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GLYPHOSATE PLUS DICAMBA SPRAY SOLUTION DEPOSITION, COVERAGE, AND EFFICACY AS INFLUENCED BY SPRAY NOZZLE DESIGN AND WEED DENSITY

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THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture, Food and Environment at the University of Kentucky

By

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Lexington, Kentucky

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2020

ABSTRACT OF THESIS

GLYPHOSATE PLUS DICAMBA SPRAY SOLUTION DEPOSITION, COVERAGE, AND EFFICACY AS INFLUENCED BY SPRAY NOZZLE DESIGN AND WEED DENSITY

Dicamba injury to sensitive soybean and other broadleaf crops due to drift is a major issue and label restrictions have been created to mitigate dicamba drift. One restriction is the mandated use of low drift nozzles to spray dicamba; these nozzles produce larger droplets and minimize the production of driftable fines. Experiments were conducted to evaluate herbicide coverage, deposition, and efficacy. Three spray nozzle designs and different weed densities were the main factors in the analysis. Dicamba plus glyphosate was applied to 5 to 10 cm tall weeds with a Turbo TeeJet (TT11005) nozzle and two drift reduction nozzles approved for dicamba applications: Turbo TeeJet Induction (TTI11005) and Pentair Ultra Lo-Drift (ULD12005). Weed densities were categorized into different levels and established in a 0.25 m^2 quadrant prior to post application. Deposition of spray solution on targeted weeds was not different despite coverage differences observed on Kromekote spray cards. The results from this research has shown that drift reduction nozzles do not reduce herbicide efficacy onto targeted weed species because spray solution deposition was equivalent across nozzle. High weed densities may reduce overall herbicide performance, and in some cases may interact with nozzle design.

KEYWORDS: Dicamba, Glyphosate, Waterhemp, Poaceae, and Drift Reduction Nozzle

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DEDICATION

In loving memory of James Paul Kramer

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Chapter 1

Literature Review

The introduction and adoption of glyphosate-resistant crops shifted weed management to the “simple and convenient” practice of using only postemergence glyphosate applications for weed control (Green and Owen 2010). Many cropping systems including corn (*Zea mays*), soybean (*Glycine max*), and cotton (*Gossypium arboretum)* have been produced with an overreliance of glyphosate; therefore, it can no longer be applied alone especially on problematic weeds which have become resistant (Green and Owen 2010).

In 2016, there were four troublesome weeds in soybean that growers struggled to control across the Midwest: tall waterhemp (*Amaranthus tuberculatus)*, horseweed (*Conyza canadensis),* Palmer amaranth (*Amaranthus palmeri),* and giant ragweed (*Ambrosia trifida)*, with waterhemp and horseweed ranking as the most troublesome (Van Wychen 2016). In a 2019 survey, results were similar with the four weeds remaining at the top and waterhemp ranking as the most troublesome (Van Wychen 2019). Growers are in desperate need for new weed management practices to control weeds. Not only are the troublesome weeds resistant to glyphosate, but they have developed resistance to other sites of action. Waterhemp and Palmer amaranth, especially have adapted resistance to ALS inhibitors (acetolactate synthase), Photosystem II inhibitors, PPO inhibitor (protoporphyrinogen oxidases), EPSP synthase inhibitors (5-enolpyruvylshikimate-3-phosphate) and in some cases multiple resistance to more than one site of action (Heap 2019). Since it is unlikely that effective new herbicide sites of action will be discovered soon, crop producers must diversify weed management practices with tools currently available.

Dicamba-Resistant Soybean

Dicamba-resistant soybean varieties were introduced to help control glyphosate resistant and problematic weeds and give growers an additional postemergence herbicide option. The trait for dicamba-resistant soybean was found in a soil bacterium, which metabolizes dicamba and coverts it to 3,6-dichlorosalicylic acid (Behrens et al. 2007). This transgene allows up to 5.6 kg ae ha^{-1} of dicamba to be applied to dicamba-resistant soybean (Behrens et al. 2007). Dicamba is a synthetic auxin herbicide and belongs to the benzoic acid family. This herbicide is commonly known as a growth regulator herbicide, synthetic auxin, or Group 4 herbicide. Dicamba mimics the natural plant hormone indole-3-acetic acid (IAA), which when present at low levels controls cell growth and development. When dicamba is introduced, it is at high levels, which mimics uncontrollable cell growth and development and will cause abnormal growth that leads to plant death (Behrens et al. 2007). Synthetic auxin herbicides control a large variety of broadleaf weeds including troublesome weeds in soybean that have evolved resistance to glyphosate (Green and Owen 2010).

Sensitivity of Soybean and Tobacco

The extreme sensitivity of broadleaf crops to dicamba, including soybean, has been a hindrance for this herbicide since its introduction (Hartlzer 2017). Hartzler (2017) demonstrated the sensitivity of soybean to dicamba comparing it to the sensitivity of corn to glyphosate. Corn showed a significant visual response to glyphosate at 1 percent of a 560 g ae ha^{-1} use rate, whereas significant visual injury to soybean occurred at a rate of dicamba as low as 0.005% of 560 g ae ha^{-1}. These findings show soybean is 200 times more sensitive to dicamba when compared to corn sensitivity to glyphosate. Dicamba produces a unique injury to soybean with symptoms that can consist of stem epinasty, leaf cupping, and bud suppression (Chang et al. 1971; Marth and Mitchell 1944). In a meta-analysis review, Kniss (2018) examined 11 field studies to determine at what rate dicamba injures soybean and reduces yield. The meta-analysis found that Robinson et al. (2013) reported the smallest visual injury of less than 5% occurs to soybean at a rate of 0.06 g ae ha^{-1}, while Johnson et al. 2012 reported greater than 25% injury can occur at a rate of 0.6 g ae ha^{-1}. Soybean yield was reduced at dicamba exposure rates of 0.196 g ae ha^{1} (Robinson et al. 2013). Griffin et al. (2013) reported soybean at R1 growth state are more than 2.5 times more vulnerable to injury than soybean at vegetative growth stage. Across all the studies in the meta-analysis soybean were consistently the most sensitive and vulnerable to dicamba injury in the reproductive stage as compared to vegetative growth stages (Kniss 2018).

In 2017, an estimated 1.6 million hectares of non dicamba-resistant soybean were injured by dicamba in the United States (Dr. Kevin Bradley personal communication). The state of Kentucky reported to have approximately 13,355 damaged hectares (Dr. Kevin Bradley personal communication). In 2018, approximately 2,428 hectares of soybean were damaged in the state of Kentucky and 202 hectares of tobacco were damaged by dicamba (Dr. Travis Legleiter and Dr. JD Green personal communication). The decrease in soybean hectares damaged is likely due to the widespread adoption of dicamba-resistant soybean and thus reduction in sensitive soybean hectares, not due to fewer dicamba applications being made.

While there is a large area of soybean production in the United States that raises a concern when applying dicamba, specialty crops that are grown on smaller scales are also a concern for dicamba injury. Off-site movement to non-tolerant crops such as tobacco is a major concern in the state of Kentucky. Due to the advancing technology of crops with resistance to herbicides such as dicamba, glufosinate, and 2,4-D, tobacco farms will be in close proximity to these crops and tobacco is susceptible to all three (Johnson 2011). In the United States, Kentucky is the second largest state growing tobacco with a total of 27,559 hectares harvested in 2018 (USDA 2018). Tobacco is often grown in close proximity to corn and soybean that are both now receiving postemergence dicamba applications.

Tobacco damaged due to dicamba exposure exhibits symptoms such as cupped and curling leaves as well as stem epinasty located at the top of the plant (Johnson 2011). Tobacco plants that are exposed to dicamba rates a 140 g ae ha^{-1} will exhibit yield losses (Johnson 2011). If tobacco growers experience visual symptom of dicamba drift injury to their crop, it could end detrimentally by leading to unmarketable plants (Inman 2019). Herbicide residues on tobacco leaves can also reduce the quality and yield of a tobacco plants; therefore, the producer of tobacco and the farmer that grows herbicide-tolerant crops such as corn and soybean are both affected by spray drift consequences (Johnson 2011).

Off-site Movement

Off-site movement of dicamba can be classified into three different categories: volatilization, tank contamination, and particle drift. Volatilization, also termed as vapor drift, is the movement of a herbicide in the form of vapor. Volatilization occurs after application to the on-site target and is influenced mainly by environmental conditions, primarily temperature and humidity (Combellack 1982). Volatilization is more likely to occur when the temperature is high and the humidity is low. When dicamba is applied the potential for the volatility is lower in the evening and greater during the day (Mueller et al. 2013). The volatilization rate in the evening was 7.5 ± 2.55 µg after 24 plus hours following application when compared to 18.7 ± 3.22 µg at 24 plus hours following application in the day time (Mueller et al. 2013). Vapor drift can also be influenced by herbicide formulation (Combellack 1982). New dicamba formulations have been developed to help lower volatility potential.

Tank contamination can occur when sprayer components such as tanks, filters, and hoses are not cleaned correctly or completely. Dicamba rates of 4.4 g ae ha^{-1} and 17.5 g ae ha^{-1} were applied to soybean which resulted in yield losses during both R1 and V3-V4 growth stages in both application rates; therefore, it is crucial to clean equipment prior to any application (Griffin et al 2013). A study conducted in Canada showed that when dicamba spray tank contamination was applied at V2 to V3 growth stages 12, 18, 25, 31, 43, 53, and 66% visual soybean injury occurred when applied at 0.75, 1.5, 3, 6, 15, 30, and 60 g ae ha^{-1}, respectively (Soltani et al. 2016). This was also true at reproductive growth stages where there was 12, 10, 14, 17, 24, 35, and 46% visible injury when applied at 0.75, 1.5, 3, 6, 15, 30, and 60 g ae ha^{-1}, respectively (Soltani et al.

2016). As the rate of dicamba increased, so did the reduction of soybean. Dicamba spray contamination as little as 0.0125% of the normal field rate can cause crop injury at both vegetative and reproductive growth stages (Soltani et al. 2016). Applicators must clean equipment thoroughly to remove dicamba residues before use in a non-dicamba resistant field to avoid crop injury and yield loss.

