016	Multiple§	1.000	0.03
	Dundee, MS	2017	AMAPA	1.000	3.43
	Brule, NE	2017	KCHSC	1.872	26.20
	Fargo, ND	2017	CHEAL	3.677	95.90
	North Platte, NE	2018	KCHSC	2.537	40.20
	North Platte, NE	2018	ERICA	1.000	47.20
Mortality	Dundee, MS	2016	AMAPA	2.102	17.10
	Dundee, MS	2017	AMAPA	1.000	2.41
	Brule, NE	2017	KCHSC	2.077	22.70
	North Platte, NE	2018	KCHSC	1.000	18.80
	North Platte, NE	2018	ERICA	1.226	34.20
Weed dry biomass per plant	Dundee, MS	2016	AMAPA	1.000	2.42
	Dundee, MS	2017	AMAPA	1.000	1.65
	Brule, NE	2017	KCHSC	2.684	40.60
	Fargo, ND	2017	CHEAL	1.623	17.00
	North Platte, NE	2018	KCHSC	1.000	5.69
	North Platte, NE	2018	ERICA	1.000	2.12

† AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters; ERICA, *Erigeron canadensis* L., horseweed.
‡ Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1 = linear model.
§ Multiple weed species at the 2016 Propser, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.

Table 6.6. Predicted droplet sizes based on a generalized additive model (GAM) to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts within individual site-years for each response variable to investigate the plausibility of site-specific weed management.

				Droplet size			
Response variable	Location	Year	Weed species†	Maximum weed control	Spray classification‡	90% of maximum weed control	Spray classification‡
				µm		µm	
Visual injury estimations	Dundee, MS	2016	AMAPA	150	F	900	UC
	Prosper, ND	2016	Multiple§	150	F	900	UC
	Dundee, MS	2017	AMAPA	900	UC	900	UC
	Brule, NE	2017	KCHSC	355	M	675	EC
	Fargo, ND	2017	CHEAL	725	EC	900	UC
	North Platte, NE	2018	KCHSC	455	VC	600	EC
	North Platte, NE	2018	ERICA	150	F	655	EC
Mortality	Dundee, MS	2016	AMAPA	900	UC	900	UC
	Dundee, MS	2017	AMAPA	900	UC	900	UC
	Brule, NE	2017	KCHSC	430	C	690	EC
	North Platte, NE	2018	KCHSC	150	F	240	F
	North Platte, NE	2018	ERICA	150	F	590	EC
Weed dry biomass per plant	Dundee, MS	2016	AMAPA	900	UC	900	UC
	Dundee, MS	2017	AMAPA	900	UC	900	UC
	Brule, NE	2017	KCHSC	405	C	565	EC
	Fargo, ND	2017	CHEAL	655	EC	900	UC
	North Platte, NE	2018	KCHSC	150	F	295	M
	North Platte, NE	2018	ERICA	150	F	610	EC

† AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters; ERICA, *Erigeron canadensis* L., horseweed.

‡ Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, C=Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

§ Multiple weed species at the 2016 Propser, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.

Figures

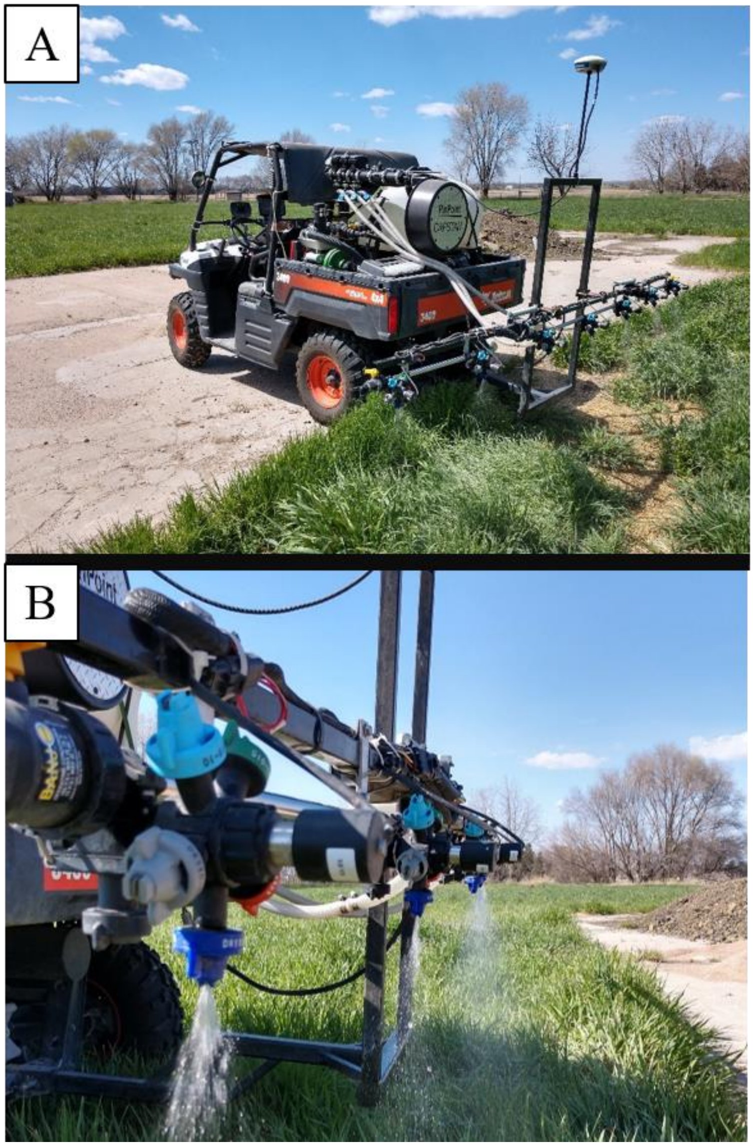

Figure 6.1. (A) Pulse-width modulation sprayer (Capstan PinPoint®) equipped and operated with (B) non-venturi nozzles (Wilger Industries Ltd., Lexington, TN, USA) used to apply droplet size treatments in this research.

