ASSESSING EVEN FLAT-FAN NOZZLES FOR SPOT SPRAY HERBICIDE APPLICATIONS

by

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Herbicide efficiency in row-crop agriculture can be improved using precision technologies for controlling weeds and minimize agronomic, economic, and environmental impacts. Site-specific weed management technologies, such as spot-sprayers, allow herbicides to be sprayed only where weeds are present in the field. Understanding application parameters and their influence on weed control for site-specific spot-spray applications is essential. This research involved laboratory and greenhouse studies to investigate the coverage and coefficient of variation (CV) of even flat-fan spray nozzles under different spot-spray application scenarios, as well as the effect of weed size and application method on the control of various weed species using a pulse width modulation system to control herbicide rate. Adjusting the nozzle angle from 0° to 30° rearward resulted in a mean reduction of 7% in spray coverage for both AI6502E and TP6502E nozzles. This adjustment also led to a 6% decrease in CV for the AI6502E nozzle, while it had no impact on the TP6502E nozzle CV. Additionally,

a 25% average increase in CV was observed when the boom height was reduced from 75 cm to 25 cm. Greenhouse research revealed that weeds exhibited high sensitivity to 2,4-D, dicamba, and clethodim, regardless of weed size and application method. In contrast, glyphosate and glufosinate provided superior control when applied at early growth stages, underscoring the importance of early postemergence herbicide management for these herbicides in variable-rate applications. The research findings from both studies enhance our understanding of how various application parameters can influence spot-spray operations and the sensitivity of weeds to different herbicides at different growth stages. This knowledge is crucial for establishing effective herbicide variable-rate strategies, optimizing weed control, and minimizing herbicide use.

Dedication

To my parents, siblings, nephew, grandparents (In Memoriam), cousins, all the rest of my family, and friends.

“The family is the first essential cell of human society”

- *Pope John XXIII*

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CHAPTER 1

An overview of potential yield losses from weeds, pesticide applications, and site-specific weed management.

Worldwide agricultural crop production is affected by the competition from weeds. Studies conducted by Soltani et. al. (2016, 2017) and Flessner et. al (2021) showed that the potential yield losses from weed interference in North America if no weed management tactics were employed could result in losses over U.S.$26.7 billion annually for corn, US $17.2 billion annually for soybeans, and US $2.19 billion annually for winter wheat. US agriculture row crop production relies heavily on the use of pesticides. In 2020, 78.4 million acres (94.3% of the total planted acres) of soybeans [Glycine max (L.) Merr] were treated with herbicides and, in 2021, 82.51 million acres (88.4% of the total planted acres) of corn (Zea mays L.) were treated with herbicides (USDA-NASS 2020, 2021). In light of the intense scrutiny of pesticide use in agriculture, it is crucial to make a concerted effort to optimize each application. The effectiveness of herbicide application significantly affects crop yield. Insufficient use of herbicides results in ineffective weed control and the potential development of weed resistant issues (Vieira et al., 2019). On the other hand, excessive application leads to increased costs, potential crop damage, and environmental concerns (Ozkan, 1987). The primary goal of pesticide applications is to deliver the smallest feasible quantity of active ingredients (a.i.) and/or acid equivalents (a.e.) that will effectively produce the intended biological effect on pests, including weeds, insects, and diseases, while ensuring safety and cost-effectiveness (Hislop, 1987). Pesticide applications are complex operations that require meticulous attention to achieve optimal results (Ebert et.al., 1999). However, a survey of ground and aerial herbicide application practices conducted in the state of Arkansas (USA) revealed that only 28% of respondents (applicators) are knowledgeable about spray nozzles (Butts et al., 2021). Furthermore, a study from Missouri found that 62% of commercial and 73% of noncommercial applicators change nozzles less than 50% of the time when switching herbicide products (Bish and Bradley, 2017). Consequently, inaccurate pesticide applications may occur due to undiagnosed issues, such as nozzle wear, incorrect sprayer setup, and incorrect nozzle selection (Ozkan et al., 1992a, 1992b; Forney et al., 2017; Klein and Kruger, 2011). The recognition of the negative effects of agricultural operations on the environment has significantly influenced the development of precision crop protection (Oerke et. al., 2010). It is imperative to optimize pesticide applications in order to minimize the risk of environmental contamination and enhance pesticide effectiveness. The use of site-specific application technology, such as spot-sprayers, will be crucial in agricultural research and practice in the future since it will help improve efficiency and decrease the total area treated with chemical-synthetic herbicides (Spaeth et. al., 2024). The effectiveness of site-specific weed management strategies relies on some factors, such as maximizing biological effect of herbicides, environmental contaminations, and cost (Butts et. al., 2019). Both preemergence and postemergence herbicide treatments can be used in site-specific herbicide applications. Usually, the features considered to perform preemergence variable rate applications are soil organic matter and soil texture (Mohammadzamani et al. 2009; Gundy, & Dille, 2022). Conversely, postemergence variable-rate herbicide applications consider the spatial variability and temporal dynamics of weed populations. The economic attractiveness of postemergence variable rate herbicide applications depends on the area within a field with weed densities below the economic threshold (Gerhards et al., 2022).

Spray coverage and pattern uniformity of spot-spray applications with a one or two-boom spray system

Pesticides are usually applied as a spray solution that covers the entire or a portion of the intended target (such as insects, leaves, or other plant components) with pesticide-containing droplets (Dorr et al., 2013). This solution is atomized by hydraulic nozzles, creating a heterogeneous mixture of droplet sizes within the spray pattern (Matthews et. al., 2014). In agricultural pesticide applications, carrier volume and spray droplet generally constitute the main components affecting the target spray coverage. The size of spray droplets is crucial in pesticide applications and can influence herbicide effectiveness (Ebert et. al., 1999; Butts et. al., 2018). Previous research has demonstrated that the efficacy of herbicides typically increases as droplet size decreases (McKinlay et. al., 1974, Knoche, 1994; Butts et. al., 2018), however the risk of herbicide spray drift on non-target areas also increases as droplet size decreases (Bueno, da Cunha, & de Santana, 2017; Butts et. al., 2018). Droplet size can be influenced by multiple factors including adjuvants (Sijs and Bonn, 2020), nozzle design, nozzle orifice size, and application pressure (Creech et. al., 2015a; Nuyttens et. al., 2007). In addition to droplet size, carrier volume is an important factor affecting herbicide coverage (Creech et. al., 2015b). This is expected since reduced carrier volume results in reduced spray coverage on the target weed species (Butts et. al., 2018). It is suggested to use a higher carrier volume to enhance the effectiveness of contact herbicide products. On the other hand, carrier volume has a lesser impact on the effectiveness of systemic herbicides (Creech et. al., 2015b). To effectively apply herbicides, the appropriate amount of chemical must be applied uniformly from the spray boom to the target surface. Appropriate spray coverage is essential for maximizing the effectiveness of spray applications and it is directly affected by spray pattern uniformity (Matthews et. al., 2014). Many studies have been conducted to access spray pattern distribution of hydraulic nozzles (Etheridge et al., 1999; Butts et. al., 2019; Forney et. al., 2017). Herbicides are usually applied uniformly over predetermined area (e.g. field) with a consistent carrier volume and dose. However, the uneven dispersion of weeds in agricultural fields allows for site-specific weed management strategies, which could result in significant reductions in herbicide usage and provide economic and ecological benefits (Oerke, 2010). Environmental concerns and growing awareness of the potential negative implications of agricultural operations are pushing modifications in pest management strategies. Among these changes is the development and adoption of precision crop protection strategies, such as spot-spraying and/or variable-rate herbicide spraying (Oerke, 2010). Herbicide savings using a site-specific weed management spot-spraying technology is highlighted in a European study by Spaeth et. al., 2024. Even flat-fan nozzles are designed for precise and targeted applications, delivering uniform coverage on specific areas or rows, while broadcast spray nozzles are suitable for covering larger areas uniformly, such as entire fields or broad target areas. (Hassen, Sidik, & Sheriff, 2013). Even flat-fan nozzles are being recommended for precise spot-spray applications as they ensure an even distribution of spray droplets throughout the spray pattern. This minimizes the number of nozzles activated on the spray boom and consequently reduces the occurrence of low pesticide dose outside target areas (Rasmussen et al., 2020; Villette et al., 2021). Some sprayers equipped with two tank-two boom systems have the ability to spot-spray and broadcast apply simultaneously. Currently, little to no research has been conducted to investigate the application parameters, such as spray coverage and pattern uniformity, of even flat-fan nozzles in spot spray applications.

Effect of weed size and application rate on the control of different postemergence herbicides and weed species

Herbicide treatments in crop production fields are usually applied as a broadcast spray operation, ensuring a uniform distribution of spray volume and herbicide dosage across the entire field. Preemergence herbicides are commonly used prior to weed germination, typically before or shortly after crop planting. Postemergence herbicides are applied after the weeds emerge usually when the crop is already growing. Weed populations in crop production fields do not usually occur uniformly throughout the area but are rather found in distinctive patches of varying size, density, and growth stage. (Gerhards & Christensen 2003; Oerke, 2010). In a survey of 12 crop fields in Nebraska, it was found that 30% of the total field area was free of broadleaf weeds, while 70% of the area did not have any grassy weeds (Johnson et al., 1995). Traditional chemical weed control methods, such as broadcast herbicide applications, do not consider the differences in weed populations across space. This leads to either using too much or too little herbicide, which can be expensive, ineffective, and harmful to the environment (Oerke et al., 2010). Some of these challenges could be addressed by site-specific weed management (SSWM) technologies, such as patch or spot spraying. The use of remote sensing with aerial or ground-based sensors, have facilitated the detection of variations within fields, resulting in the development of intelligent sprayers that can spot spray and adjust application rates based on the identified weed population (Oerke et al. 2010; Christensen, 2009; López-Granados; 2011;). To establish an effective postemergence weed management program to reduce pesticide inputs in agriculture, it is important to estimate weed populations on a field scale (Marshall, 1988; Klingaman et. al., 1992; Oerke et al. 2010). Determining the optimal amount of active ingredient (a.i.) and or acid equivalent (a.e.) required to achieve the desired biological response in weeds can lead to more precise and efficient pesticide spray applications. Herbicide effectiveness is determined by the weed spectrum, selected herbicide dose level, weed infestation level, and weed growth or development stage at application time (Dieleman et al. 1998). The initial effect of any herbicide application is a decrease in weed pressure. Changes in weed biomass, density, and leaf area serve as qualitative and quantitative indicators of this reduction in weed pressure (Dieleman et al. 1998). Dose-response studies offer a quantitative evaluation of herbicide effectiveness across various dosages (Knezevic, Streibig, & Fuerst, 1995; Dieleman et. al. 1998). In trials conducted by Jensen and Kudsk (1988), parallel displacements of dose-response curves demonstrated the effect of three different weed growth stages on herbicide efficacy. The development of new technologies in agriculture, such as site-specific spot spray herbicide applications, opens several possibilities to improve crop protection operations. This thesis will provide research findings addressing spray coverage and pattern uniformity of spot-spray applications in a one or two-boom spray system and weed sensitivity to post emergence herbicides influenced by weed size and herbicide rate controlled by a pulse width modulation system. Therefore, objectives of the present studies were to assess spray coverage and pattern uniformity of even flat-fan nozzles in spot spray applications using a one or two-boom spraying system and evaluate the effect of weed size and herbicide application rate on the control of multiple weed species. This research not only helps to promote sustainable agricultural practices, but it also develops strategies aimed at novel site-specific weed management technologies.

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CHAPTER 2

Spray coverage and pattern uniformity of even flat-fan nozzles in spot spray applications with a one or dual-boom spray system.

Abstract

Chemical weed control in row crops is usually performed as a broadcast application (i.e., whole field treatment) using standard broadcast flat fan nozzles. Previous studies using site-specific weed management have shown up to a 75% herbicide reduction compared to broadcast applications. Spot spraying application technology is an alternative to broadcast herbicide application, spraying only parts of the field where weeds are present. Even flat-fan nozzles are being considered for targeted applications in some of the newly developed spot sprayers. Some sprayers equipped with dual-tank dual-boom systems have the ability to spot-spray and broadcast apply simultaneously. Understanding the spray coverage of even flat-fan nozzles and their interactions with broadcast nozzles is crucial for optimizing spray applications. The objective of the study was to evaluate even flat-fan nozzle spray coverage and pattern uniformity for spot spraying applications with a one-boom (even flat-fan nozzle) or two-boom (even flat-fan nozzle + broadcast flat-fan nozzle combination) system. Laboratory studies were conducted at the University of Nebraska – Lincoln's West Central Research, Extension and Education Center in North Platte, NE. Spray solutions were applied using a three-nozzle research spray chamber. For the spot-spray treatments, we evaluated the AI6502E and TP6502E (Teejet® Technologies)

even-flat fan nozzles. The broadcast treatments were assessed using the TT11002, AIXR11002, TTI11002, TT11006, AIXR11006, and TTI11006 (Teejet® Technologies) nozzles. All spot-spray treatments were sprayed at angles of 0° and 30° rearward to evaluate the impact of nozzle angle on coverage and spray pattern distribution. Our findings highlight the complex interaction of various application parameters and their combined impact on spray coverage and pattern distribution (CV) of even flat-fan nozzles. Changing the nozzle rearward angle from 0° to 30° always resulted in decreased spray coverage and CV always increased as boom height decreased. The results contribute to more efficient and effective pesticide applications, offering guidance for manufacturers, researchers, and practitioners seeking to enhance precision spraying technologies.

