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Optimum Droplet Size Using a Pulse-Width Modulation Sprayer for Applications of 2,4-D Choline Plus Glyphosate

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ABSTRACT

The delivery of an optimum herbicide droplet size using pulse-width modulation (PWM) sprayers can reduce potential environmental contamination, maintain efficacy, and provide more flexible options for pesticide applicators. Field research was conducted in 2016, 2017, and 2018 across three locations (Mississippi, Nebraska, and North Dakota) for a total of 6 site-years. The objectives were to evaluate the efficacy of a range of droplet sizes (150 µm [Fine] to 900 µm [Ultra Coarse]) using a 2,4-D choline plus glyphosate pre-mixture and to create novel weed management recommendations using PWM sprayer technology. A pooled site-year generalized additive model explained less than 5% of the model deviance, so a site-specific analysis was conducted. Across the Mississippi and North Dakota sites, a 900-µm (Ultra Coarse) droplet size maintained 90% of the maximum weed control. In contrast, at the Nebraska sites, droplet sizes between 565 and 690 µm (Extremely Coarse) were almost exclusively required to maintain 90% of the maximum weed control, likely due to weed leaf architecture. Severe reductions in weed control were observed as droplet size increased at several site-years. Alternative drift reduction practices must be identified; otherwise, weed control reductions will be observed. This research illustrated that PWM sprayers paired with appropriate nozzle–pressure combinations for 2,4-D choline plus glyphosate pre-mixture could be effectively implemented into precision agricultural practices by generating optimum herbicide droplet sizes for site-specific management plans. To fully optimize spray applications using PWM technology, future research must holistically investigate the influence of application parameters and conditions.

Core Ideas

- Model fit increased by predicting optimum droplet sizes for site-specific scenarios.
- Generally, an Extremely Coarse spray would be recommended for a 2,4-D choline plus glyphosate application.
- Site-specific weed management using PWM sprayers was both manageable and effective.
- Weed control reductions were observed as droplet size increased at several site-years.
- Alternative drift reduction efforts must be identified to avoid weed control losses.

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

Pulse-width modulation (PWM) sprayers provide an alternative method to optimize pesticide applications because they allow for several factors, including application pressure and spray droplet size, to be maintained across a range of sprayer speeds while variably controlling the flow rate. Flow rate is controlled by pulsing an electronically actuated solenoid valve placed directly upstream of the nozzle (Giles and Comino, 1989). The solenoid valves are typically pulsed on a 10 Hz frequency, and the relative proportion of time each valve is open (duty cycle) determines the flow rate. This system allows real-time flow rate changes to be made without manipulating application pressure, as with other variable-rate spray application systems (Anglund and Ayers, 2003). Additionally, PWM solenoid valves buffer some negative impacts observed with other rate controller systems (Luck et al., 2011; Sharda et al., 2011, 2013). Furthermore, PWM sprayers have the capability of producing up to a 10:1 turndown ratio in flow rate with no pressure or nozzle-based

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Abbreviations: edf, estimated degrees of freedom; GAM, generalized additive modeling; PWM, pulse-width modulation.

Table 1. Site-year, GPS coordinates, weed species, application date, weather conditions at herbicide application timing, and data collected to understand the impact of droplet size on herbicide efficacy of 2,4-D choline plus glyphosate.

Year	Location	GPS coordinates	Weed species†	Application date	Application weather conditions			Visual injury estimations	Mortality	Weed dry biomass
					Wind speed	Air temperature	Relative humidity			
					m s^{-1}	°C	%			
2016	Dundee, MS	34.54°N, 90.47°W	AMAPA	17 June	0.5	27	90	X‡	X	X
2016	Prosper, ND	47.00°N, 97.12°W	Multiple§	29 June	3.1	27	44	X		
2017	Dundee, MS	34.54°N, 90.47°W	AMAPA	10 Aug.¶	0.9	30	69	X	X	X
2017	Brule, NE	41.16°N, 102.00°W	KCHSC	9 June	3.6	36	24	X	X	X
2017	Fargo, ND	46.93°N, 96.86°W	CHEAL	6 June	3.6	24	35	X		X
2018	North Platte, NE	41.05°N, 100.75°W	Multiple#	5 June	3.6	32	41	X	X	X

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

‡ An "X" indicates that the respective response variable data were collected from the respective site-year.