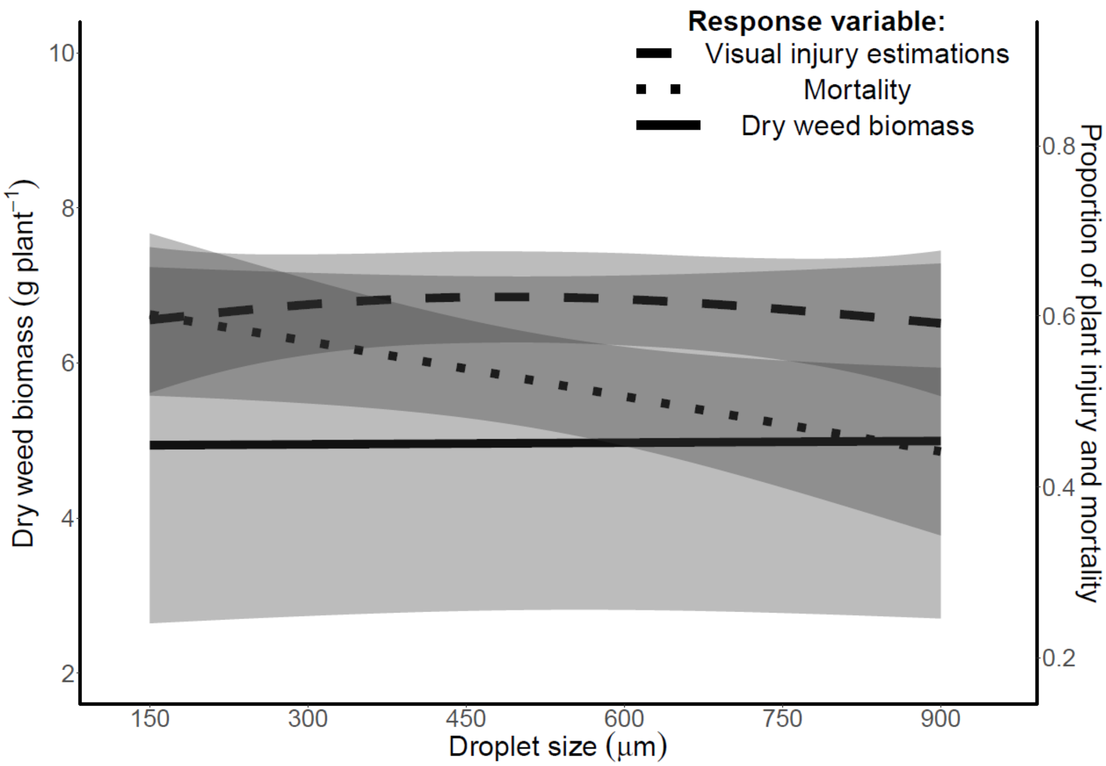

Figure 6.2. Visual injury estimation proportion, mortality proportion, and weed dry biomass per plant 28 days after treatment as affected by droplet size were pooled across six, four, and five site-years, respectively, and predicted using generalized additive models (GAM). The grey shaded area indicates the 95% confidence limits.

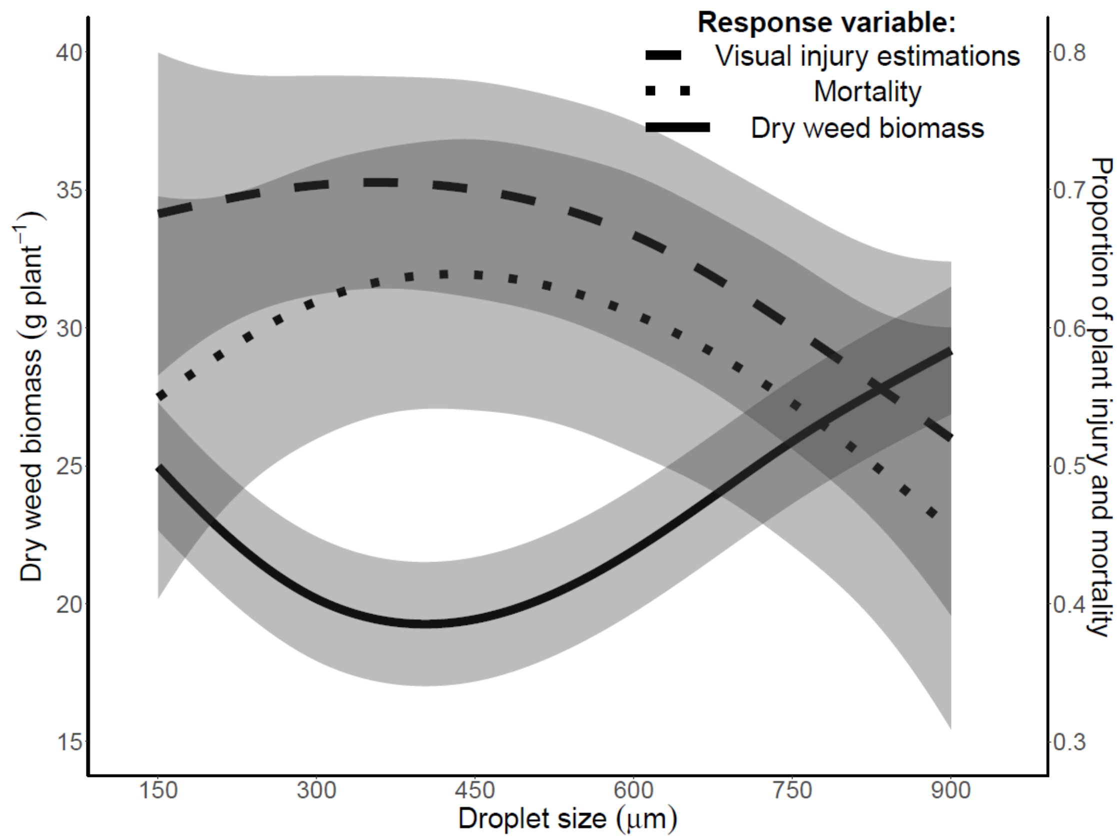

Figure 6.3. Visual injury estimation proportion, mortality proportion, and weed dry biomass per plant generalized additive models (GAM) for the 2017 Brule, NE, USA site-year to assess the plausibility of site-specific weed management strategies. The grey shaded area indicates the 95% confidence limits.

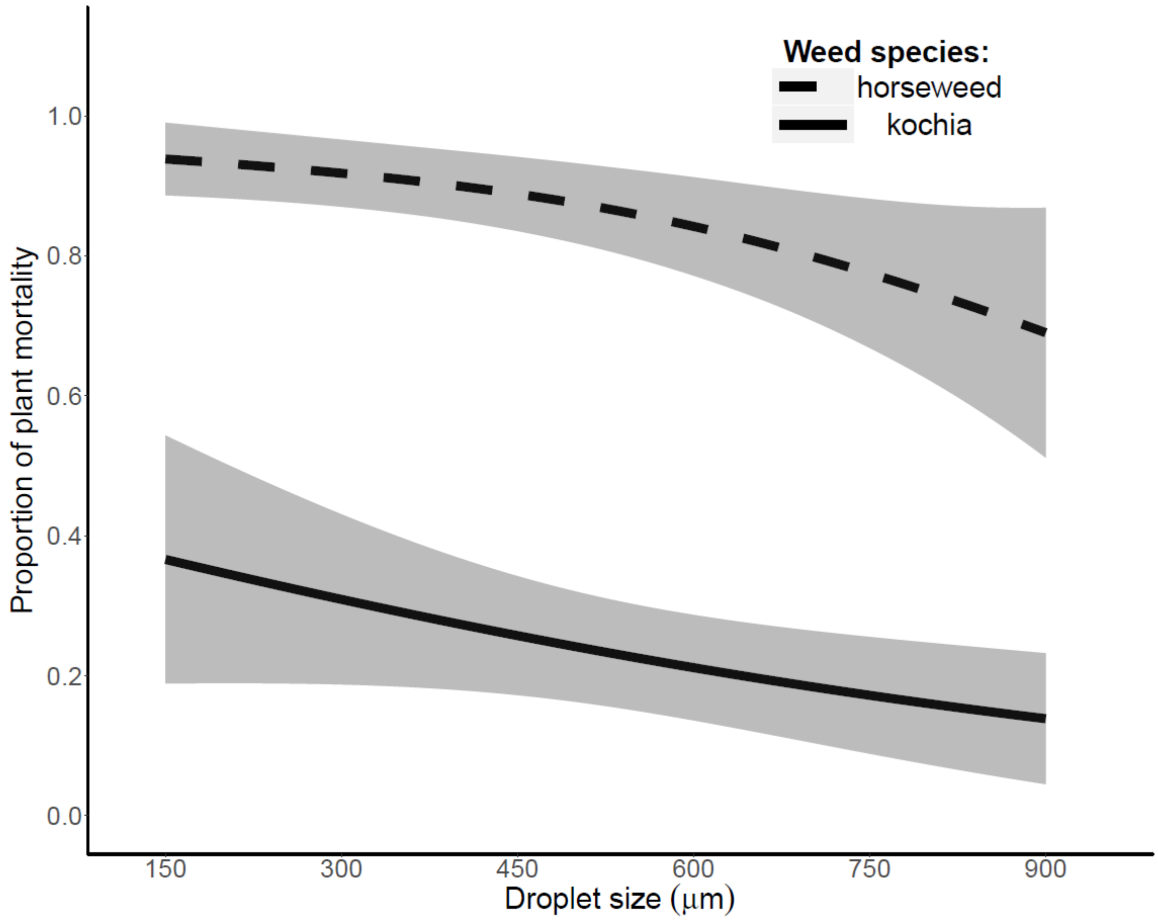

Figure 6.4. Mortality proportion generalized additive models (GAM) for the horseweed (*Erigeron canadensis* L.) and kochia [*Bassia scoparia* (L.) A.J. Scott] weed species at the 2018 North Platte, NE, USA site-year. The grey shaded area indicates the 95% confidence limits.