Particle drift, also termed as physical drift, is the direct movement of a herbicide from an application site to an off-target location by wind or air movement (Combellack 1982). Drift is affected by a combination of two things: the environmental conditions to which the spray is exposed and droplet size (Smith and Thomson 2003). It is crucial for herbicides to land on the intended target to effectively control weed species (Smith and Thomson 2003). Smith et al. (1982) reported that environmental conditions affected 10% to 32% of all off-target drift. The environmental conditions that specifically influence particle drift are wind speed, air temperature, and humidity, but wind speed is the most critical (Carlsen et al. 2006). Carlsen et al. (2016) found that when using a flat fan nozzle with a wind velocity of 4.8 m s^{-1}, deposition distances were further than compared to a wind velocity of 2.0 m s^{-1}. Sousa Alves et al. (2017b) analyzed four different nozzles types (XR, TT, AIXR, TTI) at four different wind speeds (0.09, 2.2, 3.6, 4.9 m s^{-1}) and concluded that with all nozzles, dicamba drift increased when wind speed increased. The amount of drift is likely to decrease as downwind distance increases (Sousa Alves et al. 2017a). Behrens and Lueschen (1979) did a similar study and found that when the distance increased, the damage to the soybean decreased, but damage occurred up to 60 m. An increase in temperature will also increase drift potential because droplets evaporate quicker at a higher temperature when compared to a lower temperature. A study using a predictive model indicated that relative humidity is a top factor that influences spray drift (Wang and Rautman 2008).

An application that is applied during the presence of a temperature inversion can also influence off-site movement. A temperature inversion is when a cooler air layer is near the soil surface level and a layer of warmer air is located above. As time passes, the cooler layer will warm and rise into the atmosphere. Temperature inversions have been noted to occur mainly during sunrise and sunset hours. An applicator should avoid applying herbicides in the presence of a temperature inversion to avoid drift.

Herbicide Drift Reduction Factors

Environmental conditions are largely out of control from the applicator, but there are several factors an applicator can adjust when making an application. The applicator has control of drift reduction parameters such as droplet size and boom height (Smith and Thomason 2003). Droplet size in microns can be measured across the spray plane spectrum and then categorized as a percentage of spray volume. The most widely used measurement term is the Dv50 or VMD (Volume Mean Diameter). It represents the droplet size (measured in microns) at which 50 percent of the droplets in the spray volume have a diameter at or below that value. The Dv10 and Dv90 represents the size at represented by droplets at 10 percent and 90 percent spray volume.

Droplet size is controlled by three main factors: the spray nozzle design, exit orifice size, and pressure of the spray liquid at the orifice exit (Combellack 1982; Nuyttens et al. 2007). The nozzle is the main link between the herbicide and the correct application to the intended target. The nozzle controls not only the droplet size, but also the pattern of the droplet spectrum and regulation of the flow rate. A single-stage nozzle will produce a different droplet size when compared to a two-staged nozzle**.** A two-stage nozzle has a two orifices: a pre orifice and an exit orifice, and a single-stage nozzle has an exit orifice**.** The size of the nozzle or the size of the exit orifice where the liquid sheet is created and the pressure at the orifice influence how the sheet breaks into a corresponding size of droplets (Combellack 1982). Nozzles that have a larger exit orifice will create a larger droplet spectrum as compared to nozzles that have a smaller exit orifice (Combellack 1982).

Spray pressure at nozzle tip affects potential drift due to the spray volume of liquid that is being distributed. In most cases, an increase in pressure will increase the flow rate, which will decrease the droplet size (Combellack and Matthews 1981). An experiment conducted by Creech et al. 2015 analyzed four different nozzle types including a flat fan nozzle and a drift reducing nozzle (XR, TT, AIXR, TTI). Drift reducing nozzles produce very coarse, extremely coarse, and ultra-coarse droplets that are classified and defined using the ASABE S572.1. procedure. The results showed that when increasing the pressure from 138 kPa to 276 kPa the percentage of driftable fines tripled. Driftable fines can be defined as the percentage of droplets less than 200 µm in diameter**.** Another researcher showed similar findings when increasing the pressure to 400 kPa resulted in a larger number of smaller droplets (Young et al. 1990). It is recommended to avoid using high pressures to reduce the percentage of driftable fines when applying herbicides.

Boom height is also an important factor affecting drift. Growers who are more likely to raise their boom heights could be in danger of increasing potential spray drift. Balasri et al. (2017) conducted a study that suggested boom height had a significant effect of the amount of driftable fines produced by a flat fan nozzle. When comparing three different boom heights at 70 cm, 50 cm, and 30 cm, the results showed that drift was greater when the boom height was set at 70 cm when compared to 50 cm and drift was higher at 50 cm compared to 30 cm (Balasri et al. 2017). The study also resulted in 50% more driftable fines from the 70 cm height when compared to the 50 cm height, and similar results when evaluating 50 cm and 30 cm.

The last thing that can influence drift is formulations of the herbicide and adjuvant packages (Carlsen et al. 2006). Since the new release of dicamba tolerant soybean, new dicamba formulations have been introduced. These new formulations have been created to reduce drift potential and lower volatility. The EPA has approved four dicamba products, Engenia (BASF)[1], Xtendimax (Bayer Crop Science)[2], FeXapan (Corteva)[3],and Tavium (Syngenta)[4] for application to dicamba-resistant soybean. The labels of these new products have a series of restrictions an applicator must follow when applying this herbicide for a postemergence application. One restriction is the type of nozzle that must be used. An applicator must use a nozzle that produces very

[1] BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709
[2] Bayer Crop Science, 800 N. Lindbergh Blvd., St. Louis, MO 63167
[3] Corteva Agriscience, 9330 Zionsville Road, Indianapolis, IN 46268
[4] Syngenta Corporation, 410 South Swing Road Greensboro, NC 27409

coarse to ultra-coarse droplets and reduces the amount of driftable fines. Very coarse, extremely coarse, and ultra-coarse droplets are classified and defined using the ASABE S572.1. procedure. Driftable fines is the percentage of droplets less than 200 µm. An additional restriction for the 2019 season is that an applicator must be certified to spray these products of dicamba and no one under their supervision is allowed to make an application without a certification. Applications can only take place between one hour after sunrise and two hours before sunset. Boom height and pressure ranges are also restricted when applying these products. These restrictions are intended to ensure that correct droplet size will be produced during dicamba postemergence applications to minimize the risk of off-target movement of dicamba.

Influence of Droplet Size and Carrier Volume on Coverage, Deposition, and Efficacy

It is extremely important to reduce off-target movement of herbicides, but it is also crucial to avoid any negative aspects that can influence the performance of the herbicide. The size of the droplet will not only impact the drift potential, but also can influence the amount of coverage, deposition, and efficacy of the herbicide.

A meta-analysis done by Knoche (1994) demonstrated that decreasing the droplet size typically resulted in an increased herbicide performance 71% of the time while 9% of the time decreasing droplet size decreased herbicide performance. Monocot plants with mainly vertical structures were more susceptible to the influence of droplet size when the droplet size was more than 150 µm. The majority of monocot plants have vertical leaf structures and dicot plants have horizontal leaf structures. Smaller monocot leaves for example; poaceae species, have less surface area to capture herbicide solution droplets when compared to dicot weed leaves (Dorr et al. 2008). The type of herbicide either a systemic or a contact can also be influenced by the droplet size. In a comparison of systemic and contact herbicides, a contact herbicide is typically more influenced by droplet size than a systemic herbicide (Knoche 1994).

Spray carrier volume can also influence the performance of an herbicide. Knoche (1994) shows that spray carrier volume affected herbicide performance, but was less consistent when compared to droplet size effects. In 24% of the experiments reviewed by Knoche (1994) when keeping the droplet size consistent and decreasing the carrier volume the herbicide performance increased. In 32% of the experiments no effect was observed and in 44% of the experiments decreasing the carrier volume decreased herbicide performance. The carrier volumes evaluated ranged from 5 to 2200 l ha^{-1}**.** Knoche (1994) also suggested that when looking at droplet size and carrier volumes, other factors should also be considered to affect herbicide performance. Those factors can include the herbicide being used, the type of weed being targeted, and canopy architecture.

However, in recent investigations when looking at droplet size and carrier volume it has been shown that carrier volume may have a greater impact on herbicide performance. Any coverage that is lost due to a larger droplet size from drift reducing nozzles can be compensated by increasing the carrier volume (Ferguson et al. 2016). Carrier volume at rates of 140 l ha^{-1} and 94 l ha^{-1} was analyzed for spray coverage using of both drift reducing nozzles and broadcast nozzles, and results suggest that carrier volume has a greater influence than spray nozzle type on the amount of coverage

(Legleiter and Johnson 2016). Meyer et al. (2016) found similar results in a study using two different spray volumes at 94 l ha^{-1} and 187 l ha^{-1}, and their results showed that when the carrier volume was decreased to 94 l ha^{-1} the herbicide performance was reduced when using a coarser nozzle for a dicamba and glyphosate application.

An experiment conducted by Legleiter et al. (2018) showed drift reduction nozzles that produce larger droplets did not influence the deposition, absorption, and the efficacy of a postemergence application of glyphosate plus dicamba. Despite the fact that coverage was reduced on spray cards in the following weed species: Palmer amaranth, waterhemp, giant ragweed, and horseweed.

Weed Density

Weed density has a major influence on potentially reducing crop yield by competing for three main resources: light, water, and nutrients. There has been little to no research conducted on the effects that weed density has on herbicide spray coverage and deposition, but it is a potential influence that needs, to be analyzed.

Objectives:

1. The first objective is to compare spray nozzles that produce droplets that range from medium to ultra-coarse and their influence on herbicide spray coverage and deposition of a postemergence application of dicamba plus glyphosate onto poaceae species and waterhemp.
2. The second objective is to evaluate how weed density levels affect herbicide spray coverage, depositions, and performance of a postemergence application of dicamba plus glyphosate.

