8-2018

The Effect of Physical Application Parameters on Herbicide Efficacy and Droplet Size.

Andre de Oliveira Rodrigues
University of Nebraska-Lincoln

de Oliveira Rodrigues, Andre, "The Effect of Physical Application Parameters on Herbicide Efficacy and Droplet Size." (2018). *Theses, Dissertations, and Student Research in Agronomy and Horticulture*. 148.
http://digitalcommons.unl.edu/agronhortdiss/148

THE EFFECT OF PHYSICAL APPLICATION PARAMETERS ON HERBICIDE EFFICACY AND DROPLET SIZE.

by

Andre de Oliveira Rodrigues

A THESIS

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor Greg R. Kruger

Lincoln, Nebraska

August, 2018

THE EFFECT OF PHYSICAL APPLICATION PARAMETERS ON HERBICIDE EFFICACY AND DROPLET SIZE.

Andre de Oliveira Rodrigues, M.S.

University of Nebraska, 2018

Adviser: Greg R. Kruger

One of the largest challenges in agriculture is weed management. Improper or sub-optimal application techniques can cause decreased weed control and increased environmental contamination. Effective weed management is highly correlated with the product and the application method. Herbicide performance are affected by environmental conditions; they influence the physiology and growth of a plant and as well the herbicide performance. Among all environmental factors, rain shortly after herbicide application is one of the most harmful issues to the performance of the herbicide. Droplet size is a key factor in pesticide applications in regards to both drift and efficacy. Droplet size can be altered by several application parameters, such as the nozzle type, pressure, orifice size and spray solution. Droplet size is a key component in pesticide application with respect to overall application efficacy and off-target movement. As tank mix ingredients can significantly influence the resulting droplet size, agitation systems are critical to ensuring proper mixing of all components and overall performance. Sitting time, a period where the tank is held in a non-agitated state, potentially affects droplet size as well.

The objectives of this research were: 1) understand the influence of nozzle spacing, boom height, nozzle type, on weed control, also expand the scientific knowledge

on aforementioned parameters. 2) Evaluate the effect of rainfall after herbicide application on weed control, following certain intervals in order to understand the wash off effect. 3) Analyze the impact of nozzle type, application speed and pressure on weed control, in order to contribute to a more reliable recommendation of such parameters.

This research highlights the impact of parameters regulated by the sprayer on weed control and allow a better understanding of how non-chemical parameters affect the efficacy on weed management, as well as a greater understanding on absorption and evaporation of herbicide plus losses of application efficacy. The results will clarify some of the most concerning question on one of the most complex process in agriculture.

For Helcio, Silvana and Guilherme.

My family, biggest supporters and my foundation.

ACKNOWLEDGMENTS

The number of people that had a participation on my path to achieve this very important goal in my life and career is extensive. Starting with my advisor Dr. Greg R. Kruger for providing a life changer opportunity. As a professional the insights provided by him and the members of my committee and the PAT Lab members helped me to build my work ethic and my standards. I am also thankful for my committee members, Drs. Brad Fritz, Cody Creech and Ulisses Antuniassi for their time in order to help my development, they composed the best discussions I ever had and were always willing to work in favor of my growth, always providing unique thoughts and perspectives, which helped me in all sides of my life.

I would also like to thank my graduate students' colleagues across the years for all the exchange of ideas and experiences, the same is truth with research technicians and undergraduate students. The best help I could ever imagine receiving they provided me and the knowledge I got from them over the years is outstanding, so for that I am very thankful for Mr. Jeffrey A. Golus, Ms. Kasey P. Schroeder, Ms. Annah Geyer and Ms. Chandra Hawley. I honestly believe we compose the best group I could ever think of.

Finally yet importantly, I must appreciate the effort and support my family provided to me during this years of graduate school, been my base and my source of strength in the moments I needed the most. They are the reason I achieved my goal with happiness and always believing that my goal was always a little bit closer even in the days where that was hard to believe. So with that, feel grateful for your contribution on my life and my academic career.

TABLE OF CONTENTS

ACKNOWLEDGMENTS……………………………………………………………...v
LIST OF TABLES…………………………………………………………………vii
LIST OF FIGURES…………………………………………………………..…viii
CHAPTER 1. Literature Review…………………………………………………….1
CHAPTER 2. Influence of Nozzle Spacing, Boom Height and Nozzle Type on the Efficacy of Dicamba, Saflufenacil, Glyphosate and Glufosinate………………………..10
  Abstract……………………………………………………………………….10
  Introduction…………………………………………………………………...11
  Material & Methods…………………………………………………………..15
  Results and Discussion……………………………………………………….17
  Literature Cited……………………………………………………………….22
CHAPTER 3. Rainfastness of Clarity, XtendiMax, Roundup Xtend, and Roundup PowerMax………………..…………………………………………………………...37
  Abstract……………………………………………………………………….37
  Introduction…………………………………………………………………...38
  Material & Methods…………………………………………………………..41
  Results and Discussion...44
  Literature Cited……………………………………………………………….47
CHAPTER 4. Influence of Nozzle Type, Speed and Pressure on Droplet Size and Weed Control from Glyphosate®, Dicamba®, and Glyphosate® plus Dicamba®……………....56
  Abstract……………………………………………………………………….56
  Introduction…………………………………………………………………...57
  Material & Methods…………………………………………………………..61
  Results and Discussion……………………………………………………….63
  Literature Cited……………………………………………………………….68

LIST OF TABLES

Table 2.1. – Application speed used based on nozzle spacing and application volume to maintain constant application volume……………………………………………25

Table 2.2. - Droplet size distribution values generated from reference nozzles described in ASAE S572.1……………………………………………………………...26

Table 2.3. – Droplet size distribution data from four nozzle types with dicamba, saflufenacil, glyphosate and glufosinate………………………………………..27

Table 3.1. – Herbicide solutions with their appropriate rate and formulation used on the study………………………………………………………………………….....51

Table 3.2. - Average percentage control for velvetleaf across intervals…………………52

Table 3.3. - Average percentage control for Palmer amaranth across intervals…………53

Table 3.4. – Rainfastness interval of herbicides according to respective labels…………54

Table 4.1. – Droplet size data from reference nozzles at the Pesticide Application Technology Laboratory, North Platte, NE and spray classification boundaries as defined by ASAE S572.1……………………………………………………………73

Table 4.2. – Combinations of speed, pressure, and orifice size for three nozzle types utilized in a study to evaluate droplet size and efficacy……………………………..74

Table 4.3. – Results for interactions and main effects on control of common lambsquarters, kochia, velvetleaf, and grain sorghum………………………………75

Table 4.4. – Droplet size distribution data for three nozzle types spraying a dicamba solution across a range of orifice sizes and pressures………………………………76

Table 4.5. – Droplet size distribution data for three nozzle types spraying a glyphosate solution across a range of orifice sizes and pressures………………………………78

Table 4.6. – Droplet size distribution data for three nozzle types spraying a glyphosate plus dicamba solution across a range of orifice sizes and pressures………………...80

LIST OF FIGURES

Figure 2.1. – Dry biomass for three nozzle spacings when dicamba was applied to common lambsquarters…………………………………………………………………..28

Figure 2.2. - Dry biomass for three nozzle spacings by nozzle type when saflufenacil was applied to common lambsquarters………………………………………………………29

Figure 2.3. - Dry biomass for three boom heights above the target when glyphosate was applied to common lambsquarters………………………………………………………30

Figure 2.4. - Dry biomass for three nozzle spacings when glufosinate was applied to common lambsquarters…………………………………………………………………..31

Figure 2.5. - Dry biomass for three nozzle spacings when dicamba was applied to velvetleaf……………………………………………………………………………....32

Figure 2.6. - Dry biomass for three nozzle spacings by nozzle type when glyphosate was applied to velvetleaf……………………………………………………………………...33

Figure 2.7. - Grams of dry biomass for three boom heights by nozzle type when glufosinate was applied to velvetleaf…………………………………………………….34

Figure 2.8. - Grams of dry biomass for three nozzle spacings by nozzle type when glufosinate was applied to velvetleaf…………………………………………………….35

Figure 2.9. - Grams of dry biomass for three nozzle spacings when glufosinate was applied to Palmer amaranth……………………………………………………………...36

Figure 4.1. – Percent control of common lambsquarters using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds…………………………………………………………………………………82

Figure 4.2. – Percent control of velvetleaf using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds…………….83

Figure 4.3. – Percent control of kochia using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds…………….84

Figure 4.4. – Percent control of grain sorghum using three nozzle types when glyphosate plus dicamba and glyphosate was sprayed with three different application speeds……..85

CHAPTER 1

Literature Review

Weed management continue to be a critical process in a successful crop system in United States. Among all pesticides used in a row crop system, herbicides classify as the most commonly used in U.S. According to USDA, herbicides were applied to 97% of planted acres of corn, followed by 13% and 12% of insecticide and fungicides respectively (Fernandez-Cornejo et al., 2014). In addition, 95% of total planted acres of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.) and soybean (*Glycine max* (L.) *Merr*) received in 2015 at least one herbicide application (USDA-NASS, 2015). Weed control in crops by herbicide application can improve crop yield (Fernandez-Cornejo et al., 2005). Weed management consists of many strategies, such as biological, cultural, mechanical and chemical this last one been the preferable strategy. Main reason for the large use of herbicides is due to the low cost and convenience to growers while providing a satisfactory weed control.

While weed management continue to increase in use among growers, the risk of particle drift, vapor drift, contamination, resistance and other sources of application losses increase due to lack of knowledge of the process (Bish and Bradley, 2017). Particle drift and vapor drift are the two mechanisms possible for movement of herbicide downwind. Particle drift consists in the movement of particles containing the active ingredient carried by the action of the air at the application time or soon after the application, outside of the intended area of treatment. While vapor drift occurs when evaporation of herbicide happens in the treated area, are suspended in the air in the form of vapor, and move outside the treated area in that form. Up to 50% of pesticides losses are estimated in the form of volatilization and particle drift (Berg et al., 1999). Spray particle drift is normally influenced by wind speed and wind direction, spray droplet size, boom height and buffers zone (Creech et al., 2015). Once weather related parameters in application cannot be controlled, droplet size rise as one of the most important components in order to control particle drift during herbicide application (Berg et al., 1999; Etheridge et al., 1999). Uneven distribution patterns (Miller and Butler Ellis, 2000), lack of coverage and deposition, are also causes of particle drift when combined with improper weather conditions resulting in reduction on the efficacy been expected (Johnson et al., 2006).

As previously stated, in order to mitigate drift droplet size is a key factor and that can be controlled mainly by nozzle type (Butler Ellis et al., 2002), pressure and orifice size (Nuyttens et al., 2007). Typically, nozzles are classified as Venturi and non-Venturi nozzles. Venturi nozzle technology consist in nozzles with a pre-orifice, air fluid mixing chamber and the exit orifice, which generates the pattern of the nozzle spray fluid. Such technology contributes to the production of larger droplets with air included in the droplets when compared versus the conventional non-Venturi fan nozzle at a known determined pressure (Etheridge et al., 1999). Nozzle type selection depends on the scenario, where herbicide been used and weed species targeted influence the nozzle type selected (Meyer et al., 2016), as well as carrier volume of the application. A common practice to increase droplet size and thus reduce particle drift is to reduce application pressure and also increase orifice size (Creech et al., 2015; Hartley and Graham-Bryce, 1980). In consequence of that if application is not adjusted for speed, application rate and efficacy will be influenced (Knoche, 1994), other feasible alternative to reduce drift potential is to change nozzle type (Henry et al., 2015; Zhu et al., 2004). In addition, alternative particle drift strategies showed to be important in order to increase droplet size once previous reported work showed losses on herbicide efficacy when droplet size increased (Butts et al., 2018), and the same trend was observed for insecticide (Ebert et al., 1999).

Herbicide particle drift can cause damage to nearby crops and sensitive plants (de Snoo and de Wit, 1998; Nordby and Skuterud, 1974) this impact is due to herbicide toxicology, especially because some modes of action are highly active at low concentrations, and distance to sensitive vegetation. Another tool for drift management are the drift reduction technologies (DRTs) which has the objective to reduce the percentage of driftable fines by increasing the viscosity of the spray reducing the number of small droplets. Other drift control adjuvants acts as a suspension inverter to improve the spray sheet breakup in order to reduce fines. More and more herbicide application are including DRTs especially near sensitive areas, at the same time the addition of adjuvants to the tank-mixture does not influence the efficacy of the herbicide, actually in the other hand adjuvants can make the herbicide applications more efficient (Mcmullan, 2000).

Droplets are generated by a process denominated atomization, which consists on breaking the liquid sheet into fine particle capable of reaching the surface of the target. Among the various process of atomization, agricultural nozzles utilizes the process of forcing the liquid through a small orifice under a certain pressure at that moment droplets are formed. There are numerous nozzles called hydraulic nozzles, which can be a flat fan, air induction, twin fluid, deflector, and both cones, hollow and full cone. Once droplets are generated, a complex process starts reaching to the intended target, retention on leaf surface, deposit of the active ingredient, absorption and biological response (Ebert and Downer, 2008; Reichard, 1988). Droplets for optimum performance and biological activity need to be delivered properly, meaning a adequate coverage and deposition in order to maximum availability of active ingredient for plant absorption, that is correlated with nozzle spacing and boom height as well (Forney et al., 2017).

Aforementioned parameters plays a role in drift as well as in coverage and deposition in order for an optimum biological response of weed control, but there is also other parameters that also play an important role in weed management, which are above mentioned, boom height and nozzle spacing which influence the homogeneity of the application. Coefficient of variation (CV) of an application is a quantification of the spray pattern uniformity (Ozkan and Ackerman, 1992) measuring the evenness of the distribution exiting the nozzle exit orifice. Once a smaller CV would be achieved with an increasing boom height and a narrower nozzle spacing (A. H. Azimi et al., 1985). CV of hydraulic nozzles versus air induction goes from 12 to 22 % respectively. Two types of methods can be used to measure pattern uniformity, static and dynamic. Static consist of a patternator composed by graduate cylinders where the spray is collected across the entire boom (A. Womac et al., 2001; Etheridge et al., 1999). Meanwhile the dynamic method involve collecting the spray in a measurement zone with water sensitive cards (A. Womac et al., 2001), petri dishes or string collectors, last two more commonly used on aerial applications.

Droplet size not only is critical for particle drift purposes but also important to application efficacy. Better crop penetration, droplet impaction, herbicide retention and increased efficacy can be obtained by smaller droplet size (Knoche, 1994). Contact herbicides are more influenced by droplet size when increasing the droplets when compared with systemic herbicides due to how the herbicide acts on the plant (Etheridge et al., 2001). Application efficacy is directly correlated with retention, absorption among other factors accordingly to targeted plants (Zwertvaegher et al., 2014) which can lead to economic losses and contamination when misconsidered. All those factors are dependent of the morphological characteristics of the plant, with the leaf surface composition with pubescence, waxy layer, and neutral.

Objectives

Pesticide applications is one of the most complex process in agriculture, applicators and growers are facing what seems to be an endless variety of options to choose when selecting the proper equipment, proper nozzle type and proper parameters to achieve an optimum application with no to little activity outside intended area of treatment. Adequate nozzle selection will influence droplet size generated and uniformity of the swath and thus will affect the efficacy of the operation and potential contamination for a given situation.

Droplet size depends on the combination of nozzle type and its orifice size, as well as characteristics of the spray solution utilized in the given scenario, just as the application pressure enforced in that process at which the liquid will be exiting the nozzle exit orifice.

This research had as main objective understand and better explain the influence of physical application parameters on herbicide efficacy and droplet size, and it was divided into three sub-objectives, which were: 1) understand the influence of nozzle spacing, boom height, nozzle type, on weed control; also expand the scientific knowledge on aforementioned parameters. 2) Evaluate the effect of rainfall after herbicide application on weed control, following certain intervals in order to understand the wash-off effect. 3) Analyze the impact of nozzle type, application speed and pressure on weed control, in order to contribute to a more reliable recommendation of such parameters.

Literature Cited

A. H. Azimi, T. G. Carpenter, D. L. Reichard, 1985. Nozzle Spray Distribution for Pesticide Application. Trans. ASAE 28, 1410–1414. https://doi.org/10.13031/2013.32451.