CHAPTER 7

DROPLET SIZE IMPACT ON DICAMBA PLUS GLYPHOSATE TANK-MIXTURE EFFICACY

Abstract

Chemical weed control remains a widely-used component of integrated weed management strategies due to its cost effectiveness and rapid removal of crop pests. Additionally, dicamba plus glyphosate tank-mixtures are a commonly recommended herbicide combination to combat herbicide resistance, specifically in recently commercially-released dicamba-tolerant soybean and cotton. However, increased spray drift concerns and antagonistic interactions require the application process to be optimized to maximize biological efficacy while minimizing environmental contamination potential. Field research was conducted in 2016, 2017, and 2018 across three locations (Mississippi, Nebraska, and North Dakota) for a total of six site-years. The objectives were to characterize the efficacy of a range of droplet sizes [150 µm (Fine) to 900 µm (Ultra Coarse)] using a dicamba plus glyphosate tank-mixture and create novel weed management recommendations utilizing pulse-width modulation (PWM) sprayer technology. Results across pooled site-years indicated a droplet size of 395 µm (Coarse) maximized weed mortality from a dicamba plus glyphosate tank-mixture at 94 L ha^{-1}. However, droplet size could be increased to 620 µm (Extremely Coarse) to maintain 90% of the maximum weed mortality while further mitigating particle drift potential. Although generalized droplet size recommendations could be

created across site-years, optimum droplet sizes within each site-year varied considerably and may be dependent on weed species, geographic location, weather conditions, and herbicide resistance(s) present in the field. The precise, site-specific application of a dicamba plus glyphosate tank-mixture using the results of this research will allow applicators to more effectively utilize PWM sprayers, reduce particle drift potential, maintain biological efficacy, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

Introduction

Chemical weed control remains a widely-used component of integrated weed management strategies due to its cost effectiveness and rapid removal of crop pests (Matthews et al., 2014). However, the complexity of the pesticide application process (Ebert et al., 1999) has contributed to inefficient and improper applications (Grisso et al., 1989; Ozkan, 1987). Current application recommendations have focused on increasing spray droplet size as it reduces downwind spray drift deposits (Alves et al., 2017b; Bueno et al., 2017; Vieira et al., 2018). The need to reduce drift, specifically with dicamba and glyphosate herbicides, was established due to the crop response that can occur on exposed susceptible crops (Alves et al., 2017a; Egan et al., 2014; Johnson et al., 2006). Although increasing spray droplet size reduces particle drift potential, negative herbicide efficacy effects on target weed species have been reported (Wolf, 2002).

Previous research demonstrated decreased control across multiple herbicides and weed species as droplet size increased (Ennis and Williamson, 1963; Knoche, 1994; Lake, 1977; McKinlay et al., 1974, 1972). Reduced biological efficacy due to increased herbicide droplet sizes were exasperated in environments with abnormally difficult to control weed species (Jensen et al., 2001). Additionally, several systemic herbicides, including two forms of dicamba [3,6-dichloro-o-anisic acid, N,N-Bis-(3-aminopropyl)methylamine and dicglycolamine salts], had efficacy reductions when droplet size increased (Butts et al., 2018b; Meyer et al., 2016a; Prasad and Cadogan, 1992). Dicamba efficacy was also influenced by interactions between droplet size and sprayer speed, carrier volume, and weed species (Butts et al., 2018b; Creech et al., 2016; Meyer et al., 2016a, 2016b). Conversely, glyphosate had greater absorption and translocation with Coarse droplets (Feng et al., 2009). Glyphosate efficacy on several winter annual grasses was not impacted by spray droplet size; therefore, an Ultra Coarse spray classification was recommended to reduce particle drift while maintaining biological efficacy (Ferguson et al., 2018).

Droplet size impacts on systemic herbicide efficacy are convoluted, especially when considering herbicide tank-mixtures such as dicamba plus glyphosate; however, site-specific weed management strategies can assist with more effectively using optimum droplet sizes (Tian et al., 1999; Wilkerson et al., 2004). Additionally, alternative optimization efforts must be identified moving into the future of agriculture, and the development and implementation of precision agriculture techniques should be one of the primary research focal points (Westwood et al., 2018).

Pulse-width modulation (PWM) sprayers provide an alternative method to optimize pesticide applications as they allow for several factors, including application pressure and spray droplet size, to be maintained across a range of sprayer speeds while variably controlling flow. Flow is controlled by pulsing an electronically-actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The solenoid valves are typically pulsed on a 10 Hz frequency (10 pulses per second), and the relative proportion of time each valve is open (duty cycle) determines the flow rate. This system allows real-time flow rate changes to be made without manipulating application pressure as in other variable rate spray application systems (Anglund and Ayers, 2003) and PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2013, 2011). Furthermore, PWM sprayers have the capability of producing up to a 10:1 turndown ratio in flow rate with no pressure or nozzle based changes, thus creating more flexible options for pesticide applicators (Giles et al., 1996; GopalaPillai et al., 1999). Application pressure based variable rate flow control devices have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). In contrast, research has shown PWM duty cycle has little to no effect on droplet size when using non-venturi nozzles (Butts et al., 2017a; Giles et al., 1996). Additionally, when PWM sprayers were operated at or above a 40% duty cycle, minimal to no negative impacts were observed on spray pattern and coverage (Butts et al., 2018a; Mangus et al., 2017; Womac et al., 2017, 2016). Therefore, it is feasible with a PWM sprayer to sustain an optimum herbicide droplet size and spray pattern throughout an application in which efficacy could be maximized and particle drift minimized, especially within site-specific scenarios.

Dicamba plus glyphosate tank-mixtures are a commonly recommended herbicide combination to combat herbicide resistance, specifically in recently commercially-released dicamba-tolerant soybean and cotton. However, an antagonistic reaction between dicamba and glyphosate in a tank-mixture was identified as translocation of both herbicides out of the treated leaf were reduced compared to applications of either herbicide alone (Ou et al., 2018). In other research, the dicamba plus glyphosate tank-mixture produced smaller droplet sizes, greater driftable fines (droplets < 100 µm), and increased downwind spray drift compared to a dicamba-only spray solution (Alves et al., 2017a). Additionally, a 2016 survey from Missouri identified further synthetic auxin application education efforts are required for applicators to efficiently and accurately apply growth regulator products (Bish and Bradley, 2017). Therefore, if the dicamba plus glyphosate tank-mixture is to be recommended moving forward, specific application practices must be identified and followed to optimize the application by maximizing efficacy while simultaneously mitigating spray drift potential.

The objectives of this research were to: (1) characterize the influence of spray droplet size on the efficacy of a dicamba plus glyphosate tank-mixture and (2) create novel application recommendations using an optimum droplet size to mitigate particle drift potential without compromising efficacy of a dicamba plus glyphosate tank-mixture. The precise, site-specific application of this herbicide tank-mixture will allow applicators to more effectively utilize PWM sprayers and reduce the selection pressure for the evolution of herbicide-resistant weeds.

Materials and Methods

EXPERIMENT DESIGN AND ESTABLISHMENT

Field trials were conducted in 2016, 2017, and 2018 in a fallow environment across three states (Mississippi, Nebraska, and North Dakota) for a total of six site-years to evaluate the droplet size effect on the efficacy of dicamba plus glyphosate (Table 7.1).