Introduction

Herbicides are usually applied uniformly over predetermined areas (e.g. field) with a consistent carrier volume and dose. However, the uneven dispersion of weeds in agricultural fields allows for site-specific weed management strategies, which could result in significant reductions in herbicide usage and provide economic and environmental benefits (Oerke, 2010; San Martín, 2016; Anita Dille, 2002)**.** In modern agricultural practices, precision and targeted approaches have become paramount for effective weed management while minimizing environmental impact and optimizing resource utilization. (Oerke, 2006; Oerke et. al., 2010). The rapid evolution of spraying technologies has transformed pesticide application methods, allowing growers to achieve greater precision and efficiency in weed control (Gerhards et al., 2022). These technologies include a variety of innovations, such as advanced nozzle designs, variable rate application systems, and digital mapping capabilities, which allow for targeted herbicide applications (Vogel, Wolf, & Dille, 2005; Gerhards, & Christensen, 2003). Site-specific weed control technologies refer to machinery or equipment that detects and manages weeds in crops while taking economic factors into account. They incorporate site-specific data on weed distribution, species composition, density, and crop yield to ensure effective weed management and maximum crop yield. (Christensen et al., 2009; Rider et al., 2006). Spot spraying has emerged as a promising method in precision agriculture, offering targeted weed control while minimizing herbicide usage. By focusing herbicide applications only where weeds are present, spot spraying reduces overall herbicide quantities, mitigating environmental, agronomical, and economic impacts (Felton, & McCloy,1992; Villette et al., 2022). Spray coverage is an important factor in determining herbicide efficacy because it directly influences the amount of chemical active ingredient and/ or equivalent acid that reaches and interacts with the target weed surface. Carrier volume and spray droplet size are typically the primary factors influencing the amount of target spray coverage in agricultural pesticide applications. The efficacy of herbicides can be significantly impacted by the size of the spray droplets (Butts et al., 2018; Legleiter, & Johnson, 2016). Spray nozzles that produce larger droplets (such as air induction design nozzles) are often recommended to minimize drift, although it is well documented that increasing droplet size generally decreases herbicide coverage and herbicide performance (Knoche, 1994; Legleiter, 2018). Previous research has suggested that higher carrier volume enhances the effectiveness of postemergence contact herbicide products. On the other hand, carrier volume has lesser impact on the effectiveness of systemic herbicides (Creech et al., 2015). Appropriate spray coverage is essential for both systemic and contact herbicides and it’s directly affected by spray pattern uniformity (Matthews et. al., 2014). For many years, spray pattern testing has been carried out using patternators to assess the spray distribution of nozzles. This distribution is typically quantified as the coefficient of variation (CV) (Forney et al, 2017). Even flat-fan nozzles are designed for precise and targeted applications, delivering uniform coverage on specific areas or rows, while broadcast spray nozzles are suitable for covering larger areas uniformly, such as entire fields or broad target areas (Hassen, Sidik, & Sheriff, 2013). Even flat-fan nozzles are being recommended for precise spot-spray applications as they ensure an even distribution of spray droplets throughout the spray pattern. This prevents excessive activation of nozzles in the spray boom and consequently reduces the occurrence of incorrectly sprayed areas outside of weed patches (Rasmussen et al., 2020; Villette et al., 2021). Some sprayers equipped with dual-tank dual-boom systems have the ability to spot-spray and broadcast apply simultaneously. Little to no research has been conducted to investigate spray coverage and pattern uniformity of even flat-fan nozzle employed in spot spray applications. Therefore, the objective of this research was to evaluate spray coverage and pattern uniformity of even flat-fan nozzles for use in spot spray applications using a one or two-boom spraying system.

Materials and methods

The studies were conducted at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research, Extension, and Education Center of the University of Nebraska – Lincoln in North Platte, NE, during the winter of 2022.

Two-boom simulation spray coverage study

The treatments were categorized as spot-spray (spot), broadcast-spray (broadcast), and a combination of broadcast followed by a spot-spray (dual). For the spot-spray treatments, we evaluated the AI6502E and TP6502E (Teejet® Technologies) even-flat fan nozzles. The broadcast treatments were assessed using the TT11002, AIXR11002, TTI11002, TT11006, AIXR11006, and TTI11006 (Teejet® Technologies) nozzles. Spray solutions were applied using a three-nozzle research spray chamber (DeVries Manufacturing, Hollandale, Minnesota, 56045). On the spot-spray treatment boom setup, we utilized only the center nozzle to perform the application, while the adjacent nozzles were sealed with Teejet® shutoff nozzle caps. The spot-spray treatment nozzles were calibrated to deliver 140 L ha^{-1} and 187 L ha^{-1} at 310 kPa, employing the even flat-fan nozzles listed above. The broadcast treatment boom setup employed three nozzles spaced 50 cm apart across the boom for application. The spray chamber was calibrated to deliver 140 L ha^{-1} and 187 L ha^{-1} at 310 kPa, employing the broadcast flat-fan nozzles listed above. The dual treatments combined broadcast spraying of 140 L ha^{-1} followed by a spot-spraying of 47 L ha^{-1} (total of 187 L ha^{-1}), and a broadcast spraying of 70 L ha^{-1} followed by a spot-spraying if 70 L ha^{-1} (total of 140 L ha^{-1}). All spot-spray treatments were sprayed at rearward angles of 0° and 30° to evaluate the impact of nozzle angle on coverage and spray pattern distribution. Table 1 lists all treatment combinations. Spray coverage collectors were made from Kromekote® photo paper, measuring 21.59 cm x 27.94 cm (603.22 cm2). Cards were sprayed with a spray solution of water and 3 g L^{-1} of Brilliant Blue FCF (Spectra Colors Corporation, Kearney, New Jersey 07032) dye. To simulate the different boom setups, one or two passes were sprayed over sets of Kromekote® cards. To collect spray coverage, Kromekote® cards were horizontally positioned at 60 cm under the spray boom and placed vertically in five positions side-by-side on the spray chamber table to collect the application swath (figure 1).

Table 1. operational parameters tested: methods, nozzles, nozzle rearward angle, and volume.

Method	Nozzle	Nozzle rearward angle	Carrier volume
			-- L ha^{-1}--
Spot	AI6502E	0°	140
	TP6502E	0°	140
	AI6502E	30°	140
	TP6502E	30°	140
	AI6502E	0°	187
	TP6502E	0°	187
	AI6502E	30°	187
	TP6502E	30°	187
Broadcast	AIXR11002	-	140
	TT11002	-	140
	TTI11002	-	140
	AIXR11006	-	187
	TT11006	-	187
	TTI11006	-	187
Dual	AIXR11002 + AI6502E	0°	70 + 70
	TT11002 + AI6502E	0°	70 + 70
	TTI11002 + AI6502E	0°	70 + 70
	AIXR11002 + AI6502E	30°	70 + 70
	TT11002 + AI6502E	30°	70 + 70
	TTI11002 + AI6502E	30°	70 + 70
	AIXR11002 + TP6502E	0°	70 + 70
	TT11002 + TP6502E	0°	70 + 70
	TTI11002 + TP6502E	0°	70 + 70
	AIXR11002 + TP6502E	30°	70 + 70
	TT11002 + TP6502E	30°	70 + 70
	TTI11002 + TP6502E	30°	70 + 70
	AIXR11006 + AI6502E	0°	140 + 47
	TT11006 + AI6502E	0°	140 + 47
	TTI11006 + AI6502E	0°	140 + 47
	AIXR11006 + AI6502E	30°	140 + 47
	TT11006 + AI6502E	30°	140 + 47
	TTI11006 + AI6502E	30°	140 + 47
	AIXR11006 + TP6502E	0°	140 + 47
	TT11006 + TP6502E	0°	140 + 47
	TTI11006 + TP6502E	0°	140 + 47
	AIXR11006 + TP6502E	30°	140 + 47
	TT11006 + TP6502E	30°	140 + 47

	TTI11006 + TP6502E	30°	140 + 47

Single even-flat fan nozzle study

To perform spray applications, the AI6502E and the TP6502E even flat-fan nozzles (Teejet® Technologies) were utilized. The experimental treatments involved varying three parameters: boom height (25 cm, 50 cm, and 75 cm), nozzle angle (0° and 30° rearward), and carrier volume (47, 70, 95, 140, and 184 L ha^{-1}). These parameters were chosen to simulate a range of operational conditions commonly encountered in agricultural spraying. All treatment combinations are detailed in Table 2 to provide clarity on the experimental structure and relationships between the variables.

Table 2. nozzles and operational parameters tested: boom height, nozzle rearward angle, and carrier volume.

Nozzle	Boom height	Nozzle Rearward Angle	Carrier volume
	--- cm ---		-- L ha^{-1} --
AI6502E and TP6502E	25	0°	47
			70
			95
			140
			187
		30°	47
			70
			95
			140
			187
	50	0°	47
			70
			95
			140
			187
		30°	47
			70
			95
			140
			187
	75	0°	47
			70
			95
			140
			187
		30°	47
			70
			95
			140
			187

Figure 1. Inside view of the spray chamber showing the arrangement of kromekote cards for spray application

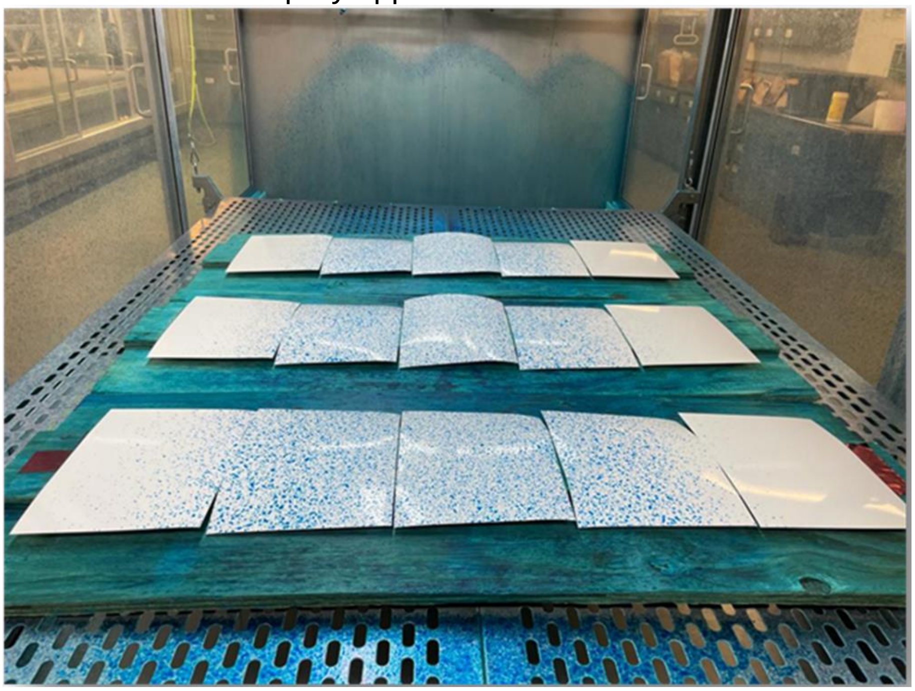
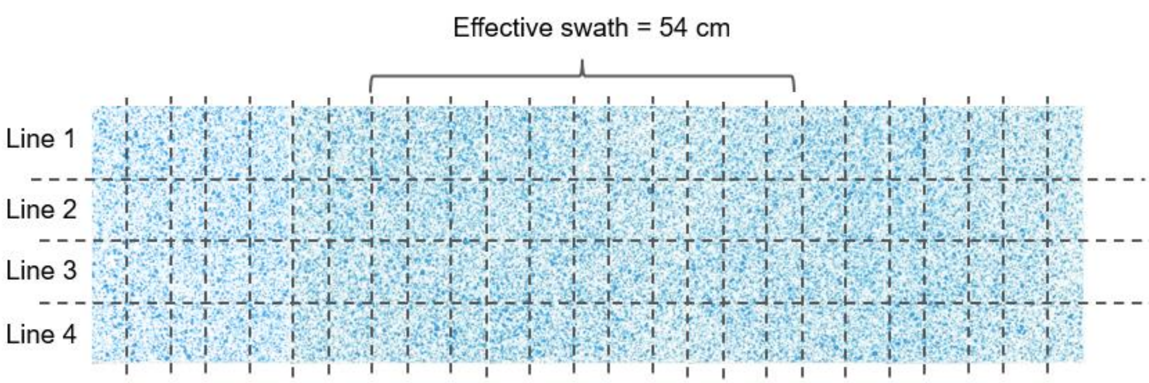


figure 2. layout of kromekote cards for coverage and spray pattern analysis



Data analysis

Each sprayed card was dried and separately scanned using an Epson V600 Photo scanner (Epson Europe B.V., Atlas Arena, Asia Buikding, Hoogoorddreef 5 1101 BA Amsterdam The Netherlands) at 31.5 dots mm^{-1} (equivalent to 800 dots $inch^{-1}$). Scanned cards were analyzed for percent spray coverage using the AccuStain 0.32 (version 2) software. Each 603.2 cm^2 card (21.6 cm x 27.9 cm) was partitioned into twenty grids of 29.2 cm^2 (4.3 cm x 6.8 cm), arranged systematically by line and position. Sets of five cards generated four lines with twenty-five positions (4.3 cm x 6.8 cm grids) per line (figure 2). Inferences were made on a 54 cm swath area beneath the center spray nozzle (27 cm on each side) to minimize edge effects of spray distribution. Percent spray coverage and spray pattern uniformity were quantified across the 54 cm swath area. Spray pattern uniformity was quantified by calculating the coefficient of variation (CV), defined as the standard deviation divided by the mean (equation [1]).

$$[1]\ CV = \left(\frac{standard\ deviation}{mean}\right) x100$$

The single even flat-fan nozzle study was designed to investigate the influence of nozzle rearward angle, and boom height variations on spray coverage and spray pattern distribution (CV) across different carrier volumes. CV results are presented in tables 5 and 7 for the TP6502E and AI6502E nozzles respectively. Interactions between nozzle rearward angle and boom height (angle * height) were analyzed for the different carrier volumes.