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Chapter 2

Introduction

Waterhemp (*Amaranthus tuberculatus)* has been ranked as the most troublesome weed that growers struggle to control in soybean over the past several growing seasons (Van Wychen 2016; Van Wychen 2019). Waterhemp joins the ranks of the top four troublesome weeds in the Midwest, which include: horseweed (*Conyza canadensis),* Palmer amaranth (*Amaranthus palmeri),* and giant ragweed (*Ambrosia trifida)* (Van Wychen 2016; Van Wychen 2019).

The majority of these weeds express characteristics that are unique, which makes them difficult to manage in agricultural row crops. Waterhemp and Palmer amaranth share a majority of the unique characteristics, while horseweed and giant ragweed differ. Horseweed, also known as marestail, is considered a winter or summer annual and seedlings typically emerge in late August to October, then the rosettes survive over the winter (Weaver, 2001). Another characteristic is the seeds are very small in size and can be distributed through the wind due to their architecture which influences the spread of this species (Weaver, 2001). Giant ragweed has a wide emergence period and the plants emerge in late March and seed in late summer or early fall (Johnson et al. 2006). This weed is a competitor for sunlight and has the ability to grow up to 5 meters tall (Johnson et al. 2006). The most unique characteristic regarding this plant is it has adapted to many different environments including wastelands, roadsides, fencerows, floodplains, and agricultural production (Johnson et al. 2006)

Waterhemp has a summer annual life cycle where seedlings typically emerge from the months of May to August, and emergence can vary. The minimum temperature to promote germination is 10°C, but temperature fluctuations are a better cue to promote germination rather than constant temperatures (Leon et al. 2004). The dormancy and germination of the seed is controlled by phytochromes which is the photoreceptor to red light response; thus, germination is promoted when the seeds are exposed to red light (Leon and Owen 2003).

Waterhemp plants are known to have prolific seed production; one female plant can produce approximately 35,000 to 1,200,000 seeds (Costea et al. 2005). These seeds are very small and can be dispersed through several mechanisms including: water, farm machinery, animals, and humans. Farmer et al. (2017) reported that *Amaranthus* seeds can potentially be dispersed long distances by waterfowl and has the ability to germinate after passing through digestive tract systems of waterfowl. The seed bank for waterhemp is persistent due to only being able to produce once a year and having a high percentage of viability. A study conducted in Iowa showed that 11 percent of seeds reminded viable after four years of being buried 5 cm deep (Buhler and Hartzler 2001).

Waterhemp plants also express relatively high growth rates. In a 2-year study conducted by Horak and Loughin (2000) they compared growth rates of four *Amaranthus* species including waterhemp. Results indicate that the maximum height increase was 0.16 cm based on centimeters per growing degree day and a maximum relative growth rate was 0.31 grams per growing degree day. Out of the four *Amaranthus* species evaluated, waterhemp was ranked having the second highest growth rate, following Palmer amaranth with the greatest.

Waterhemp plants are dioecious, i.e., male and female flowers are produced on separate plants (Costea et al. 2005). This unique characteristic has allowed genetic diversity for waterhemp plants and increased the likelihood to select for resistance to herbicides following numerous repeated applications in soybean systems. Waterhemp plants have developed resistance to many different modes of action including ALS inhibitors (acetolactate synthase), Photosystem II inhibitors, PPO inhibitor (protoporphyrinogen oxidases), EPSP synthase inhibitors (5-enolpyruvylshikimate-3-phosphate) and in some cases multiple resistance to more than one site of action (Heap 2019).

Dicamba-resistant soybean varieties became available in the 2016 growing season providing growers another site of action to combat troublesome weeds. In 2017, new dicamba formulations were approved for application to dicamba-resistant soybean (EPA 2017). Over the past three years the majority of Kentucky growers (Dr. Travis Legleiter and Dr. JD Green, personal communication) have implemented the dicamba-resistant soybean system into their weed management programs to control weeds such as waterhemp, Palmer amaranth, giant ragweed, and horseweed. It has given growers an additional site of action for postemergence weed control, but in the short time since its release concerns have arisen due to an increase in off-site movement causing damage to sensitive plants. Dicamba injury is unique and consists of stem epinasty, leaf cupping and curling, bud suppression; at high rates leaf necrosis can also occur (Chang and Born 1971; Johnson 2012; Marth and Mitchell 1944). Crops such as non dicamba-resistant soybean, tobacco, and tomato are all sensitive to dicamba drift. Soybean and tobacco can show visual injury at rates of 0.06 g ae ha^{-1} and 140 g ae ha^{-1} and yield losses in tomato occur at rate of 2.3 g ae ha^{-1} (Robinson et al. 2013; Johnson et al. 2012; Kruger et al. 2012).

There are many factors that influence physical drift during a postemergence application including environmental factors of wind speed, air temperature, and humidity; wind speed has the greatest influence (Carlsen et al. 2006). When wind speed is increased, depositions produced from the nozzle are recorded at further downwind distances (Carlsen et al. 2006; Sousa Alves et al. 2017). Environmental conditions contributed to 10 to 32 percent of off-target drift (Smith et al. 1982). Even though environmental factors are out of control of the applicator, they must still be aware of their potential influence. There are many factors that an applicator can manipulate to aid in reducing physical drift. The applicator can control droplet size by selecting a nozzle that produces a very coarse, extremely coarse, and ultra-coarse droplet that reduces the amount of driftable fines present in the spray volume. Very coarse, extremely coarse, and ultra-coarse droplets are classified and defined using the ASABE S572.1. procedure and contain minimal driftable fines. Driftable fines are defined as droplets with a diameter less than 200 µm**.** The nozzle type that the applicator selects is vital to ensure a correct placement of the herbicide onto the target plant. Boom height, pressure, and spray speed all affect physical drift when making an herbicide application. Increasing any of these three factors is likely to increase potential drift. A series of restrictions to address these factors have been placed on dicamba labels to reduce drift issues.

Increasing the droplet size not only influences potential drift during an application, but also influences the amount of coverage and the overall performance of the herbicide. Droplet size has been noted to have more of an influence when compared to spray carrier volume regarding herbicide performance (Knoche 1994), but recent investigations have suggested that carrier volume may be have more influence than droplet size on herbicide performance (Legleiter and Johnson 2016; Meyer et al. 2016). Legleiter et al. (2018) reported that deposition and efficacy of a postemergence application of glyphosate plus dicamba was equivalent across drift reducing nozzles and broadcast nozzles.

Weed density also has a potential effect on the overall performance of herbicides. In a study conducted by Bensch et al. (2003), it was reported that when eight waterhemp plants per square meter grew in competition with soybean, the yield was negatively impacted by 56%. While it is known that higher levels of weed density can affect the overall crop yield, little to no work has been conducted looking at the influence weed density has on herbicide spray coverage and deposition.

The objective of this study was to evaluate three different levels of waterhemp weed density and three spray nozzle designs. A traditional broadcast nozzle and two drift reducing nozzles were analyzed with a glyphosate plus dicamba postemergence applications. Spray solution coverage, deposition, and overall efficacy of the herbicides were analyzed.

Materials and Methods

Site

Two field experiments were conducted during the summer of 2019 on a farmer owned field near Princeton, Kentucky. Both experiments were conducted on the same field, but were separated spatially and temporally**.** This site had a well- established population of suspected glyphosate-resistant waterhemp. The soil type at this location is a Sadler silt loam. Dicamba-resistant soybean was planted on May 24, 2019 and June 18, 2019 in 38-cm rows. Both trials were planted using a Precision Planting vacuum planter at an approximate seeding rate of 370,500 seeds ha^{-1}. Plots were maintained to control existing vegetation including any emerged waterhemp plants prior to planting, therefore a burndown application of glufosinate at a rate of 655 g ai ha^{-1} was applied to the first trial. The second trial received an application of paraquat at a rate of 560 g ai ha^{-1}.

Experimental design

The experimental design was a two-way factorial treatment structure in a randomized complete block with four replications. Individual plot measurements were 3 m by 8 m with 6 m alleyways between blocks. The two factors included three nozzle designs and three weed densities. The three nozzles included a Turbo TeeJet[5] (TT11005) nozzle and two drift reduction nozzles approved for dicamba applications: Turbo TeeJet Induction[6] (TTI11005) and Pentair Ultra Lo-Drift[7] (ULD12005). The second factor in the factorial design was three weed densities that were approximately 100%, 50% and 25% of the natural density of the field population. A 0.25 m^2 quadrant was established in each plot to contain the different levels of weed density and the average weed density

[5]TeeJet Technologies, 200 W. North Ave, Glendale Heights, IL 60139
[6] TeeJet Technologies, 200 W. North Ave, Glendale Heights, IL 60139
[7] Pentair, 5500 Wayzata Blvd #800, Minneapolis, MN 55416

in each 0.25 m^2 is shown in Table 2.1. The 25% weed density or lowest density for the first trial was manipulated with a preemergence herbicide application of flumioxazin at 90 g ai ha^{-1} and pyroxasulfone at 110 kg ai ha^{-1}. The preemergence herbicide application was applied using a CO_2 backpack sprayer pressurized at 221 kPa while traveling at six kph fitted with XR11002 nozzles spaced at 50 cm. The plots that contained the 50% and 100% densities were hand weeded to the appropriate ranges. Due to the excessively low weed densities in the treatments receiving the preemergence herbicide, the second trial did not receive a preemergence herbicide and all 0.25 m^2 quadrants were hand thinned to the appropriate weed density.