The trials were randomized complete block experimental designs replicated a minimum of three times spatially. This research was conducted using similar methods as previous droplet size research (Butts et al., 2018b). Treatments consisted of six targeted droplet sizes (150, 300, 450, 600, 750, and 900 µm) determined from the $D_{v0.5}$ of the measured droplet size distribution. The $D_{v0.5}$ parameter represents the droplet diameter such that 50% of the spray volume is contained in droplets of smaller diameter. One nontreated control per site-year was used for comparison which provided a total of seven treatments. The herbicide tank-mixture of dicamba (Clarity®, 0.48 kg ae L^{-1}, BASF, Research Triangle Park, NC 27709) plus glyphosate (Roundup WeatherMAX®, 0.54 kg ae L^{-1}, Monsanto Company, St. Louis, MO 63167) was applied postemergence to 15-cm tall or greater weeds at 0.28 kg ae ha^{-1} dicamba plus 0.87 kg ae ha^{-1} glyphosate with a carrier volume of 94 L ha^{-1}. No additional adjuvants were tank-mixed into the solution to eliminate confounding effects and evaluation of treatments could occur solely on the herbicide.

Treatments were applied using a PinPoint® PWM research sprayer (Capstan Ag Systems, Inc., Topeka, KS 66609). The benefits of using a PWM sprayer in this research were two-fold. First, PWM allows spray output to become independent from nozzle orifice size, sprayer speed, and application pressure. Therefore, the application process was simplified and standardized for operators across a range of spray environments. Second, as previous research highlighted PWM duty cycle had a minimal effect on droplet characteristics (Butts et al., 2017a, 2017b) and spray pattern (Butts et al., 2018a), a nozzle type, orifice size, and application pressure combination could be selected to provide a consistent droplet size treatment while maintaining the appropriate spray output (94 L ha^{-1}) throughout an application.

Nozzle type, orifice size, and application pressure required to create droplet size treatments were determined through droplet size measurements made using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) in the low-speed wind tunnel at the Pesticide Application Technology (PAT) Laboratory in North Platte, NE (Table 7.2). Creech et al. (2015) and Henry et al. (2014) provide in-depth details regarding the low-speed wind tunnel at the PAT Laboratory, and Butts et al. (2017) provides an illustration for further clarification of wind tunnel construction and operation. Only Wilger Industries, Ltd. non-venturi nozzles were used in this research as: (1) only non-venturi nozzles are recommended for use on PWM systems (Butts et al., 2017a; Capstan Ag Systems Inc., 2013) and (2) nozzle designs were similar (flat-fan, non-venturi, straight flow path) to eliminate confounding spray characteristic factors. Spray classifications were assigned in accordance with ASABE S572.1 (ASABE, 2009).

DATA COLLECTION

Each collaborating university collected data from their respective sites. Visual injury estimation proportions were recorded approximately 28 days after treatment (DAT) for entire plots. Further, ten individual weeds per plot were marked at the time of application. At 28 DAT, marked plants were individually evaluated for mortality (alive or dead) and the total number of deceased plants were divided by ten to provide mortality proportion measurements for each plot. The individual weeds were then clipped at the soil surface, harvested, and dried at 55°C to constant mass. The dry plants were pooled into one dry biomass measurement per plot, and were divided by ten for average weed dry shoot biomass per plant measurements.

STATISTICAL ANALYSES

Generalized additive modeling (GAM) analysis was conducted in R 3.5.0 statistical software using the mgcv package to model spray droplet size with each respective response variable to provide an estimate of the optimum spray droplet size for weed control (Crawley, 2013). To meet model assumptions, visual injury estimation and mortality proportions were analyzed using a beta distribution as the data were bound between 0 and 1, and weed dry biomass per plant data were subjected to a natural log transformation. Backtransformed data are presented for clarity. Models consisted of one smoothed variable (droplet size) (Equation 7.1).

$$\text{Response variable} \sim s(\text{Target droplet size}) \qquad [7.1]$$

Data were pooled across site-years to provide overall droplet size recommendations; however, GAM analysis was also conducted for data on individual site-years to assess droplet size efficacy implications in a site-specific weed management scenario. Models were used to predict the droplet size for maximum weed control and the droplet size at which 90% of maximum weed control was attained for drift mitigation recommendations.

Results and Discussion

Individual site-year information including GPS coordinates, weed species, weather conditions at the time of application, and data collected are presented in Table 7.1. Visual injury estimation, weed mortality, and weed dry biomass per plant data were collected from six, four, and five site-years, respectively. Additionally, droplet sizes discussed throughout the results and discussion refer to the $D_{v0.5}$ measurement (average droplet size) of the droplet size distribution.

POOLED SITE-YEARS

The GAM models for visual injury estimation proportion, mortality proportion, and dry weed biomass per plant response variables across pooled site-years are presented in Figure 7.1. The model smooth term estimated degrees of freedom (edf) and deviance explained for each response variable are presented in Table 7.3. A smooth term edf of one is equal to a linear model with model fluctuation increasing as the smooth term edf increases. The explained deviance provides an estimate of the discrepancy between model predicted estimates and actual observations with a larger percentage indicating a smaller discrepancy and overall better model fit.

Pooled site-years GAM models for visual injury estimation and mortality response variables had smooth term edf values greater than one indicating models were more complex (more fluctuation) than a linear regression (Table 7.3) (Figure 7.1). Conversely, the weed dry biomass per plant response variable GAM model was linear (smooth term edf=1.000), but droplet size was not a good predictor of weed dry biomass per plant as the explained deviance was 0%. The average deviance explained of the GAM models across response variables was 6.25% meaning less than 7% of the model variation could be explained by droplet size. The droplet size which maximized weed control ranged from 395 to 900 µm (Coarse to Ultra Coarse) depending on the response variable (Table 7.4). However, for visual injury estimations and weed dry biomass per plant response variables, the model slope was relatively flat as droplet size increased and 90% of the maximum weed control could still be achieved with a droplet size of 900 µm (Ultra Coarse). A more severe droplet size penalty was observed for the weed mortality response variable as 90% of weed control could only be maintained with a 620 µm (Extremely Coarse) droplet size. Therefore, to achieve complete plant death and reduce additional weed seeds from replenishing the seedbank, a 620 µm (Extremely Coarse) droplet size would be recommended across site-years to maintain 90% of the maximum weed control while reducing particle drift potential.

The differences observed in predicted droplet sizes for maximum weed control across response variables could be attributed to the method in which visual injury estimations are made, especially with dicamba, and the lack of correlation between weed biomass and plant death (Norsworthy et al., 2018). The weed species present across the Mississippi (Palmer amaranth, *Amaranthus palmeri* S. Wats) and Nebraska [kochia, *Bassia scoparia* (L.) A.J. Scott] site-years were glyphosate-resistant (data not shown); therefore, dicamba was the only effective herbicide site-of-action within these applications. When visually assessing plots for dicamba injury, it was not uncommon to see similar plant damage and biomass accumulation across a range of droplet sizes. However, upon closer inspection of mortality, the plants sprayed with greater droplet sizes often were still alive leading to decreased weed control as droplet size increased.

This research supports the conclusion that care should be taken in future herbicide research, especially with dicamba, to determine weed mortality as opposed to strictly observing visual injury symptoms or weed biomass to fully evaluate herbicide effectiveness (Norsworthy et al., 2018).

The reduction in efficacy for dicamba plus glyphosate tank-mixtures across droplet size treatments when evaluated using weed mortality may be attributed to an antagonism between the two herbicides. Previous research in kochia identified when dicamba plus glyphosate were tank-mixed, translocation of both herbicides out of the treated leaf were reduced compared to applications of either herbicide alone (Ou et al., 2018). Therefore, if dicamba plus glyphosate tank-mixtures continue to be recommended in areas in which herbicide resistance is a primary concern, applications should be optimized, including using a droplet size between 395-620 µm (Coarse to Extremely Coarse) when applied at 94 L ha^{-1}, to limit the negative consequences of the antagonistic reaction. Future research should investigate the influence of carrier volume on a dicamba plus glyphosate tank-mixture as increasing spray carrier volume may buffer the impact of increasing droplet size on the resulting biological efficacy (Butts et al., 2018b).