The two-boom simulation spray coverage study was designed to assess coverage and CV of even flat-fan nozzles in a one or two-boom application method. On the two-boom simulation spray coverage trials the main factors method (Spot, Broadcast, and Dual), nozzle rearward angle (0° and 30°), and its interactions (method * angle) were separated by GPA (140 L ha^{-1} and 187 L ha^{-1}). Results from both studies were submitted to ANOVA using the analysis of variance function, and Tukey HSD multiple comparison tests were performed using the Estimated Marginal Means package (Searle, 1980). Visualization of results was achieved using ggplot2 (Wickham, 2016) in R packages in RStudio (R Core Team 2022)

Results and discussion

The CV is a commonly used technique for evaluating the consistency of spray pattern distribution, which measures the level of variation across the entire spray boom. Greater CV values indicate increased variability within the pattern. A CV below 10% indicates a desirable level of uniformity, while a CV between 11% and 15% is considered acceptable. However, a CV above 15% is considered unacceptable. (Ozkan et al., 1992; Krishnan et al, 1988; Siebe, & Luck 2016; Forney et al, 2017).

Single even flat-fan nozzle study

The data analysis revealed a statistically significant interaction (p-value < 0.05) between the nozzle rearward angle * boom height across carrier volumes, affecting both spray pattern distribution and coverage (tables 5, 6, 7, and 8). Furthermore, carrier volume was a significant factor influencing spray pattern distribution (CV) across different nozzle rearward angles and boom heights. These interactions emphasize the complex relationship between these factors and their collective influence on spray coverage and spray pattern distribution for even flat-fan nozzles. Overall, regardless of nozzle type (AI6502E and TP6502E), nozzle rearward angle (0° and 30°), and the carrier volume (47, 70, 95, 140, and 187 L ha^{-1}) tested, the highest spray coverage and the highest CV values were observed at 25 cm boom height. On the other hand, the lowest spray coverage and lowest CV values were observed at 50 cm and 75 cm boom height. (tables 5, 6, 7, and 8).

Spray pattern uniformity

Spray pattern uniformity (CV) varied depending on the nozzle type, rearward angle, boom height, and carrier volume. When using the TP6502E nozzle at a 25 cm boom height, there was a consistent increase in CV as carrier volume increased, regardless of nozzle rearward angle. However, at boom heights of 50 cm and 75 cm, CV decreased with increasing carrier volume. A similar trend was observed for treatments using the AI6502E nozzle at the 25 cm boom height, although there were no significant changes in CV as carrier volume increased at 50 cm and 75 cm boom heights.

25 cm boom height.

When testing the TP6502E nozzle at a 0° rearward angle and 25 cm boom height, the CV values ranged from 39% to 56% (17% increase) as carrier volume was increased from 47 L ha^{-1} to 187 L ha^{-1}. At a 30° rearward angle and the same boom height, CV ranged from 30% to 42% (a 12% increase) as carrier volume was increased from 47 L ha^{-1} to 187 L ha^{-1}. This indicates that changing the nozzle rearward angle from 0° to 30° decreased total CV variations by 5%. A similar effect was observed for the AI6502E nozzle at 25 cm boom height. Treatments sprayed with the AI6502E nozzle at 0° rearward angle and 25 cm boom height, the CV values ranged from 33% to 53% (20% increase) as carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1}. At 30° rearward angle, the CV value ranged from 27% to 42% (15% increase) as carrier volume increased from

47 L ha^{-1} to 187 L ha^{-1}. It was observed that changing the nozzle rearward angle from 0° to 30° also lowered total CV variation by 5% (table 7).

50 cm boom height.

For the TP6502E nozzle at a 0° rearward angle, CV values ranged from 19% to 9% (a 10% decrease) as carrier volume increased from 47 L ha-^{1} to 187 L ha^{-1}. Similarly, at a 30° rearward angle, CV ranged from 19% to 7% (a 12% decrease) as carrier volume increased from 47 L ha-^{1} to 187 L ha^{-1}. This demonstrates that changing the rearward nozzle angle from 0° to 30° at a 50 cm boom height led to a 2% reduction in total CV variation. While carrier volume increase had significant impact on CV variation for the TP6502E nozzle at 50 cm boom height, no significant decrease in CV was observed when altering nozzle rearward angle from 0° to 30°.

For the AI6502E nozzle at a 0° rearward angle, the CV initially increased from 22% at 47 L ha^{-1} to 30% at 70 L ha-1, however consistent CV values (32%) were observed from 70 L ha-1 up to 187 L ha^{-1}. On the other hand, at a 30° rearward angle, CV had a small variation from 18% at 47 L ha-1 to 16% at 187 L ha^{-1}. This represents an average CV decrease of 11% when changing nozzle rearward angle from 0° to 30° at 50 cm boom height. Interestingly, while carrier volume had little impact on CV variations for the AI6502E nozzle at 50 cm boom height, there was a significant decrease in CV when altering the rearward angle from 0° to 30°. The influence of nozzle angle orientation was also analyzed by Yates et al (1983) and similar results were found by Krishnan et al., (1989) when testing spray pattern displacement with different nozzle rearward angle for TK-SS2.5

flood tip nozzles. That is explained by the increase in nozzle pattern size when angling nozzle in spray operations, consequently increasing the size of the spot to be treated. Also angled nozzle showed to enhance pesticide coverage depending on the architecture of the biological target to be treated (White et al., 2023).

75 cm boom height.

Evaluating the TP6502E nozzle at a 0° rearward angle, the CV initially decreased from 21% at 47 L ha^{-1} to 12% at 70 L ha^{-1}, but consistent CV values were maintained (12%) up to 187 L ha^{-1}. At a 30° rearward angle, the CV decreased from 27% at 47 L ha^{-1} to 18% at 70 L ha^{-1}, and then further decreased to 11% at 95 L ha^{-1}. From 95 L ha^{-1} up to 187 L ha^{-1}, CV exhibited a minor variation, ranging between 11% and 14%. Changing the TP6502E rearward angle from 0° to 30° at a 75 cm increased led to an increase in CV at lower carrier volumes (47 L ha^{-1} and 70 L ha^{-1}) compared to the 0° angle configuration. However, at medium to high carrier volumes (95 L ha^{-1}, 140 L ha^{-1}, and 187 L ha^{-1}), the CV values remained relatively consistent between the two rearward angles (table 5). The AI6502E nozzle, positioned at both 0° and 30° rearward angles with a 75 cm boom height, consistently demonstrated low CV variations across varying carrier volumes. Specifically, at a 0° rearward angle, the CV ranged from 16% to 13%, with the highest CV values observed at 70 L ha^{-1} and 95 L ha^{-1}, and the lowest values observed at 147 L ha^{-1} and 187 L ha^{-1}. At a 30° rearward angle, the CV ranged from 12% to 17%, with the highest CV values observed at 95 L ha^{-1}, and the lowest values observed at 47 L ha^{-1} and 87 L ha^{-1}. We observed an 1% average reduction in CV across all carrier volumes tested when we changed the nozzle rearward angle from 0° to 30°.

Spray coverage.

Lower boom heights and higher carrier volumes consistently resulted in increased spray coverage for both nozzles and rearward angles tested (tables 6 and 8). Across both AI6502E and TP6502E nozzle types, a consistent trend emerged where spray coverage decreased as boom height increased and the nozzle angle changed from 0° to 30°. The highest spray coverage was consistently achieved at a 0° nozzle rearward angle and 25 cm boom height. In contrast, the lowest coverage was consistently noted at a 30° nozzle rearward angle and 75 cm boom height.

25 cm boom height.

TP6502E nozzle at a 0° rearward angle presented a spray coverage variation from 30% to 55% as the carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1} (table 6). Conversely, at a 30° rearward angle, spray coverage ranged from 24% to 63% under the same circumstances. A 6-8% drop in spray coverage was observed at carrier volumes of 47 L ha-1, 70 L ha^{-1}, and 95 L ha^{-1} when the nozzle angle changed from 0° to 30°. However, at a carrier volume of 140 L ha^{-1}, spray coverage remained consistent for both nozzle angles, while at 187 L ha^{-1}, the spray coverage increased by 11% when the nozzle was adjusted to a 30° rearward angle (table 6).

The AI6502E nozzle at a 0° rearward angle exhibited a spray coverage varied from 20% to 51% as the carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1}. at a 30° rearward angle, spray coverage ranged from 13% to 50% across the tested carrier volumes. 7% decrease in spray coverage was observed at carrier volumes of 47 L ha^{-1}, 70 L ha^{-1}, and 95 L ha^{-1}, while there was only a 1% variation in spray coverage from a 0° to a 30° nozzle angle at 140 L ha^{-1} and 187 L ha^{-1} carrier volumes (table 8).

50cm boom height

The TP6502E nozzle at a 0° rearward angle showed a variation in spray coverage, ranging from 20% to 68% as the carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1} at the 50 cm boom height. On the other hand, at a 30° rearward angle, the spray coverage ranged from 13% to 58% over the same carrier volume range. We observed an 8% average reduction in spray coverage across all carrier volumes tested when we changed the nozzle rearward angle from 0° to 30° (table 6). Using the AI6502E nozzle at a 0° rearward angle, spray coverage ranged from 12% to 45%, from 47 L ha^{-1} to 187 L ha^{-1}. At a 30° rearward angle, spray coverage ranged from 8% and went up to 38%, from 47 L ha^{-1} to 187 L ha^{-1}. We observed a 6% average reduction in spray coverage across all carrier volumes tested when we changed the nozzle rearward angle from 0° to 30° (table 8).

75 cm boom height

For the TP6502E nozzle at a 0° rearward angle, spray coverage values ranged from 14% to 49% as carrier volume increased from 47 L ha^{-1} to 187 L ha^{-1}. At a

30° rearward angle, spray coverage ranged from 10% to 43% with the same increase in carrier volume. Changing nozzle angle rearward from 0° to 30° led to an average 6% reduction in total spray coverage variations across all carrier volumes applied using the TP6502E nozzle (table 6). Using the AI6502E nozzle at a 0° rearward angle, spray coverage ranged from 8% to 36%, from 47 L ha^{-1} to 187 L ha^{-1}. At a 30° rearward angle, the variation started at 6% and went up to 26% under the same carrier volume increase. Similarly to the TP6502E results, an average 6% reduction in total spray coverage variations across all carrier volumes by changing nozzle angle from 0° to 30° applied using the AI6502E nozzle (table 8).

In field-scale pesticide application operations, the sprayer may experience high fluctuations in boom height relative to the spray target, depending on the topographic conditions of the field (Lardoux et al., 2007; Wang & Wang, 2018). This study's findings provide valuable insights into how variations in boom height and nozzle rearward angle conditions may affect spray coverage and pattern uniformity in spot spray operations using even flat-fan nozzles. To ensure consistent and efficient treatment across target areas, we must balance high spray coverage, an important factor in spray operations, with maintaining uniform spray patterns (low CV) as lower CV values are associated with uniform spray pattern distribution (Ozkan et al., 1992; Krishnan et al, 1988). At a 25 cm boom height, both the TP6502E and AI6502E nozzles exhibited their highest spray coverage and coefficient of variation (CV) values, suggesting that this boom height does not offer an optimal balance between coverage and pattern uniformity. Conversely, at a 50 cm boom height, there was a decrease in both spray coverage and CV values for both nozzle types, indicating a more consistent droplet distribution. Research conducted by Negrisoli et al. (2021) demonstrated that herbicide spraying utilizing angled nozzle designs did not decrease overall weed control when compared to horizontal flat-fan nozzle designs

Table 5. Coefficient of variation data for TP6502E nozzle at different rearward angles, boom heights, and carrier volumes.