A. Womac, R. Etheridge, A. Seibert, D. Hogan, S. Ray, 2001. SPRAYER SPEED AND VENTURI–NOZZLE EFFECTS ON BROADCAST APPLICATION UNIFORMITY. Trans. ASAE 44. https://doi.org/10.13031/2013.7011.

Berg, F.V.D., Kubiak, R., Benjey, W.G., Majewski, M.S., Yates, S.R., Reeves, G.L., Smelt, J.H., Linden, A.M.A.V.D., 1999. Emission of Pesticides into the Air, in: Fate of Pesticides in the Atmosphere: Implications for Environmental Risk Assessment. Springer, Dordrecht, pp. 195–218. https://doi.org/10.1007/978-94-017-1536-2_9.

Bish, M.D., Bradley, K.W., 2017. Survey of Missouri Pesticide Applicator Practices, Knowledge, and Perceptions. Weed Technol. 31, 165–177. https://doi.org/10.1017/wet.2016.27.

Butler Ellis, M.C., Swan, T., Miller, P.C.H., Waddelow, S., Bradley, A., Tuck, C.R., 2002. PM—Power and Machinery: Design Factors affecting Spray Characteristics and Drift Performance of Air Induction Nozzles. Biosyst. Eng. 82, 289–296. https://doi.org/10.1006/bioe.2002.0069.

Butts, T.R., Samples, C.A., Franca, L.X., Dodds, D.M., Reynolds, D.B., Adams, J.W., Zollinger, R.K., Howatt, K.A., Fritz, B.K., Hoffmann, W.C., Kruger, G.R., 2018. Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci In Review, Manuscript ID: PM-18-0032.

Creech, C.F., Henry, R.S., Fritz, B.K., Kruger, G.R., 2015. Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. Weed Technol. 29, 298–310. https://doi.org/10.1614/WT-D-14-00049.1.

de Snoo, G.R., de Wit, P.J., 1998. Buffer Zones for Reducing Pesticide Drift to Ditches and Risks to Aquatic Organisms. Ecotoxicol. Environ. Saf. 41, 112–118. https://doi.org/10.1006/eesa.1998.1678.

Ebert, T., Downer, R., 2008. Insecticide Application: The Dose Transfer Process, in: Encyclopedia of Entomology. Springer, Dordrecht, pp. 1958–1974. https://doi.org/10.1007/978-1-4020-6359-6_1540.

Etheridge, R.E., Hart, W.E., Hayes, R.M., Mueller, T.C., 2001. Effect of Venturi-Type Nozzles and Application Volume on Postemergence Herbicide Efficacy. Weed

Technol. 15, 75–80. https://doi.org/10.1614/0890-037X(2001)015[0075:EOVTNA]2.0.CO;2.

Etheridge, R.E., Womac, A.R., Mueller, T.C., 1999. Characterization of the Spray Droplet Spectra and Patterns of Four Venturi-Type Drift Reduction Nozzles. Weed Technol. 13, 765–770. https://doi.org/10.1017/S0890037X00042202.

Fernandez-Cornejo, J., Hendricks, C., Mishra, A., 2005. Technology Adoption and Off-Farm Household Income: The Case of Herbicide-Tolerant Soybeans. J. Agric. Appl. Econ. 37, 549–563. https://doi.org/10.1017/S1074070800027073.

Fernandez-Cornejo, J., Nehring, R.F., Osteen, C., Wechsler, S., Martin, A., Vialou, A., 2014. Pesticide Use in U.S. Agriculture: 21 Selected Crops, 1960-2008 (SSRN Scholarly Paper No. ID 2502986). Social Science Research Network, Rochester, NY.

Forney, S.H., Luck, J.D., Kocher, M.F., Pitla, S.K., 2017. Laboratory and Full Boom-Based Investigation of Nozzle Setup Error Effects on Flow, Pressure, and Spray Pattern Distribution. Appl. Eng. Agric. 33, 641–653. https://doi.org/10.13031/aea.12043.

Hartley, G.S., Graham-Bryce, I.J., 1980. Physical principles of pesticide behaviour. Phys. Princ. Pestic. Behav.

Henry, R.S., Fritz, B.K., Hoffmann, W.C., Kruger, G.R., 2015. An Evaluation of Three Drift Reduction Adjuvants for Aerial Application of Pesticides. GSTF J. Agric. Eng. JAE 1, 1–10. https://doi.org/10.7603/s40872-015-0006-3.

Johnson, A.K., Roeth, F.W., Martin, A.R., Klein, R.N., 2006. Glyphosate Spray Drift Management with Drift-Reducing Nozzles and Adjuvants. Weed Technol. 20, 893–897. https://doi.org/10.1614/WT-05-162.1.

Knoche, M., 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot. 13, 163–178. https://doi.org/10.1016/0261-2194(94)90075-2.

Mcmullan, P.M., 2000. Utility Adjuvants. Weed Technol. 14, 792–797. https://doi.org/10.1614/0890-037X(2000)014[0792:UA]2.0.CO;2.

Meyer, C.J., Norsworthy, J.K., Kruger, G.R., Barber, T., 2016. Effects of Nozzle Selection and Ground Speed on Efficacy of Liberty and Engenia Applications and Their Implication on Commercial Field Applications. Weed Technol. 30, 401–414. https://doi.org/10.1614/WT-D-15-00145.1.

Miller, P.C.H., Butler Ellis, M.C., 2000. Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. Crop Prot., XIVth

International Plant Protection Congress 19, 609–615. https://doi.org/10.1016/S0261-2194(00)00080-6.

Nordby, A., Skuterud, R., 1974. The effects of boom height, working pressure and wind speed on spray drift. Weed Res. 14, 385–395. https://doi.org/10.1111/j.1365-3180.1974.tb01080.x.

Nuyttens, D., Baetens, K., De Schampheleire, M., Sonck, B., 2007. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosyst. Eng. 97, 333–345. https://doi.org/10.1016/j.biosystemseng.2007.03.001.

Ozkan, H.E. (Ohio S.U.), Ackerman, K.D., 1992. An automated computerized spray pattern analysis system. Appl. Eng. Agric. USA.

Reichard, D.L., 1988. Drop Formation and Impaction on the Plant. Weed Technol. 2, 82–87. https://doi.org/10.1017/S0890037X00030153.

USDA-NASS, 2015. 2015 Survey: National Level Data [WWW Document]. URL https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/ (accessed 4.18.17).

Zhu, H., Dorner, J.W., Rowland, D.L., Derksen, R.C., Ozkan, H.E., 2004. Spray Penetration into Peanut Canopies with Hydraulic Nozzle Tips. Biosyst. Eng. 87, 275–283. https://doi.org/10.1016/j.biosystemseng.2003.11.012.

Zwertvaegher, I.K., Verhaeghe, M., Brusselman, E., Verboven, P., Lebeau, F., Massinon, M., Nicolaï, B.M., Nuyttens, D., 2014. The impact and retention of spray droplets on a horizontal hydrophobic surface. Biosyst. Eng. 126, 82–91. https://doi.org/10.1016/j.biosystemseng.2014.07.013.

CHAPTER 2

Influence of nozzle spacing, boom height and nozzle type on the efficacy of dicamba, saflufenacil, glyphosate and glufosinate.

Abstract

One of the largest challenges in agriculture is weed management. Effective weed management is highly correlated with the product and the application method. The objective of this research was to find which combinations of nozzle spacing, boom height, and nozzle type are most efficacious with dicamba, saflufenacil, glyphosate and glufosinate when applied on common lambsquarters (*Chenopodium album L.*), velvetleaf (*Abutilon theophrasti Medik.*), Palmer amaranth (*Amaranthus palmeri S. Wats.*). The study was conducted under greenhouse conditions and treatments were applied to plants were 10 to 15 cm in height. Nozzle spacings of 38, 50, and 76 cm were used in a 1.67 x 4.2 m spray chamber with a single-track three nozzle boom. Herbicides were applied at 276 kPa, and the application rates were 94 L ha^{-1} (glyphosate, saflufenacil, and dicamba) or 140 L ha^{-1} (glufosinate). Herbicides were applied at rates of 140 g ae ha^{-1} dicamba, 37 g ai ha^{-1} saflufenacil, 473 g ae ha^{-1} glyphosate and 286 g ai ha^{-1} glufosinate. Applications were made using four TeeJet nozzles: XR11004, AIXR11004, TT11004 and TTI11004 and the boom heights tested were 31, 46, and 61 cm. The experimental design was a completely randomized factorial design (four nozzle types x three boom heights x three nozzles spacing x four herbicides x four weed species). Data were subjected to ANOVA and means were separated using Fisher's Protected LSD test. Results showed significant main effects interactions between nozzle type, nozzle spacing, and boom height for each

herbicide solution within each weed species. These data suggest the need to adjust our application techniques for different situations in order to promote greater weed control efficacy. Narrower nozzle spacings were more effective compared to wider nozzle spacings, carried truth across herbicides and weed species used. XR nozzle type were the least affected by boom height or nozzle spacings among nozzle types used. Application parameters analyzed in this study proved the necessity of better understanding of their effects in order for an optimal weed control.

Introduction

Weed management is currently one of the biggest challenges in agriculture and a key factor for crop productivity. Several factors can influence successful weed management including spray boom height (Jong et al. 2000), nozzle type and pressure (Creech et al. 2015), nozzle spacing (Murphy et al. 2000) and spray distribution (Debouche et al. 2000). In addition, weather conditions such as wind speed, temperature, crop temperature and humidity can significantly impact the success of a pesticide application (Craig et al. 1998). Applications made outside the recommended arrangement of parameters can lead to particle drift, uneven distribution patterns (Miller and Butler Ellis 2000), or even lacks in coverage and deposition (Taylor et al. 2004), all of which may lead to possible decreases in weed control. Sub-lethal doses may lead to resistance (Busi and Powles 2009) and reduced efficacy (Johnson et al. 2006).

Nozzle spacing and boom height can influence particle drift and coverage and are typically optimized to delivering proper amount of chemical uniformly from the boom to the target to provide good coverage and weed control (Forney et al. 2017) while mitigating particle drift. Coefficient of variation (CV) is a quantification of spray pattern uniformity (equation 1) (Ozkan, H.E., & Ackerman, K. D. 1992) providing a measure how even the distribution is coming out of a nozzle. Higher CV indicates poor distribution and lower CV indicates good distribution. Higher boom heights also have the potential for the wind speeds at the nozzle exit to be greater than if the nozzle were positioned at a lower boom height, potentially resulting in increased particle drift (M. E. Teske and H. W. Thistle 1999). In aerial applications, boom height and wind speed are two of the most critical factors, in addition to droplet size, impacting drift and deposition (Bird et al. 1996, M. E. Teske and J. W. Barry 1993).

$$\text{CV}\ (\%) = (100\%) - (\sqrt{}\Sigma(x_i - \bar{x})^2 / n - 1) / (\Sigma x_i / n) \qquad [1]$$

Where:
x_i = flow rate of the i^{th} sample across spray pattern in mL min^{-1}
$\bar{x}$ = mean flow rate in mL min^{-1}
n = number of collection tubes.

The CV decreases as the boom height increases (A. H. Azimi et al. 1985) preventing proper overlap resulting in an adequate an variable coverage (Forney et al. 2017). Similar to boom height, nozzle spacing can affect CV. Nozzle spacing is the distance between the nozzles positioned across the boom section. Typically, recommendations for nozzle spacing can be obtained from the manufacturers. As an example, for a TeeJet 80˚ flat fan nozzle the recommended nozzle spacing is 50 cm for a 75 cm boom height, while for 110˚ flat fan nozzle the recommended nozzle spacing is 50 cm for the same boom height (TeeJet Technologies, 2014). Correct nozzle spacing guarantees an appropriate overlap of the spray sheets. Typically as nozzles are positioned closer together, the CV decreases (A. H. Azimi et al. 1985). With reduced nozzle spacing, the number of nozzles needed will increase potentially resulting in an over application of product that can cause phytotoxic problems. The effects of nozzle spacing on spray uniformity with nozzle spacings outside of recommended values are not widely reported (Forney et al. 2017).

Another factor influencing distribution and particle drift is nozzle type. Each nozzle type provides a different spatial distribution pattern and droplet size potentially requiring different boom heights and nozzle spacing to achieve optimal coverage. Air incorporation in the solution happens in different manners and for tested nozzles in this study two scenarios were used, first with two air inlets (AIXR) one by each side of the nozzle. While only one air inlet and two internal air inlets (TTI) in the second nozzle, coupled with a mixing chamber before exiting the nozzle with a 15° angle from vertical position (Matthews. et al. 2014; TeeJet Technologies, 2014).

When particle drift from conventional boom sprayers is a concern, changes in nozzle type offer the easiest and most effective method for altering droplet size to reduce drift potential (Zhu et al. 2004; Henry et al. 2015). Generally, nozzles are characterized Venturi or non-Venturi. Venturi nozzles are constructed with a pre-orifice, an air-mixing chamber, and an exit orifice, which is responsible for creating the pattern. Typically, Venturi nozzles generate larger droplets at the same application pressure when compared to non-Venturi nozzles (Etheridge et al. 1999). The optimal nozzle type required depends on the herbicide type and the weed species targeted (Meyer et al. 2016)

Common lambsquarters is among the weeds more problematic to obtain control in crops. Summer annual weed species with fast emergence in the beginning of the growing season, other characteristics which contributes for common lambsquarters to be problematic is the capacity of germination in shallow depths combined with poor activity from some herbicides used post emergence (Westhoven et al. 2008). In the world, common lambsquarters is classified as the forth weed species most important with herbicide resistance (Heap 2007). Common lambsquarters given aforementioned characteristics competes with row crops such as corn and soybeans.

Velvetleaf competes highly with crops and became a major problem in weed management in row crops that are grown in United States. Seed production is very high with large number of seeds per plant produced with the capacity of longevity staying viable in the soil (Paszkowski and Kremer 1988). Leaf composition of velvetleaf is highly pubescent, with the plant shooting its leaves trying to capture the most of sun light and compete the most with the crops.

Palmer amaranth constitutes of an erect, branched herbaceous summer annual weed species with a terminal spike inflorescence containing male and female flower on two different plants (dioecious) (Klingaman and Oliver 1994). The competitiveness of this weed species is mainly due to prolific seed production allowing greatness in seed spreading. Palmer amaranth competes for light, water and nutrients mainly due to its rapid growth and allopathic potential. Leaf structure composes of alternate leaves, plain for greater competition potential. According to Heap (2007) Palmer amaranth has 60 herbicide resistant cases reported across the world, proving to be prone to those cases with many modes of actions.

The objective of this study was to determine which combinations of nozzle spacing, boom height and nozzle type were most efficacious with dicamba, saflufenacil, glyphosate and glufosinate when applied to common lambsquarters (*Chenopodium album L.*), velvetleaf (*Abutilon theophrasti Medik.*), and Palmer amaranth (*Amaranthus palmeri S.*).

Material & Methods

A greenhouse study was conducted at the University of Nebraska – Lincoln Pesticide Application Technology Laboratory (PAT Lab) in North Platte, NE USA on the following weed species: common lambsquarters, velvetleaf, and Palmer amaranth. These species were selected based on their diversity in leaf surface type (waxy, hairy and neutral), family and other physiological characteristics.

Application. Carrier volume for this study was 94 L ha^{-1}. Clarity® (dicamba) at 140 g ae ha^{-1}, Sharpen® (saflufenacil) at 37 g ai ha^{-1}, and Roundup PowerMax® (glyphosate) at 473 g ae ha^{-1} were applied. Liberty® (glufosinate) was applied at 286 g ai ha^{-1} in 140 L ha^{-1} based in label record. Ammonium sulfate was added to glyphosate and glufosinate at 5% v v^{-1} rate and methylated seed oil was added to saflufenacil at 1% v v^{-1}. Applications were made using a 1.67 x 4.2 m single-track three nozzle boom spray chamber (DeVries Manufacturing, Hollandale, MN 56045). Nozzle spacings were 38, 50 or 76 cm and boom height was 31, 46 or 61 cm from the target. Four nozzles were used in this study; air induction extended range flat spray tips (AIXR), turbo TeeJet wide angle flat fan spray tips (TT), Turbo TeeJet Induction flat fan spray tips (TTI), Extended Range flat spray tips (XR) (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139 USA). Nozzles were 110˚ flat fans with 04-orifice size.