Herbicide application

Herbicide application methods were designed to mimic a commercial post emergence herbicide application. Applications were made using an all-terrain vehicle (ATV) with a 3-m side boom traveling at a speed of 16 kph with an output of 140 l ha^{-1}. The 3-m side boom was outfitted with four nozzles on 50 cm spacing and pressurized to 262 to 290 kPa depending on the nozzle**.** Applications were made when waterhemp plants were approximately 5 to 10 cm tall. In Trial 1, the post applications were made on two different days due to the 25% density, being manipulated with a preemergence herbicide application. The preemergence delayed the waterhemp plants in reaching the 5 to 10 cm height as compared to the 50 and 100% density treatments. The first application in Trial 1 for the 50% and 100% density levels was made on June 14, 2019 and the second application for the 25% density was made on June 25, 2019. All dates of application, crop growth stage, and weather data for postemergence applications are listed in Table 2.2. The tank mixture for all applications consisted of the following: 1100 g ae ha^{-1} of glyphosate (Roundup PowerMax)[8], 560 g ae ha^{-1} of dicamba (Xtendimax with Vapor Grip)[9], plus 0.5% v/v of On Target[10]. Vision Pink[11] and Spectra Trace SH-P (PTSA)[12] dyes were also added to the tank mixture to facilitate analysis of spray solution coverage and deposition at 0.25% v/v and 600 ppm, respectively.

Data collection and analysis

Droplet spectrum analysis

A droplet spectrum analysis was conducted to determine the droplet sizes for the spray nozzles used in these experiments**.** The same spray nozzles and tank mixture with the exception of the Vision Pink and PSTA dyes used in the field experiments were used during the analysis. Only one nozzle per nozzle type was tested and was selected from the boom at random. The analysis was conducted in North Platte, Nebraska at the University of Nebraska Pesticide Application Technology Laboratory (PAT Lab). The PAT Lab has two wind tunnels with high and low wind speeds; for this analysis the nozzles were evaluated in the low wind tunnel with a constant wind speed of 24 kph to evacuate droplets from the spray plume to avoid duplicate droplet measurements. The droplet spectrum produced by the nozzle was evaluated using laser diffraction with a Sympatec Helos Vario KR particle size analyzer assembled with an R7 lens. The spray plume was traversed through the laser three times to represent three replications. The

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[8] RoundUp Powermax® Bayer Crop Science, 800 N. Lindbergh Blvd., St. Louis, MO 63167
[9] Xtendimax TM, Bayer Crop Science, 800 N. Lindbergh Blvd., St. Louis, MO 63167
[10] On Target®, WinField United Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164-0589
[11] Vision PinkTM, Garrco Products Inc, P.O. Box 619, Converse, IN 46919-0619
[12] Spectra Trace SH-P, Spectra Colors Corporation, 25 Rizzolo Road, Kearny, New Jersey 07032

report from the analysis included the Dv10, Dv50, and Dv90, which translates into 10%, 50%, and 90%, of the droplets in the spray volume that are at or below the reported diameter in microns (Pesticide Environment Stewardship 2020). The report also gives the percentage of droplets less than 200 µm, which represents the percentage of driftable fines each nozzle produces. Based on the Dv10, Dv50, and Dv90 values each nozzle is classified into a droplet size category.

Spray card herbicide spray coverage and deposition

Kromekote spray cards (22 cm by 28 cm) were used to measure herbicide spray coverage. The Vision Pink dye that was added to the herbicide tank mix allows for visual markings of depositions onto the spray cards. Prior to the herbicide application, spray cards were placed within the soybean canopy so that each card was centered between two of the three middle rows within the plot. After the application the cards were allowed enough time to dry, collected from the field, and transferred back to the lab. Each card was scanned into 600 by 600-dpi, 24- bit color digital images using a duplex scanner. An analysis was conducted using APS Assess Software which separates the pink depositions from the white background on the card. The output from the software was area of coverage measured in cm^2 and deposition counts, which were converted into percent of coverage and depositions per cm^2 using the known the size of the cards**.**

Herbicide solution deposition onto waterhemp

A fluorescent dye (PTSA) was added to the tank mixture as a tracer to analyze spray solution deposition. Two waterhemp plants measuring in height between 5 to 10 cm were harvested from the 0.25 m^2 quadrant at the soil surface immediately after the post application to collect herbicide spray solution deposition. Each harvested plant was washed in a 200 ml solution consisting of water and Triton X-100 (0.1% v/v Triton X-100). After each treatment materials used to harvest plant samples were rinsed using a 1:1 solution of water and methanol to avoid cross contamination. After washing, each plant sample was placed in an envelope and transferred back to the lab to conduct further analysis. Prior to the field sample analysis, a standard linear curve of raw fluorescent values was established using standardized wash solutions that contained 0.0001 to 1 ppm PTSA. Raw fluorescence for each field wash solution was measured three times by a Trilogy Laboratory Fluorometer manufactured by Turner Designs equipped with the PSTA specific module. A LI-COR LI-3000 area meter was used to analyze whole plant leaf area in cm^2 for each sample. By knowing the concentration of PTSA in the herbicide tank mixture, the amount of wash solution used (200ml), the leaf area of the plant (cm^2), and concentration of PTSA in the wash solutions, calculations were made to determine how much spray solution was deposited onto the waterhemp samples in µl cm^{-2}.

Herbicide efficacy and biomass

Visual evaluations based on a scale of 0 to 100 percent were conducted at 14 and 21 days after application to analyze herbicide efficacy. Zero percent represented no control and 100 percent represented complete weed death or full control. At 21 days after application any waterhemp remaining in the 0.25 m^2 quadrant were collected for above ground biomass. The samples were cut at the soil surface and placed in envelopes and transferred back to the lab where they were placed in a SC-400 model dryer manufactured by the Grieve Corporation. The samples were dried for approximately 48 hours with a constant temperature at 57 C and then dry weight (g) recorded. Biomass (g) from each plot was divided by the density of plants collected to represent biomass (g) per plant.

Data analysis

Normality and equality of variances were checked prior to data analysis. Square root transformations were conducted when assumptions were not met. After each assumption was met differences were determined using analysis of variance with SAS 9.4 PROC GLIMMIX. Means were separated at alpha = 0.05 adjusted with Tukey HSD when effects were significant and the means for all data are presented using the raw data. Trial analysis were conducted for herbicide spray solution deposition, visual evaluations 21 days after treatment, and biomass. Interactions between trials were based on the factors of spray nozzle design, weed density, and the interaction between the two were used in the analysis. No trial interactions occurred for 21 days after treatment and biomass. Trials were analyzed separately for herbicide spray solution deposition due to a significant interaction between trial*nozzle (Table 2.3).

Results and Discussion

Droplet spectrum analysis

Using the standard for nozzles established by ASABE S572.1., a standard curve was established for droplet classification at PAT Laboratory. The Dv10, Dv50, Dv90 values from the three nozzles used in the trials were plotted onto the standard curve to establish droplet size classifications for each nozzle. The TT11005 nozzle was classified as a very coarse droplet size, while both the ULD12005 and TTI11005 were classified in the ultra-coarse droplet size category (Table 2.4). As expected, the TT11005 nozzle has the lowest Dv (10, 50, and 90,) values when compared to the two drift reducing nozzles (ULD12005 and TTI11005). The TTI11005 nozzle produced the smallest percentage of driftable fines at 0.6 percent, while the TT11005 recorded the greatest driftable fine percentage at 7.8 percent. The ULD12005 percentage of driftable fines was between the two TeeJet nozzles at 2.2 percent (Table 2.4).

Spray card herbicide coverage and deposition

Results were similar across the two trials regarding percent coverage and depositions per cm^2 onto the spray cards with differences occurring between nozzle types (Table 2.5). In Trial 1, the TT11005 and ULD12005 nozzle recorded similar percent coverage at 49 and 44 percent, respectively, when compared to the TTI11005 nozzle that recorded 26 percent coverage. In Trial 2, the results were somewhat similar with the TTI11005 nozzle reducing coverage by 14 to 21 percent on spray cards compared to the TT11005 and ULD12005 nozzles at 49 and 42 percent, respectively (Table 2.6).

Depositions per cm^2 results had a similar trend in differences between nozzle types as the percent coverage results. In Trial 1, the TT11005 and the ULD12005 nozzles were similar and recorded the greatest number of depositions with 45 and 42 depositions per cm^2. The TTI11005 nozzle recorded the lowest depositions per cm^2 with 25 depositions per cm^2 (Table 2.6). In Trial 2, all three spray nozzles recorded different deposition counts with the TT11005 nozzle having the greatest depositions per cm^2 at 47, the ULD12005 nozzle was next with 40 depositions per cm^2, and finally the TTI11005 nozzle recorded the lowest at 27 depositions per cm^2. Results from the spray card data show the ULD12005 nozzle was similar to the TT11005 nozzle in Trial 1, but not in Trial 2.

Depositions per cm^2 results indicate the ULD 12005 nozzle and the TT11005 nozzle are similar in one trial which is not expected. The differences across the nozzle types suggest there is variability between the two trials due to the ULD 12005 being similar to the TT11005 nozzle in one trial and all nozzles observing differences in Trial 2.

Herbicide solution deposition on target weeds

The influence of nozzle type and weed density on dicamba plus glyphosate spray solution volume deposited onto waterhemp were similar in both trials. Trial 1 and Trial 2 did not show an interaction between the two factors of spray nozzle design and weed density (Table 2.7). The deposition volume of herbicide spray solution ranged from 0.65 to 1.24 µl cm^{-2} in Trial 1 and from 0.52 to 1.03 µl cm^{-2} in Trial 2 (Table 2.8 and Table 2.9). The two factors were analyzed separately since no observation of an interaction occurred. Weed density did not influence the amount of spray solution deposition volume and ranged from 0.82 to 1.0 µl cm^{-2} for Trial 1 *(P=0.2636)* and 0.69 to 0.81 µl cm^{-2} for Trial 2 *(P=0.3522)*. Spray nozzle design also did not have an influence on spray deposition in Trial 1 *(P=0.0792)* with a range of 0.81 to 1.08 µl cm^{-2}, but in Trial 2 deposition ranged from 0.68 to 0.88 µl cm^{-2} and spray nozzle design did have a significant P-value less than 0.05 *(P=0.0434).* Despite the fact that the p-value for spray nozzle design was significant, the Tukey test was unable to separate difference between nozzle types (Table 2.10). In efforts to gain more knowledge a Student Newman Keuls (SNK) test was conducted on both trials looking at spray solution deposition. The SNK test results were similar to the Tukey test, and was unable to separate out any differences between spray nozzle design (Table 2.10).