	Rearward angle (degrees)					
	0°			30°		
	Boom height (cm)					
Volume	25	50	75	25	50	75
l ha^{-1}	--- % ---			--- % ---		
47	39 aA	19 aB	21 aB	30 aD	19 aB	27 aD
70	38 aA	16 aB	12 bC	33 aD	18 aB	18 bB
95	40 aA	11 bB	12 bB	38 bA	12 bB	11 cB
140	49 bA	9 bB	12 bBC	42 cD	10 bcBC	14 bcC
187	56 cA	9 bBC	13 bC	42 cD	7 cB	14 bcC

Means followed by the same letter are not statistically different (p.value < 0.05); Lowercase = differences within column; Uppercase = differences within row

Table 6. Spray coverage data for TP6502E nozzle at different rearward angles, boom heights, and carrier volumes.

	Rearward angle (degrees)					
	0°			30°		
	Boom height (cm)					
Volume	25	50	75	25	50	75
l ha^{-1}	--- % ---			--- % ---		
47	30 A	20 B	14 C	24 D	13 C	10 E
70	42 A	30 B	20 C	37 D	21 C	15 D
95	51 A	43 B	26 C	43 B	29 D	19 E
140	55 A	61 B	39 C	56 A	44 D	31 E
187	54 A	68 B	49 C	63 D	58 E	43 F

Means followed by the same letter are not statistically different (p.value < 0.05); Uppercase = differences within row

Table 7. Coefficient of variation for AI6502E nozzle at different rearward angles, boom heights, and carrier volumes.

	Rearward angle (degrees)					
	0°			30°		
	Boom height (cm)					
Volume	25	50	75	25	50	75
l ha^{-1}	%			%		
47	33 aA	22 aB	15 aC	27 aD	18 aBC	12 aC
70	37 aA	30 bB	16 aC	29 aB	17 aC	14 aC
95	37 aA	32 bA	16 aB	37 bA	20 aB	17 aB
140	47 bA	32 bB	13 aC	41 cD	18 aC	14 aC
187	53 bA	30 bB	13 aC	42 cD	16 aC	13 aC

Means followed by the same letter are not statistically different (p.value < 0.05); Lowercase = differences within column; Uppercase = differences within row

Table 8. Spray coverage for AI6502E nozzle at different rearward angles, boom heights, and carrier volumes.

	Rearward angle (degrees)					
	0°			30°		
	Boom height (cm)					
Volume	25	50	75	25	50	75
l ha^{-1}	%			%		
47	20 A	12 B	8 C	13 B	8 C	6 C
70	28 A	17 B	13 C	21 D	12 C	9 E
95	36 A	23 B	16 C	29 D	16 C	11 E
140	46 A	33 B	26 C	45 A	28 C	19 D
187	51 A	45 B	36 C	50 A	38 D	26 E

Means followed by the same letter are not statistically different (p.value < 0.05); Uppercase = differences within row

Two-boom simulation spray coverage studies

Interaction Effects on Spray Coverage and Coefficient of Variation

The interaction of the main effects—nozzle rearward angle and application method (angle * method)—was found to be statistically significant for spray coverage ($p < 0.0001$). This indicates that the combination of these factors significantly affects the spray coverage. However, this interaction was not significant for the coefficient of variation (CV) ($p = 0.124$). In contrast, the main effect method alone had a significant effect on CV ($p < 0.0001$).

Impact of Nozzle Rearward Angle on Spray Coverage and CV

A decrease in spray coverage was observed with the spot spray (spot) method as the nozzle angle was adjusted from 0° to 30°. Specifically, this change resulted in a 7% decrease in spray coverage for the spot treatment at a carrier volume of 140 L ha^{-1} and an 8% decrease at 187 L ha^{-1} (Tables 3 and 4). However, no significant differences in spray coverage were observed in the dual boom system when the nozzle angle was adjusted.

Nozzles are typically adjusted to a rearward angle in spot-spray systems to increase the time between weed detection and nozzle activation. This extended time allows the sensor to process weed detection information and activate the nozzle for spot spraying. The results of this study highlight the tradeoffs of adjusting the nozzle rearward angle in spot spray operations, given the observed decrease in overall coverage. Although the nozzle reward angle led to reduced spray coverage on our spray collectors, Foqué and Nuyttens (2011) research demonstrated that angling the nozzles resulted in improved canopy penetration.

Method Comparison at 140 L ha^{-1} Carrier Volume

At a carrier volume of 140 L ha^{-1}, no significant differences in spray coverage were observed between the broadcast and dual methods, at both 0° and 30° rearward angles. However, the CV was statistically different, with the broadcast method exhibiting the highest CV. The spot method, at both angles, showed overall lower coverage and higher CV compared to the broadcast method (table 3).

Method Comparison at 187 L ha^{-1} Carrier Volume

At a carrier volume of 187 L ha^{-1}, the broadcast method demonstrated the highest spray coverage value. Similar coverage was observed for the spot and dual methods at both nozzle rearward angles. However, the highest CV was noted for the spot method, indicating greater variability in spray application (table 4).

The higher CV observed in the spot method highlights the need for further optimization to reduce variability in spray pattern distribution and enhance the effectiveness of spot-spraying.

As concluded by Villette et al. (2021), increasing the number of nozzles and reducing the total patch sprayed by each individual nozzle resulted in better weed control and less use of chemicals in spot-spray applications. Therefore, the use of narrower angle nozzles and narrower nozzle spacing might overcome high CV values observed in the spot method.

Table 3. Spray coverage and coefficient of variation (CV) at 140 L ha^{-1} for tested methods, nozzles, rearward angle, and volume.

Method	Rearward Angle	Spray coverage		CV	
		----------%----------			
Spot	0°	33	b	14	bc
	30°	26	a	15	c
Broadcast	0°	38	c	11	b
Dual	0°	37	c	8	a
	30°	35	bc	7	a

Means followed by the same letter or number are not statistically significant (p.value>0.05); lowercase letters = differences within column.

Table 4**.** Spray coverage and coefficient of variation (CV) at 187 L ha^{-1} for tested methods, nozzles, rearward angle, and volume.

Method	Rearward Angle	Spray coverage		CV	
		----------%----------			
Spot	0°	45	b	12	b
	30°	37	a	12	b
Broadcast	0°	50	c	7	a
Dual	0°	43	b	8	a
	30°	41	ab	6	a

Means followed by the same letter or number are not statistically significant (p.value>0.05); lowercase letters = differences within column.

Conclusions

Uniform spray pattern distribution and coverage is crucial for ensuring that herbicides are effectively distributed across target areas, maximizing efficacy and minimizing unintended crop damage (Wang et al., 1995, Butts et al., 2019). This study highlights the significant impact of operational factors such as application method, nozzle rearward angle, and boom height on spray coverage and pattern uniformity in spot spray operations.

The use of even flat-fan nozzles in spot-spray pesticide applications requires careful evaluation due to their reliance on minimal fan overlap. Our data demonstrated that 65° angle even flat-fan nozzles spaced at 50 cm are highly sensitive to boom height fluctuations, as observed by high CV values at a 25 cm boom height. This sensitivity can lead to uneven coverage and potentially uncontrolled weeds. Adjusting the nozzle angle to 30° rearward reduced the total sprayed area in all treatments with even flat-fan nozzles alone.

Furthermore, the dual boom system shows promise in mitigating application gaps caused by boom height fluctuations in spot-spray operations. This method exhibited lower CV values, indicating more consistent spray pattern distribution. These findings suggest that a dual boom system can enhance the effectiveness of spot-spray applications by ensuring more uniform coverage.

Future research should focus on narrower angle even flat-fan nozzles and reduced nozzles spacing to further explore the feasibility of using even flat-fan nozzles in spot-spray pesticide applications. Such studies will help refine application techniques, enhancing herbicide efficacy and operational efficiency in agricultural practices.

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CHAPTER 3: Effect of weed size and application rate on the control of different postemergence herbicides and weed species

Abstract

As application technology advances, the ability to deliver weed specific herbicide doses will likely become feasible. Determining susceptibility of weed species at different growth stages would allow for the use of precise and effective postemergence herbicide programs. This will help address environmental concerns, regulatory demands, and delay the evolution of herbicide resistance. The objective of this study was to evaluate the effect of weed size and herbicide application rate on the control of multiple weed species. Greenhouse studies were conducted at the University of Nebraska – Lincoln's West Central Research, Extension and Education Center in North Platte, NE using five weed species (palmer amaranth, *Amaranthus palmeri*; common waterhemp, *Amaranthus tuberculatus;* kochia, *Bassia scoparia;* giant ragweed, *Ambrosia trifida*; horseweed, *Erigeron Canadensis*; green foxtail, *Setaria viridis)* at three different heights. Postemergence herbicides consisted of glyphosate (Roundup Powermax 3), glufosinate (Liberty), dicamba (Engenia), 2,4-D (Enlist One), clethodim (Select Max), and topramezone (Armezon). Two different application methods were evaluated; the first maintained 140 L ha^{-1} carrier volume across the different herbicide doses and the second varied both herbicide rates with a pulse width modulation (PWM) rate controller system. The results indicated that weed species and growth stage significantly influenced herbicide efficacy. Lower doses were effective for some species and growth stages, while others required

higher doses for adequate control. Overall, 2,4-D and dicamba performed better on weeds, regardless of size, while glufosinate and glyphosate demonstrated a better performance on smaller weeds. Incorporating these findings into variable-rate herbicide management strategies can enhance application efficiency and reduce herbicide use, supporting the development of precision agriculture practices.

Introduction

Worldwide, corn and soybeans production is affected by competition from weeds. According to Oerke's (2006), the estimated yield loss from weeds in corn is 40% and is greater than the combined potential losses from viruses (3%), diseases (9%) and animal pests (16%). In soybean, weed competition reduces global production by about 37%, which is three times greater than the combined potential losses from viruses, diseases, and animal pests. For these crops, herbicides are the primary weed control tool, but they come with a significant economic cost to farmers. In the US, herbicides were applied to more than 94% of the soybean-growing area in 2020 and 8% of the corn-growing area in 2021. (USDA-NASS 2020, 2021). Usually, these herbicides are uniformly applied across a field as a broadcast spray that delivers a consistent volume and dose. Weeds are typically not evenly distributed throughout the field, but instead are found in distinct patches of varying size and density (Dille, 2002). In a survey of 12 crop fields in Nebraska, it was found that 30% of the total field area was free of broadleaf weeds, while 70% of the area did not have any grassy weeds (Johnson et al., 1995). The use of traditional chemical weed control measures, such as broadcast herbicide applications, may result in either an excessive or insufficient dosage, which can be expensive, ineffective, and environmentally hazardous (Oerke et al., 2010). Some of these challenges could be addressed by site-specific weed management (SSWM) technologies, such as spot-spraying. As concluded by Oerke et al. (2010), understanding the spatial and temporal variability of weed populations can lead to more effective control methods that use fewer herbicides, reduce residues in the environment and food chain. Site specific weed management technologies utilize machinery or equipment to detect weeds within the crop and take action to control them while taking into consideration factors such as economics and weed distribution across the field (Christensen, S. et al., 2009). While SSWM considers the spatial variability of weeds within the field, variable rate application (VRA) considers the heterogeneous features inside the spot to be treated, such as weed density and weed size (Oerke et al., 2010). Diverse agricultural processes, including seeding, fertilizing, irrigation, and crop protection, have utilized technologies to employ site-specific variable rate applications to deliver inputs using site specific quantities at the appropriate location and time. The use of mapping technology and sensors has enabled the identification of field heterogeneities, leading to the development of sprayers capable of adjusting the application rate according to the detected weed population (Oerke et. al, 2010). Multiple investigations have been conducted on the utilization of variable rate applications for post-emergence (POST) herbicides (Heisel et al. 1999, Gerhards et al. 2002, Dammer and Wartenberg 2007). Variable-rate pesticide applications can be achieved through various methods and technologies, including total flow control, twin fluid nozzles, variable orifice nozzles, multiple nozzle holders (VarioSelect®), Injection metering systems, and Pulse Width Modulation. (Oerke et al., 2010, Walker and Bansal 1999, Giles et al. 1996, Western et al. 1989, Grella et al. 2021). Application rate can be controlled by operational parameters, such as speed, pressure, nozzle spacing, and nozzle flow rate. Several factors, including application pressure and spray droplet size, can be standardized across a range of sprayer speeds using pulse-width modulation (PWM) systems, while flow can be varied to increase application precision (Butts et al. 2018). In a PWM system, nozzle flow is controlled by pulsing an electronically actuated solenoid valve placed directly upstream of the nozzle (Giles & Comino, 1989) and the relative time each solenoid valve is opened is called duty cycle (DC) (Butts et al. 2018). Establishing an effective herbicide program as part of an integrated weed management strategy requires determining the susceptibility of various weed species at different growth stages (Dieleman et al. 1998). More precise and efficient pesticide spray applications could be achieved by determining the right amount of active ingredient necessary to achieve the desired biological response on weeds. Many dose-response studies have been conducted to determine weed and/or crop susceptibility to herbicides. (Knezevic et al. 2009, Kruger et al. 2008, Sarangi et al. 2015, Faleco et al. 2022). Carrier volume, along with herbicide dose, significantly influences the effectiveness of post-emergence (POST) herbicide applications (Knoche 1994, Creech et al. 2015, Butts et al. 2018). However, the efficacy of pre-emergence (PRE) herbicide applications was less affected by the carrier volume (Striegel et al. 2021). Advancements in technology are revolutionizing modern agriculture, offering growers unprecedented tools to enhance weed management practices. To successfully implement spot-spray variable-rate herbicide application as part of a site-specific weed management strategy, it is critical to understand how different weed species at different growth stages respond to different herbicide rates. The objective of this study was to evaluate the effect of weed size and application method on the control of various weed species using a pulse width modulation system to control herbicide rate

Materials and Methods

Greenhouse bioassays

The studies were conducted over the fall of 2022, winter, and spring of 2023 at the Pesticide Application Technology Laboratory of the University of Nebraska – Lincoln, Located in North Platte, Nebraska, USA.