Applications were made with a spray pressure of 276 kPa. To ensure that the same volume was applied for all treatments, different speeds were used for each nozzle spacing (Table 2.1.). Plants were treated when they were 10 to 15 cm tall. After treatment, plants were placed back in the greenhouse to complete their life cycles. Visual estimations of injury were collected at 28 days after application (DAA) with ratings ranging from 0 (no injury) to 100 (plant death). Immediately after rating, plants were harvested at the soil surface, placed in a dryer at 60 C until they reached a constant mass and the dry weights were recorded. The full study was repeated twice with each run having four replications.

Droplet size. Droplet spectrum for each treatment combination was evaluated using a low-speed wind tunnel. The droplet spectrum for each treatment was analyzed using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) controlled by WINDOX 5.7.0.0 software (Sympatec Inc., Clausthal, Germany). This lens was capable of detecting droplets in a range from 18 to 3500 μm. The spray plume was oriented perpendicular to the air flow. An actuator traversed the nozzle at a constant speed of 0.2 m s^{-1} such that the entire spray plume passed through the laser beam. The exit orifice of the nozzles were 30 cm from the laser beam and a concurrent airflow velocity of 6.7 m s^{-1} was maintained, as described by (Creech et al. 2016). A minimum of three replications were made and $Dv_{0.1}$, $Dv_{0.5}$, and $Dv_{0.9}$ values were recorded. These are the droplet diameters (μm) at which 10, 50 and 90% of the total spray volume is comprised of droplets of smaller or equal diameters respectively. Percentage fines (expressed as the percentage of the total spray volume comprised of droplets with a diameter less than a 150 μm) and relative span (RS) were also recorded. RS is a non-dimensional parameter, which indicates the variation in the size distribution:

$$RS = (Dv_{0.9} - Dv_{0.1}) / Dv_{0.5} \qquad [2]$$

A RS value that approaches zero is preferable, representing a more homogeneous droplet spectrum.

Statistical analysis. The experimental design was structured as a completely randomized factorial design (four weed species X four herbicides X four nozzle types X three boom height X three nozzle spacing). Dry weights were subjected to ANOVA and means were separated using Fisher's Protected LSD test at α=0.05 using SAS version 9.4 (SAS Institute Inc., Cary, NC). Dry biomass was compared using a generalized linear mixed model analysis of variance (GLIMMIX) (Littell et al. 2006). A Gamma distribution was used for glufosinate on velvetleaf in order to satisfy ANOVA assumptions (Butts, T. R. 2017, Stroup, W.W. 2013). Back transformation data are presented.

Results and Discussion

Analysis of response variables across both weed species and herbicides did not reveal any clear patterns; as such the results and discussion are discussed within each weed species and herbicide solution based on significance at $\alpha = 0.05$ level.

Common Lambsquarters. Nozzle spacing was significant within dicamba and glufosinate ($p = 0.0035$ and <0.0001 respectively) applications. With dicamba (Figure 2.1.), 38 cm nozzle spacing provided greater control than 76 cm nozzle spacing while with glufosinate (Figure 2.4.) 38 and 50 cm nozzle spacing provided greater weed control than 76 cm nozzle spacing. These results support pervious findings demonstrating that narrower nozzle spacings decrease CV (improve deposition uniformity) and improve overall weed control compared to larger nozzle spacing intervals (A. H. Azimi et al. 1985).

Boom height was a significant factor (p = 0.0158) for glyphosate applications (Figure 2.3.) with the higher boom height of 61 cm resulting in greater weed control than the 31 cm boom height. When boom heights are not optimized for the specific nozzle type and nozzle spacing used, a loss in pattern uniformity and efficacy can occur. Forney et al. (2017) found that narrower flat fan nozzles and higher boom heights contributed for a greater CV.

The nozzle spacing*nozzle type interaction was significant (p = 0.0120) when spraying saflufenacil (Figure 2.2.) There were no differences in control between the TTI and XR nozzle types, regardless of nozzle spacing. However, with the TT and AIXR nozzles, 50 and 76 cm nozzle spacing provided a greater control than 38 cm nozzle spacing. This suggests that deflector type nozzles that integrate air inclusion technology (Ferguson et al. 2015; Matthews. et al. 2014) (TTI) remove the influence of nozzle spacing on weed control.

Velvetleaf. Nozzle spacing was significant for dicamba on velvetleaf (p = 0.0008) (Figure 2.5.) with the narrower nozzle spacings of 38 and 50 cm providing better control than 76 cm nozzle spacing, which again supports previous findings where narrow nozzle spacing with a lower CV providing for better weed control efficacy (A. H. Azimi et al. 1985).

The nozzle spacing*nozzle type interaction was significant for both glyphosate and glufosinate (p = 0.0363 and 0.0157, respectively). With velvetleaf (Figure 2.6.), similar to the common lambsquarters results, there was no difference in control between the TTI and XR nozzles using glyphosate. However, with the AIXR nozzle the 38 cm nozzle spacing had greater weed control compared with the largest nozzle spacing of 76 cm. With the TT nozzle, a 50 cm nozzle spacing provided greater control compared to 76 cm nozzle spacing, which provided the least among nozzle spacings.

The boom height*nozzle type interaction was significant when spraying glufosinate (p = 0.0235) (Figure 2.7.). While the AIXR and XR nozzles showed equal control across boom heights, the TT nozzle had the best control at 31 cm nozzle spacing while the TTI nozzle had better control at 31 and 46 cm nozzle spacing. The Extended Range nozzle technology (AIXR and XR nozzles) resulted in no differences in control regardless of the boom height while the Turbo TeeJet nozzle technology (TT and TTI) had greater control at lower boom heights. Mainly, the differences between nozzle technologies was droplet size, which is due to the construction on those nozzles. Air induction nozzles (AIXR and TTI) showed greater flexibility with tested parameters versus non-air inclusion nozzles (XR and TT) in result of air inlets incorporating air to the solution and making droplets with more volume, explaining the preference to lower boom heights.

Glufosinate had a significant nozzle spacing*nozzle type (p = 0.0157) interaction (Figure 2.8.). The XR nozzle had the same control at all nozzle spacings. The TTI nozzle had better control at the narrower nozzle spacings. The AIXR and TT nozzles had the greatest control at 38 and 50 cm nozzle spacings.

Palmer amaranth. Only nozzle spacing resulted in a significant effect (p-value = 0.0193) (Figure 2.9.). The 38 and 50 cm nozzle spacing had the greater control than, once again demonstrating that narrower nozzle spacings typically resulted in the greater control.

Droplet size. Droplet size data had the same trend along all measurements where two groups were created by nozzle technology. Venturi nozzles had higher $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ values and less fines (<150 μm) compared to conventional flat fan nozzles (XR and TTI) (Table 2.3.). RS showed similar trends of values on two-group separation by nozzle technology. The AIXR nozzle was more prone to changes in herbicide solution, especially in the case of glyphosate and glufosinate (Table 2.3.). Creech et al. (2015) found similar results where the TT, AIXR and TTI nozzles ranged from Coarse to Ultra Coarse sprays (Table 2.3.)

Nozzle spacing had a similar effect across herbicide used and weed species targeted. Narrower nozzle spacings proved to be more effective than the wider nozzle spacing due to the findings of A. H. Azimi et al. (1985) where it was concluded that narrower nozzle spacings produced a more stable distribution. These results also showed that nozzle selection and droplet size is an important factor on weed control supported by the findings of Creech et al. (2015) where it was reported that XR, TT, AIXR, AI and TTI had droplet sizes in this order from smallest to largest. The XR nozzles were not affected by nozzle spacing or boom height and the authors hypothesize that the smaller droplet size observed (Fine Spray – Table 2.3.) allowed for more uniform dispersion of the spray and a greater number of overall droplets, which likely provided greater and more uniform coverage. The coarser spray qualities mean larger and fewer droplets which contribute to greater potential for efficacy to be affected by nozzle spacing, particularly on some weed species, though no clear trends were observed. When setting up a spray boom, herbicide type, weed species, nozzle type, nozzle spacing and boom height must all be considered to optimize weed control.

Literature Cited

Azimi, A. H., Carpenter, T. G., & Reichard, D. L. (1985). Nozzle Spray Distribution for Pesticide Application. *Transactions of the ASAE*, *28*(5), 1410–1414. https://doi.org/10.13031/2013.32451.

Bird, S. L., Esterly, D. M., & Perry, S. G. (1996). Off-Target Deposition of Pesticides from Agricultural Aerial Spray Applications. *Journal of Environmental Quality*, *25*(5), 1095–1104. https://doi.org/10.2134/jeq1996.00472425002500050024x.

Busi, R., & Powles, S. B. (2009). Evolution of glyphosate resistance in a *Lolium rigidum* population by glyphosate selection at sublethal doses. *Heredity*, *103*(4), 318–325. https://doi.org/10.1038/hdy.2009.64.

Butts, T. R., Moraes, J. G., & Kruger, G. R., Impact of plugged venturi-nozzle air inclusion ports on droplet size distribution, Pesticide Formulation and Delivery Systems: Innovative Application, Formuluation, and Adjuvant Technologies **38**, ed. by Fritz BK and Butts TR, ASTM International, West Conshohocken, PA (2017).

Craig, I., Woods, N., & Dorr, G. (1998). A simple guide to predicting aircraft spray drift. *Crop Protection*, *17*(6), 475–482. https://doi.org/10.1016/S0261-2194(98)00006-4.

Creech, C. F., Henry, R. S., Fritz, B. K., & Kruger, G. R. (2015). Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. *Weed Technology*, *29*(2), 298–310. https://doi.org/10.1614/WT-D-14-00049.1.

Creech, C. F., Moraes, J. G., Henry, R. S., Luck, J. D., & Kruger, G. R. (2016). The Impact of Spray Droplet Size on the Efficacy of 2,4-D, Atrazine, Chlorimuron-Methyl, Dicamba, Glufosinate, and Saflufenacil. *Weed Technology*, *30*(2), 573–586. https://doi.org/10.1614/WT-D-15-00034.1.

Debouche, C., Huyghebaert, B., & Mostade, O. (2000). Simulated and Measured Coefficients of Variation for the Spray Distribution under a Static Spray Boom. *Journal of Agricultural Engineering Research*, *76*(4), 381–388. https://doi.org/10.1006/jaer.2000.0552.

Etheridge, R. E., Womac, A. R., & Mueller, T. C. (1999). Characterization of the Spray Droplet Spectra and Patterns of Four Venturi-Type Drift Reduction Nozzles. *Weed Technology*, *13*(4), 765–770. https://doi.org/10.1017/S0890037X00042202.

Ferguson, J. C., O'Donnell, C. C., Chauhan, B. S., Adkins, S. W., Kruger, G. R., Wang, R., & Hewitt, A. J. (2015). Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. *Crop Protection*, *76*, 1–6. https://doi.org/10.1016/j.cropro.2015.06.008.

Forney, S. H., Luck, J. D., Kocher, M. F., & Pitla, S. K. (2017). Laboratory and Full Boom-Based Investigation of Nozzle Setup Error Effects on Flow, Pressure, and Spray Pattern Distribution. *Applied Engineering in Agriculture*, *33*(5), 641–653. https://doi.org/10.13031/aea.12043.

Heap I. M. 2007. International Survey of Herbicide Resistant Weeds. www.weedscience.com. Accessed May 2018.

Henry R. S., Fritz B. K., Hoffmann W. C., & Kruger G. R. (2015) An Evaluation of Three Drift Reduction Adjuvants for Aerial Application of Pesticides. GSTF J Agric Eng JAE 1:1–10.

Johnson, A. K., Roeth, F. W., Martin, A. R., & Klein, R. N. (2006). Glyphosate Spray Drift Management with Drift-Reducing Nozzles and Adjuvants. *Weed Technology*, *20*(4), 893–897. https://doi.org/10.1614/WT-05-162.1.

Jong, A. de, Michielsen, J. M. G. P., Stallinga, H., & Zande, J. C. van de. (2000). Effect of sprayer boom height on spray drift. *Mededelingen - Faculteit Landbouwkundige En Toegepaste Biologische Wetenschappen, Universiteit Gent*, *65*(2b), 919–930.

Klingaman, T. E., & Oliver, L. R. (1994). Palmer Amaranth (Amaranthus palmeri) Interference in Soybeans (Glycine max). *Weed Science*, *42*(4), 523–527.

Littell R. C., Milliken G. A., Stroup W. W., Wolfinger R. D., & Schabenberger O. (2006) SAS for mixed models. 2nd edn. Cary, NC: SAS institute., Inc.

Matthews, G., Bateman, R., & Miller, P., 2014. Pesticide Application Methods, 4th Edition, 4th ed. Wiley-Blackwell.

Meyer, C. J., Norsworthy, J. K., Kruger, G. R., & Barber, T. (2016). Effects of Nozzle Selection and Ground Speed on Efficacy of Liberty and Engenia Applications and Their Implication on Commercial Field Applications. *Weed Technology*, *30*(2), 401–414. https://doi.org/10.1614/WT-D-15-00145.1.

Miller, P. C. H., & Butler Ellis, M. C. (2000). Effects of formulation on spray nozzle performance for applications from ground-based boom sprayers. *Crop Protection*, *19*(8), 609–615. https://doi.org/10.1016/S0261-2194(00)00080-6.

Murphy, S. D., Miller, P. C. H., & Parkin, C. S. (2000). The Effect of Boom Section and Nozzle Configuration on the Risk of Spray Drift. *Journal of Agricultural Engineering Research*, *75*(2), 127–137. https://doi.org/10.1006/jaer.1999.0491.

Ozkan, H. E. (Ohio S. U., Ackerman, K. D. (1992). An automated computerized spray pattern analysis system. *Applied Engineering in Agriculture (USA)*. Retrieved from http://agris.fao.org/agris-search/search.do?recordID=US9327805.

Paszkowski, W. L., & Kremer, R. J. (1988). Biological activity and tentative identification of flavonoid components in velvetleaf (*Abutilon theophrasti Medik.*) seed coats. *Journal of Chemical Ecology*, *14*(7), 1573–1582. https://doi.org/10.1007/BF01012523

Stroup WW, Generalized Linear Mixed Models: Modern Concepts, Methods and Applications, CRC Press, Taylor & Francis Group (2013).

Taylor W. A., Womac A. R., Miller P. C. H., & Taylor B. P. (2004) An attempt to relate drop size to drift risk. Pages 210–223 in Proceedings of the International Conference on Pesticide Application for Drift Management. Pullman, WA: Washington State University.

TeeJet Technologies. 2014. Broadcast nozzles selection guide. Wheaton, IL. Retrieved from http:/www.teejet.com/spray_application/nozzles.shtml8-13.

Teske, M. E., & Thistle, H. W. (1999). POULTRY A SIMULATION OF RELEASE HEIGHT AND WIND SPEED EFFECTS FOR DRIFT MINIMIZATION. *Transactions of the ASAE*, *42*(3), 583–591. https://doi.org/10.13031/2013.13218.

Teske, M. E., & Barry, J. W. (1993). Parametric Sensitivity in Aerial Application. *Transactions of the ASAE*, *36*(1), 27–33. https://doi.org/10.13031/2013.28310.

Westhoven, A. M., Kruger, G. R., Gerber, C. K., Stachler, J. M., Loux, M. M., & Johnson, W. G. (2008). Characterization of Selected Common Lambsquarters (Chenopodium album) Biotypes with Tolerance to Glyphosate. *Weed Science*, *56*(5), 685–691. https://doi.org/10.1614/WS-08-018.1.

Zhu, H., Dorner, J. W., Rowland, D. L., Derksen, R. C., & Ozkan, H. E. (2004). Spray Penetration into Peanut Canopies with Hydraulic Nozzle Tips. *Biosystems Engineering*, *87*(3), 275–283. https://doi.org/10.1016/j.biosystemseng.2003.11.012.

Table 2.1. – Application speed used based on nozzle spacing and application volume to maintain constant application volume.

Application volume	Nozzle spacing	Application speed
(L ha^{-1})	(cm)	(km hr^{-1})
94	38	25
	50	19
	76	12
140	38	17
	50	13
	76	8

Table 2.2. - Droplet size distribution values generated from reference nozzles described in ASAE S572.1.