Although this research was conducted in a fallow environment, similar results could be expected within a cropping system scenario as previous research demonstrated similar spray coverage at the bottom of a soybean canopy across a range of droplet sizes (Legleiter and Johnson, 2016). Therefore, the droplet size effect on dicamba plus glyphosate tank-mixture efficacy observed in this research must be due to other factors than spray coverage such as droplet impaction efficiency, retention, absorption, and translocation.

SITE-SPECIFIC WEED MANAGEMENT

Prior to field trial establishment, it was hypothesized that identifying and applying an optimum herbicide droplet size would be more appropriate as a site-specific management strategy. Additionally, previous research highlighted the potential need for a site-specific weed management approach if an optimum droplet size is to be utilized as differing weed species each had a unique response to applications of dicamba and glyphosate made with differing nozzle types (Meyer et al., 2015). Therefore, each respective site-year was analyzed separately to determine if the deviance explained for each GAM model could be improved and optimum droplet size predictions made more robust.

The GAM model smooth term edf values and deviance explained for each respective site-year and response variable are presented in Table 7.5. The complexity of individual site-year models varied from a linear relationship (smooth term edf = 1.000) to very complex, high fluctuation relationships (smooth term edf = 4.695). Additionally, the average deviance explained for individual site-year models across response variables was 28.63% indicating over 1/4th of the model variability could be explained from the droplet size treatment. This is a marked improvement (4-fold) compared to the pooled site-year model average deviance explained of approximately 7%; therefore, optimizing dicamba plus glyphosate tank-mixture applications with a specific droplet size should be implemented using a site-specific approach.

An example of the site-specific GAM model approach, the 2017 Brule, NE site-year, is presented in Figure 7.2. Similar to the pooled site-year analysis, a severe reduction in weed mortality was observed as droplet size increased past a critical point, while visual injury estimations had a relatively flat slope resulting in a minimal droplet size impact. Optimum droplet size predictions for each site-year and response variable are presented in Table 7.6. Droplet size predictions to maximize weed control varied widely across site-years and response variables from 150 µm (Fine) to 900 µm (Ultra Coarse). However, in general across individual site-years and response variables, an Extremely Coarse (570 µm) to Ultra Coarse (900 µm) spray classification maintained 90% of maximum weed control and would assist with particle drift mitigation efforts.

The wide array of predicted optimum droplet sizes across site-years is likely due to convoluted droplet size interactions and diverse weed structures influencing droplet retention on varied leaf surfaces. Previous research demonstrated greater impaction and retention efficiency on vertical leaf surfaces with finer droplets in the presence of horizontal winds (Lake, 1977); however, coarser droplets had greater impaction efficiency on horizontal leaf surfaces (Spillman, 1984). Unfortunately, droplet adhesion was reduced with increasing droplet size as droplets bounced or shattered upon impact (Forster et al., 2005). Therefore, a complex interaction between droplet size, plant architecture, and leaf structure influences droplet retention and thereby herbicidal efficacy (Massinon et al., 2017; Nairn et al., 2013).

The primary weed species in Mississippi and North Dakota was Palmer amaranth and common lambsquarters (*Chenopodium album* L.), respectively. Both Palmer amaranth and common lambsquarters have flat, horizontal leaf surfaces which helps to explain the coarser optimum droplet size of 900 µm corroborating findings from Spillman (1984). Conversely, the primary weed species' in Nebraska was kochia and horseweed (*Erigeron canadensis* L.) which have a much smaller and narrower leaf structure paired with relatively vertical plant architecture compared to Palmer amaranth and common lambsquarters. Therefore, smaller droplet sizes were required to achieve 90% of maximum weed control across measured response variables for the Nebraska site-years compared to the Mississippi and North Dakota site-years validating Lake (1977) findings.

Additional differences in optimum droplet sizes were observed between the kochia and horseweed populations within the 2018 North Platte, NE site-year further supporting the conclusion optimum herbicide droplet sizes differ among weed species (Figure 7.3). Overall, the dicamba plus glyphosate tank-mixture provided less control of horseweed and required smaller droplet sizes to maintain 90% of maximum weed control compared to kochia. This difference in weed control may be attributed to weed height and density as horseweed tended to be taller and denser than kochia within the respective site-year (data not shown).

The results of the site-specific analysis corroborated previous research in which it was recommended that each herbicide and weed species interaction required a tailored, site-specific approach to maximize efficacy (Butts et al., 2018b; Creech et al., 2016; Meyer et al., 2015). Future research should holistically investigate the influence of weather conditions, weed species, geographic location, herbicide antagonism, and herbicide resistance paired with droplet size to create more robust models and fully optimize spray applications.

Conclusions

This research identified across a broad geographic setting and diverse weed spectrum that tank-mixture applications of dicamba plus glyphosate should utilize a 620 µm (Extremely Coarse) droplet size when applying with a carrier volume of 94 L ha^{-1} as weed mortality would be maintained, the addition of weed seeds to the soil seedbank would be reduced, and particle drift potential would be simultaneously mitigated. However, more precise applications could be achieved by applying the optimum herbicide droplet sizes in a site-specific approach. Approximately 1/4th of the model variability could be explained from the droplet size treatment when analyzed using the site-specific approach as opposed to less than 1/10th when analyzed in a pooled site-year analysis. Generally, 90% of maximum weed control across individual site-years was achieved with droplet sizes ranging from 570 µm (Extremely Coarse) to 900 µm (Ultra Coarse). These differences in optimum droplet sizes across individual site-years were likely due to weed species plant structure and leaf architecture; however, numerous other factors such as weather conditions at application, geographic location, herbicide antagonism, and herbicide resistance played a significant role in final herbicidal efficacy (Kudsk, 2017). Finally, to effectively reduce particle drift potential from future herbicide applications, alternative drift reduction strategies other than increasing spray droplet size must be identified and implemented to avoid weed control losses and mitigate the evolution of herbicide-resistant weeds.

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Tables

Table 7.1. Site-year, GPS coordinates, weed species, average application weather conditions, and data collected to understand the impact of droplet size on herbicide efficacy of dicamba plus glyphosate.

				Application weather conditions					
Year	Location	GPS coordinates	Weed species[a]	Wind speed	Air temperature	Relative humidity	Visual injury estimations	Mortality	Weed dry biomass
				$m\ s^{-1}$	°C	%			
2016	Dundee, MS	34.54°N, 90.47°W	AMAPA	0.9	33	55	X[b]	X	X
2016	Prosper, ND	47.00°N, 97.12°W	Multiple[c]	3.1	27	44	X		
2017	Dundee, MS	34.54°N, 90.47°W	AMAPA	2.2	32	65	X	X	X
2017	Brule, NE	41.16°N, 102.00°W	KCHSC	4.5	31	38	X	X	X
2017	Fargo, ND	46.93°N, 96.86°W	CHEAL	3.6	24	35	X		X
2018	North Platte, NE	41.05°N, 100.75°W	Multiple[d]	2.7	27	57	X	X	X

[a] AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters.
[b] An "X" indicates the respective response variable data were collected from the respective site-year.
[c] Multiple weed species from the 2016 Prosper, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.
[d] Multiple weed species from the 2018 North Platte, NE site-year included: KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; and ERICA, *Erigeron canadensis* L., horseweed.