Despite the fact that differences were observed between spray nozzles on the spray cards regarding percent coverage and depositions per cm^2, there were no differences observed among spray nozzles on the amount of spray solution volume deposited onto waterhemp plants. The two drift reducing nozzles (TTI11005 and ULD 12005) provided equivalent amount of spray solution deposition compared to the traditional broadcast nozzle (TT11005). Percent coverage and depositions per cm^2 is a measurement regarding area, while spray solution deposition represents volume. Two different measurements were conducted; therefore, differences could occur between one measurement and not the other.

There also were no observed differences in deposition recorded with the influence of waterhemp density using the sampling methods conducted in these experiments.

Herbicide efficacy and biomass

Differences in percent waterhemp control 21 days after treatment (DAT) resulted in different observations between Trial 1 and 2. In Trial 1, no interaction was observed between nozzle type and weed density *(P=0.4705),* while an interaction did occur in Trial 2 *(P=0.0251)* (Table 2.11). In Trial 1, the control of waterhemp ranged from 69 to 96 percent. The control of waterhemp ranged from 60 to 99 percent in Trial 2 with control being reduced with the use of the TTI11005 nozzle at the highest waterhemp density level as compared to all the other nozzle and density combinations (Table 2.12). In Trial

1, weed density had an influence on waterhemp control at the highest density by reducing waterhemp control by 16 percent as compared to the lowest density (25%) *(P=0.0017)* (Table 2.13), while nozzle type did not have any influence on waterhemp control *(P=0.4810)*.

Trial 1 results indicate that a reduction in percent control occurs at the highest density which is expected. Results from Trial 2 are also as expected, at the highest density and with the use of the TTI11005 nozzle producing an ultra-coarse droplet a reduction in percent control is observed.

Analysis of biomass reduction did not show an interaction between the two factors of nozzle type and weed density for Trial 1 *(P=0.1992)* or Trial 2 *(P=0.4205)* (Table 2.14). The biomass ranged from 0.01 to 0.17 grams per plant in Trial 1 and 0.01 to 0.21 grams per plant in Trial 2 (Table 2.15 and Table 2.16). The two factors were analyzed separately due to no interaction between the two factors (nozzle type and weed density). In both trials, initial weed density did not influence the amount of biomass within the 0.25 m^2 quadrant *(P=0.2761 and P=0.4588)* (Table 2.14). Spray nozzle design did not have any influence in Trial 1 (*P=0.7632*), but in Trial 2 a difference did occur (*P=0.0004).* The use of the ULD 12005 nozzle resulted in the lowest biomass per plant located within the 0.25 m^2 quadrant as compared to the TTI11005 and the TT11005 (Table 2.17).

As might be expected, the TTI11005 nozzle with the largest droplet spectrum resulted in the greatest waterhemp biomass per plant 21 DAT. Although it would be expected that the two drift reducing nozzles (ULD12005 and TTI11005) would be similar, the results indicate that the TTI11005 nozzle is similar to the TT11005 nozzle, and not the ULD12005. The ULD12005 nozzle, an ultra-coarse droplet producing nozzle, actually had the lowest waterhemp biomass or greatest control which would not be expected when considering droplet size alone.

Summary

Results from Trial 1 indicate that weed density could influence herbicide performance on waterhemp despite the fact that no differences were observed in herbicide spray solution deposition onto waterhemp plants. Results from Trial 2 indicate that the use of the low-drift spray nozzle, particularly the TTI11005 at the increased waterhemp density could reduce herbicide performance. It is important to note the sampling method used during the experiments may not have captured a complete representation of solution deposition in the high density quadrants. The crew members randomly selected two waterhemp samples to harvest, but this did not account for a smaller plants growing under the waterhemp canopy. Smaller plants likely had reduced deposition at post application, which would suggest a reduction in herbicide performance in the high density quadrants of 54 plants. In both trials, weed density at the highest level reduced waterhemp control.

Overall, the results of these experiments emphasize the importance of limiting initial weed density prior to the post application. The effective use of a preemergence herbicide is key to avoiding high density situations where control of targeted weeds can be reduced, especially when using low-drift nozzles as mandated by dicamba labels. A study conducted by Vyn et al. (2007) that evaluated multiple preemergence herbicides concluded that effective herbicides provided 96 to 98 percent control of waterhemp plants and reduced the density to 1 to 2 waterhemp plants m^{-2} compared to the untreated check of 53 to 126 plants m^{-2}. When considering the data from Vyn et al. (2007), it can be concluded that targeted waterhemp plants can be effectively controlled with dicamba plus glyphosate using a low drift nozzle as long as plant densities are maintained at low levels with the use of a preemergence herbicide.

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Table 2.1 Average actual density of waterhemp plants located in 0.25 m^2 quadrant established based on the natural field population

Desired relative density level	Trial 1	Trial 2
	------------- waterhemp plants per 0.25 m^2--------------	
25%	4	6
50%	26	27
100%	54	54

Table 2.2 Date, time, and weather conditions at the time of postemergence herbicide application

	Trial 1 Application 1[a]	Trial 1 Application 2[b]	Trial 2
Application Date	6/14/2019	6/25/2019	7/8/2019
Application Time	8:42-9:20 a.m.	10:20-10:58 a.m.	9:08-9:54 a.m.
Temperature	22 C	27 C	28 C
Relative Humidity	56 %	65 %	79 %
Wind Speed	Max=3.0 kph Avg=1.4 kph	Max=3.4 kph Avg=1.7 kph	Max=3.4 kph Avg=2.4 kph
Crop Stage	V2	V5-V6	V2-V3

[a] Applied to plots containing 50 and 100% density when weeds reached approximately 5 to 10 cm
[b] Applied to plots containing 25% density when weeds reached approximately 5 to 10 cm tall

Table 2.3 Analysis of variance table for herbicide spray solution deposition onto waterhemp plants as influenced by trial, nozzle, density, and all interactions

	Num DF	Den DF	P-value
Trial	1	51	0.0056
Nozzle	2	51	0.1491
Trial*Nozzle	**2**	**51**	**0.0318**
Density	2	51	0.1147
Trial*Density	2	51	0.8744
Nozzle*Density	4	51	0.2607
Trial*Nozzle*Density	4	51	0.1305

Table 2.4 Dv10, Dv50, Dv90, percent of driftable fines, and spray classification for each nozzle at field use rate of dicamba plus glyphosate plus a drift reduction agent

Nozzle Type[a]	Dv10	Dv50	Dv90	Percent <200 microns	Spray Classification[b]
	---------------µm[c]---------------			-----%[c]-----	
TT11005	223 A	526 A	908 A	7.9 A	Very Coarse
ULD 12005	342 B	700 B	1052 B	2.2 B	Ultra Coarse
TTI11005	494 C	952 C	1345 C	0.6 C	Ultra Coarse

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift TTI: Turbo TeeJet Induction.

[b] Spray Classification based on reference curve using the UNL PAT Lab ASABE S542.1.

[c] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 2.5 Analysis of variance table for spray card percent coverage and depositions per cm^2 for both trials as influenced by nozzle type

	Trial 1			Trial 2		
	-------percent coverage-------					
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	<.0001	2	33	<.0001
	-------depositions per cm^2-------					
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	<.0001	2	33	<.0001

Table 2.6 Herbicide spray solution of dicamba plus glyphosate percent coverage and depositions per cm^2 on spray cards as influenced by nozzle type

Nozzle Type[a]	Trial 1	Trial 2	Trial 1	Trial 2
	--------%coverage[b]--------		------deposition per cm^{2b}------	
TT11005	49 A	49 A	45 A	47 A
ULD 12005	44 A	42 A	42 A	40 B
TTI11005	26 B	28 B	25 B	27 C

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

[b] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 2.7 Analysis of variance table for herbicide spray solution deposition onto waterhemp plants as influenced by nozzle, density, and the interaction

	Trial 1			Trial 2		
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	0.0792	2	24	0.0434
Density	3	33	0.2636	2	24	0.3522
Nozzle*Density	6	33	0.1939	4	24	0.1334

Table 2.8 The interaction of spray nozzle design and weed density influence on herbicide spray solution deposition onto waterhemp plants for Trial 1

	Trial 1		
	Nozzle Types[a]		
Average Density (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
		------------------μl cm^{-2}----------------	
4	0.90	0.91	0.65
26	1.03	1.24	0.72
54	0.76	1.08	1.06
P		*0.1939*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift TTI: Turbo TeeJet Induction.

Table 2.9 The interaction of spray nozzle design and weed density influence on herbicide spray solution deposition onto waterhemp plants for Trial 2

Average Density (plants / 0.25 m^2)	Trial 2		
	Nozzle Types[a]		
	TT11005	ULD12005	TTI1005
	--------------------μl cm^{-2}------------------		
6	0.76	0.52	0.78
27	1.03	0.68	0.71
54	0.85	0.84	0.62
P		*0.1334*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift TTI: Turbo TeeJet Induction.

Table 2.10 Herbicide spray solution deposition post-hoc means separation as influenced by spray nozzle design.

Nozzle Type[a]	Tukeys		Student Newman Keuls	
	Trial 1	Trial 2	Trial 1	Trial 2
	----- μl cm^{-2}[b] -----		-----μl cm^{-2}[b]-----	
TT11005	0.8974 A	0.8796 A	0.8974 A	0.8796 A
ULD 12005	1.0754 A	0.6781 A	1.0754 A	0.6781 A
TTI11005	0.8087 A	0.7052 A	0.8087 A	0.7052 A

[a] TT: Turbo TeeJet. ULD: Hypro Low-Drift TTI: Turbo TeeJet Induction.

[b] Values within a column followed by a different letter are significantly different.