Nozzle	$Dv_{0.1}$[a]	$Dv_{0.5}$	$Dv_{0.9}$	RS	<150µm	Boundary
	———	µm	———		%	
11001	64	142	248	1.29	54.17	Very Fine/Fine
11003	112	251	410	1.19	18.84	Fine/Medium
11006	160	350	562	1.15	8.51	Medium/Coarse
8008	189	426	706	1.21	5.87	Coarse/Very Coarse
6510	228	511	836	1.19	3.78	Very Coarse/Extremely Coarse
6515	310	655	1012	1.07	1.54	Extremely Coarse/ Ultra Coarse

[a] Abbreviations: $D_{v0.5}$, $D_{v0.5}$, and $D_{v0.9}$: Parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or lesser values, respectively; RS: Relative span = $(D_{v0.9} - D_{v0.1})/ D_{v0.5}$.

Table 2.3. – Droplet size distribution data from four nozzle types with dicamba, saflufenacil, glyphosate and glufosinate.

Solution	Nozzle	$Dv_{0.1}$[a]	$Dv_{0.5}$	$Dv_{0.9}$	RS	<150μm	Spray classification[b]
		———	μm	———		— % —	
Clarity	XR	102 d	231 d	393 c	1.26 b	23.03 a	Fine
	TT	164 c	394 c	714 b	1.40 a	7.97 b	Coarse
	AIXR	234 b	472 b	719 b	1.03 c	3.13 c	Very Coarse
	TTI	409 a	811 a	1197 a	0.97 d	0.39 d	Ultra Coarse
Saflufenacil	XR	125 d	251 d	411 d	1.14 b	16.32 a	Medium
	TT	157 c	327 c	553 c	1.21 a	8.74 b	Medium
	AIXR	257 b	481 b	700 b	0.92 d	1.77 c	Very Coarse
	TTI	347 a	661 a	990 a	0.97 c	0.59 d	Ultra Coarse
Glyphosate	XR	94 d	215 d	385 c	1.35 b	27.42 a	Fine
	TT	159 c	377 c	696 b	1.42 a	8.58 b	Coarse
	AIXR	200 b	429 b	693 b	1.15 c	4.67 c	Very Coarse
	TTI	383 a	774 a	1171 a	1.02 d	0.44 d	Ultra Coarse
Glufosinate	XR	86 d	203 d	362 d	1.36 b	30.92 a	Fine
	TT	149 c	367 c	700 b	1.50 a	10.09 b	Coarse
	AIXR	180 b	402 b	656 c	1.19 c	6.53 c	Coarse
	TTI	364 a	757 a	1159 a	1.05 d	0.63 d	Ultra Coarse

Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

[a] Abbreviations: $D_{v0.5}$, $D_{v0.5}$, and $D_{v0.9}$: Parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or lesser values, respectively; RS: Relative span = $(D_{v0.9} - D_{v0.1})/ D_{v0.5}$.

[b] Spray classification of $D_{v0.5}$ based on ASAE S572.1 standards from reference curves created in table 2.2.

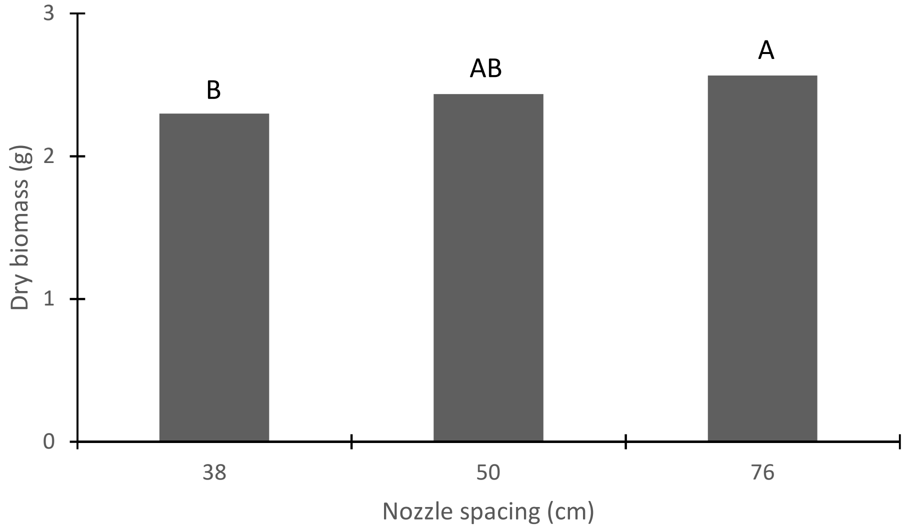

Figure 2.1. – Dry biomass for three nozzle spacings when dicamba was applied to common lambsquarters.

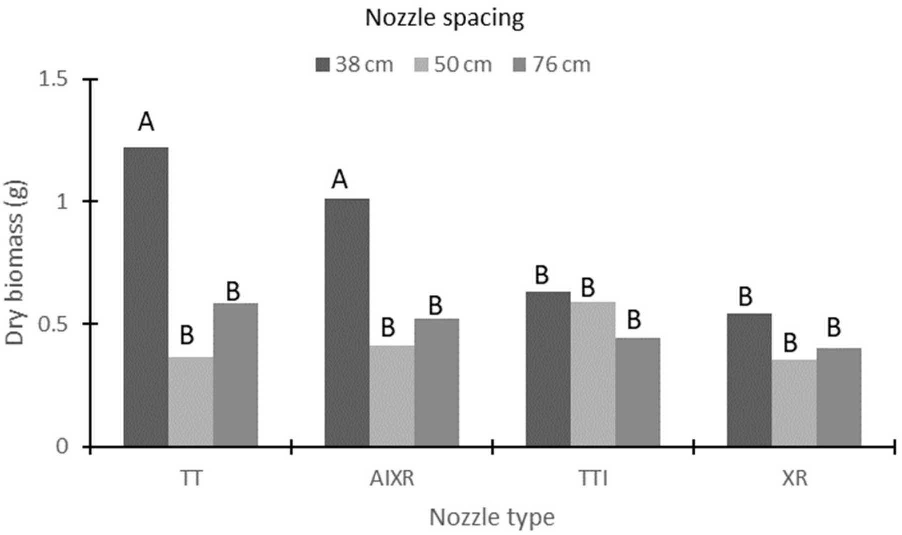

Figure 2.2. - Dry biomass for three nozzle spacings by nozzle type when saflufenacil was applied to common lambsquarters.

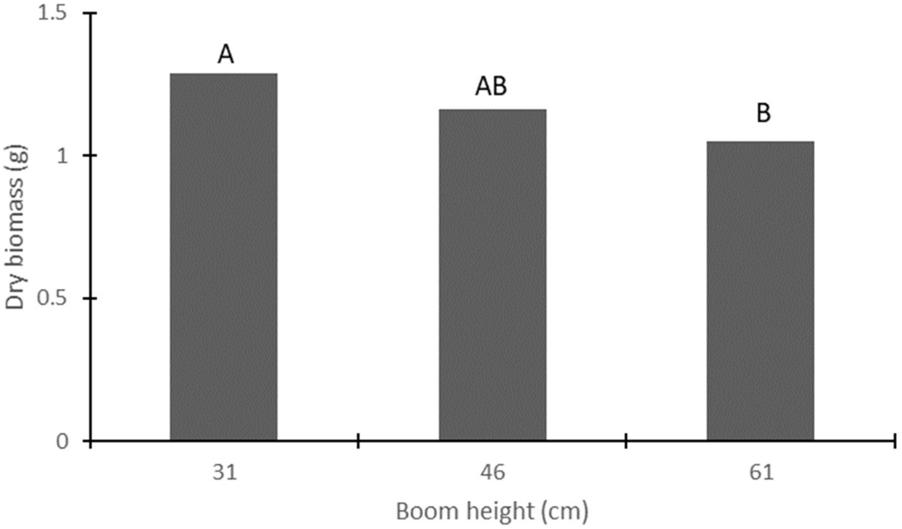

Figure 2.3. - Dry biomass for three boom heights above the target when glyphosate was applied to common lambsquarters.

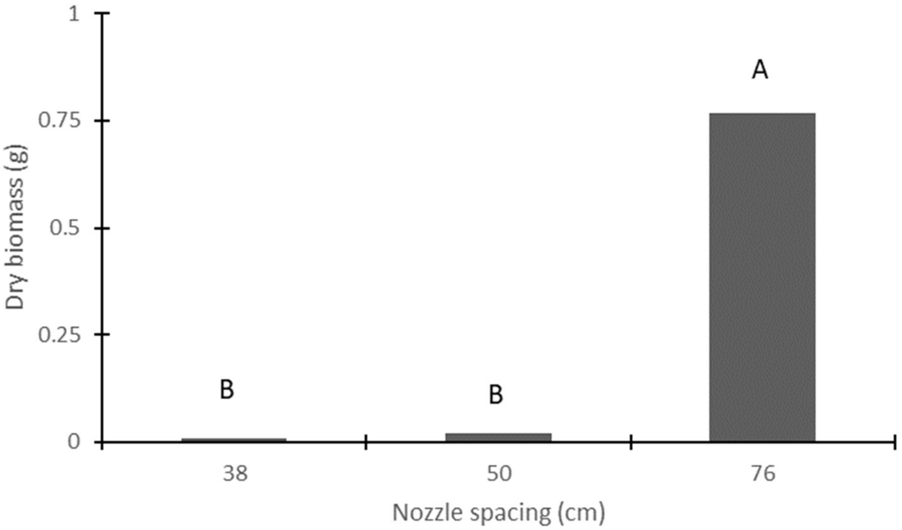

Figure 2.4. - Dry biomass for three nozzle spacings when glufosinate was applied to common lambsquarters.

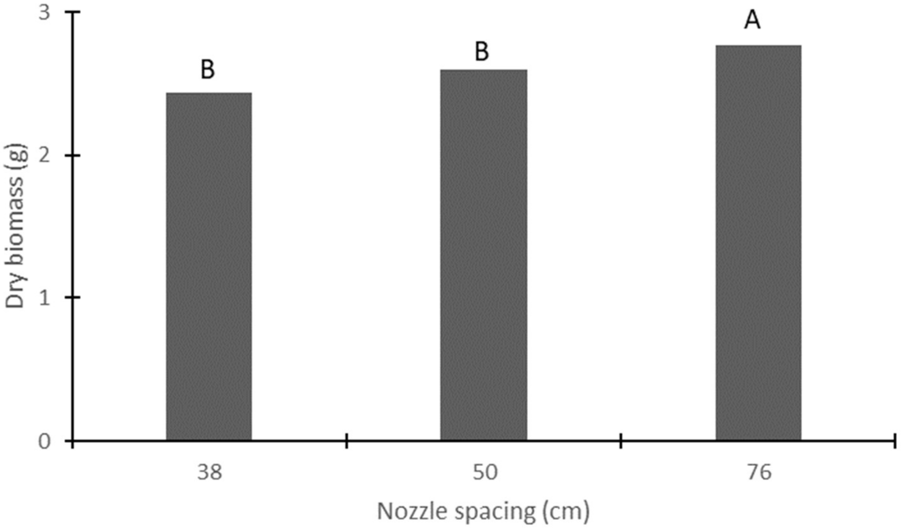

Figure 2.5. - Dry biomass for three nozzle spacings when dicamba was applied to velvetleaf.

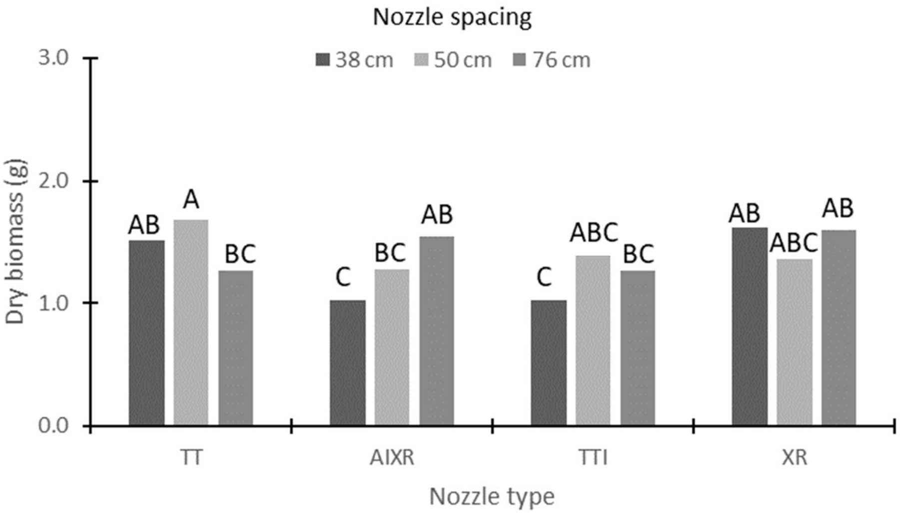

Figure 2.6. - Dry biomass for three nozzle spacings by nozzle type when glyphosate was applied to velvetleaf.

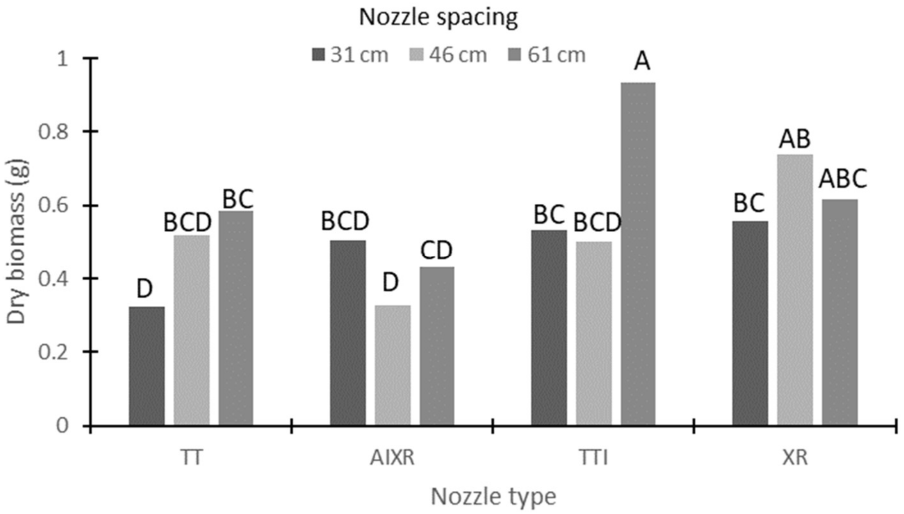

Figure 2.7. - Grams of dry biomass for three boom heights by nozzle type when glufosinate was applied to velvetleaf.

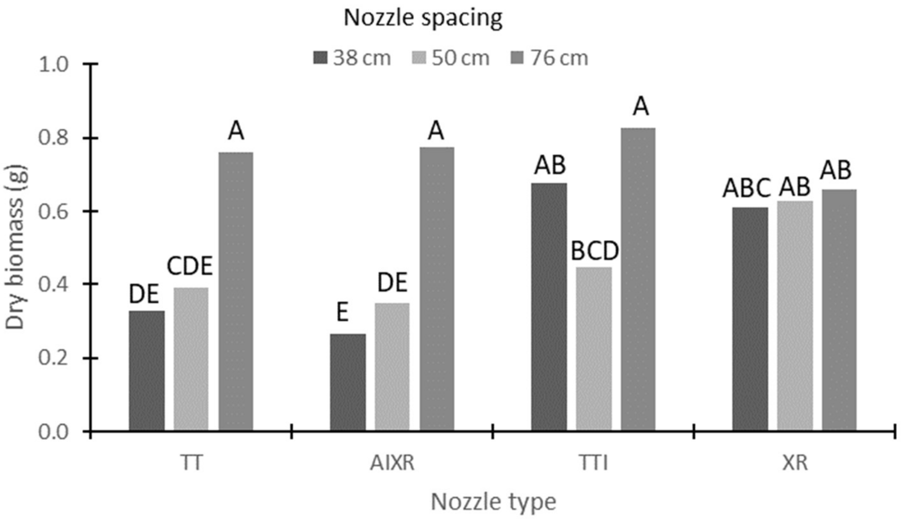

Figure 2.8. - Grams of dry biomass for three nozzle spacings by nozzle type when glufosinate was applied to velvetleaf.