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

¶ Due to adverse weather conditions, multiple tillage events occurred at the 2017 Dundee, MS, site-year to stimulate new flushes of Palmer amaranth so the appropriate weed height could be achieved at the time of application.

Multiple weed species at the 2018 North Platte, NE, site-year included the following: ERICA, horseweed (*Erigeron canadensis* L.); KCHSC, kochia [*Bassia scoparia* (L.) A.J. Scott].

changes, thus creating more flexible options for pesticide applicators (Giles et al., 1996; GopalaPillai et al., 1999). Application pressure–based variable-rate flow control devices have slow response time and affect nozzle performance, specifically droplet size (Giles and Comino, 1989). In contrast, research has shown that the PWM duty cycle has little to no effect on droplet size when using non-venturi nozzles (Butts et al., 2019a; Giles et al., 1996). Additionally, when PWM sprayers were operated at or above a 40% duty cycle, minimal to no negative impacts were observed on spray pattern and coverage (Butts et al., 2019b; Mangus et al., 2017; Womac et al., 2016, 2017). Therefore, it is feasible with a PWM sprayer to sustain an optimum herbicide droplet size and spray pattern throughout an application in which efficacy could be maximized and particle drift minimized.

Spray drift mitigation efforts have primarily focused on increasing spray droplet size because finer droplets have been shown to drift further downwind (Bueno et al., 2017; Vieira et al., 2018). Numerous application factors have been determined to affect droplet size, including adjuvants (Butler Ellis et al., 1997; Chapple et al., 1993), pesticide formulations (Miller and Butler Ellis, 2000), nozzle design (Barnett and Matthews, 1992; Butler Ellis et al., 2002; Etheridge et al., 1999), nozzle orifice size (Nuyttens et al., 2007), and application pressure (Creech et al., 2015). Due to the complex interactions affecting droplet size formation, a more thorough understanding of the application process is required for sprayer optimization. Furthermore, as a result of increasing spray droplet size to reduce particle drift, noticeable negative biological consequences have occurred (Wolf, 2002).

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

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

MATERIALS AND METHODS

Experiment Design and Establishment

Field trials were conducted in 2016, 2017, and 2018 in a fallow environment across three states (Mississippi, Nebraska, and North Dakota) for a total of 6 site-years to evaluate the droplet size effect on the efficacy of 2,4-D choline plus glyphosate pre-mixture (Enlist Duo, 0.19 kg ae L^{-1} 2,4-D, 0.20 kg ae L^{-1} glyphosate; Dow AgroSciences, Indianapolis, IN) (Table 1). The trials were randomized complete block experimental designs replicated a minimum of three times spatially within each site. This research