Table 2.11 Analysis of variance table for 21 DAT percent control of waterhemp plants as influenced by nozzle, density, and the interaction

	Trial 1			Trial 2		
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	24	0.4810	2	33	0.0002
Density	2	24	0.0017	3	33	<.0001
Nozzle*Density	4	24	0.4705	6	33	0.0251

Table 2.12 The interaction of spray nozzle design and weed density influence on 21 DAT percent control of waterhemp plants for Trial 2

	Trial 2		
	Nozzle Types[a]		
Average Density (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	------------------% control[b] -----------------		
6	95 AB	99 A	93 AB
27	90 AB	95 AB	86 AB
54	81 B	89 AB	60 C

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.
[b] Values followed by a different letter are significantly different. Tukey HSD ($\alpha = 0.05$)

Table 2.13 The influence of average density for 21 DAT percent control of waterhemp plants in Trial 1

Average Density (plants / 0.25 m^2)	Trial 1
	-------------% control[a]---------------
4	94 A
26	93 A
54	78 B

[a]Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 2.14 Analysis of variance table for 21 DAT aboveground biomass of waterhemp plants as influenced by nozzle, density, and the interaction

	Trial 1			Trial 2		
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	16	0.7632	2	24	0.0004
Density	2	16	0.2761	2	24	0.4588
Nozzle*Density	4	16	0.1922	4	24	0.4205

*Square root transformation in Trial 1 and Trial 2

Table 2.15 The interaction of spray nozzle design and weed density influence on 21 DAT aboveground biomass of waterhemp plants for Trial 1

Average Density[b] (plants / 0.25 m^2)	Trial 1		
	Nozzle Types[a]		
	TT11005	ULD12005	TTI1005
	----------------grams per plant---------------		
4	0.11	0.10	0.06
26	0.01	0.03	0.07
54	0.17	0.04	0.07
P		*0.4705*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift TTI: Turbo TeeJet Induction.

[b] Initial weed density prior to post application and collection of biomass samples

Table 2.16 The interaction of spray nozzle design and weed density influence on 21 DAT aboveground biomass of waterhemp plants for Trial 2

	Trial 2		
	Nozzle Types[a]		
Average Density[b] (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	------------------grams per plant-----------------		
6	0.07	0.01	0.21
27	0.07	0.02	0.07
54	0.06	0.03	0.11
P		*0.4205*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift TTI: Turbo TeeJet Induction.

[b] Initial weed density prior to post application and collection of biomass samples

Table 2.17 The influence of spray nozzle design for 21 DAT aboveground biomass waterhemp plants in Trial 2

Nozzle Type[a]	Trial 2 --grams per plant[b]--
TT11005	0.07 A
ULD 12005	0.02 B
TTI11005	0.13 A

[a] TT: Turbo TeeJet. ULD: Hypro Low-Drift TTI: Turbo TeeJet Induction.

[b] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Chapter 3

Introduction

Weed management programs have changed considerably over the years. The use of glyphosate-resistant crops such as corn, soybean, and cotton made the control of many weed species “simple and convenient” (Green and Owen 2010). The constant use of one mode of action, for instance glyphosate, has left growers in need of more diverse weed management programs (Green and Owen 2010). The dicamba-resistant soybean system was introduced to help control the top four problematic weeds, namely tall waterhemp (*Amaranthus tuberculatus)*, horseweed (*Conyza canadensis),* Palmer amaranth (*Amaranthus palmeri),* and giant ragweed (*Ambrosia trifida)* (Van Wychen 2016; Van Wychen 2019). In addition to these difficult to control and troublesome broadleaf weeds, growers are as also now struggling to control certain grass species.

Over the past few growing seasons many growers and agriculture personnel have expressed concern regarding dicamba applications. Since the introduction of dicamba, it has been reported that soybean is extremely sensitive to a majority of the formulations (Hartlzer 2017). The evaluation of susceptibility of soybean and other crops to dicamba has been evaluated by numerous researchers. In a meta-analysis review, Kniss (2018), looked at 11 different studies and reported that Robinson et al. (2013) identified the lowest dicamba rate of 0.06 g ae ha^{-1} that caused visual injury. Tobacco exposed to the rate of dicamba at 140 g ae ha^{-1} results in yield reductions (Johnson 2011). Tomato plants are also sensitive to dicamba and can exhibit visual damage at the rate as low as 2.3 g ae ha^{-1} (Kruger et al. 2012).

In 2017, the state of Kentucky experienced around 13,355 hectares of non dicamba-resistant soybean damaged due to off-target dicamba drift (Dr. Kevin Bradley personal communication). In 2018, only approximately 2,428 hectares of non dicamba-resistant soybean, but 202 hectares of tobacco was damaged by dicamba, and in 2019 even fewer acres for both crops were damage (Dr. Travis Legleiter and Dr. JD Green, personal communication). The decrease in the amount of soybean acres damaged can likely be contributed to the wider adoption of the dicamba-resistant soybean system and improvements on application methods.

A series of factors contribute to the amount of off-site target movement during dicamba applications. Weather conditions at the time of application is a major factor the applicator cannot control but must be aware. Other factors that an applicator can control are boom height, sprayer speed, tank mixtures, pressure, and droplet size (Carlsen et al. 2006; Combellack1982). The United States Environmental Protection Agency (USEPA) has mandated numerous stringent restrictions on the new dicamba herbicide formulation labels that are intended to help reduce physical drift during an application. One restriction is the use of low drift spray nozzles that have been approved to spray dicamba. These nozzles produce very coarse to ultra-coarse droplets and minimize the production of driftable fines. Very coarse, extremely coarse, and ultra-coarse droplets are classified and defined using the ASABE S572.1. procedure and driftable fines is the percentage of droplets less than 200 µm**.** Larger droplets produced by these nozzles will increase the mass of the droplet which results in reduction of horizontal movement and decrease the amount of time the droplet is in the state of fall, thus decreasing drift potential (Bode 1987).

Spray nozzles that produce extremely coarse to ultra-coarse droplets not only reduce off-target movement potential, but consequently also reduce herbicide spray coverage, which can lead to decreased herbicide efficacy (Knoche, 1994). Herbicide coverage and efficacy are influenced by numerous factors, but an additional factor that needs to be considered when evaluating the effect of spray coverage on herbicide efficacy is herbicide type (Knoche 1994). The use of drift reducing nozzles when applying a systemic herbicide, glyphosate, did not influence dry weight of grass species, but results were mixed with the use of drift reducing nozzles for a paraquat application, which is a contact herbicide (Ferguson et al. 2018).

Another factor that could play a role is the weed density level and the type of weed species that is being targeted. Weed density influences soybean yield negatively and has been intensely studied, but the influence that density has on spray coverage and deposition has not been investigated in depth.

The architecture of the weed being targeted can also affect herbicide spray coverage and deposition. Grass species are classified as monocots and broadleaf weeds are classified as dicots. Dicot weed leaves have a greater surface area to capture herbicide solution droplets when compared to a smaller monocot leaves (Dorr et al. 2008). Growers who use an air-induction nozzle type that produces an ultra-coarse droplet versus a coarse droplet producing nozzle could see a reduction in annual grass control (Carter et al. 2017).

While it is extremely important to account for off-target movement when making an herbicide application, it is critical to also ensure maximum performance of the herbicide to control target weeds. Legleiter et al. (2018) studied the control of four problematic weeds: Palmer amaranth, waterhemp, giant ragweed, and horseweed. He reported that the use of low-drift nozzles did not reduce herbicide efficacy of these weed species despite of the fact that spray coverage was reduced on spray cards. Many experiments have been organized to analyze the influence of droplet size on broadleaf weed efficacy with very few looking at grass species.

The objective of this study was to determine the influence of spray nozzle type and weed density on herbicide coverage, deposition, and efficacy of a dicamba and glyphosate postemergence application onto grass species with the use of two low-drift spray nozzles and a traditional broadcast nozzle.

Materials and Methods

Site

Field experiments were conducted during 2018 and 2019 at The University of Kentucky Research and Education Center located near Princeton, Kentucky. The soil type for this location is a Crider silt loam. In 2018, the grass species population that predominated the site was goosegrass *(Eleusine indica*). In 2019, there was a variety of grass species which consisted of large crabgrass (*Digitaria sanguinalis*), goosegrass, yellow foxtail (*Setaria faberi*), and Johnson grass (*Sorghum halepense*) with majority of the population being large crabgrass*.* Dicamba-resistant soybean varieties were planted in 38-cm rows at an approximate seeding rate of 346,000 seeds ha^{-1} on May 15, 2018 and April 30, 2019 with a Precision Planting vacuum planter. Plots were maintained to control weeds prior to the post application, therefore a burndown application of Roundup PowerMax at 1260 g ae ha^{-1} was applied prior to planting. In addition, dicamba at 560 g ae ha^{-1} was applied on May 30, 2018 and June 3, 2019 to control the non-grass species weeds such as marestail (*Conyza canadensis)* and giant ragweed (*Ambrosia trifida*).

Experimental design

The experimental design was a randomized complete block with four replications. A two-way factorial treatment structure was used and plot measurements were 3-m by 8-m with 6-m alleyways between blocks. The two factors included three nozzle designs and four weed densities. The three nozzles included a Turbo TeeJet[13] (TT11005) nozzle and two drift reduction nozzles approved for dicamba applications: Turbo TeeJet Induction[14] (TTI11005) and Pentair Ultra Lo-Drift[15] (ULD12005).

The weed densities were manipulated by a preemergence herbicide applications made on May 16, 2018 and April 30, 2019. Pyroxasulfone was used as the preemergence herbicide and was applied at three different rates: a full rate at 280 g ai ha^{-1}, a reduced rate at 180 g ai ha^{-1}, and the lowest rate at 90 g ai ha^{-1}. A fourth treatment consisted of no preemergence herbicide to represent the highest naturally occurring density at this site. Pyroxasulfone applications were made using a CO_2 backpack sprayer with XR11002 nozzles spaced 51 cm apart pressurized at 221 kPa traveling at 4.8 kph. Prior to the postemergence application a 0.25 m^2 quadrant was

[13]TeeJet Technologies, 200 W. North Ave, Glendale Heights, IL 60139
[14] TeeJet Technologies, 200 W. North Ave, Glendale Heights, IL 60139
[15] Pentair, 5500 Wayzata Blvd #800, Minneapolis, MN 55416

established in each plot which contained the weed densities. The four different weed densities ranged from an average of 6 to 25 plants per quadrant. Averages of weed densities in the 0.25 m^2 quadrant for both years can be found in Table 3.1.