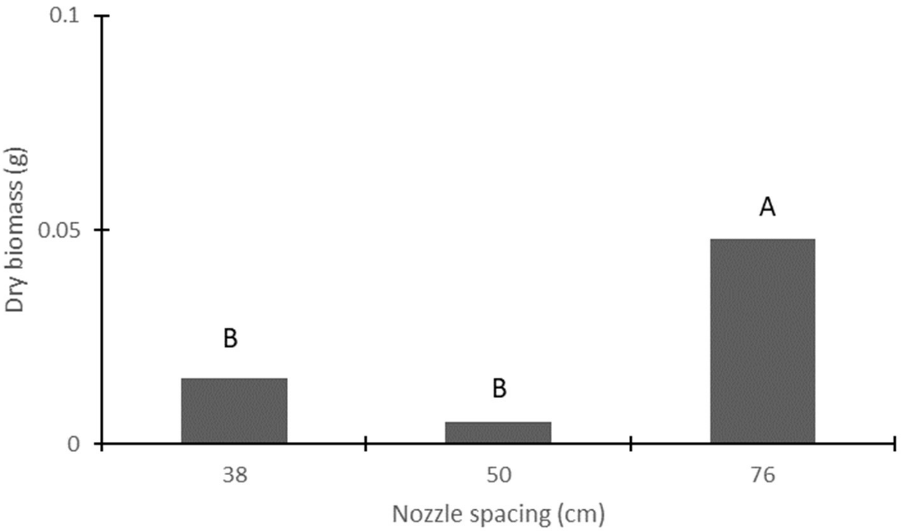

Figure 2.9. - Grams of dry biomass for three nozzle spacings when glufosinate was applied to Palmer amaranth.

CHAPTER 3

Rainfastness of Clarity, XtendiMax, Roundup Xtend, and Roundup PowerMax

Abstract

Herbicide performance is affected by environmental conditions, which can influence the physiology and growth of a plant prior to and after a given application. Among environmental factors, rainfall shortly after herbicide application is one of the most detrimental events that can reduce the performance of postemergence herbicides. A greenhouse study examining rainfastness of various pesticide formulations was conducted at the University of Nebraska-Lincoln at the West Central Research and Extension Center in North Platte, NE on the following weed species: velvetleaf, *Abutilon theophrasti Medik*, glyphosate-susceptible Palmer amaranth, *Amaranthus palmeri S. Wats*. Four herbicides were evaluated as part of the study: Clarity, XtendiMax, Roundup Xtend, and Roundup PowerMax. XtendiMax and Clarity were tested alone and in tank-mixture with Roundup PowerMax, with the exception of Roundup Xtend. Rain simulations were conducted at intervals of 0.5, 1, 2, 4, 8 hours after application in a spray chamber at the Pesticide Application Technology Laboratory. A no-rain treatment was included as a control. Herbicide treatments were made when weed species were 10 to 15 cm tall using a carrier volume of 94 L ha^{-1} at 24 km hr^{-1} with an application pressure of 434 kPa using a TTI11004 nozzle. After herbicide application rain simulations were conducted using a single-track laboratory research sprayer. The rainfastness had different responses based on weed species, once leaf characteristics influence absorption and thus herbicide efficacy. Rainfastness for Palmer amaranth had little to no effect on herbicide performance with just four herbicide reduction cases with both dicamba formulations,

meanwhile for velvetleaf, a more pubescent leaf, herbicide reduction was observed in several cases but most important was to observe that even with hours greater than stated in herbicide label, rainfastness was happening in most of the cases.

Introduction

Herbicide performance can be affected by environmental conditions which can influence the physiology and growth of a plant. Among potential environmental factors affecting efficacy, rainfall shortly after an application can cause significant reductions in the performance of the herbicide once rain due to dilution, redistribution or physical removal from the target (Thacker and Young 1999). Efficient herbicide applications depend on the success of several stages of the application process, including deposition, retention, uptake and translocation of the applied product (Zwertvaegher et al. 2014). Unsatisfactory efficacy may result in economic losses, environmental contamination and food safety issues.

Rainfastness period for a herbicide is the time period after an application in which a rain event can compromise herbicide efficacy and performance (James et al. 2008). Rainfastness of a herbicide is related to the susceptibility of the deposit to be dissolved at the target reducing uptake rate (McCann 1983). A post-application rainfall results in a wash-off effect where all, or part of, the deposited herbicide is washed off the plant without being absorbed and activated in the plant. Soil applied herbicides are less influenced by environmental conditions then foliar applied herbicides.

Herbicide composition is also important to rainfastness. Generally, lipophilic herbicides have a rainfastness time of two hours, while water soluble herbicides require a rain free period of more than six hours (Bryson 1987, 1988). Kudsk and Kristensen (1997) showed that esters when affected by rainfall resulted in greater decrease of herbicide efficacy when compared to salts. This is similar result to what is reported for 2,4-D, where the ester formulation had a greater decrease in efficacy versus the salt formulations.

Glyphosate applied to quackgrass (*Elymus repens (L.) Gould)* was shown to be rainfast quicker as relative humidity rises (Caseley 1975), highlighting the need to control environmental conditions during a study as rainfastness results can potentially differ from a controlled ambient environment study compared to a study conducted under uncontrolled, outdoor ambient conditions (Behrens and Elakkad 1981, Kudsk, P. 1989).

During rainfastness studies, factors that influence the interaction between herbicide and its absorption include quantity, intensity and frequency of rain (Cabras et al. 2001, Fife and Nokes 2002), time required for herbicide deposits to dry (Duarte 2008, Schepers 1996), formulation type (Kudsk et al. 1991), application rate (Schilder 2010), adjuvants (Kudsk et al. 1991)*,* and composition of leaf surface sprayed (Debortoli, 2008). However, even with all of these factors, the interval between the application and the rainfall event has the greatest impact, followed closely by the actual volume of rain applied.

Studies have shown that low-volume rain events may increase herbicide efficacy regardless of the wash-off effect (Caseley and Coupland 1980, Skuterud and Caseley 1980), while higher rain volumes can result in decreased herbicidal efficacy (Kudsk and Kristensen 1997). Normally, increasing rain volume will increase wash-off effect, though there is a level of reduction after which no further decrease is expected. Kudsk and

Kristensen (1997) showed that increasing rain volume from 3 to 5 mm had little impact on herbicidal activity, which supported previous works observing that a few mm of rain have marginal impact on wash off and herbicide performance (Anderson and Arnold 1985, Nalewaja and Adamczewski 1988, Nalewaja and Woznica 1985).

Plant architecture and leaf structure also can play an important role in the rainfastness of applied herbicides. Leaf surface varies between weed species influencing spreading and absorption characteristics of the herbicide into the tissue (Sanyal et al. 2006). Hairy leaves require more rainfall to wash-off enough herbicide to reduce herbicidal efficacy compared to waxy leaf surfaces (Behrens and Elakkad 1981). Waxy leaf surfaces reduce the wettability of leaf surface as compared to hairy leaf surfaces (Taylor 2011). Hair on the leaf surfaces can delay the contact between droplets and leaf cuticle making the deposits more prone to wash off (Yu et al. 2009). Rainfastness is further complicated as it is often hard to determine if the differences in efficacy response levels are the result of differences in weed species response or due to the rainfastness differences that result from the leaf surface differences between weed species. Leaf surface structures affect the wetting and penetration pattern of foliar applied herbicides (Hess 1985, Hull et al. 1982, McWhorter 1985, Wanamarta and Penner 1989). These leaf surface characteristics that affect the herbicide application include the cuticle, leaf age and development, leaf angle and position, and number of stomata and trichromes (Hess 1985, Hull et al. 1982, McWhorter 1985, Wanamarta and Penner 1989). Herbicide absorption is facilitated with either cuticular or stomatal infiltration, but while there is not a good understanding of what species are affected in what way, it is clear that different species respond differently (Hess 1985, Wanamarta and Penner 1989).

A waxy leaf surface is an effective barrier to herbicide absorption (Chachalis et al. 2001). Palmer amaranth leaf cuticles have an absence of hairs and a thinner wax layer than many species. With the physical removal of epicuticular wax by chloroform, absorption of glyphosate was increased in coca (*Erythroxylum coca var. coca* (Lam)) when compared to plants with thick waxy cuticles (Ferreira and Reddy 2000). Yu et al. (2009) reported that among four surfaces, droplets had the longest evaporation time on the hydrophobic surface, waxy leaf, hydrophilic surface, and had the shortest evaporation time on the hairy leaf surface respectively.

Spray retention is a key factor of leaf surfaces for uptake and biological activity of pesticides (Grangeot et al. 2006). Retention on a leaf surface is controlled by several factors, such as dynamic surface tension of the solution, properties of the leaf, contact angle of the droplet on the leaf, droplet size, exit velocity, adjuvant type, carrier volume, plant density, and canopy (Taylor 2011). The objective of this study was to investigate the rainfastness of dicamba on several common, difficult-to-control weed species.

Material and Methods

A greenhouse study was conducted at the University of Nebraska-Lincoln at the West Central Research and Extension Center's (UNL-WCREC) Pesticide Application Technology Laboratory (PAT Lab) in North Platte, NE on velvetleaf (*Abutilon theophrasti Medik*) and glyphosate-susceptible Palmer amaranth (*Amaranthus palmeri S.* Wats). These weed species were selected based on their representativeness, availability, leaf surface type, plant structure, and greenhouse growth characteristics. Four herbicides were tested: Clarity was applied at 1,120 g ae ha^{-1}, XtendiMax was applied at 1,117 g ae ha^{-1}, Roundup Xtend was applied at 1,122 g ae ha^{-1} of dicamba and 2,244 g ae ha^{-1} of glyphosate, and Roundup PowerMax was applied at 1,262 g ae ha^{-1} (Table 3.1.). XtendiMax and Clarity were tested alone and in tank-mixtures with Roundup PowerMax while Roundup Xtend was tested alone. Rainfall simulations were conducted at 0.5, 1, 2, 4, and 8 hours after application (HAA), with one treatment having no rainfall. Six mm of rain was produced using a Generation III single-track research spray chamber (DeVries Manufacturing, Hollandale, MN 56045).

Application. Plants were treated using a 1.67 m wide by 4.2 m long a three nozzle track sprayer with nozzles spaced 50 cm apart (Generation 4 Research Track Sprayer, DeVries Manufacturing Hollandale, MN). Plants were positioned 50 cm below the exit orifice of the nozzle. Herbicide treatments were made to 10 to 15 cm tall weed with five replications. An individually potted plant grown on greenhouse potting soil (Pro Mix BX by Premiere Tech, Quebec, Canada) were considered an individual replication. Two independent, identical runs were conducted for this experiment.

Applications were made at a carrier volume of 94 L ha^{-1} using a speed of 24 km hr^{-1}. Turbo TeeJet Induction Flat Spray Tip (TTI) TTI11004 nozzles (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL) were used at an application pressure 434 kPa producing an Ultra Coarse (UC) droplet size (Volume Median Diameter (VMD) > 622 μm based on manufacturer data).

After herbicide treatments were applied, plants were placed out of the laboratory. Following the intervals between application and simulated rainfall, plants were brought back to the laboratory in order to perform rain simulation. Rain simulations were conducted using a single-nozzle research track sprayer (Generation III, DeVries

Manufacturing Hollandale, MN) using a Hi-Flow (HF) HF14015 spray nozzle (Pentair Hypro, New Brighton, MN) operated for six minutes at track speed of 3 km hr^{-1} to obtain 6 mm rainfall. When rainfall applications were complete, plants were moved to the greenhouse for continuation of their life cycle. Visual estimations of injury were collected at 28 days after application (DAA), with the estimations ranging from 0-100 %, where 0% is no control and 100% is complete plant death. At 28 DAA, plants were clipped at the soil surface, dried to a constant mass at 60 C, and dry weights were recorded.

Statistical analysis. Percent biomass reduction of treated plants was calculated using dry weights relative to the average biomass of the untreated control plants as defined by the equation 1:

$$\text{Percent biomass reduction} = (1 - (B / C))*100 \qquad [1]$$

B = Biomass of a single plant after being treated

C = Mean biomass of the untreated control replicates.

Values of biomass reduction were analyzed using a generalized linear mixed model analysis of variance (GLIMMIX) procedure (Littell et al. 2006). Simple effects were evaluated, and means were separated by LSD test ($\alpha = 0.05$) using a mixed effect model in SAS v9.4 (SAS Institute Inc., Cary, NC) as a complete randomized design.

Results and Discussion

Results are presented by herbicide solution within each weed species if the response variable was significant at $\alpha = 0.05$ level. Results, expressed as a percentage control of dry biomass, is presented by herbicide for velvetleaf and Palmer amaranth are presented on Tables 3.2- 3.3.

Velvetleaf. For Clarity, only the 0.5 and 1 hour post application rainfall events reduced velvetleaf control as compared to the no rain even treatment. With Roundup Powermax added to the Clarity all rain event intervals in the study had decreased velvetleaf control based on dry weight. The reduced efficacy was less at four hours after application than shorter rainfall intervals. Interestingly, the Clarity plus Roundup Powermax treatment also shows the need for evaluating commonly used tank-mixtures for rainfastness and not just individual herbicides.

Like Clarity, Xtendimax sprayed alone had the greatest loss in efficacy at the 0.5 hour interval. Surprisingly, there was a difference in control between the four and eight hour intervals, which was not found in any of the other spray solutions. Tank-mixtures of Xtendimax and Roundup Powermax was sensitive to rain wash-off up to one hour after application. In addition, at 4 hours after application, the same level of control was observed as that seen with no rain simulation treatment.

Roundup Xtend, a pre-mixture of dicamba and glyphosate, showed a decrease in control resulting from rainfall events at one, four and eight hours after application, though there was no significant loss in control at 0.5 and 2 hours post-application. Results of herbicide dry biomass percentage control according to all test rain intervals to velvetleaf are presented on Table 3.3.

Palmer amaranth. Palmer amaranth showed a decrease in control when there was a 0.5 hour rainfall event after application of Clarity. No other decreases in efficacy were observed for Clarity or any other solution tested on Palmer amaranth. With Clarity alone on Palmer amaranth, only a 3% reduction was observed with a 0.5 hour rainfall event. Beyond two hours after application, complete control was observed with Palmer amaranth treated with Clarity. The remaining tank-mixtures showed no losses in control at any post-application rainfall interval.

The primary factors driving the observed results were the varying leaf structures and plant composition among the two weed species along with the formulation differences between the selected herbicides formulations. Leaf structure and composition influences absorption, retention, evaporation and by consequence uptake leading to efficiency. Velvetleaf has a pubescent leaf surface with short and dense hairs, which can affect interact with depositing droplets, altering the performance of the herbicide, especially with droplets that are not at the optimum droplet size. Palmer amaranth leaf and stem surfaces are absence of pubescence and are more neutral in characteristic.

Formulation of a herbicide is important to the efficiency and rainfastness. Clarity is a composition 58% of diglycolamine salt of dicamba (BASF 2010.) (3, 6-dichloro-o-anisic acid) with the remaining of its constituents being other ingredients. While Xtendimax contains 42% diglycolamine salt of dicamba (Monsanto 2016) with the rest been inert ingredients. One of the inert ingredients is VaporGrip technology.

Above mentioned fact explain the need for a higher dose of Xtendimax® versus Clarity® given that active ingredient concentration is 16% higher on Clarity® versus Xtendimax® is likely caused by the fact that spray retention is a key factor influencing herbicide uptake. Interestingly, Xtendimax® provided a better percentage control compared to Clarity® with both species.

In conclusion, this study emphasizes the need for reading and following pesticide product label for effective control. Information such as rainfastness period of an herbicide can be critical to the ultimate success of any application. While the results presented observed indicate that label requirements for a four hour rainfastness period may be conservative (Table 3.4), allowing for the extra time interval can only enhance the efficacy of an application. While rainfastness is critical, it is also important to understand the characteristics of the troublesome weed species targeted and take them into consideration when making an application.

Literature Cited

Anderson MD, Arnold WE (1985) Rainfall Effects on Desmedipham and Phenmedipham Performance. Weed Sci 33:391–394.

BASF Corporation Clarity herbicide EPA Registration No. 7969-137. Research Triangle Park, 2010.