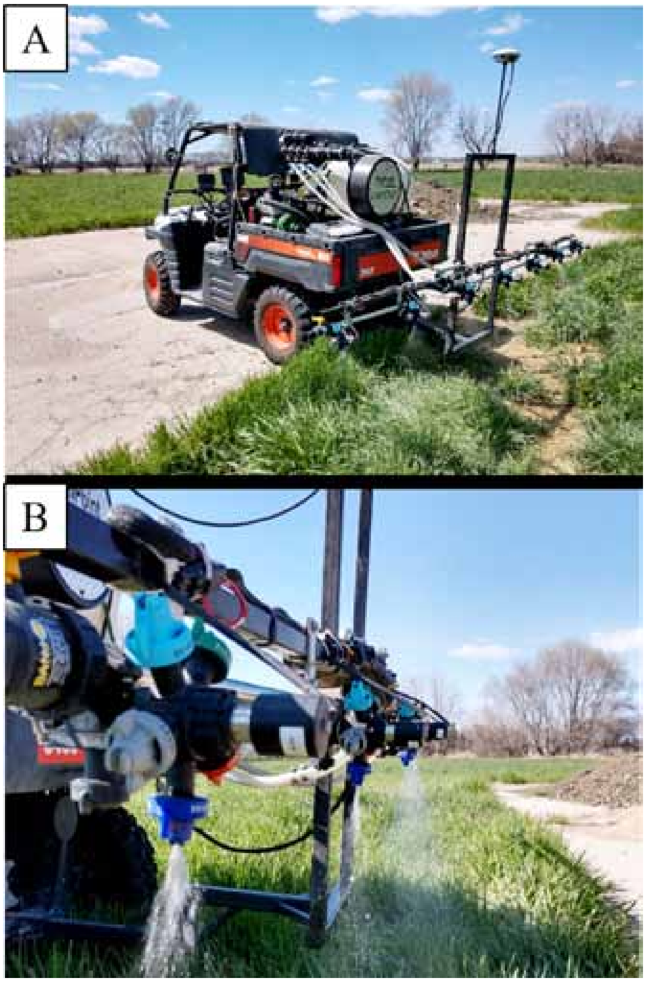

Fig. 1. (A) Pulse-width modulation sprayer equipped and operated with (B) non-venturi nozzles used to apply droplet size treatments in this research.

was conducted using similar methods as used in previous droplet size efficacy research (Butts et al., 2018b). Treatments consisted of six targeted droplet sizes (150, 300, 450, 600, 750, and 900 μm) determined from the $D_{v0.5}$ of the measured droplet size distribution. The $D_{v0.5}$ parameter represents the droplet diameter at which 50% of the spray volume is contained in droplets of smaller diameter. One nontreated control treatment per site-year was used for comparison, which provided a total of seven treatments. The herbicide pre-mixture of 2,4-D choline plus glyphosate was applied postemergence to ≥15-cm tall weeds at 0.79 kg ae ha^{-1} 2,4-D plus 0.84 kg ae ha^{-1} glyphosate (4.09 L ha^{-1} formulated product) with a carrier volume of 94 L ha^{-1}. No additional adjuvants were tank-mixed into the solution to eliminate confounding effects and to allow evaluation of treatments solely based on the herbicide.

Treatments were applied using a PinPoint PWM research sprayer (Capstan Ag Systems, Inc., Topeka, KS) (Fig. 1). The benefits of using a PWM sprayer in this research were two-fold. First, PWM allows spray output to become independent from nozzle orifice size, sprayer speed, and application pressure. Therefore, the application process was simplified and standardized for operators across a range of spray environments. Second, because previous research highlighted PWM duty cycle had a minimal effect on droplet characteristics (Butts et al., 2018a, 2019a) and spray pattern (Butts et al., 2019b), a nozzle type, orifice size, and application pressure combination could be selected to provide a

Table 2. Nozzle type, orifice size, and application pressure combinations for each 2,4-D choline plus glyphosate droplet size treatment when applied at 0.79 kg ae ha^{-1} 2,4-D plus 0.84 kg ae ha^{-1} glyphosate with a carrier volume of 94 L ha^{-1} in Mississippi, Nebraska, and North Dakota from 2016 to 2018.†

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

† Target droplet sizes were the designed droplet size treatments used in data analysis. Actual droplet sizes were the experimentally measured droplet sizes from spray solution, nozzle, and application pressure combinations. Actual droplet sizes were within 1.1% of the target droplet sizes with the exception of the 150-μm treatment because 168 μm was the smallest possible droplet size capable of being generated.

‡ Flat fan, non-venturi nozzles.

§ Spray classifications determined using ASABE S572.1. F, Fine; M, Medium; VC, Very Coarse; EC, Extremely Coarse; UC, Ultra Coarse.

consistent droplet size for each treatment while maintaining the appropriate spray output (94 L ha^{-1}) throughout an application.

Nozzle type, orifice size, and application pressure required to create droplet size treatments were determined through droplet size measurements made using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) in a low-speed wind tunnel at the Pesticide Application Technology Laboratory in North Platte, NE (Table 2). Henry et al. (2014) and Creech et al. (2015) provide in-depth details regarding the low-speed wind tunnel at the Pesticide Application Technology Laboratory, and Butts et al. (2019a) provide an illustration for further clarification of wind tunnel construction and operation. Only non-venturi nozzles (Wilger Industries, Ltd., Lexington, TN) were used in this research because (i) only non-venturi nozzles are recommended for use on PWM systems (Butts et al., 2019a; Capstan Ag Systems Inc., 2013) and (ii) nozzle designs were similar (flat-fan, non-venturi, straight flow path) to eliminate confounding spray characteristic factors. Spray classifications were assigned in accordance with ASABE S572.1 (ASABE, 2009).