Pulse width modulation dose-response study

Treatments consisted of five POST emergence herbicides, five herbicide doses, five weed species, and three weed heights. Herbicide treatments included: glyphosate (Roundup PowerMAX® 3, 575 g ae L^{-1}, Bayer), glufosinate (Liberty® 280 SL, 280 g ai L^{-1}, Basf), dicamba (Engenia, 600 g ae L^{-1}, Basf), 2,4-D (Enlist One®, 455 g ae L^{-1}, Corteva™ agriscience), and clethodim (Select Max, 116 g ai L^{-1},Valent®). Weed species included: palmer amaranth, *Amaranthus palmeri*; common waterhemp, *Amaranthus tuberculatus*~~;~~ giant ragweed, *Ambrosia trifida*; horseweed, *Erigeron canadensis*; green foxtail, *Setaria viridis*. Herbicides were mixed in 3 L bottles at the full dose recommended by the manufacturer label and sprayed using the PWM system. Glyphosate was mixed at 13.2 g ae L^{-1} and applied at 1848, 1663, 1293, 924, and 554 g ae ha^{-1}, glufosinate was mixed at 6.3 g ai L^{-1} and applied at 879, 791, 615, 440, and 264 g ai ha^{-1}, 2,4-D was mixed at 7.6 g ae L^{-1} and applied at 1063, 957, 745, 531, and 319 g ae ha^{-1}, dicamba was mixed at 4 g ai L^{-1} and applied at 561, 504, 392, 280, and 168 g ae ha^{-1}, and clethodim was mixed at 1 g ai L^{-1} and applied at 140, 126, 98, 70, and 42 g ae ha^{-1}. To deliver different herbicide doses, the PWM DC was set to 100%, 80%, 60%, 40%, and 20%, respectively. Synthetic auxin herbicides, such as 2,4-D and dicamba, were applied only to broadleaf weed species and the ACCase inhibitor (clethodim) was only applied to green foxtail. All herbicides, except dicamba, were tank-mixed with sprayable Ammonium Sulfate (AMS) at 2% w/v (20 g L^{-1}) as a water conditioner. Plants were sprayed using a 1.67 x 4.2 m track spray chamber equipped with with a CapstanAG EVO Pulse Width Modulation (PWM) spray system and a TP6502E (Teejet®) nozzle at 275 kPa calibrated to deliver 140 L ha^{-1} at 100% DC. All plants were sprayed at 50 cm height from the spray nozzle tip to the top of the plant. Plants were applied in order from lowest to highest herbicide concentration and spray chamber was washed and flushed thoroughly between treatments to prevent cross-contamination. Three plants per treatment of giant ragweed and common waterhemp; and four plants per treatment of horseweed, green foxtail, and palmer amaranth were planted into cone pots filled with Pro-Mix BX5 (Premier Tech Horticulture Ltd, Rivière-du-Loup, Canada) general purpose growing medium to perform the experiment. To assess the effect of weed size on herbicide efficacy, all weeds were spayed at three different heights, classified as *S* (7-10 cm), *M* (15-20 cm), and *L* (25-30 cm). For horseweed, this approach was based on the plant diameter instead of height, where plants were sprayed at three different diameters classified as small (*S*) (2.5 - 5 cm), medium (*M*) (7-10 cm), and large (*L*) (12-15 cm). Plants were grown under controlled greenhouse conditions with a daytime temperature ranging from 26°C to 28°C degrees Celsius and a night temperature ranging from 18°C to 22°C degrees Celsius. The daylight period was extended to 16 hours using a LED light of 520 μmol s^{-1} (Philips Lighting, Somerset, NJ, USA). Plants were watered daily using a commercial liquid fertilizer (UNL 5-1-4; Wilbur-Ellis Agribusiness, Aurora, CO, USA) at 0.2% v v^{-1} incorporated with water. After spraying, plants were kept in the greenhouse and organized as a randomized complete block design. Visual injury estimation and aboveground plant biomass harvest were performed 21 days after the applications. Harvested material was kept in a drier at 65°C until constant weight was achieved.

Variable dose with PWM vs. variable dose with fixed volume study

This study employed two methods to change herbicide rate, the variable dose with fixed carrier volume and variable dose with PWM. The variable dose with fixed carrier volume method will be referred as conventional, and it changed the herbicide rate by adjusting the herbicide mix concentration. The variable dose with PWM will be referred to as PWM and used different duty cycles of a pulse width modulation system to change herbicide rates. This study focused on evaluating three postemergence herbicides: glyphosate, glufosinate, and 2,4-D, across three weed species: common waterhemp, palmer amaranth, and kochia, at two growth stages (8.6 cm and 17.6 cm). The conventional method maintained 140 L ha^{-1} carrier volume across the different herbicide rate treatments and the PWM method varied both herbicide rate and carrier volume using a PWM system. For the conventional method treatments, different bottles were mixed to adjust herbicide rate. Glyphosate was mixed at 6.5 g ae L^{-1} and applied at 920, 736, 552, and 368 g ae ha^{-}1, glufosinate was mixed at 3 g ai L^{-1} and applied at 440, 352, 264, and 176 g ai ha^{-1}, and 2,4-D was mixed at 4 g ae L^{-1} and applied at 532, 426, 319, and 213 g ae ha^{-1}. On the PWM method, different PWM duty cycles were used to adjust herbicide rate and treatments were sprayed at 140, 112, 84, and 56 L ha^{-1} carrier volume by adjusting PWM duty cycle to 100%, 70%, 50%, and 30%, respectively. Glyphosate was mixed to deliver 920 g ae ha^{-1} at 100% duty cycle, glufosinate was mixed to deliver 440 g ai ha^{-1} at 100% duty cycle, and 2,4-D was mixed to deliver 532 g ae ha^{-1} at 100% duty cycle and adjusted to the same rates used in the first method by adjusting carrier volume. All treatments were tank-mixed with sprayable Ammonium Sulfate (AMS) at 2% w/v (20 g L^{-1}) as a water conditioner. All plants were sprayed at 50 cm height from the spray nozzle tip to the top of the plant. Plants were applied in order from lowest to highest herbicide concentration and spray chamber was washed and flushed thoroughly between treatments to prevent cross-contamination. Five plants per treatment of *Amaranthus palmeri, Amaranthus viridis*, and *Bassia scoparia* were planted into cone pots filled with Pro-Mix BX5 (Premier Tech Horticulture Ltd, Rivière-du-Loup, Canada) general purpose growing medium.

Plants were grown under the same greenhouse conditions mentioned on the study above. To evaluate weed growth stage effect on herbicide efficacy, all weeds were sprayed at two different heights. One set was sprayed when plants were on average 8.6 cm and another set was sprayed when plants were an average of 17.8 cm. After spraying, plants were kept in the greenhouse with temperatures ranging from 21 to 26 °C and organized as a Randomized Complete Block Design. Visual injury estimation and aboveground plant biomass harvest were performed 28 days after the applications. Harvested material was kept in a drier at 65°C until constant weight was achieved and weighed.

Statistical analysis

Greenhouse biomass data over the two runs from both studies were analyzed with nonlinear regression using the *DRC package* (Ritz et al., 2015) in R (R Core Team 2022). Total plant biomass was analyzed to evaluate the response of each weed species at each different growth stage to the herbicide rate applied. Models were chosen based on the lowest Akaike information criterion (AIC) value in a model comparison and lack-of-fit test ($P \leq 0.05$) was performed to confirm nonlinear regression model fits. For the PWM dose response study, all total plant dry biomass was regressed against the herbicide dose expressed in grams of active ingredient and/or acid equivalent per hectare. The models tested were the three-parameter log-logistic dose-response model (equation [1]), the three-parameter log-normal dose-response model (equation [2]), four-parameter log-normal dose-response model (equation [3]), the four-parameter logistic dose-response model (equation [4]), and the four-parameter log-logistic dose-response model (equation [5]). For the variable dose with PWM vs. variable dose with fixed volume study the models tested were three-parameter log-logistic dose-response model (equation [1]), and the three-parameter log-normal dose-response model (equation [2])

$$f(x) = \frac{d}{1 + \exp\big(b(\log(x) - \log(e))\big)} \quad [1]$$

$$f(x) = c + \Big(\Phi\big(b(\log(x) - e)\big)\Big) \quad [2]$$

$$f(x) = c + (d - c)\Big(\Phi\big(b(\log(x) - e)\big)\Big) \quad [3]$$

$$f(x) = c + \frac{d - c}{\big(1 + \exp\big(b(x - e)\big)\big)} \quad [4]$$

$$f(x) = c + \frac{d - c}{1 + \exp\big(b(\log(x) - \log(e))\big)} \quad [5]$$

Results and Discussion

Variable dose with PWM vs. variable dose with fixed volume study

The results from this study provide insights into herbicide sensitivity of different weed species and growth stages, while comparing two different application methods to determine the plausibility of using PWM technology for herbicide variable-rate applications. The assessment of herbicide efficacy through dose-response studies is fundamental in determining the optimal application rates for effective weed control (Seefeldt et. al., 1995). The analysis focused on determining ED_{50} and ED_{90} values, representing the effective doses required to achieve 50% and 90% control, respectively, of the weed tested (Knezevic, Streibig, & Fuerst, 1995)

Glufosinate

Table 3-6 and figure 3-1 shows common waterhemp treated with glufosinate using the conventional and PWM methods. At 8.6 cm height, common waterhemp showed ED50 values below the minimum dose tested (< 176 g ai ha^{-1}) for both application methods. At 17.8 cm, ED50 values for the conventional and PWM methods were raised to 201 (±34) g ai ha^{-1} and 255 (±70) g ai ha^{-1}, respectively. However, at the larger 17.8 cm height, the ED90 values exceeded the maximum tested dose (> 440 g ai ha^{-1}) for both weed sizes on the PWM method and for 17.8 cm waterhemp on the conventional method. The 8.6 cm common waterhemp had the lowest ED90 value (332 [±41] g ai ha^{-1}). Overall, the conventional method demonstrated better performance due to its reduced ED90 value to control smaller common waterhemp plants. The better performance of the conventional method suggests a reliance on the herbicide glufosinate for a higher carrier volume. Creech et al. (2015) and Butts et al. (2018) observed similar results, demonstrating the need for higher carrier volumes to effectively control weeds using glufosinate.

On the conventional method, the ED50 for Palmer amaranth at 8.6 cm was 242 (±40) g ai ha^{-1}, and at 17.8 cm height, the ED50 value exceeded the maximum tested dose (> 440 g ai ha^{-1}). The ED90 values for both 8.6 cm and 17.8 cm plants were higher than the maximum dose tested (> 440 g ai ha^{-1}). On the PWM method, palmer amaranth at 8.6 cm showed ED50 values lower than the minimum tested dose (< 176 g ai ha^{-1}) and above the maximum dose tested (> 440 g ai ha^{-1}) for 17.6 cm plants. ED90 value at 8.6 cm height exceeded the maximum tested dose, indicating limitations in achieving full control even at higher herbicide rates. The model couldn't estimate the ED90 value at 17.6 cm plants due to limitations imposed by the doses employed in this study (Table 3-6 and figure 3-2). The elevated ED90 values observed in both methods indicate a dose limitation in our study, where the highest tested dose was insufficient to effectively manage palmer amaranth plants.

Glyphosate

Table 3-7 and figure 3-3 shows common waterhemp treated with glyphosate using the conventional and PWM methods. At 8.6 cm height, common waterhemp showed ED50 values below the minimum dose tested (< 368 g ae ha^{-1}) for both application methods. At 17.8 cm, the ED50 value for the conventional method was 653 (±104) g ae ha-1, and for the PWM method, it was 474 (±88) g ae ha-1. However, at the larger 17.8 cm height, the ED90 values exceeded the maximum tested dose (> 920 g ae ha^{-1}) for both sizes on the conventional method and for 17.8 cm plants on the PWM method. The model didn't estimate ED90 for 8.6 cm of waterhemp sprayed using the PWM method. Overall, both methods tested demonstrated similar performance, as shown by ED90 values above the maximum tested dose. This highlights the importance of correctly selecting the dose when controlling common waterhemp using glyphosate.

However, Sarangi et al. (2015) have already confirmed glyphosate-resistant waterhemp populations in Nebraska, suggesting that glyphosate may not be the most effective option for controlling this weed.

Both application methods demonstrated similar control against kochia, evidenced by similar ED50 and ED90 values across different sizes and application methods. The ED90 values for both methods exceeded the maximum tested dose, indicating limitations in achieving complete control of kochia with the tested doses. (Table 3-7 and figure 3-4).