Behrens R, Elakkad MA (1981) Influence of Rainfall on the Phytotoxicity of Foliarly Applied 2,4-D. Weed Sci 29:349–355.

Bryson CT (1987) Effects of Rainfall on Foliar Herbicides Applied to Rhizome Johnsongrass. Weed Sci 35:115–119.

Bryson CT (1988) Effects of Rainfall on Foliar Herbicides Applied to Seedling Johnsongrass (*Sorghum halepense*). Weed Technol 2:153–158.

Cabras P, Angioni A, Garau VL, Melis M, Pirisi FM, Cabitza F, Pala M (2001) The Effect of Simulated Rain on Folpet and Mancozeb Residues on Grapes and on Vine Leaves. J Environ Sci Health Part B 36:609–618.

Caseley JC, Coupland D (1980) Effect of simulated rain on retention, distribution, uptake, movement and activity of difenzoquat applied to Avena fatua. Ann Appl Biol 96:111–118.

Chachalis D, Reddy KN, Elmore CD, Steele ML (2001) Herbicide efficacy, leaf structure, and spray droplet contact angle among Ipomoea species and smallflower morningglory. Weed Sci 49:628–634.

Debortoli, M. P. *Efeito do "Rainfastness" e adjuvante na aplicação de fungicidas foliares em cultivares de soja*. 2008. Dissertação (Mestrado em Engenharia Agrícola) – Universidade de Santa Maria, Santa Maria.

Duarte AR (2008) Remoção de resíduos de fungicidas por meio de chuva simulada e de irrigação em batateira e tomateiro. Removal of fungicides residue by simulated rain and irrigation in potato and tomato.

Fife JP, Nokes SE (2002) Evaluation of the effect of rainfall intensity and duration on the persistence of chlorothalonil on processing tomato foliage. Crop Prot 21:733–740.

Grangeot M, Chauvel B, Gauvrit C (2006) Spray retention, foliar uptake and translocation of glufosinate and glyphosate in Ambrosia artemisiifolia. Weed Res 46:152–162.

Hess, F. D. 1985. Herbicide absorption and translocation and their relationship to plant tolerances and susceptibility. Pages 191–214 *in* S. O. Duke, ed. Weed Physiology. Volume II. Herbicide Physiology. Boca Raton, FL: CRC Press.

Hull, H. M., D. G. Davis, and G. E. Stoltenberg. 1982. Actions of adjuvant on plant surfaces. Pages 26–67 *in* Adjuvants for Herbicides. Lawrence, KS: Weed Science Society of America.

James TK, Rahman A, Cliffe A (2008) Rainfastness of phenoxy herbicide formulations on four pasture weeds. Proc 16th Aust Weeds Conf Cairns Conv Cent N Qld Aust 18-22 May 2008:316–318.

Kudsk, P. (1989). Herbicide rainfastness on indoor and outdoor pot -grown plants. Aspects of Applied Biology, 21, Comparing laboratory and field pesticide performance, pp. 133-4.

Kudsk P, Kristensen JL (1997) Effect of environmental factors on herbicide performance. Proceedings of First International Weed Control Congress, Melbourne 1992. 173-186.

Kudsk P, Mathiassen SK, Kirknel E (1991) Influence of formulations and adjuvants on the rainfastness of maneb and mancozeb on pea and potato. Pestic Sci 33:57–71.

Littell RC, Milliken GA, Stroup WW, Wolfinger RD, Schabenberger O (2006) SAS for mixed models. 2nd edn. Cary, NC: SAS institute., Inc.

McWhorter, C. G. 1993. Epicuticular wax on Johnsongrass (*Sorghum halepense*) leaves. Weed Sci. 41:475–482.

Monsanto Company "XtendiMax with VaporGrip^{TM} Technology" EPA registration No. 524-617. St Louis, 2016.

Nalewaja JD, Adamczewski KA (1988) Thiameturon Phytotoxicity to Kochia (*Kochia scoparia*). Weed Sci 36:296–300.

Nalewaja JD, Woznica Z (1985) Environment and Chlorsulfuron Phytotoxicity. Weed Sci 33:395–399.

Sanyal D, Bhowmik PC, Reddy KN (2006) Leaf characteristics and surfactants affect primisulfuron droplet spread in three broadleaf weeds. Weed Sci 54:16–22.

Schepers HT a. M (1996) Effect of rain on efficacy of fungicide deposits on potato against Phytophthora infestans. Potato Res 39:541–550.

Schilder, A. Fungicides properties and weather conditions. *Plant & Pest Advisory*, New Jersey, v. 15, n. 12, p. 1-3, 2010.

Skuterud R, Caseley JC (1980) Effect of simulated rain on bentazone activity against meadow fescue, timothy and white mustard. Proc 1980 Br Crop Prot Conf - Weeds: 573–580.

Taylor P (2011) The wetting of leaf surfaces. Curr Opin Colloid Interface Sci 16:326–334.

Thacker JRM, Young RDF (1999) The effects of six adjuvants on the rainfastness of chlorpyrifos formulated as an emulsifiable concentrate. Pestic Sci 55:198–200.

Wanamarta, G. and D. Penner. 1989. Foliar absorption of herbicides. Rev. Weed Sci. 4:215–231.

Yu Y, Zhu H, Frantz JM, Reding ME, Chan KC, Ozkan HE (2009) Evaporation and coverage area of pesticide droplets on hairy and waxy leaves. Biosyst Eng 104:324–334.

Zwertvaegher IK, Verhaeghe M, Brusselman E, Verboven P, Lebeau F, Massinon M, Nicolaï BM, Nuyttens D (2014) The impact and retention of spray droplets on a horizontal hydrophobic surface. Biosyst Eng 126:82–91.

Table 3.1. – Herbicide solutions with their appropriate rate and formulation used on the study.

Solutions	Rate
	g ae ha^{-1}
Clarity[a]	1,120 dicamba
Xtendimax[b]	1,117 dicamba
Clarity[a] + Roundup PowerMax[b]	1,120 dicamba + 1,262 glyphosate
Xtendimax[b] + Roundup PowerMax[b]	1,117 dicamba + 1,262 glyphosate
Roundup Xtend[b]	1,122 dicamba 2,244 glyphosate

[a] BASF Corporation, Research Triangle Park, NC, 27709.

[b] Monsanto Corporation, St. Louis, MO, 63141.

Table 3.2. - Control of velvetleaf across rainfall intervals for five solutions containing dicamba.

Intervals (hours)	Clarity[a]	Xtendimax	Clarity + Roundup PowerMax	Xtendimax + Roundup PowerMax	Roundup Xtend
	——	——	—— % ——	——	——
0.5	56 b	66 c	74 bc	66 c	81 ab
1	57 b	70 abc	75 bc	75 bc	73 b
2	70 ab	78 abc	63 c	78 abc	81 ab
4	76 a	69 bc	77 bc	73 bc	77 b
8	71 ab	84 a	82 b	85 ab	78 b
None	79 a	83 ab	100 a	94 a	94 a

[a] Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

Table 3.3. Control of Palmer amaranth across rainfall intervals for five solutions containing dicamba.

Intervals (hours)	Clarity[a]	Xtendimax	Clarity + Roundup PowerMax	Xtendimax + Roundup PowerMax	Roundup Xtend
	%				
0.5	97 b	98 a	100 a	100 a	100 a
1	99 ab	100 a	100 a	100 a	100 a
2	100 a	97 a	100 a	100 a	100 a
4	100 a	100 a	100 a	100 a	100 a
8	100 a	100 a	100 a	100 a	100 a
None	100 a	100 a	100 a	100 a	100 a

[a] Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

Table 3.4. – Rainfastness interval of herbicides according to respective labels.

Solution	Rainfastness (hours)
Clarity[a]	4
Xtendimax[b]	4
Roundup PowerMax[b]	6
Roundup Xtend[b]	6

[a] BASF Corporation, Research Triangle Park, NC, 27709.
[b] Monsanto Corporation, St. Louis, MO, 63141.

CHAPTER 4

Influence of nozzle type, speed and pressure on droplet size and weed control from Glyphosate®, Dicamba®, and Glyphosate® plus Dicamba®.

Abstract

Improper or sub-optimal application techniques can cause decreased weed control and increased environmental contamination. Droplet size is a key factor in pesticide applications in regards to both drift and efficacy. Droplet size can be altered by several application parameters, such as the nozzle type, pressure, orifice size and spray solution. The objective of this study was to evaluate the influence of nozzle type, application speed and pressure when using glyphosate, dicamba, or glyphosate plus dicamba on droplet size and control of common lambsquarters, velvetleaf, kochia, and grain sorghum. The study was conducted with two herbicides, glyphosate at 0.77 kg ae ha^{-1} and dicamba at 0.56 kg ae ha^{-1}, tested alone and in combination. The application rate was 94 L ha^{-1} at three different speeds 8, 16, and 24 kph and the pressures used were a low, medium and high pressure for each speed and orifice size combination. The pressures were combined with the appropriate orifice size to deliver a fixed spray volume. An XR, AIXR, and TTI (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139 USA) nozzle were used (two of which are venturi nozzle designs). Droplet size ranged from 219 µm to 232 µm for XR nozzle across the three solutions. From 440 µm to 482 µm for AIXR nozzle and from 740 µm to 828 µm for TTI nozzle. Solutions using dicamba resulted in the largest droplet size, followed by glyphosate and then the combination. There were no significant interactions for nozzle by herbicide across all species.

Introduction

Herbicides play an important role in chemical weed control worldwide. Herbicides are the most commonly applied pesticide in the U.S. According to USDA, herbicides were applied to 97% of planted acres of corn, while insecticides and fungicides were applied to 13% and 12%, respectively (Fernandez-Cornejo et al., 2014). Herbicides have been a major component in increasing crop yields over the past five decades. Optimal applications of herbicides can improve crop yield by controlling weeds (Fernandez-Cornejo et al., 2005). Herbicide applications are the preferred method used for weed management strategies in crops among a variety of methods that include biological, cultural and mechanical controls. Herbicides can provide satisfactory weed control at low cost and convenience to growers.

The increasing dependence on the use of herbicides brings concerns such as drift (in the form of vapor and particle drift), resistance, contamination of water resources, and harm to susceptible vegetation, wildlife and human health. Improper or sub-optimal applications can occur with ineffective selection of application parameters (speed, nozzle type, nozzle spacing, boom height, pressure, and orifice size) or environmental conditions (wind speed and direction, temperature, humidity). Van den Berg et al. estimated that volatilization and drift could be responsible for up to 50% of pesticides losses (Berg et al., 1999). Spray particle drift is primarily influenced by wind speed and direction, spray droplet size, boom height and buffers (Creech et al., 2015). Given that wind speed cannot be controlled by the applicator, control of droplet size is a key component in controlling drift when herbicide applications are made (Berg et al., 1999; Etheridge et al., 1999).

Droplet size is a key factor in pesticide applications in regards to both drift and efficacy. As herbicide passes through a nozzle, a range of droplets is produced. Theoretically, more efficient herbicide applications are the ones with narrower spray droplet distribution, meaning a more homogeneous application pattern (Hartley and Graham-Bryce, 1980). Normally, larger orifice sizes for a given nozzle type will produce larger droplets (Nuyttens et al., 2007). Improper or sub-optimal application techniques can cause decreased weed control and increased environmental contamination.

In order to reduce particle drift, a common practice is to increase the overall droplet sizes in the spray by reducing application pressure or increasing the orifice size of the spray nozzle or selecting a difference nozzle (Creech et al., 2015; Hartley et al., 1980). According to Etheridge et al. droplets with diameters smaller than 200 µm are those with the greatest drift potential (Etheridge et al., 1999), while Yates et al. states droplets with diameters of 150 µm or less as those with greatest drift potential (Wesley E. Yates et al., 1985). Different nozzle types will affect the way liquid sheets are formed and breaks into droplets. Increasing droplet size by reducing pressure or using larger orifice sizes will change application rate and potentially herbicide efficacy if not properly accounted for with additional nozzles or adjustment to application speed (Knoche, 1994). Differences in droplet spectra, deposition pattern and potentially efficacy might be observed with applications made with slower speeds when compared with those made with faster speeds (Meyer et al., 2016), as also reported by (Wolf et al., 1997). Absorption of glyphosate increased as droplet size increased from 326 to 977µm when sprayed with constant concentration (Liu et al., 1996). In addition, weed control of equal or greater efficacy was obtained when comparing drift reduction nozzles to a flat fan nozzle with different herbicides when sprayed to several weed species (Ramsdale and Messersmith, 2001). Same trend of results was reported by Feng et al. with glyphosate and AI nozzle in comparison with XR nozzle (Feng et al., 2003). Non-target vegetation and organisms may also be affected due to herbicide drift (de Snoo and de Wit, 1998; Freemark and Boutin, 1995). Particle drift not only alters nearby areas but also can decrease weed control on the intended area through loss of spray material (Johnson et al., 2006). Increasing spray pressure leads to a larger proportion of the spray volume being small droplets and by consequence drift potential is increased. Larger nozzle orifice size typically results in larger spray droplets, with lower drift potential. Larger droplets can lower coverage, while smaller droplets may have higher drift potential and evaporation rate with better coverage (Spillman, 1984). Also, morphology of leaf and composition of cuticle might affect deposition of the spray in a leaf surface, and droplet rebound culminating in lower spray retention (Feng et al., 2004).

Nozzle type is an important tool for reducing drift potential. Proper nozzle selection is also important for satisfactory weed control. Thus, it is common to discuss Venturi and non-Venturi nozzle types. Venturi nozzles consist of a pre-orifice, an air fluid mixing chamber and a fan orifice that creates the pattern for the nozzle. Venturi type nozzles generate larger droplets compared with conventional fan nozzles at a known pressure (Etheridge et al., 1999). Nozzle type selection depends on herbicide and species targeted for evaluation (Meyer et al., 2016). Proper nozzle type selection regarding target, herbicide, and purpose of application, helps to mitigate lack of coverage and deposition on intended target and by consequence weed control.

Application parameters other than nozzle selection are also important. In terms of application speed, the recommendation normally is in the range of 8 to 16 kph. Application speed will have an impact on the herbicide coverage and deposition, which are directly related to herbicide efficacy especially for contact herbicides. On the other hand, systemic herbicides are not necessarily directly affected but could be impacted by the quantity of active ingredient delivered to the plant and the plants ability to uptake and translocate the active ingredient. It is common to assume that contact herbicides, may be more negatively affected by the increase of droplet size when compared to systemic herbicides (Etheridge et al., 2001). Applications must be according to the label and following the instructions provided in the catalogs.

Numerous studies have been conducted evaluating factors that affect drift and weed control but not many have investigated those factors acting at the same time impacting both drift and weed control. Furthermore, no consistent trend was found in studies that evaluate droplet size related to drift and weed control and some cases the results have been contradictory as reported by Knoche et al. (Knoche, 1994). In addition, limited data exists to support nozzle selection, pressure and speed recommendations for herbicide applications to achieve both optimum droplet size and weed control. The objective of this experiment was to investigate and understand the influence of speed, pressure and different nozzle types and orifice sizes on weed control for troublesome weed species across the USA. Understanding these factors that contribute to deliver the herbicide to the plant and impact on weed control can lead to increased weed control and reduced off-target movement.

Material & Methods

A greenhouse study was conducted at the University of Nebraska – Lincoln's West Central Research and Extension Center (UNL-WCREC) in North Platte, NE. Plant species tested were common lambsquarters (*Chenopodium album L.*), velvetleaf (*Abutilon theophrasti Medik*), kochia (*Kochia scoparia (L.) Schrad.*), and grain sorghum (*Sorghum bicolor (L.) Moencch subsp. Bicolor*). These species were selected based on representativeness, availability, leaf surface type and greenhouse growth characteristics. Two commonly used foliar applied, post emergence systemic herbicides, dicamba (Clarity$^{®}$) at 0.56 kg ae/ha and glyphosate (Roundup PowerMax$^{®}$) at 0.77 kg ae/ha were applied. The glyphosate plus tank-mixture was tested on grass species because dicamba has little effect on grasses and the dicamba plus tank-mixture was tested on broadleaf species. The objective of this study was to evaluate the influence of nozzle type, application speed and pressure when combined with glyphosate, dicamba, or glyphosate plus dicamba on droplet size and control of common lambsquarters, velvetleaf, kochia, grain sorghum.