Table 7.2. Nozzle type, orifice size, and application pressure combinations for each dicamba plus glyphosate droplet size ($D_{v0.5}$) treatment.[a]

Nozzle[b]	Application pressure	Target droplet size	Actual droplet size	Standard error	Spray classification[c]
	kPa	————	μm	————	
ER110015	345	150	154	0.33	F
SR11004	241	300	298	0.69	M
DR11003	255	450	453	0.54	VC
UR11004	276	600	600	0.62	EC
UR11006	207	750	749	4.37	EC
UR11010	193	900	917	1.24	UC

[a] Target droplet sizes were the designed droplet size treatments used in data analysis. Actual droplet sizes were the experimentally measured droplet sizes from spray solution, nozzle, and application pressure combinations. Actual droplet sizes were within 2.7% of the target droplet sizes.
[b] Flat fan, non-venturi nozzles; Wilger Industries Ltd., Lexington, TN, USA
[c] Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

Table 7.3. Generalized additive model (GAM) smoothing parameters and deviance explained for each response variable across pooled site-years.

Response variable	Site-years	Smooth term edf[a]	Deviance explained
			%
Visual injury estimations	6	2.666	11.50
Mortality	4	2.133	7.25
Weed dry biomass per plant	5	1.000	0.00

[a] Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1.000 = linear model.

Table 7.4. Predicted droplet sizes based on a generalized additive model (GAM) to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts for each response variable across pooled site-years.

		Droplet size			
Response variable	Site-years	Maximum weed control	Spray classification[a]	90% of maximum weed control	Spray classification[a]
		μm		μm	
Visual injury estimations	6	500	VC	900	UC
Mortality	4	395	C	620	EC
Weed dry biomass per plant	5	900	UC	900	UC

[a] Spray classifications determined using ASABE S572.1 where C=Coarse, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

Table 7.5. Generalized additive model (GAM) smoothing parameters and deviance explained within individual site-years for each response variable to investigate the plausibility of site-specific weed management.

Response variable	Site	Year	Weed species[a]	Smooth term edf[b]	Deviance explained
					%
Visual injury estimations	Dundee, MS	2016	AMAPA	1.596	8.25
	Prosper, ND	2016	Multiple[c]	4.695	92.60
	Dundee, MS	2017	AMAPA	1.000	0.17
	Brule, NE	2017	KCHSC	1.982	21.10
	Fargo, ND	2017	CHEAL	4.549	97.20
	North Platte, NE	2018	KCHSC	3.266	68.30
	North Platte, NE	2018	ERICA	1.000	24.60
Mortality	Dundee, MS	2016	AMAPA	1.000	0.84
	Dundee, MS	2017	AMAPA	2.390	27.40
	Brule, NE	2017	KCHSC	3.188	58.80
	North Platte, NE	2018	KCHSC	2.417	28.20
	North Platte, NE	2018	ERICA	1.322	14.10
Weed dry biomass per plant	Dundee, MS	2016	AMAPA	1.000	1.99
	Dundee, MS	2017	AMAPA	1.371	13.70
	Brule, NE	2017	KCHSC	1.901	13.90
	Fargo, ND	2017	CHEAL	2.307	36.00
	North Platte, NE	2018	KCHSC	1.056	2.70
	North Platte, NE	2018	ERICA	1.000	5.54

[a] AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters; ERICA, *Erigeron canadensis* L., horseweed.

[b] Smooth term estimated degrees of freedom (edf) provides an estimate of the model fluctuation. A smooth term edf of 1.000 = linear model.

[c] Multiple weed species from the 2016 Prosper, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.

Table 7.6. Predicted droplet sizes based on a generalized additive model (GAM) to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts within individual site-years for each response variable to investigate the plausibility of site-specific weed management.

				Droplet size			
Response variable	Location	Year	Weed species[a]	Maximum weed control	Spray classification[b]	90% of maximum weed control	Spray classification[b]
				µm		µm	
Visual injury estimations	Dundee, MS	2016	AMAPA	610	EC	855	UC
	Prosper, ND	2016	Multiple[c]	325	M	900	UC
	Dundee, MS	2017	AMAPA	900	UC	900	UC
	Brule, NE	2017	KCHSC	370	C	900	UC
	Fargo, ND	2017	CHEAL	765	EC	900	UC
	North Platte, NE	2018	KCHSC	460	VC	660	EC
	North Platte, NE	2018	ERICA	150	F	530	VC
Mortality	Dundee, MS	2016	AMAPA	150	F	900	UC
	Dundee, MS	2017	AMAPA	580	EC	705	EC
	Brule, NE	2017	KCHSC	410	C	570	EC
	North Platte, NE	2018	KCHSC	460	VC	680	EC
	North Platte, NE	2018	ERICA	150	F	245	F
Weed dry biomass per plant	Dundee, MS	2016	AMAPA	150	F	485	VC
	Dundee, MS	2017	AMAPA	900	UC	900	UC
	Brule, NE	2017	KCHSC	425	C	620	EC
	Fargo, ND	2017	CHEAL	495	VC	735	EC
	North Platte, NE	2018	KCHSC	900	UC	900	UC
	North Platte, NE	2018	ERICA	150	F	405	C

[a] AMAPA, *Amaranthus palmeri* S. Wats, Palmer amaranth; KCHSC, *Bassia scoparia* (L.) A.J. Scott, kochia; CHEAL, *Chenopodium album* L., common lambsquarters; ERICA, *Erigeron canadensis* L., horseweed.

[b] Spray classifications determined using ASABE S572.1 where F=Fine, M=Medium, C=Coarse, VC=Very Coarse, EC=Extremely Coarse, and UC=Ultra Coarse.

[c] Multiple weed species from the 2016 Prosper, ND site-year included: CHEAL, *Chenopodium album* L., common lambsquarters; AMARE, *Amaranthus retroflexus* L., redroot pigweed; and SETPU, *Setaria pumila* (Poir.) Roem. & Schult., yellow foxtail.

Figures

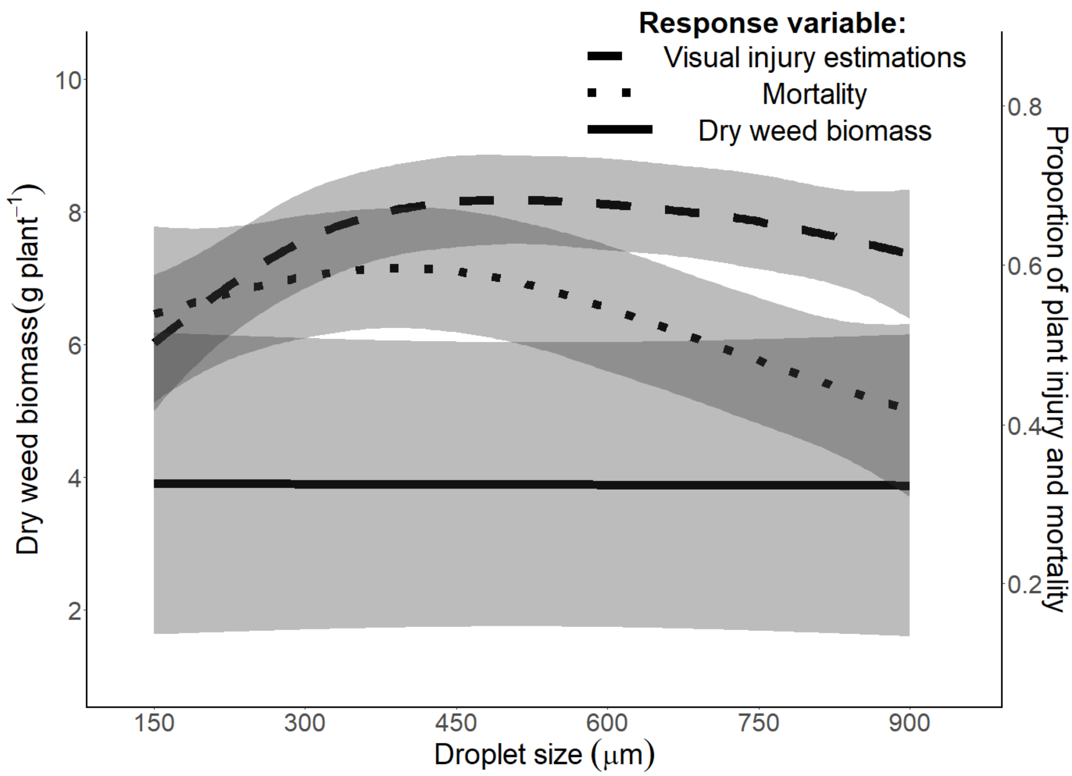

Figure 7.1. Visual injury estimation proportion, mortality proportion, and weed dry biomass per plant 28 days after treatment as affected by droplet size were pooled across six, four, and five site-years, respectively, and predicted using generalized additive models (GAM). The grey shaded area indicates the 95% confidence limits.