2,4-D

Regardless of the size, the ED50 values for common waterhemp sprayed with 2,4-D in both the conventional and PWM methods were below the minimum tested dose (< 213 g ae ha^{-1}). ED90 values for 8.6 cm plants sprayed in the conventional method, as well as for both sizes (8.6 cm and 17.8 cm) sprayed in the PWM method, showed doses below the minimum tested dose (< 213 g ae ha^{-1}). On the other hand, ED90 values for 17.6 cm of plants sprayed using the conventional method were higher than the maximum dose tested (> 532 g ae ha^{-1}). 2,4-D controlled both small and large Common waterhemp plants with minimum 2,4-D doses. This does not include the 17.6 cm plants that were sprayed with the conventional method, where ED90 was higher than the highest dose tested (table 3-8, figure 3-5).

On palmer amaranth plants, ED50 values at 8.6 cm height were lower than the minimum tested dose (< 213 g ae ha^{-1}) for both methods, and 17.8 cm plants showed slightly higher ED50 values of 321 (±96) g ae ha^{-1} and 235 (±63) g ae ha^{-1} for the conventional and PWM methods, respectively. However, the ED90 values exceeded the maximum tested dose for both methods and plant sizes, indicating challenges in achieving complete control of larger Palmer amaranth plants with the tested herbicide rates. Due to similarities in the ED values, the findings suggest that no differences were observed between the PWM and the conventional method, supporting the use of PWM technology to perform variable rate herbicide applications to control palmer amaranth to spray 2,4-D in palmer amaranth (table 3-8, figure 3-6).

Due to dose limitations, in most cases, our study couldn't draw meaningful conclusions for some herbicides and weed species relative to the application method tested. Further research must be conducted using a wider range of herbicide doses to arrive at more significant conclusions. The study's findings indicate that one must carefully consider the herbicide to use and the growth stage of the weed to be controlled. Given that herbicide rate change is based on spray volume changes, the relative range of maximum and minimum herbicides is limited (Vogel, Wolf, & Dille, 2005) and can potentially result in reduced herbicide effectiveness for contact herbicides (Knoche, 1994; Creech et al., 2015; Butts et al., 2018). 2,4-D proportioned, overall, the best control for palmer amaranth and common waterhemp across all heights and methods employed, as seen on table 3-8 and figures 3-5 and 3-6.

Table 3-6. Estimated glufosinate dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds in different application methods at different sizes.

Glufosinate				
Weed species	Method	Weed size	ED_{50}	ED_{90}
		--- cm ---	g ai or ae ha^{-1} (±SE)	
Common waterhemp	CONV	8.6	< 176	332 (±41)
		17.8	201 (±34)	> 440
	PWM	8.6	< 176	> 440
		17.8	255 (±70)	> 440
Palmer amaranth	CONV	8.6	242 (±40)	> 440
		17.8	> 440	> 440
	PWM	8.6	< 176	> 440
		17.8	> 440	-

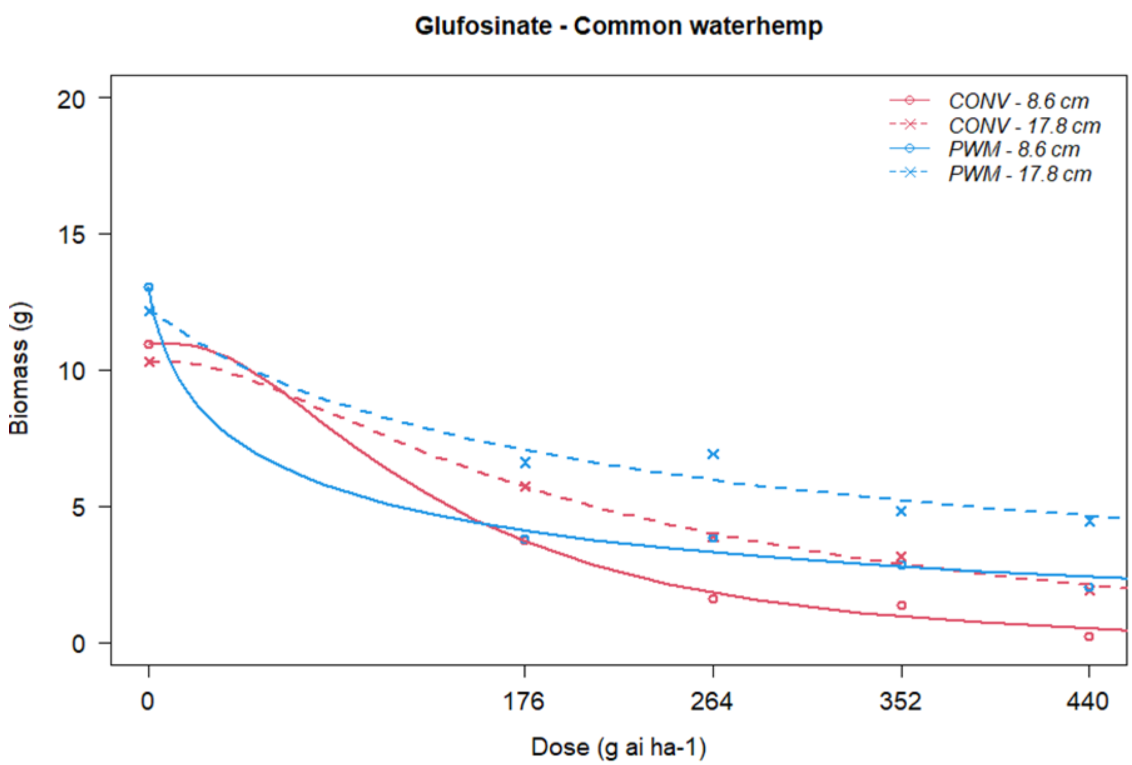

Figure 3-1. biomass reduction of common waterhemp over the dose range applied of glufosinate. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

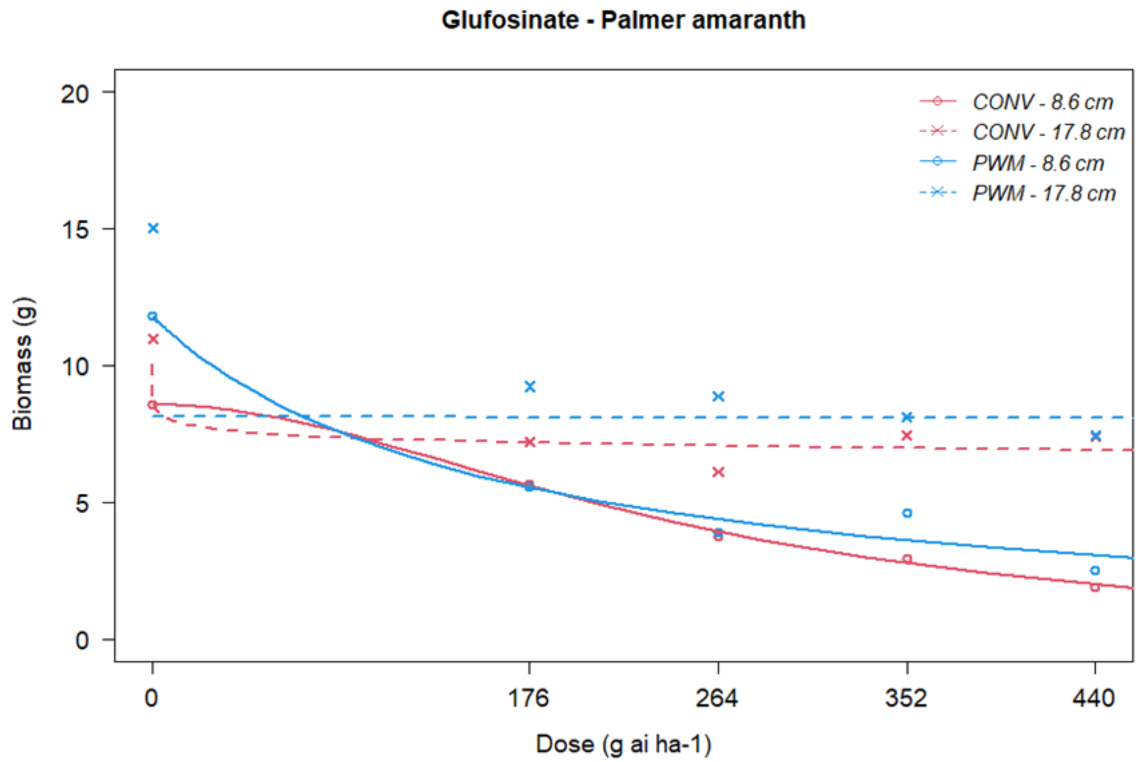

Figure 3-2. biomass reduction of palmer amaranth over the dose range applied of glufosinate. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

Table 3-7. Estimated glyphosate dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds in different application methods at different sizes.

		Glyphosate		
Weed species	Method	Weed size	ED_{50}	ED_{90}
		--- cm ---	g ae ha^{-1} (±SE)	
Common waterhemp	CONV	8.6	< 368	> 920
		17.8	653 (±104)	> 920
	PWM	8.6	< 368	-
		17.8	474 (±88)	> 920
Kochia	CONV	8.6	838 (±49)	> 920
		17.8	849 (±61)	> 920
	PWM	8.6	798 (±129)	> 920
		17.8	820 (±155)	> 920

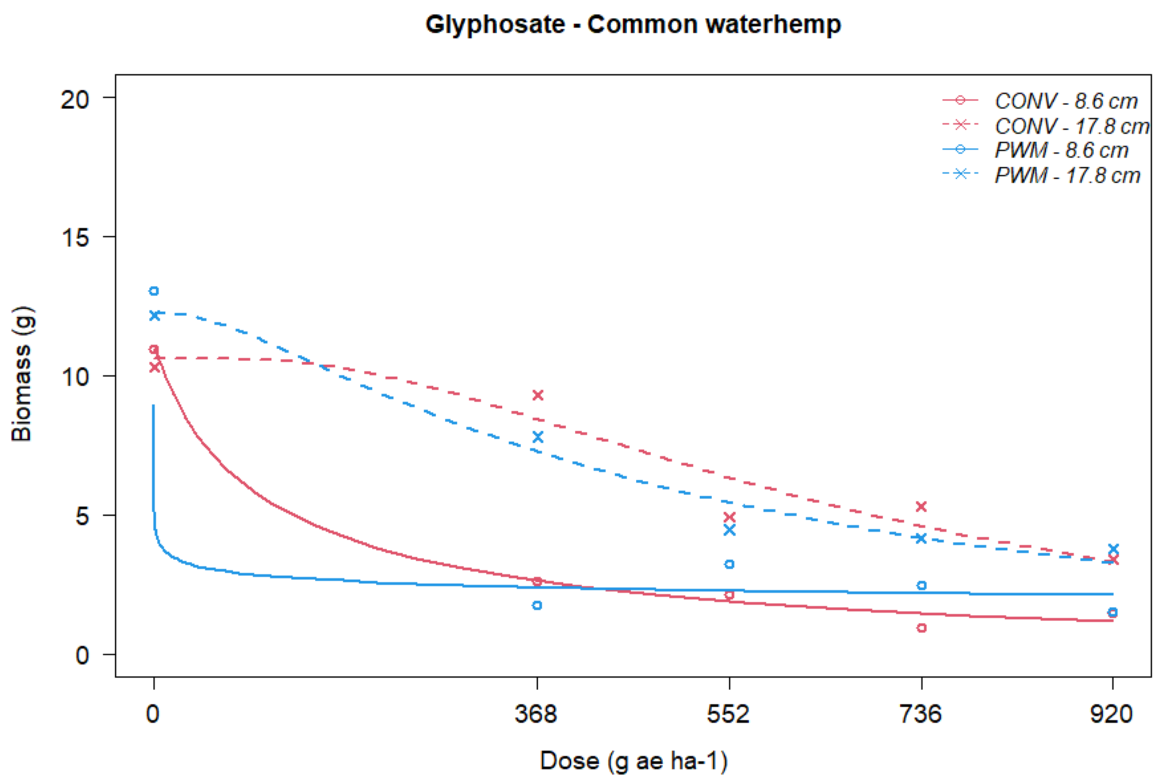

Figure 3-3. biomass reduction of common waterhemp over the dose range applied of glyphosate. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose

with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

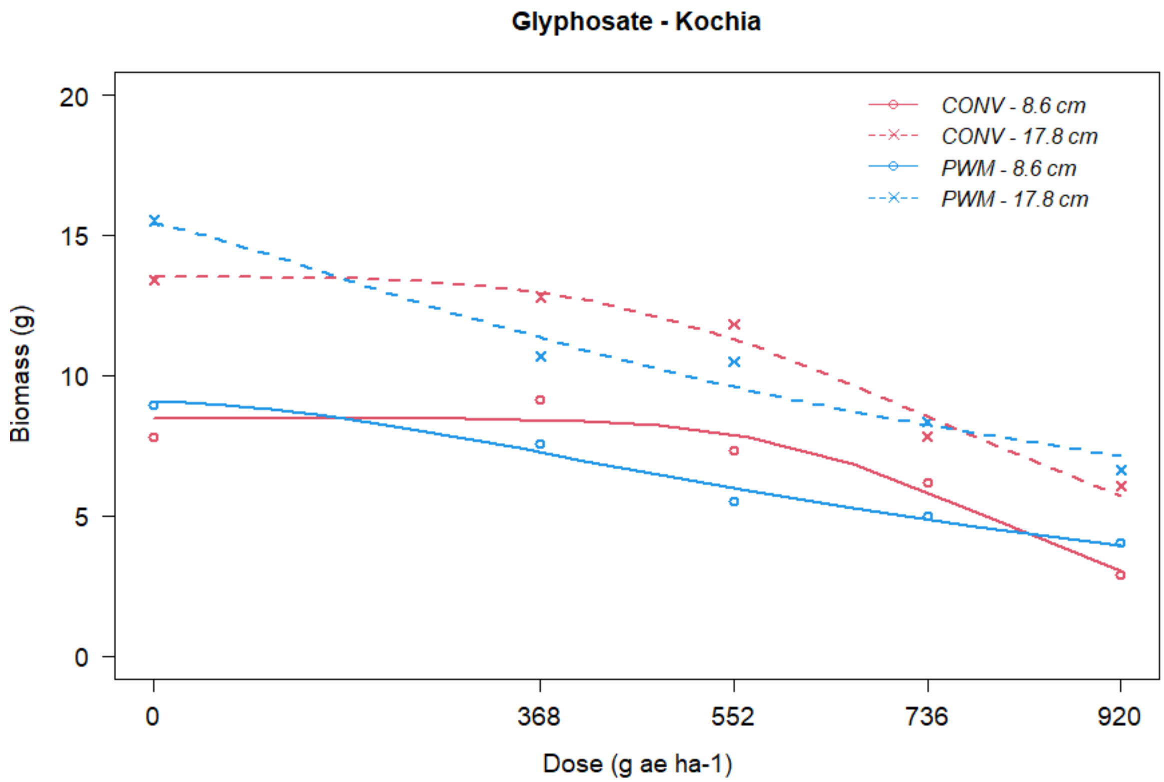

Figure 3-4. biomass reduction of kochia over the dose range applied of glyphosate. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

Table 3-8. Estimated 2,4-D dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds in different application methods at different sizes.

2,4-D				
Weed species	Method	Weed size	ED_{50}	ED_{90}
		--- cm ---	g ae ha^{-1} (±SE)	
Common waterhemp	CONV	8.6	< 213	< 213
		17.8	< 213	> 532
	PWM	8.6	< 213	< 213
		17.8	< 213	< 213
Palmer amaranth	CONV	8.6	< 213	> 532
		17.8	321 (±96)	> 532
	PWM	8.6	< 213	> 532
		17.8	235 (±63)	> 532

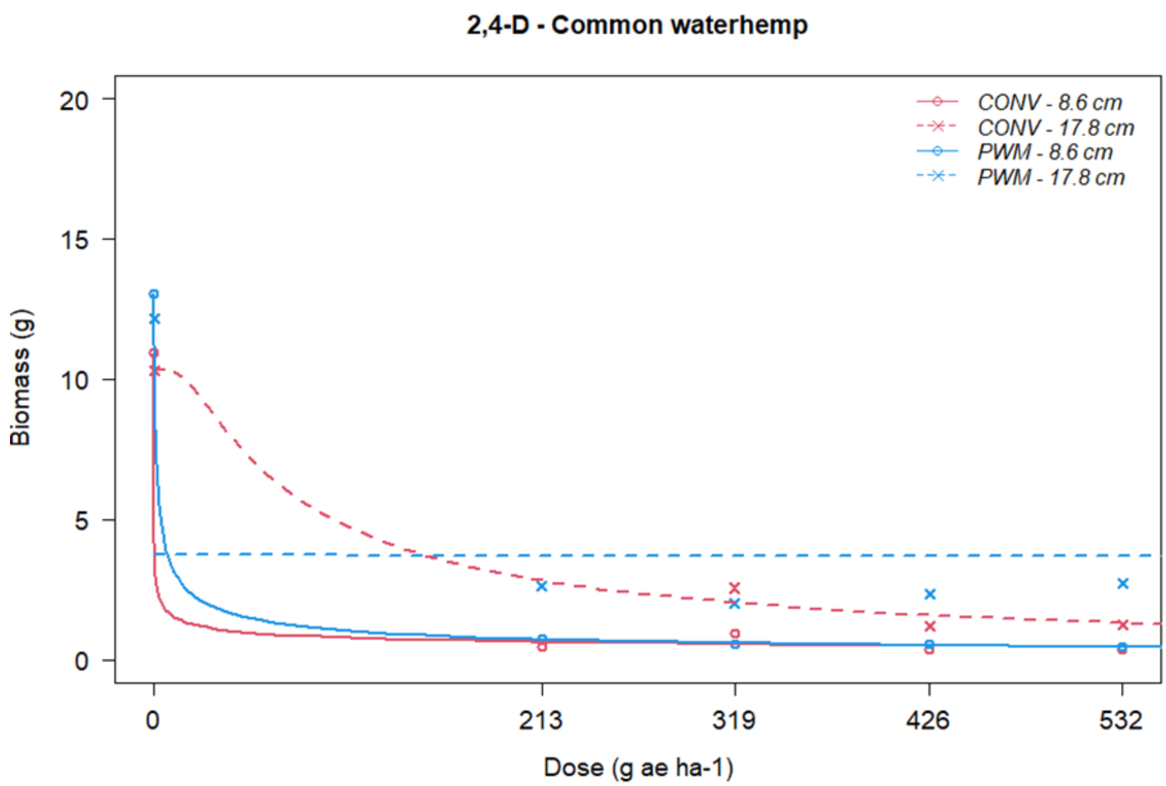

Figure 3-5. biomass reduction of common waterhemp over the dose range applied of 2,4-D. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

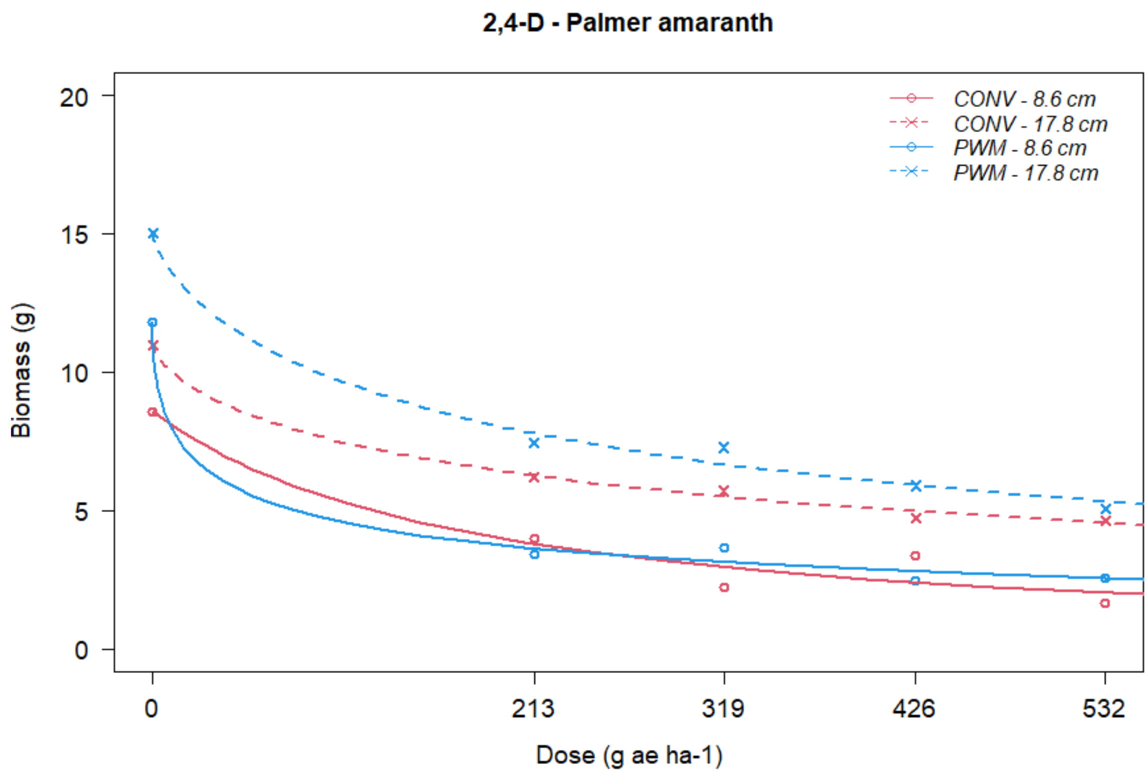

Figure 3-6. biomass reduction of palmer amaranth over the dose range applied of 2,4-D. Abbreviations: CONV – 8.6 cm, variable dose with fixed volume method sprayed on 8.6 cm plants; CONV – 17.8 cm, variable dose with fixed volume method sprayed on 17.8 cm plants; PWM – 8.6 cm, variable dose with PWM method sprayed on 8.6 cm plants; PWM – 17.8 cm, variable dose with PWM method sprayed on 17.8 cm plants.

Pulse width modulation dose-response study.

In this study, we utilized pulse width modulation (PWM) technology to apply different herbicide rates for five postemergence herbicides (glyphosate, glufosinate, 2,4-D, dicamba, and clethodim) five weed species common waterhemp, giant ragweed, palmer amaranth, and giant foxtail, horseweed at three weed heights (8.5 cm, 17.5 cm, and 27.5 cm), or weed diameters in the case of horseweed (3.75 cm, 8.5 cm, and 13.5 cm). The ED_{50} and ED_{90} values will offer insights into herbicide sensitivity across different weed species and growth stages, ultimately guiding precise herbicide application strategies. Data will be presented by herbicide.

Glyphosate

Table 3-1 contains the results for glyphosate treatment on each weed species at different heights. ED50 values for common waterhemp were found to be below the minimum dose tested (< 554 g ae ha^{-1}) at both 8.5 cm and 17.5 cm heights. However, at 27.5 cm height, the ED50 increased to 886 (±140) g ae ha^{-1}. ED90 values at 8.5 cm and 17.5 cm heights were 678 (±98) and 1509 (±835) g ae ha^{-1} of glyphosate, respectively. On the other hand, common waterhemp at 27.5 cm exhibited an ED90 value exceeding the maximum tested dose (>1,848 g ae ha^{-1}). The results for giant ragweed treated with glyphosate show a similar trend to common waterhemp (Table 3-1). At 8.5 cm, the ED50 value was below the minimum dose tested (< 554 g ae ha^{-1}), indicating high sensitivity to glyphosate. At 17.5 cm, the ED50 was 755 (±291) g ae ha^{-1}. However, as giant ragweed reached a height of 27.5 cm, the ED50 increased to 886 (±140) g ae ha^{-1}. The

ED90 values were not estimated by the model at 8.5 cm and 17.5 cm since the highest dose tested wasn't sufficient to control 90% of the plants, but at 27.5 cm, the ED90 valued showed to be higher than the maximum dose tested (>1,848). The results for green foxtail treated with glyphosate reveal a high sensitivity across different growth stages (Table 3-1). The ED50 and ED90 values were consistently below the minimum dose tested (< 554 g ae ha^{-1}) at all three weed heights (8.5 cm, 17.5 cm, and 27.5 cm). High susceptibility of green foxtail to glyphosate was observed, even at low application rates. Results highlight the potential for effective control of green foxtail with minimal glyphosate use. However, careful consideration is essential when reducing herbicide dosages to mitigate the potential for herbicide resistance development (Vieira et. al., 2019) Among the tested weeds, green foxtail exhibited the highest susceptibility to glyphosate, consistently showing ED90 values below the minimum tested dose across all growth stages. On the other hand, common waterhemp and giant ragweed showed better weed control at early stages, highlighting the importance of early glyphosate application for those weeds when using PWM to perform variable rate applications. In this case, early weed management for reduced herbicide dose strategies coincide with what was proposed by Dieleman et al. (1998).

Glufosinate

The results for common waterhemp treated with glufosinate indicate varying sensitivities based on weed height and the herbicide's rate (Table 3-2). At 8.5 cm and 17.5 cm heights, the ED50 values were lower than the minimum dose tested, implying high susceptibility to glufosinate even at low application rates. However, at 27.5 cm, the ED50 increased to 836 (±68) g ai ha^{-1}, indicating decreased sensitivity at taller growth stages. ED90 values showed similar trends. At 8.5 cm and 17.5 cm, the ED90 values were also below the minimum dose tested, reinforcing the high sensitivity of common waterhemp to glufosinate. However, the ED90 value at 27.5 cm was estimated to be above the maximum dose tested (> 879 g ai ha^{-1}), suggesting reduced herbicide efficacy at this height.