Application. Applications were made when weed species were 10 to 15 cm tall. Plants were sprayed in a 1.67 m x 4.2 m spray chamber (Generation 4 Research Track Sprayer DeVries Manufacturing, Hollandale, MN) with a three-nozzle track sprayer with nozzles spaced 50 cm apart and 50 cm above the top of the plants. A factorial arrangement of treatments was used. Each combination of nozzle type, application speed and spray solution was replicated five times. Spray treatments consisted of three different speeds (8, 16, and 24 kph); and three nozzle types (XR, AIXR, and TTI) (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139 USA) with a range of orifice sizes (015 to 06). Spray pressure was adjusted to deliver 94 L ha^{-1}. Treatment combinations generated droplet size classifications from fine to ultra-coarse depending on the combination used as shown in (Table 4.1.).

The treatment list presented in (Table 4.2.) shows all parameters used for all three nozzle types and also all possible combinations with those parameters. These combinations resulted in 81 treatments for each weed species (27 combinations per species X 3 nozzle types). After application, plants were placed back into the greenhouse for continuation of their cycle and post treatment efficacy evaluation. Visual estimations of injury were collected in the greenhouse at 7, 14, 21, and 28 days after treatment (DAT), the estimations ranged from 0-100, where 0 is no control and 100 is complete plant death. At 28DAT, plants were clipped at the soil surface, wet weights were recorded, plants were dried to constant mass, and dry weights were recorded.

Analysis of Spray Droplet Size. All treatments combinations were tested in the low speed wind tunnel at the Pesticide Application Technology Laboratory (PAT Lab). Droplet measurements were made using a Sympatec HELOS-VARIO/KR (Sympatec, Inc., Pennington, NJ) laser diffraction system in the PAT Lab low speed wind tunnel as described by Creech et al. (Creech et al., 2016). The nozzle is located 30 cm from the laser beam. Laminar wind speed velocity used was 6.7 m/s (Fritz et al., 2014). Droplet size classification for this study were based on reference curves created from reference nozzle data at the PAT Lab according to ASAE 572.1 (Feng et al., 2003) as shown on (Table 4.2.). Comparisons between treatments were based on the measurements of $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ (the droplet sizes at which 10, 50, and 90% of the spray volume of application is contained in droplets of smaller diameter). In addition, Relative Span (RS) was calculated which is a non-dimensional value indicating the uniformity of the spray droplet spectrum and it is defined by the equation: $RS = (D_{v0.9} - D_{v0.1})/ D_{v0.5}$.

Statistical Analysis. The means were analyzed using ANOVA, simple effects were evaluated and means were separated by LSD test $\alpha = 0.05$ mixed effect model in SAS v9.4 as a Complete Randomized Design (CRD). Two independent and identical runs were conducted for this experiment.

Results and Discussion

Across all weed species, nozzle type was not a significant effect, though speed and speed*nozzle were for lambsquarters ($P<0.0001$ and $P=0.0315$, respectively) (Table 4.3.). While nozzle and speed were treated as main effects and nozzle*speed as an interaction, it is worth considering what these main effects and interactions represent. While only three nozzle types were used in the study, within each nozzle type multiple orifice sizes and spray pressures were used, as appropriate, to ensure that the spray rate remained at 94 L ha^{-1}. This resulted in a range of droplet sizes within each nozzle type for each solution. (Tables 4.4.-4.6.) Generally speaking dicamba produced the largest overall droplet sizes followed by glyphosate and then glyphosate plus dicamba. Similarly, the TTI nozzles generally produced the largest overall droplet size followed by the AIXR and XR nozzles, agreeing with previously reported work by Creech et al. (Creech et al., 2015). Also captured within the main effect nozzle are differences in fluid exit velocities at differing pressures and nozzle types as well as orientation of the spray fan with the TTI having a 15 degree forward angle. The main effect speed captures the forward traverse speed of the track but also results in differing orifice sizes and spray pressures (thus differing droplet sizes) within each nozzle type. The nozzle*speed interaction term becomes a bit more convoluted as it also incorporates these changes in orifice, pressure and ultimately droplet size.

Given this, and examining the ANOVA results (Table 4.3.) emphasis that herbicide type was the driving factor in the observed results for this work. Across all weed species, nozzle type and speed with the combination of glyphosate and dicamba provide superior control as compared to glyphosate or dicamba alone. Further discussion of result nuances within each weed species are discussed in following sections.

Common Lambsquarters. Both herbicide ($P > 0.0001$) and track speed ($P < 0.0001$) main effects were highly significant (Table 4.3.). However, as discussed previously it is difficult to discern the root cause behind the track speed significance as with each change in track speed, for each nozzle, orifice size and pressure were adjusted within each nozzle to provide a constant spray rate of 94 L ha^{-1}, meaning droplet size with nozzle varied. For example, at 8 kph the AIXR 110015 spraying dicamba at 345 kPa had a VMD of 411 µm. While the 110025 at 124 kPa pressure had a VMD of 658 µm, an almost 250 µm difference. Similarly, the TTI nozzle ranged in droplet size from 757 to 1101 µm at 8 kph and the XR from 215 to 297 µm (Table 4.4.). With speed and speed*herbicide being significant effects, the results show reduced control at higher speeds for dicamba only (Figure 4.1.). At 24 kph, each nozzle type uses a larger orifice and higher spray pressure, which generally resulting in larger overall droplet sizes at 24 kph, though there are a few exceptions (Table 4.4.). Without an assessment of at- or on-target deposition rates, we can only conjecture as to the cause of the reduce control. The change in droplet size across the three nozzle types is much greater than that within each nozzle type, which coupled with no significant control differences between nozzle type (which is essentially droplet size), removes droplet size as a causal factor. This leaves either the track speed or changes in nozzle exit velocities as a result of pressure as potential factors, though this work does not have data to objectively delineate which.

Velvetleaf. Velvetleaf follows a very similar pattern as lambsquarters with the herbicide ($P<0.0001$), and speed ($P = 0.0288$) main effects and speed*herbicide ($P = 0.0003$) interactions being significant predictors of control (Table 4.3.). While nozzle*speed control results are less consistent for the dicamba plus glyphosate blend than seen with lambsquarters, the dicamba only solution follows the same trends (Figure 4.2.). It should be noted in the scenario of common lambsquarters and velvetleaf, that while significant control differences were observed within each nozzle*speed*herbicide combination, when analyzing within herbicide the numerical differences were less than 10%.

Kochia. The only significant main effect with kochia was herbicide ($P<0.0001$), though speed*herbicide and nozzle*speed*herbicide interactions were also significant (Table 4.3.). These results and the lack of significance in the nozzle and speed main effects couple with their being part of a significant interaction effect further illustrate to difficulty in determining the root causal factor, beyond the herbicide effect, driving these differences. Similar to lambsquarters and velvetleaf, there are significant differences in the observed controls, though these were inconsistent within nozzle type, speed and nozzle by speed combinations, and numerically differed by no more than 10-15% within nozzle/speed combination for each herbicide (Figure 4.3.).

Grain Sorghum. There were no significant main effects with the observed control of grain sorghum and while speed*herbicide interaction was significant, as previously discussed discerning the root cause of this interaction not possible with the data collected during this study. The antagonistic effect with mixing glyphosate and dicamba resulting in reduced glyphosate toxicity in grain sorghum was not observed as reported by Flint et al. (Flint and Barrett, 1989) with johnsongrass *(Sorghum halapense (L.) Pers.)* (Figure 4.4.).

Only herbicide type was shown to be a consistent, significant effect in the observed control across the four weed species and three tank mixture explored in this study. Universally, dicamba plus glyphosate provided superior control, regardless of nozzle type, orifice size, spray pressure, droplet size and track speed for the weed species tested. These results would tend to favor a recommendation that when looking to optimize control of lambsquarters, velvetleaf, kochia or grain sorghum, a combination of glyphosate and dicamba should be used. Further, to reduce drift potential from these applications, nozzle type, orifice size and spray pressure should be selected to generate droplet size that have fewer fine droplets. While it may be tempting to recommend using the largest size possible, further work examining deposition efficiency on plant surfaces with reduced spray deposition are needed. The use of a dicamba/glyphosate blend offers applicators a great deal of flexibility in setting up their sprays system for reduced off-target deposition while maintaining optimum control efficacy.

Literature Cited

Berg, F.V.D., Kubiak, R., Benjey, W.G., Majewski, M.S., Yates, S.R., Reeves, G.L., Smelt, J.H., Linden, A.M.A.V.D., 1999. Emission of Pesticides into the Air, in: Fate of Pesticides in the Atmosphere: Implications for Environmental Risk Assessment. Springer, Dordrecht, pp. 195–218. https://doi.org/10.1007/978-94-017-1536-2_9.

Creech, C.F., Henry, R.S., Fritz, B.K., Kruger, G.R., 2015. Influence of Herbicide Active Ingredient, Nozzle Type, Orifice Size, Spray Pressure, and Carrier Volume Rate on Spray Droplet Size Characteristics. Weed Technol. 29, 298–310. https://doi.org/10.1614/WT-D-14-00049.1.

Creech, C.F., Moraes, J.G., Henry, R.S., Luck, J.D., Kruger, G.R., 2016. The Impact of Spray Droplet Size on the Efficacy of 2,4-D, Atrazine, Chlorimuron-Methyl, Dicamba, Glufosinate, and Saflufenacil. Weed Technol. 30, 573–586. https://doi.org/10.1614/WT-D-15-00034.1.

de Snoo, G.R., de Wit, P.J., 1998. Buffer Zones for Reducing Pesticide Drift to Ditches and Risks to Aquatic Organisms. Ecotoxicol. Environ. Saf. 41, 112–118. https://doi.org/10.1006/eesa.1998.1678.

Etheridge, R.E., Hart, W.E., Hayes, R.M., Mueller, T.C., 2001. Effect of Venturi-Type Nozzles and Application Volume on Postemergence Herbicide Efficacy. Weed Technol. 15, 75–80. https://doi.org/10.1614/0890.

Etheridge, R.E., Womac, A.R., Mueller, T.C., 1999. Characterization of the Spray Droplet Spectra and Patterns of Four Venturi-Type Drift Reduction Nozzles. Weed Technol. 13, 765–770. https://doi.org/10.1017/S0890037X00042202.

Feng, P.C.C., Chiu, T., Sammons, R.D., Ryerse, J.S., 2003. Droplet size affects glyphosate retention, absorption, and translocation in corn. Weed Sci. 51, 443–448. https://doi.org/10.1614/0043-1745(2003)051.

Feng, P.C.C., Tran, M., Chiu, T., Douglas Sammons, R., Heck, G.R., CaJacob, C.A., 2004. Investigations into glyphosate-resistant horseweed (Conyza canadensis): retention, uptake, translocation, and metabolism. Weed Sci. 52, 498–505. https://doi.org/10.1614/WS-03-137R.

Fernandez-Cornejo, J., Hendricks, C., Mishra, A., 2005. Technology Adoption and Off-Farm Household Income: The Case of Herbicide-Tolerant Soybeans. J. Agric. Appl. Econ. 37, 549–563. https://doi.org/10.1017/S1074070800027073.

Fernandez-Cornejo, J., Nehring, R.F., Osteen, C., Wechsler, S., Martin, A., Vialou, A., 2014. Pesticide Use in U.S. Agriculture: 21 Selected Crops, 1960-2008 (SSRN Scholarly Paper No. ID 2502986). Social Science Research Network, Rochester, NY.

Flint, J.L., Barrett, M., 1989. Antagonism of Glyphosate Toxicity to Johnsongrass (*Sorghum halepense*) by 2,4-D and Dicamba. Weed Sci. 37, 700–705. https://doi.org/10.1017/S0043174500072660.

Freemark, K., Boutin, C., 1995. Impacts of agricultural herbicide use on terrestrial wildlife in temperate landscapes: A review with special reference to North America. Agric. Ecosyst. Environ. 52, 67–91. https://doi.org/10.1016/0167-8809(94)00534-L.

Fritz, B.K., Hoffmann, W.C., Kruger, G.R., Henry, R.S., Hewitt, A., Czaczyk, Z., 2014. Comparison Of Drop Size Data From Ground And Aerial Application Nozzles At Three Testing Laboratories. At. Sprays 24. https://doi.org/10.1615/AtomizSpr.2013009668.

Hartley, G.S., Graham-Bryce, I.J., 1980. Physical principles of pesticide behaviour. Phys. Princ. Pestic. Behav.

Johnson, A.K., Roeth, F.W., Martin, A.R., Klein, R.N., 2006. Glyphosate Spray Drift Management with Drift-Reducing Nozzles and Adjuvants. Weed Technol. 20, 893–897. https://doi.org/10.1614/WT-05-162.1.

Knoche, M., 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot. 13, 163–178. https://doi.org/10.1016/0261-2194(94)90075-2.

L. E. Bode, B. J. Butler, C. E. Goering, 1976. Spray Drift and Recovery As Affected by Spray Thickener, Nozzle Type, and Nozzle Pressure. Trans. ASAE 19, 0213–0218. https://doi.org/10.13031/2013.35997.

Liu, S.H., Campbell, R.A., Studens, J.A., Wagner, R.G., 1996. Absorption and Translocation of Glyphosate in Aspen (Populus tremuloides Michx.) as Influenced by Droplet Size, Droplet Number, and Herbicide Concentration. Weed Sci. 44, 482–488.

Meyer, C.J., Norsworthy, J.K., Kruger, G.R., Barber, T., 2016. Effects of Nozzle Selection and Ground Speed on Efficacy of Liberty and Engenia Applications and Their Implication on Commercial Field Applications. Weed Technol. 30, 401–414. https://doi.org/10.1614/WT-D-15-00145.1.

Monsanto Company XtendiMax with VaporGrip^{TM} Technology EPA registration No. 524-617. St Louis, 2016.

Nordby A, Skuterud R. The effects of boom height, working pressure and wind speed on spray drift Weed Res 1974;14:385–95. doi:10.1111/j.1365-3180.1974.tb01080.x.

Nuyttens, D., Baetens, K., De Schampheleire, M., Sonck, B., 2007. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosyst. Eng. 97, 333–345. https://doi.org/10.1016/j.biosystemseng.2007.03.001.

Ramsdale, B.K., Messersmith, C.G., 2001. Drift-Reducing Nozzle Effects on Herbicide Performance. Weed Technol. 15, 453–460. https://doi.org/10.1614/0890-037X(2001)015.

Spillman, J.J., 1984. Spray impaction, retention and adhesion: An introduction to basic characteristics. Pestic. Sci. 15, 97–106. https://doi.org/10.1002/ps.2780150202.

Wesley E. Yates, Robert E. Cowden, Norman B. Akesson, 1985. Drop Size Spectra from Nozzles in High-Speed Airstreams. Trans. ASAE 28, 405–410. https://doi.org/10.13031/2013.32268.

Wolf, T.M., Liu, S.H., Caldwell, B.C., Hsiao, A.I., 1997. Calibration of Greenhouse Spray Chambers: The Importance of Dynamic Nozzle Patternation. Weed Technol. 11, 428–435.

Table 4.1. – Droplet size data from reference nozzles at the Pesticide Application Technology Laboratory, North Platte, NE and spray classification boundaries as defined by ASAE S572.1.

Nozzle[a]	Pressure	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	Boundary
	kPa	———	µm	———	
11001	450	66	147	276	Very Fine/Fine
11003	300	113	250	414	Fine/Medium
11006	200	158	347	561	Medium/Coarse
8008	250	198	437	735	Coarse/Very Coarse
6510	200	234	517	855	Very Coarse/Extremely Coarse
6515	150	305	655	1060	Extremely Coarse/Ultra Coarse

[a] Reference flat spray nozzle as defined by ASAE S572.1

Table 4.2. – Combinations of speed, pressure, and orifice size for three nozzle types utilized in a study to evaluate droplet size and efficacy.

kph	kPa	Angle	Orifice size[a]
8	124	110°	025
8	207	110°	02
8	345	110°	015
16	207	110°	04
16	345	110°	03
16	482	110°	025
24	207	110°	06
24	276	110°	05
24	517	110°	04

[a] Nozzle types for this study were XR, AIXR and TTI (TeeJet Technologies, Spraying Systems Co., Glendale Heights, IL 60139 USA).