Herbicide application

Herbicide postemergence applications were made when weeds reached approximately 5 to 10 cm tall. The post application was using an all-terrain vehicle (ATV) with a 3- m side boom which held of four nozzles on 51 cm spacing. To mimic a commercial post-application, the ATV was traveling at 16 kph with a pressure range of 262 to 290 kPa depending on the nozzle to achieve an application rate of 140 l ha^{-1}. The tank mixture consisted of: 1100 g ae ha^{-1} of glyphosate (Roundup PowerMax)[16], 560 g ae ha^{-1} of dicamba (Xtendimax with Vapor Grip)[17], 0.5% v/v of On Target[18], 0.25% v/v of Vision Pink[19] foam marker dye and 600 µg ml^{-1} of Spectra Trace SH-P (PTSA)[20]. The two dyes added to the tank mixture are used analyze spray solution coverage and deposition. Date of application, crop growth stage, and weather data are listed in Table 3.2.

Data collection and analysis

Droplet spectrum analysis

Droplet spectrum analysis was conducted at the Pesticide Application Technology Laboratory (PAT Lab) located at the University of Nebraska West Central Research and Extension Center located in North Platte, Nebraska. Each nozzle type was represented by randomly selecting a nozzle from the units used in the field experiments.

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[16] RoundUp Powermax® Bayer Crop Science, 800 N. Lindbergh Blvd., St. Louis, MO 63167
[17] Xtendimax TM, Bayer Crop Science, 800 N. Lindbergh Blvd., St. Louis, MO 63167
[18] On Target®, WinField United Solutions, LLC, P.O. Box 64589, St. Paul, MN 55164-0589
[19] Vision PinkTM, Garrco Products Inc, P.O. Box 619, Converse, IN 46919-0619
[20] Spectra Trace SH-P, Spectra Colors Corporation, 25 Rizzolo Road, Kearny, New Jersey 07032

The droplet spectrum analysis was conducted in a low speed wind tunnel with a constant wind speed of 24 kph. A laser diffraction Sympatec Helos Vario KR particle size analyzer assembled with an R7 lens was used to analyze the droplet size. To represent three replications, the spray plume was traversed though the laser for analysis three times. The same tank mix that was used in the field experiments was used when conducting the analysis with the exception of the Vision Pink and PTSA dyes. The report of the analysis included the DV10, DV50, and DV90 which translates into 10%, 50%, and 90%, of the droplets in the spray volume that are at or below the reported diameter (Pesticide Environment Stewardship 2020). Percentage of droplets less than 200 µm, which represents the percentage of driftable fines was also reported for each nozzle type. Each nozzle was classified into a droplet size category based on the DV10, DV50, and DV90 output by using a reference curves established at the UNL PAT Lab based on the ASABE S572.1 procedure.

Herbicide spray coverage

Herbicide spray coverage and deposition were collected with Kromekote spray cards that measure 22 cm by 28 cm. The cards are coated allowing definitive markings of depositions from the Vision Pink foam marker dye that was included in the herbicide tank mix. Spray cards were placed in one of the three middle rows in the center of the plot and directly in the center of the inter-row prior to the herbicide post-application. After the application the spray cards were transferred back to the lab and scanned into 600 by 600 dpi, 24-bit color digital images using a duplex scanner. Once in digital form, each card was analyzed using APS Assess Software. The software separates the pink depositions from the white background of the card. Area of coverage in cm^2 and deposition counts were reported from the output of the software then transformed into percent of coverage and depositions per cm^2 by using the known size of the cards.

Herbicide solution deposition on target weeds

Herbicide spray deposition onto target weeds was collected by adding a fluorescent dye to the herbicide tank mixture as a tracer. Two grass plants were cut at the soil surface from the designated 0.25 m^2 quadrant immediately following the post application. The collected weeds were then individually washed in a 200 ml solution of water and 0.1% v/v surfactant (Triton X-100). Each plant was washed in a separate solution container, placed in an envelope, and transferred back to the lab. To avoid cross contamination, after each treatment the materials used to cut and wash the plants were washed with a 1:1 water and methanol solution.

In the lab, leaf area (cm^2) of the grass samples was collected using a LI-COR LI-3000 leaf area meter. The raw fluorescence from the wash solutions was determined using a Trilogy Laboratory Fluorometer manufactured by Turner Designs installed with the PSTA specific module. Prior to analysis of the samples from the field, raw fluorescent values of standard solutions containing 0.0001 to 1 ppm PTSA were plotted on a linear curve to calculate the amount of PTSA in the field wash solutions. By knowing the rate of PTSA in the herbicide tank mixture, the amount of wash solution used (200ml), the leaf area of the plant (cm^2), and amount of PTSA in the wash solutions, calculations were made to determine how much spray solution was deposited onto the targeted weed.

Herbicide efficacy and biomass

Herbicide efficacy ratings were taken 21 days after treatment (DAT). Each plot was evaluated visually on a scale from 0 to 100 percent. No control was represented by 0 and 100 indicated full or complete control. Above ground biomass samples were harvested 21 DAT from within each 0.25 m^2 quadrant. Samples were placed in envelopes and transferred to a dryer manufactured by the Grieve Corporation model SC-400. The dryer temperature was set to 57 C and samples were given at least 48 hours to dry and then dry weight (g) was taken. Biomass (g) calculations were made based on density level to represent biomass per plant.

Data analysis

Prior to analysis all data were checked for normality and equality of variances. If assumptions were not met, a square root or log transformation was performed and the raw data were used for all means. When both assumptions were met, data differences were determined using analysis of variance with SAS 9.4 PROC GLIMMIX, means were separated at alpha = 0.05 adjusted with Tukey HSD when significant. In 2018, leaf area (cm^2) of plants collected for herbicide solution deposition were variable which resulted in larger plants collected; therefore, a covariance using leaf area *(P= 0.0001)* was added into the analysis of variance (Table 3.6). Due to plant size being consistent in 2019, leaf area (cm^2) was not added into the analysis of variance. Years were analyzed separately due to difference in grass species between the two site years.

Results and Discussions

Droplet spectrum analysis

A standard curve was established using the Dv10, Dv50, and Dv90 values for each nozzle and placed into the appropriate category based on the ASABE S572.1

procedure. The TT11005 produced very coarse droplets and the two drift reducing spray nozzles (ULD 12005 and TTI11005) produced ultra-coarse droplets (Table 3.3). The TT11005 nozzle produced the smallest Dv10, Dv50, Dv90 values, while the two drift reducing spray nozzles reported higher values with the TTI11005 nozzle having the largest size for all three values. The percentage of driftable fines was determined looking at the droplets less than 200 µm. As expected the TT11005 produces the greatest percentage of driftable fines at 7.8 percent when compared to the drift reducing spray nozzles and the TTI11005 recorded the lowest percent at 0.6 percent (Table 3.3).

Herbicide spray coverage

Results from the spray cards indicated differences among nozzles for 2018 and 2019 when considering percent coverage and depositions per cm^2 (Table 3.4). Herbicide spray solution percent coverage recorded a reduction with the use of TTI11005 nozzle in both years (2018 and 2019) when compared to the TT11005 nozzle (Table 3.5). In 2018, the ULD 12005 nozzle had similar coverage compared to both TeeJet nozzle types (TT11005 and TTI11005). In 2019, the ULD 12005 nozzle that produced ultra-coarse droplets, and was approved to make dicamba applications, did not decrease coverage when compared to the TT11005 nozzle that produces very coarse droplets which is not approved to spray dicamba (Table 3.5).

Depositions per cm^2 were the greatest for the TT11005 nozzle producing very coarse droplets in both years with averages of 39 and 45 depositions per cm^2 when compared to the TTI11005 nozzle type that produced ultra-coarse droplets (Table 3.5).

In 2018, the ULD 12005 recorded a decrease in deposition counts to 28 per cm^2 and the TTI11005 had the lowest deposition counts with 18 per cm^2 (Table 3.5). In 2019, despite the fact the ULD 12005 is considered a drift reducing nozzle no differences were observed compared to the TT11005 nozzle. As expected the TTI11005 produced the fewest depositions per cm^2. These results were expected and supported previous literature when increasing droplet size spectrum; the percent coverage and deposition density were reduced (Knoche 1994).

Herbicide solution deposition on target weeds

Dicamba plus glyphosate volume deposition onto targeted grass species did not show an interaction between the three nozzle types and four levels of weed density in 2018 *(P=0.2167)* or 2019 *(P=0.2728)* (Table 3.6). Analysis of spray nozzle type *(P=0.7513 and P= 0.4698)* and weed density *(P=0.5606 and P=0.2877)* also showed a lack of influence on spray solution deposition in both years. In 2018, herbicide spray solution deposition onto grass species ranged from 1.02 to 2.26 µl cm^{-2} and in 2019 deposition ranged from 0.46 to 0.84 µl cm^{-2} (Table 3.7 and 3.8). Overall, the plant samples collected in 2018 exhibited larger average leaf area of 35.73 cm^2 per plant as compared to samples collected in 2019 which had an average of 14.91 cm^2.

Despite the fact that different grass species were analyzed between years, overall there were no differences observed between the drift reducing nozzles and the traditional broadcast nozzle**.** The drift reducing nozzles (TTI11005 and ULD 12005) producing ultra-coarse droplets provided equivalent herbicide spray solution volume deposition compared to the very coarse droplet producing nozzle (TT11005). Differences in weed density did not influence the amount of herbicide spray solution deposition.

Herbicide efficacy and biomass

In both years, no interaction occurred between the two factors (*P= 0.3221 and P= 0.2028).* In 2018, grass control ranged from 84 to 99 percent and in 2019 from 58 to 99 percent among the nozzle type and weed density treatments. Each factor was analyzed separately due to no interactions. Differences in percent control 21 days after application (DAT) only occurred in 2019 with the factor for weed density (Table 3.9). Weed density levels influenced the percent control in 2019 *(P=0.0002).* The highest density, with an average of 29 plants per quadrant, reduced percent control of grass species by 24 percent when compared to the other density levels. In 2018, observable differences relative to weed density levels influencing the percent control of grass species *(P=0.2478)* (Table 3.9). In 2018 and 2019, no differences in percent control of grass species were observed between the three nozzle types *(P= 0.5144 and P=0.0983)* (Table 3.9 and Table 3.11).