The results for giant ragweed treated with glufosinate suggest a consistent high susceptibility across different weed heights (Table 3-2). At 8.5 cm, 17.5 cm, and 27.5 cm heights, the ED50 values were lower than the minimum dose tested < 264 g ai ha^{-1}), indicating effective control even at very low application rates. Similarly, the ED90 values showed a high level of effectiveness across all weed heights. At 8.5 cm and 17.5 cm, the ED90 values were also below the minimum dose tested, reinforcing the herbicide's strength against giant ragweed. At 27.5 cm, the ED90 value was estimated to be 452 (±122) g ai ha^{-1}, further demonstrating the efficacy of glufosinate across various growth stages of giant ragweed.

The results for green foxtail treated with glufosinate reveal a consistent and high sensitivity of this weed species to the herbicide across different heights (Table 3-2). At 8.5 cm, 17.5 cm, and 27.5 cm heights, both the ED50 and ED90 values were lower than the minimum dose tested (< 264 g ai ha^{-1}), indicating effective control even at extremely low application rates.

The results for Palmer amaranth treated with glufosinate also indicate a high sensitivity on small plants (Table 3-2). ED50 values at all weed heights (8.5 cm, 17.5 cm, and 27.5 cm), were lower than the minimum dose tested (< 264 g ai ha^{-1}). ED90 values were also below the minimum dose tested (< 264g ai g ai ha^{-1}) at 8.5 cm, 17.5 cm weed size. At 27.5 cm weed size, the ED90 was higher than maximum dose tested (< 879 g ai g ai ha^{-1}).

Horseweed consistently exhibited high sensitivity to glufosinate, with all ED50 values falling below the minimum tested dose (< 264g g ai ha^{-1}). At 3.75 cm diameter, the ED90 value remained below the minimum tested dose. At 8.5 cm and 13.5 cm, the ED90 values ranged from 269 (±37) to 277 (±27) g ai ha^{-1}, indicating consistent herbicide efficacy across varying plant heights.

Results from glufosinate showed a height-dependent response, with taller palmer amaranth and common ragweed plants requiring higher herbicide doses for optimal control, as indicated by the ED90 values (Table 3-2). On the other hand, green foxtail, giant ragweed, and horseweed demonstrated high sensitivity, with ED90 values below the minimum dose tested in most cases, regardless of weed height. This information can be instrumental in developing optimized herbicide application strategies for effective weed management practices based on weed height, where minimum doses of the herbicide were sufficient to control certain weed species. The consistent performance of glufosinate at low doses, especially for smaller weeds, underscores its potential as a valuable tool in weed management strategies for variable-rate herbicide management and reduced herbicide rates, reinforcing what was concluded by Steckel et al. (1997) in a study utilizing glufosinate for POST weed management at different weed growth stages.

2,4-D

The results for common waterhemp treated with the herbicide 2,4-D reveal its efficacy across different plant heights (Table 3-3). All ED50 values across the tested heights (8.5 cm, 17.5 cm, and 27.5 cm) were below the minimum dose tested (< 319 g ae ha^{-1}). At the 8.5 cm height, the ED90 value also fell below the minimum tested dose and at 17.5 cm height, the ED90 value increased to 659 (±98) g ae ha^{-1}. The ED90 was not estimated by the model at 27.5 cm height since at this size, we couldn't reach low biomass even though the plants were controlled by the herbicide.

Results for giant ragweed treated with the herbicide 2,4-D indicate strong efficacy across different plant heights (Table 3-3). All ED50 and ED90 values for giant ragweed across the tested heights (8.5 cm, 17.5 cm, and 27.5 cm) were below the minimum dose tested (< 319 g ae ha^{-1}).

For Palmer amaranth all ED50 values across the tested heights (8.5 cm, 17.5 cm, and 27.5 cm) were below the minimum dose tested (< 319 g ae ha^{-1}). ED90 values for Palmer amaranth at 8.5 cm and 17.5 cm heights were also below the minimum dose tested, suggesting that higher herbicide concentrations were not necessary to achieve 90% biomass reduction at these heights. However, at 27.5 cm height, the ED90 value exceeded the maximum dose tested (> 1063 g ae ha^{-1}).

Based on the results for Horseweed treated with the herbicide 2,4-D, ED50 and ED90 values for Horseweed at all tested diameters (3.75 cm, 8.5 cm, and 13.5 cm) were below the minimum dose tested (< 319 g ae ha^{-1}).

Results from 2,4-D highlight its strong efficacy against horseweed and giant ragweed across different growth stages. Even at low application rates, 2,4-D demonstrates high effectiveness for these weeds, regardless of their height (Table 3-3). Results also suggest that 2,4-D is generally effective against palmer amaranth and common waterhemp across various growth stages. However, taller plants (27.5 cm height) required higher herbicide doses to achieve the desired level of control, reinforcing the idea of early POST weed control when adopting reduced herbicide dose strategies in variable-rate herbicide applications (Dieleman et al. 1998).

Dicamba

The results for Common waterhemp treated with Dicamba suggest a high susceptibility across different weed heights (Table 3-4). At 8.5 cm and 17.5 cm heights, the ED50 values were lower than the minimum dose tested (< 168 g ae ha^{-1}). At 27.5 cm height, the ED50 value was 281 (±63) g ae ha^{-1}, representing a slightly higher dose requirement compared to lower heights. The ED90 value at 8.5 cm was below the minimum dose tested. The model did not estimate ED90 values for 17.5 cm and 27.5 cm heights, suggesting that achieving 90% biomass reduction may not have been possible within the tested dose range for these heights.

The ED50 values for Giant ragweed at 8.5 cm, 17.5 cm, and 27.5 cm heights were all below the minimum dose tested (< 168 g ae ha^{-1}) and the ED90 value at 27.5 cm height was 339 (±565) g ae ha^{-1} (Table 3-4). The model did not estimate ED90 values for 8.5 cm and 17.5 cm heights, possibly due to the extremely effective nature of Dicamba even at lower doses, controlling 90% of the weed population even at the lowest doses tested.

The ED50 values for Palmer amaranth at all three heights (8.5 cm, 17.5 cm, and 27.5 cm) were below the minimum dose tested (< 168 g ae ha^{-1}). The ED90 values for palmer amaranth plants measuring 8.5 cm and 17.5 cm were also below the minimum dose tested. This indicates that even at the lowest doses tested, Dicamba was effective in reducing small to medium Palmer amaranth biomass by 90%. The model did not estimate ED90 values for Palmer amaranth at 27.5 cm (Table 3-4). This suggests that the doses used were not sufficient to achieve a 90% biomass reduction at this height within the range tested.

Based on the results for Horseweed treated with Dicamba, ED50 and ED90 values at all plant diameters tested (8.5 cm, 17.5 cm, and 27.5 cm) were below the minimum dose tested (< 168 g ae ha^{-1}), indicating that achieving 90% biomass reduction did not require doses higher than the minimum tested in this study (Table 3-4).

The results indicate that dicamba presented high efficacy against horseweed and giant ragweed, irrespective of plant height, with very low doses significantly reducing biomass. Additionally, dicamba shows consistent effectiveness against palmer amaranth and common waterhemp across different growth stages, but taller plants may necessitate higher herbicide doses for optimal control. Incorporating these insights into variable-rate weed management can enhance herbicide efficiency, reduce overall herbicide use, and potentially mitigate herbicide resistance issues.

Clethodim

In this study, we focused on evaluating the efficacy of clethodim for green foxtail control. The results for green foxtail treated with Clethodim (Table 3-5) demonstrate a high sensitivity of this weed species to the herbicide across different heights. The ED50 values were below the minimum dose tested at all three heights (8.5 cm, 17.5 cm, and 27.5 cm). Similarly, the ED90 values remained below the minimum dose tested at all heights, reinforcing the efficacy of Clethodim against Green foxtail across various growth stages (Burke et al. 2004). These results indicate the potential for minimizing herbicide usage while still achieving desirable weed control outcomes.

Table 3-1. Estimated glyphosate dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds at different sizes.

Glyphosate			
Weed species	**Weed size**	**ED_{50}**	**ED_{90}**
	-- cm --	**g ae ha^{-1} (±SE)**	
Common waterhemp	8.5 (±1.5)	< 554	678 (±98)
	17.5 (±2.5)	< 554	1509 (±835)
	27.5 (±2.5)	886 (±140)	>1,848
Giant ragweed	8.5 (±1.5)	< 554	-
	17.5 (±2.5)	755 (±291)	-
	27.5 (±2.5)	1,119 (±204)	>1,848
Green foxtail	8.5 (±1.5)	< 554	< 554
	17.5 (±2.5)	< 554	< 554
	27.5 (±2.5)	< 554	< 554

Table 3-2. Estimated glufosinate dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds at different sizes.

	Glufosinate		
Weed species	Weed size	ED_{50}	ED_{90}
	-- cm --	g a.i. ha $^{-1}$ (±SE)	
Common waterhemp	8.5 (±1.5)	< 264	< 264
	17.5 (±2.5)	< 264	-
	27.5 (±2.5)	836 (±68)	> 879
Giant ragweed	8.5 (±1.5)	< 264	< 264
	17.5 (±2.5)	< 264	< 264
	27.5 (±2.5)	< 264	452 (±122)
Green foxtail	8.5 (±1.5)	< 264	< 264
	17.5 (±2.5)	< 264	< 264
	27.5 (±2.5)	< 264	< 264
Palmer amaranth	8.5 (±1.5)	< 264	< 264
	17.5 (±2.5)	< 264	< 264
	27.5 (±2.5)	< 264	< 879
Horseweed	3.75 (±1.75)	< 264	< 264
	8.5 (±1.5)	< 264	277 (±27)
	13.5 (±1.5)	< 264	269 (±37)

Table 3-3. Estimated 2,4-D dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds at different sizes.

	2,4-D		
Weed species	Weed size	ED_{50}	ED_{90}
	-- cm --	g ae ha^{-1} (±SE)	
Common waterhemp	8.5 (±1.5)	< 319	< 319
	17.5 (±2.5)	< 319	659 (98±)
	27.5 (±2.5)	< 319	-
Giant ragweed	8.5 (±1.5)	< 319	< 319
	17.5 (±2.5)	< 319	< 319
	27.5 (±2.5)	< 319	< 319
Palmer amaranth	8.5 (±1.5)	< 319	< 319
	17.5 (±2.5)	< 319	< 319
	27.5 (±2.5)	< 319	> 1063
Horseweed	3.75 (±1.75)	< 319	< 319
	8.5 (±1.5)	< 319	< 319
	13.5 (±1.5)	< 319	< 319

Table 3-4. Estimated Dicamba dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for weeds at different sizes.

Dicamba			
Weed species	Weed size	ED_{50}	ED_{90}
	-- cm --	g ae ha $^{-1}$ (±SE)	
Common waterhemp	8.5 (±1.5)	< 168	< 168
	17.5 (±2.5)	< 168	-
	27.5 (±2.5)	281(±63)	-
Giant ragweed	8.5 (±1.5)	< 168	< 168
	17.5 (±2.5)	< 168	-
	27.5 (±2.5)	< 168	339 (±565)
Palmer amaranth	8.5 (±1.5)	< 168	< 168
	17.5 (±2.5)	< 168	< 168
	27.5 (±2.5)	< 168	-
Horseweed	3.75 (±1.75)	< 168	< 168
	8.5 (±1.5)	< 168	< 168
	13.5 (±1.5)	< 168	< 168

Table 3-5. Estimated clethodim dose to achieve 50% (ED_{50}) and 90% (ED_{90}) of biomass reduction for green foxtail at different sizes.

Clethodim			
Weed species	Weed size	ED_{50}	ED_{90}
	-- cm --	g a.i. ha^{-1} (±SE)	
Green foxtail	8.5 (±1.5)	< 42	< 42
	17.5 (±2.5)	< 42	< 42
	27.5 (±2.5)	< 42	< 42

Conclusion

The herbicide product label provides a comprehensive list of weed species that can be controlled by using the recommended dosage. Yet, many species may be controlled with lower doses and dose response curves need to be derived for each species (Kudsk, 1989). Furthermore, when considering reduced dose applications, it is important to consider the timing of application, which is indicated by the size or growth stage of the weeds (Dieleman, 1998).

The outcomes of these studies emphasize the importance of determining weed sensitivity and herbicide efficacy across various herbicides, weed species, growth stages, and application methods. Weed species exhibit varying sensitivities to herbicides at different growth stages, suggesting the need for variable-rate application strategies. Early postemergence herbicide application proves crucial for effective weed control, regardless of the herbicide and weed species.

Incorporating herbicide sensitivity data into variable-rate herbicide management strategies can enhance efficiency and reduce herbicide use. For example, our study showed that glyphosate was effective at low doses for green foxtail across all growth stages, but higher doses were needed for taller common waterhemp and giant ragweed plants. Similarly, glufosinate demonstrated high efficacy at low doses for most weed species, but taller Palmer amaranth and common ragweed required higher doses for optimal control.

The comparison between conventional and pulse width modulation (PWM) methods revealed that while both methods performed similarly for some herbicides and weed species, certain combinations showed better performance with conventional methods, likely due to the need for higher carrier volumes. This highlights the importance of considering application methods when developing precision herbicide strategies.

Future research with a wider range of herbicide doses, different herbicides, and weed species is needed to draw more meaningful conclusions. Understanding the interaction between herbicide rate, spray volume, and weed growth stage will help optimize herbicide application strategies for enhanced weed control efficacy in precision application technology operations.

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