Table 4.3. – Results for interactions and main effects on control of common lambsquarters, kochia, velvetleaf, and grain sorghum.

Effect	common lambsquarters	kochia	velvetleaf	grain Sorghums
	——— Pr > F ———			
nozzle	0.7087	0.1875	0.5284	0.7407
speed	**<0.0001**	0.9916	0.0288	0.1081
nozzle*speed	**0.0315**	0.2381	0.1147	0.9411
herbicide	**<0.0001**	**<0.0001**	**<0.0001**	0.1421
nozzle*herbicide	0.8774	0.2815	0.0876	0.8234
speed*herbicide	**0.0007**	**0.0056**	**0.0003**	**0.0274**
nozzle*speed*herbicide	0.4369	**0.0132**	0.6956	0.8477

*Bolded numbers are significant at α=0.05.

Table 4.4. – Droplet size distribution data for three nozzle types spraying a dicamba solution across a range of orifice sizes and pressures.

			Dicamba[a]			
Nozzle type	**Orifice size**	**Pressure**	**$Dv_{0.1}$**[b]	**$Dv_{0.5}$**[b]	**$Dv_{0.9}$**[b]	**RS**[c]
		kPa		**µm**		
	0.15	345	212 n	411 m	634 k	1.03 jk
	0.2	207	230 m	430 l	635 k	0.94 m
	0.25	124	339 h	658 i	985 h	0.98 l
	0.25	482	192 p	399 n	619 l	1.07 hi
AIXR	0.3	345	204 o	414 m	630 k	1.03 jk
	0.4	207	271 k	529 k	808 j	1.02 k
	0.4	517	183 q	387 o	597 m	1.07 hi
	0.5	276	260 l	529 k	820 j	1.06 i
	0.6	207	294 j	586 j	900 i	1.04 j
Average			243	482	737	
	0.15	345	389 f	757 f	1094 f	0.93 m
	0.2	207	437 c	837 d	1193 d	0.90 n
	0.25	124	602 a	1101 a	1540 a	0.85 o
	0.25	482	343 h	707 g	1067 g	1.02 jk
TTI	0.3	345	371 g	774 e	1210 d	1.08 h
	0.4	207	452 b	904 b	1351 b	0.99 l
	0.4	517	302 i	666 h	1139 e	1.25 de
	0.5	276	401 e	839 d	1309 c	1.08 h
	0.6	207	415 d	865 c	1347 b	1.08 h
Average			412	828	1250	
	0.15	345	73 x	167 v	294 u	1.33 b
	0.2	207	95 u	210 t	354 s	1.23 ef
	0.25	124	123 s	259 s	426 p	1.17 g
XR	0.25	482	82 w	186 u	329 t	1.32 b
	0.3	345	93 v	213 t	365 r	1.28 c
	0.4	207	125 s	280 q	466 o	1.22 f
	0.4	517	93 v	215 t	385 q	1.36 a

	0.5	276	118 t	270 r	463 o	1.27 cd
	0.6	207	132 r	297 p	494 n	1.22 f
Average			104	233	397	

---

[a] Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

[b] Abbreviations: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$: Parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or lesser values, respectively;

[c] RS: Relative span = $(D_{v0.9} - D_{v0.1}) / D_{v0.5}$.

Table 4.5. – Droplet size distribution data for three nozzle types spraying a glyphosate solution across a range of orifice sizes and pressures.

			Glyphosate[a]			
Nozzle type	**Orifice**	**Pressure**	**$Dv_{0.1}$**[b]	**$Dv_{0.5}$**[b]	**$Dv_{0.9}$**[b]	**RS**[c]
		kPa	**µm**			
AIXR	0.15	345	208 k	405 l	624 i	1.03 op
	0.2	207	186 n	386 n	592 k	1.05 mn
	0.25	124	252 i	491 j	749 h	1.01 p
	0.25	482	192 m	395 m	605 j	1.04 no
	0.3	345	200 l	406 l	616 ij	1.02 op
	0.4	207	213 j	453 k	746 h	1.18 h
	0.4	517	182 o	383 n	591 k	1.07 lm
	0.5	276	250 i	512 i	805 g	1.08 jk
	0.6	207	253 i	532 h	842 f	1.11 i
Average			215	440	686	
TTI	0.15	345	356 f	664 g	933 e	0.87s
	0.2	207	371 d	746 d	1110 c	0.99 q
	0.25	124	514 a	990 a	1429 a	0.93 r
	0.25	482	344 g	700 f	1067 d	1.03 nop
	0.3	345	364 e	739 e	1120 c	1.02 op
	0.4	207	417 b	852 b	1331 b	1.07 h
	0.4	517	303 h	659 g	1072 d	1.17h
	0.5	276	400 c	838 c	1317	1.09 kl
	0.6	207	395 c	834 c	1334 b	1.13 ij
Average			385	740	1190	
XR	0.15	345	72 v	165 u	287 s	1.32 abc
	0.2	207	87 t	197 s	348 q	1.33 ab
	0.25	124	119 p	262 p	435 n	1.20 g
	0.25	482	82 u	188 t	329 r	1.31 bcd
	0.3	345	92 s	211 r	361 p	1.27 f
	0.4	207	110 r	251 q	434 n	1.29 def
	0.4	517	93 s	215 r	382 o	1.34 a

	0.5	276	113 q	261 p	447 m	1.28 ef
	0.6	207	119 p	277 o	480 l	1.30 cde
Average			98	225	389	

---

[a] Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

[b] Abbreviations: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$: Parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or lesser values, respectively;

[c] RS: Relative span = $(D_{v0.9} - D_{v0.1}) / D_{v0.5}$.

Table 4.6. – Droplet size distribution data for three nozzle types spraying a glyphosate plus dicamba solution across a range of orifice sizes and pressures.

			Glyphosate plus dicamba[a]			
Nozzle type	**Orifice**	**Pressure**	**$Dv_{0.1}$**[b]	**$Dv_{0.5}$**[b]	**$Dv_{0.9}$**[b]	**RS**[c]
		kPa	**µm**			
AIXR	0.15	345	187 m	383 n	599 j	1.08 jk
	0.2	207	193 l	395 m	597 j	1.02 n
	0.25	124	290 h	592 i	919 g	1.06
	0.25	482	179 n	377 o	588 k	1.09 j
	0.3	345	185 m	384 n	596 j	1.07 klm
	0.4	207	227 k	474 l	778 i	1.16 f
	0.4	517	167 o	361 p	581 l	1.15 g
	0.5	276	235 j	492 k	782 i	1.11 i
	0.6	207	259 i	534 j	832 h	1.07 kl
Average			213	444	697	
TTI	0.15	345	356 e	692 f	1026 f	0.97 o
	0.2	207	390 c	760 d	1122 e	0.96 o
	0.25	124	514 a	969 a	1404 a	0.92 p
	0.25	482	323 g	663 g	1028 f	1.06 lm
	0.3	345	350 f	725 e	1174 d	1.14 gh
	0.4	207	418 b	849 b	1319 b	1.06 m
	0.4	517	292 h	650 h	1125 e	1.28 cd
	0.5	276	384 d	814 c	1303 c	1.13 h
	0.6	207	383 d	815 c	1306 bc	1.13 h
Average			379	771	1201	
XR	0.15	345	71 v	161 x	284 t	1.33 b
	0.2	207	88 t	197 v	339 r	1.27 d
	0.25	124	113 q	249 s	418 o	1.23 e
	0.25	482	78 u	179 w	314 s	1.32 b
	0.3	345	89 t	201 u	350 q	1.30 c

	0.4	207	113 q	256 r	429 n	1.23 e
	0.4	517	90 s	208 t	370 p	1.35 a
	0.5	276	109 r	251 s	432 n	1.29 c
	0.6	207	120 p	273 q	471 m	1.28 cd
Average			97	219	379	

[a] Means within a column followed by the same letter are not statistically different ($P \leq 0.05$).

[b] Abbreviations: $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$: Parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or lesser values, respectively;

[c] RS: Relative span = $(D_{v0.9} - D_{v0.1}) / D_{v0.5}$

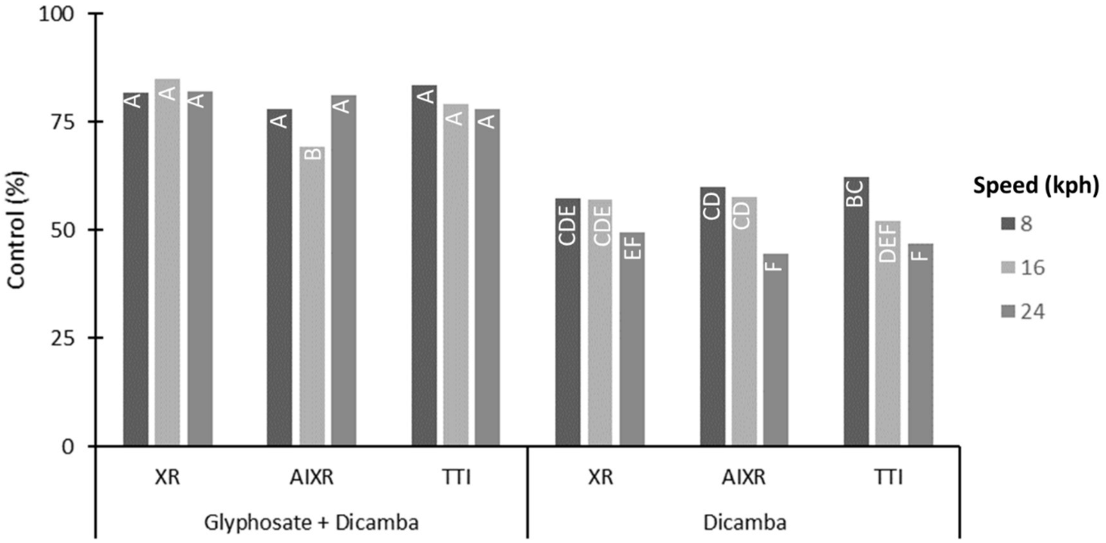

Figure 4.1. – Percent control of common lambsquarters using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds.

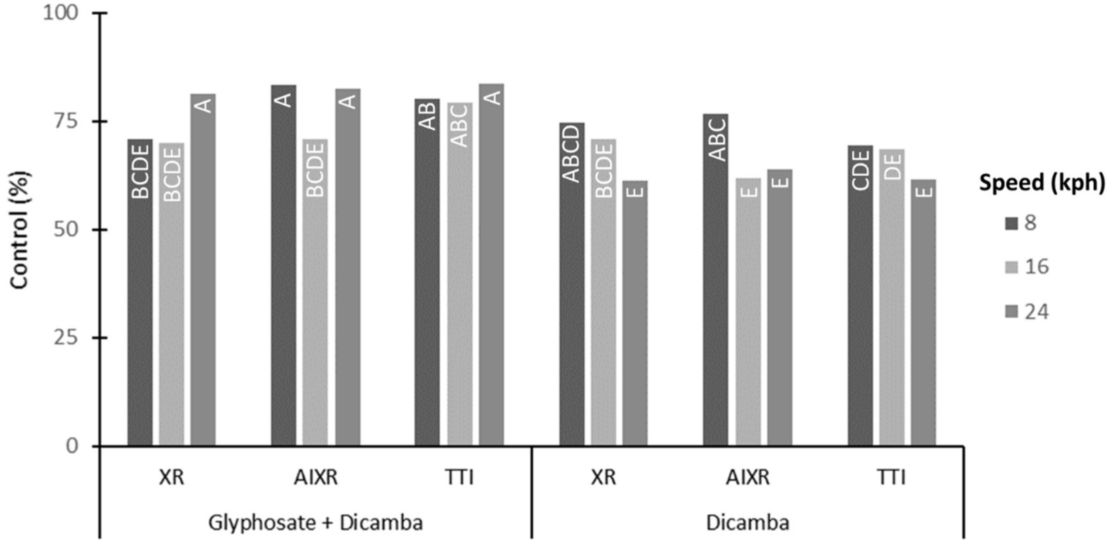

Figure 4.2. – Percent control of velvetleaf using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds.

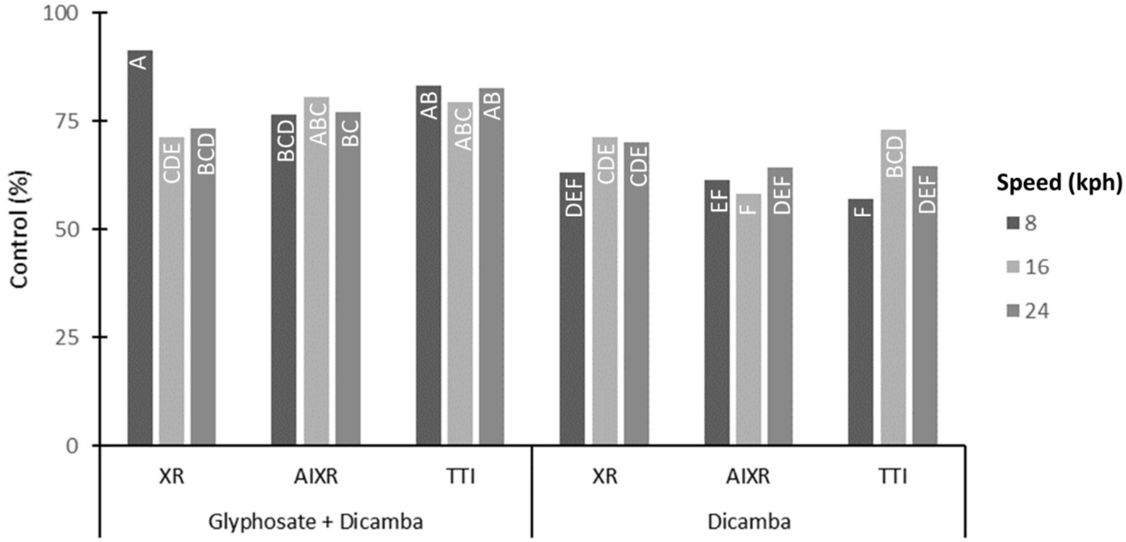

Figure 4.3. – Percent control of kochia using three nozzle types when glyphosate plus dicamba and dicamba was sprayed with three different application speeds.

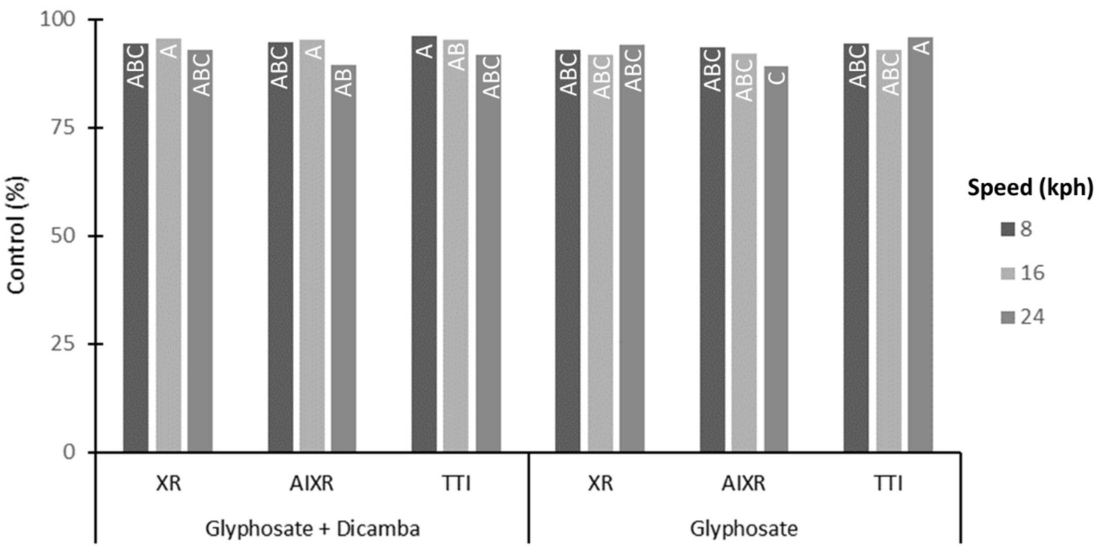

Figure 4.4. – Percent control of grain sorghum using three nozzle types when glyphosate plus dicamba and glyphosate was sprayed with three different application speeds.