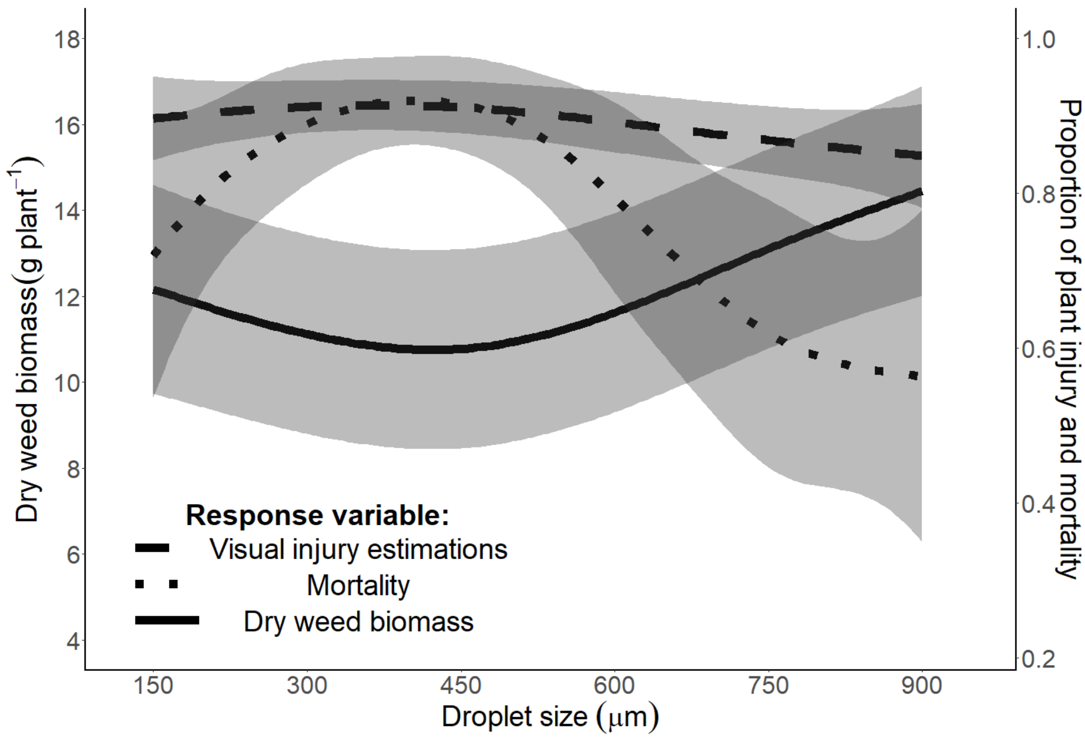

Figure 7.2. Visual injury estimation proportion, mortality proportion, and weed dry biomass per plant generalized additive models (GAM) for the 2017 Brule, NE, USA site-year to assess the plausibility of site-specific weed management strategies. The grey shaded area indicates the 95% confidence limits.

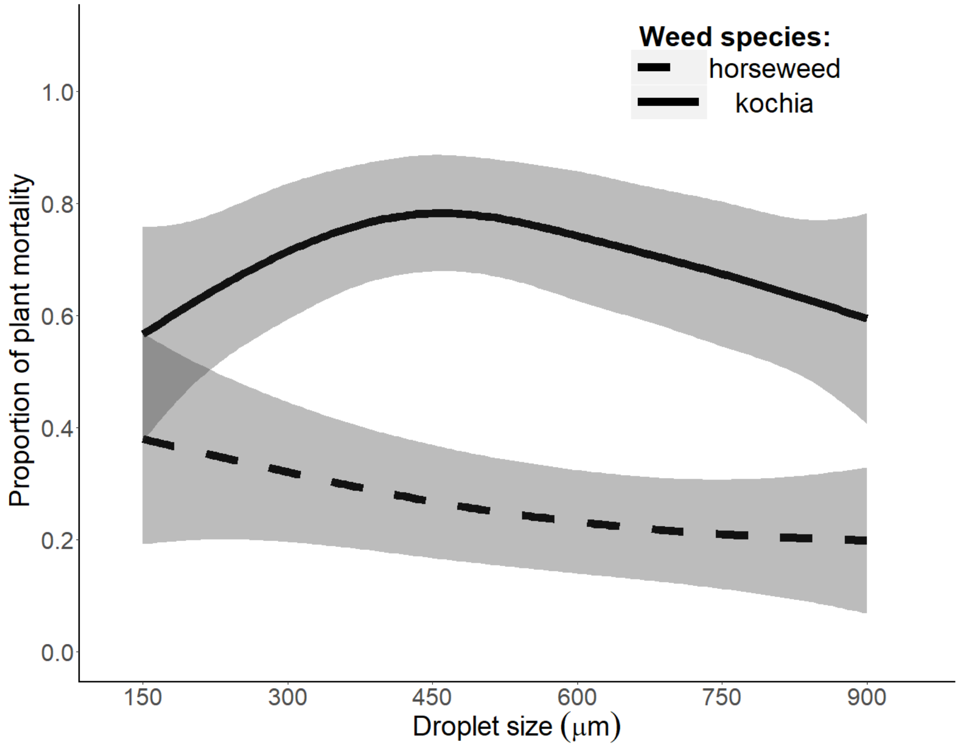

Figure 7.3. Mortality proportion generalized additive models (GAM) for the horseweed (*Erigeron canadensis* L.) and kochia [*Bassia scoparia* (L.) A.J. Scott] weed species from the 2018 North Platte, NE, USA site-year. The grey shaded area indicates the 95% confidence limits.

CHAPTER 8

SUMMARY OF FINDINGS AND FUTURE WORK

The results of this research have led to more precise pulse-width modulation (PWM) sprayer operation through clear and concise best use recommendations to assist with the reduction of spray particle drift and increase the overall application effectiveness. Additionally, site-specific weed management strategies were effectively established and optimum herbicide droplet sizes were estimated across a wide range of geographies and weed species. Although, convoluted interactions were identified between droplet size, carrier volume, and other application parameters in regards to their effect on herbicide efficacy. As a result of this research, applicators can more effectively utilize PWM sprayers, reduce herbicide inputs, mitigate spray particle drift, and reduce the selection pressure for the evolution of herbicide-resistant weeds.

Generally, as PWM duty cycle decreased, spray droplet size ($D_{v0.5}$) increased by approximately 0.55 µm for every 1% decrease in duty cycle. Nozzle tip pressures generally followed the expected square wave electrical signal trend (but not exactly), and were minimally impacted by duty cycle and pressure. However, applicators using a PWM sprayer should also acknowledge a pressure loss across the solenoid valve. The decreased pressure, especially for greater orifice size nozzles, could create coarser droplet sizes than desired for biological control, and affect nozzle performance by reducing pressure at the nozzle below manufacturer’s recommended minimum pressures. Non-venturi nozzles, with and without pre-orifices, minimized variation in droplet size and nozzle tip pressure across duty cycles compared with venturi nozzles. Furthermore, the 20% duty cycle resulted in greater variability in the resulting spray droplet sizes across nozzles.