Biomass results differed between the two site years. In 2018 no interaction of factors occurred *(P=0.5401)* while an interaction was observed in 2019 *(P=0.0152)* (Table 3.12). In 2018, biomass per plant ranged from 0.02 to 0.62 grams per plant when evaluating the interaction of the nozzle type and weed density (Table 3.13). Furthermore, no interactions occurred in 2018 between the two factors each factor was analyzed separately and no differences were observed between the three nozzle types *(P=0.9476)* or between the four levels of weed density *(P=0.3846)*. The results from 2018 were expected as no differences in percent control in 2018 occurred. Differences occurred in 2019 observed in an interaction of nozzle type and density with a biomass per plant range from 0.59 to 0.01 grams per plant (Table 3.14). The TT11005 nozzle had in the greatest biomass at the highest weed density level and was greater than all three nozzles at the lowest density (Table 3.14).

The biomass results from 2019 do not align with the percent control results from 2019. As expected, the highest weed density level reduces control, but the interaction in 2019 of nozzle type and weed density suggests that the use of TT11005 nozzle grass control was reduced at the highest density as compared to the ULD12005 drift reducing nozzles which was not expected.

Summary

In conclusion, the influence of drift reducing nozzles such as the TTI nozzle could influence the overall performance of a postemergence application of dicamba plus glyphosate when evaluating factors such as herbicide coverage. Despite the fact that herbicide deposition volume was equivalent across the three nozzle types and four levels of weed density the efficacy of glyphosate plus dicamba on grass species was reduced by higher weed densities in at least one year.

A reduction in dicamba plus glyphosate efficacy of grass species could be attributed to many factors. The tank mixture itself could be influencing the performance of the herbicide. Some literature suggests that there may be antagonism between, that tank mixtures of dicamba plus glyphosate could antagonize between the two chemicals. In a study conducted by Ou et al. (2018), greenhouse and field experiments were conducted looking at tank mixtures of dicamba plus glyphosate in effort to control

Kochia scoparia. Results from these experiments show that glyphosate alone controlled *Kochia scoparia* better when compared to any combination of glyphosate and dicamba, which suggests that antagonism may be occurring between these herbicides by reducing translocation that leads to a reduction of herbicide efficacy.

Broadleaf signalgrass *(Urochloa platyphylla*), Johnsongrass, and large crabgrass showed antagonistic effects with low rates of both dicamba plus glyphosate and decreased control when compared to glyphosate alone (Huff 2010). When the rates of dicamba are increased antagonism is no longer recorded in any of the species (Huff 2010). Barnyardgrass *(Echinochloa crus-galli)* observed antagonism at rates of 0.14, 0.28, 0.42 kg ae ha^{-1} of dicamba depending on the rate of glyphosate, but when the rate of dicamba is increased antagonism was no longer observed. Overall, it is important to note that increasing the rate of dicamba with glyphosate effectively controls many grass species, but translocation of dicamba can be altered when glyphosate is added to the tank mix (Huff, 2010)

The sampling method used in the experiments may not have captured a complete representation of spray solution deposition in the high density quadrants. The crew members were instructed to randomly select two grass samples to collect, but this did not account for a smaller flush of plants growing under the weed canopy. Smaller plants under the canopy could have the ability to survive the post application which suggests herbicide performance could have been reduced in the high density quadrants of 25 to 29 plants, which was observed in at least one year.

Overall, a reduction in herbicide performance is likely to occur in high density situations, when herbicide deposition fails to reach smaller plants. Therefore, it is important for growers to keep densities low to assure postemergence control of a variety of grass species.

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Table 3.1 Average actual density for grass species located in 0.25 m^2 quadrant for years 2018 and 2019

	Year	
Desired relative density level	2018	2019
	-------------grass plants per 0.25 m^2--------------	
25%	6	6
50%	12	12
75%	17	17
100%	25	29

Table 3.2 Date, time, and weather conditions at the time of postemergence herbicide application for years 2018 and 2019

	Year	
	2018	2019
Application Date	6/18/18	6/12/18
Application Time	9:11 -12:20 a.m.	9:14-10:42 a.m.
Temperature	31 C	20 C
Relative Humidity	73 %	55 %
Wind Speed	Avg = 6.6 kph Max = 10.0 kph	Avg = 2.7 kph Max = 4.8 kph
Crop Stage	R1-R2	R1

Table 3.3 Spray classification for each nozzle type, Dv10, Dv50, Dv90, and percent of driftable fines at the field use rate of dicamba plus glyphosate including a drift reduction agent

Nozzle Type[a]	Dv10	Dv50	Dv90	Percent <200 microns	Spray Classification[b]
	---------------μm[c]---------------			-----%[c]-----	
TT11005	223 A	526 A	908 A	7.8 A	Very Coarse
ULD 12005	342 B	700 B	1052 B	2.2 B	Ultra Coarse
TTI11005	494 C	952 C	1345 C	0.6 C	Ultra Coarse

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

[b] Spray Classification based on reference curve using the UNL PAT Lab ASABE S542.1.

[c] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 3.4 Analysis of variance table for spray card percent coverage and depositions per cm^2 2018 and 2019 as influenced by nozzle type

	2018			2019		
	-------percent coverage-------					
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	<.0001	2	33	<.0001
	-------depositions per cm^2-------					
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	<.0001	2	33	<.0001

Table 3.5 Herbicide spray solution of dicamba plus glyphosate percent coverage and depositions per cm^2 on spray cards as influenced by nozzle type

Nozzle Type[a]	2018	2019	2018	2019
	--------%coverage[b]--------		------deposition per cm^{2}[b]------	
TT11005	21 A	34 A	39 A	45 A
ULD 12005	17 AB	39 A	28 B	41 A
TTI11005	12 B	23 B	18 C	22 B

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

[b] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 3.6 Analysis of variance table for dicamba plus glyphosate volume deposition onto targeted grass species as influenced by leaf area, nozzle, density, and the interaction

	Year					
	2018			2019		
	Num DF	Dem DF	P-value	Num DF	Dem DF	P-value
Leaf area (cm^2)	1	32	<.0001	-	-	-
Nozzle	2	32	0.7513	2	33	0.4698
Density	3	32	0.5606	3	33	0.2877
Nozzle*Density	6	32	0.2167	6	33	0.2728

Table 3.7 The interaction of spray nozzle design and weed density influence on herbicide spray solution deposition onto grass plants in 2018

	2018		
	Nozzle Types[a]		
Average Density (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	------------------------$\mu l\ cm^{-2}$----------------------		
6	1.81	1.63	1.70
12	1.44	2.05	1.44
17	1.26	1.18	1.02
25	2.26	1.36	1.48
P		*0.7390*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

Table 3.8 The interaction of spray nozzle design and weed density influence on herbicide spray solution deposition onto grass plants in 2019

	2019		
	Nozzle Types[a]		
Average Density (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	---------------------μl cm^{-2}-------------------		
6	0.82	0.46	0.84
12	0.51	0.73	0.64
17	0.67	0.56	0.82
29	0.28	0.66	0.50
P		*0.2728*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

Table 3.9 Analysis of variance table for 21 DAT percent control of grass species as influenced by, nozzle, density, and their interaction

	Year					
	2018			2019		
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	0.5144	2	33	0.0983
Density	3	33	0.2478	3	33	0.0002
Nozzle*Density	6	33	0.3221	6	33	0.2028

Table 3.10 The influence of grass density on21 DAT percent control of grass plants for both years

Average Density (plants / 0.25 m^2)	2018	2019
	-------------% control[a]---------------	
6	93 A	98 A
12	91 A	90 A
17	98 A	92 A
25 to 29	94 A	74 B

[a] **c** Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 3.11 The influence of spray nozzle design for 21 DAT percent control of grass plants for both years

Nozzle Type[a]	Year	
	2018	2019
	------------------ % control[b] ----------------------	
TT11005	95 A	83 A
ULD 12005	95 A	93 A
TTI11005	92 A	89 A

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

[b] Values within a column followed by a different letter are significantly different. Tukey HSD (α = 0.05)

Table 3.12 Analysis of variance table on 21 DAT aboveground biomass of grass plants as influenced by nozzle, density, and the interaction

	2018			2019		
	Num DF	Den DF	P-value	Num DF	Den DF	P-value
Nozzle	2	33	0.9476	2	33	0.0417
Density	3	33	0.3846	3	33	0.0074
Nozzle*Density	6	33	0.5401	6	33	0.0152

*Square root transformation performed in 2018 and log in 2019

Table 3.13 The interaction of spray nozzle design and weed density influence on 21 DAT aboveground biomass of grass plants for 2018

	2018		
	Nozzle Types[a]		
Average Density[b] (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	------------------------	grams per plant	----------------------
6	0.02	0.03	0.34
12	0.30	0.04	0.12
17	0.02	0.05	0.15
25	0.39	0.62	0.05
P		*0.5401*	

[a] TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.

[b] Initial weed density prior to post application and collection of biomass samples

Table 3.14 The interaction of spray nozzle design and weed density influence on 21 DAT aboveground biomass of grass plants for 2019

	2019		
	Nozzle Types[a]		
Average Density[c] (plants / 0.25 m^2)	TT11005	ULD12005	TTI1005
	------------------------grams per plant[b]----------------------		
6	0.12 B	0.06 B	0.01 B
12	0.26 AB	0.04 B	0.13 B
17	0.06 B	0.27 AB	0.20 AB
29	0.59 A	0.10 B	0.21 AB
P		*0.0152*	

[a]TT: Turbo TeeJet. ULD: Pentair Hypro Ultra Low Drift. TTI: Turbo TeeJet Induction.
[b]Values followed by a different letter are significantly different. Tukey HSD ($\alpha = 0.05$)
[c] Initial weed density prior to post application and collection of biomass samples

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