Similar trends were observed for spray droplet velocities and pattern uniformity. Spray solution had little to no effect on the droplet size, droplet velocity, nozzle tip pressure, and pattern uniformity trends observed across duty cycles when pulsed. Droplet velocities and pattern uniformity decreased as PWM duty cycle decreased across nozzles and pressures. Additionally, increased pressures and non-venturi nozzles reduced variability in droplet velocities and pattern uniformity, thereby mitigating spray drift potential and increasing canopy penetration and proper coverage; however future research should directly investigate the PWM effect on these spray application outcomes.

Three analysis methods for spray pattern uniformity, coefficient of variation (CV), root mean square error (RMSE), and average percent error (APE), evaluated in this research each provided unique observations into spray pattern characteristics. The APE spray pattern analysis may provide the best guidance for determining optimum sprayer setup as it takes into account both uniformity and flow rate accuracy; however future research should fully evaluate all analyses for their specific benefits and drawbacks.

Based on the aforementioned results, the following best use PWM practices were developed to optimize each application:

1. PWM sprayers should be operated at or above a 40% duty cycle. Droplet size, velocity, and pattern uniformity were severely affected and observed trends were inconsistent when pulsed at the 20% duty cycle tested in this research.
2. PWM sprayers should be operated at or above 276 kPa gauge pressure. This practice buffers the pulsing impact on droplet size, velocity, and pattern

uniformity, and remains above nozzle manufacturers' recommended pressures due to the pressure loss across the solenoid valve.

3. Only non-venturi nozzles should be equipped and operated on PWM sprayers. Venturi nozzles, especially dual-fan venturi nozzles, caused pattern irregularities, droplet size and velocity variation, and nozzle tip pressure fluctuations when pulsed. Additionally, spray solution can be forced out of the air inclusion ports negating their drift reduction benefits. Venturi nozzles simply do not provide the same consistency and precision in spray pattern and droplet size as non-venturi nozzles when pulsed.

Additional research investigating the influence of PWM on spray characteristics will be needed with the advent of new nozzle designs, solenoid valves, and other equipment manufacturer specific sprayer designs. Future research should also determine any effects of the electrical frequency controlling the solenoid valves to potentially determine an optimum number of pulses per second for more precise applications. Another PWM research opportunity moving forward would be to determine the interactive effects of sprayer speed and PWM duty cycle on dynamic spray coverage.

As a result of this current research, site-specific pest management strategies could be implemented as droplet size, velocity, and pattern uniformity were relatively unaffected by PWM sprayers if the PWM best use practices were followed, and several confounding application factors could be eliminated. Therefore, applicators could choose a nozzle and pressure combination to achieve a specific droplet size that would reduce drift potential while simultaneously maximizing efficacy of the given pesticide in their unique geographic and weed species environment. This was the foundational concept to evaluate the droplet size and carrier volume impact on the efficacy of several herbicides utilizing the PWM best use practices previously identified.

Spray droplet size and carrier volume impacted weed control with both dicamba (systemic) and glufosinate (contact) herbicides across the Mississippi, Nebraska, and North Dakota site-years. From this research, 900 µm (Ultra Coarse) droplets paired with 187 L ha^{-1} carrier volume was recommended for dicamba applications as this combination provided the greatest weed control with the least particle drift potential across six pooled site-years. A 310 µm (Medium) droplet size across carrier volumes was recommended for glufosinate applications across pooled site-years; however, if particle drift concerns exist, glufosinate droplet size could be increased to 605 µm (Extremely Coarse) and 90% of the maximum weed control can still be achieved. Further, if no water conditioning adjuvants are used in conjunction with glufosinate, a lower carrier volume should be utilized as more concentrated droplets are better able to overcome the antagonistic free cations within hard water, but applicators should keep in mind greater weed control is often observed with the combination of water conditioning adjuvants and increased carrier volume.

Across a broad geographic setting and diverse weed spectrum, applications of 2,4-D choline plus glyphosate pre-mixture (Enlist Duo®) should utilize a 430 µm (Coarse) droplet size when applied with a carrier volume of 94 L ha^{-1} to maintain weed mortality while simultaneously mitigating particle drift potential. More precise applications of 2,4-D choline plus glyphosate pre-mixture could be achieved by applying the herbicide droplet sizes in a site-specific approach. Across Mississippi and North Dakota sites, a 900 µm (Ultra Coarse) droplet size was recommended, while across

Nebraska sites, a droplet size of 565 – 690 µm (Extremely Coarse) was typically needed to maintain 90% of the maximum weed control.

Tank-mixture applications of dicamba plus glyphosate should utilize a 620 µm (Extremely Coarse) droplet size across Mississippi, Nebraska, and North Dakota site-years when applied with a carrier volume of 94 L ha^{-1} as weed mortality would be maintained, the addition of weed seeds to the soil seedbank would be reduced, and particle drift potential would be simultaneously mitigated. However, approximately 1/4th of the model variability could be explained from the droplet size treatment when analyzed using the site-specific approach as opposed to less than 1/10th when analyzed in a pooled site-year analysis. Generally, 90% of maximum weed control across individual site-years was achieved with droplet sizes ranging from 570 µm (Extremely Coarse) to 900 µm (Ultra Coarse).

The differences in optimum droplet sizes within herbicide solutions across the individual site-years were likely due to weed species plant structure and leaf architecture; however, numerous other factors such as weather conditions at application, geographic location, time of day, herbicide antagonism, and herbicide resistance evolution, may have played a significant role in final herbicidal efficacy. Future herbicide droplet size research is needed to fully evaluate the interactions between geography, weed species, weather conditions at application, and droplet size to account for more variability and provide stronger droplet size recommendations across broad geographic regions and weed spectrums. Additionally, future research needs to identify and evaluate these other variables as potential model parameters to create more robust model predictions and determine the most influential application factors.

This research highlighted using PWM sprayers to apply optimum droplet sizes in a site-specific weed management approach is both manageable and effective. With the ever increasing droplet size database, appropriate nozzle*pressure combinations to achieve specific droplet sizes for a multitude of herbicide spray solutions may soon be readily available. The use of PWM sprayers paired with appropriate nozzle*pressure combinations could be effectively implemented to optimize an application through precise droplet size control in site-specific management approaches. However, future research fully characterizing the effects of droplet size and other application parameters on the efficacy of different herbicides and tank-mixtures is required, especially in site-specific scenarios. Additional explorative research is needed to identify and implement alternative drift reduction strategies other than increasing spray droplet size to effectively reduce particle drift potential from future herbicide applications, avoid weed control losses, and mitigate the evolution of herbicide-resistant weeds.

Pesticide application and the resulting biological impacts are complex processes that are difficult to effectively manage. This research highlighted an alternative method of application using PWM sprayers in conjunction with identified best use practices to apply optimum droplet sizes in a site-specific weed management approach. There is a critical droplet size for maintaining satisfactory weed control even with systemic type herbicides such as dicamba, 2,4-D, and glyphosate. However, droplet size often accounted for less than 50% of the deviance within models indicating numerous alternative factors, such as weed species, geographic location, and weather conditions at application, also play a significant role in the success of a pesticide application. Therefore, to optimize spray applications using droplet size, application parameters should be tailored for site-specific weed management approaches to more effectively accommodate the changing application elements to reduce herbicide inputs and reduce selection pressure for the evolution of herbicide-resistant weeds. Additionally, to effectively reduce particle drift potential from future herbicide applications, alternative precautions other than increasing spray droplet size must be identified and implemented to avoid reductions in weed control.