Data Collection

Each collaborating university collected data from their respective sites. Visual injury estimation proportions were recorded on a 0 to 1 scale (0, no injury; 1, complete plant death) approximately 28 d after treatment for entire plots from 6 site-years. Furthermore, 10 individual weeds per plot for each weed species present were marked at the time of application, excluding the 2016 Prosper, ND, site-year. At 28 d after treatment, marked plants were individually evaluated for mortality (alive or dead), and the total number of dead plants was divided by 10 to provide mortality proportion measurements for each plot from 4 site-years. The individual weeds were then clipped at the soil surface, harvested, and dried at 55°C to constant mass. The dry plant weights were pooled into one dry biomass measurement per plot for each weed species and were divided by 10 for average weed dry shoot biomass per plant measurements from 5 site-years.

Table 3. Generalized additive model smoothing parameters and deviance explained for each response variable across pooled site-years from applications in Mississippi, Nebraska, and North Dakota from 2016 to 2018.

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

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

Statistical Analysis

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

$$\text{Response variable} \sim s(\text{Target droplet size}) \qquad [1]$$

Once models were fit, the smooth term estimated degrees of freedom (edf) and deviance explained for each response variable were generated. A smooth term edf of 1 is equal to a linear model with model fluctuation increasing as the smooth term edf increases. The explained deviance provides an estimate of the discrepancy between model predicted estimates and actual observations, with a larger percentage indicating a smaller discrepancy and overall better model fit. Droplet sizes determined for treatments, used in model predictions, and discussed herein refer to the $D_{v0.5}$ measurement (average droplet size) of the droplet size distribution. Initially, data were pooled across site-years for a broad-spectrum analysis; however, GAM analysis was also conducted for individual site-years to assess droplet size efficacy implications in a site-specific weed management scenario. Models were used to predict the droplet size for maximum weed control and the droplet size at which 90% of maximum weed control was attained for drift mitigation recommendations.

RESULTS AND DISCUSSION

Pooled Site-Years

The GAM model smooth term edf and deviance explained for visual injury estimation proportion, mortality proportion, and dry weed biomass per plant are presented in Table 3. The smooth term edf for the visual injury estimation, mortality, and weed dry biomass per plant GAM model indicated the herbicide efficacy and droplet size relationship was linear (smooth term edf = 1.000) or nearly linear (smooth term edf = 1.474) when site-years were pooled (Table 3).

Although models could be established across a wide range of geographies from the pooled site-year analysis, the deviance

Table 4. Generalized additive model smoothing parameters and deviance explained within individual site-years from applications in Mississippi, Nebraska, and North Dakota from 2016 to 2018 for each response variable to investigate the plausibility of site-specific weed management.

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

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

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

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

explained for each GAM model was low (<5%) (Table 3). These models suggest that, across the pooled site-years, a maximum of 4.19% of the herbicide efficacy variability could be attributed to droplet size. Therefore, predictions from these models were deemed inaccurate and thereby contributed to the necessity of the site-specific analysis approach. Numerous other factors that influence herbicide efficacy, such as weather conditions, time of day, weed species, and geographic location (Kudsk, 2017), may have been more important drivers in final biological efficacy as opposed to droplet size for the pre-mixture of 2,4-D choline plus glyphosate. Future research should investigate the influence of each of these specific application factors on 2,4-D choline plus glyphosate pre-mixture efficacy, and more robust models should be established implementing each factor as a parameter to fully optimize spray applications using this herbicide.

Site-Specific Weed Management

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

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

Maximum weed control across site-years and response variables ranged from an optimum droplet size of 150 µm (Fine) to 900 µm (Ultra Coarse) (Table 5). However, across the four Mississippi and North Dakota site-years, 90% of the maximum weed control was achieved with a 900-µm (Ultra Coarse) droplet size and would be recommended for spray applications of 2,4-D choline plus glyphosate pre-mixture to reduce particle drift potential. In contrast, across the two Nebraska site-years, 90% of the maximum weed control was almost exclusively achieved between droplet sizes of 565 to 690 µm (Extremely Coarse). Severe reductions in

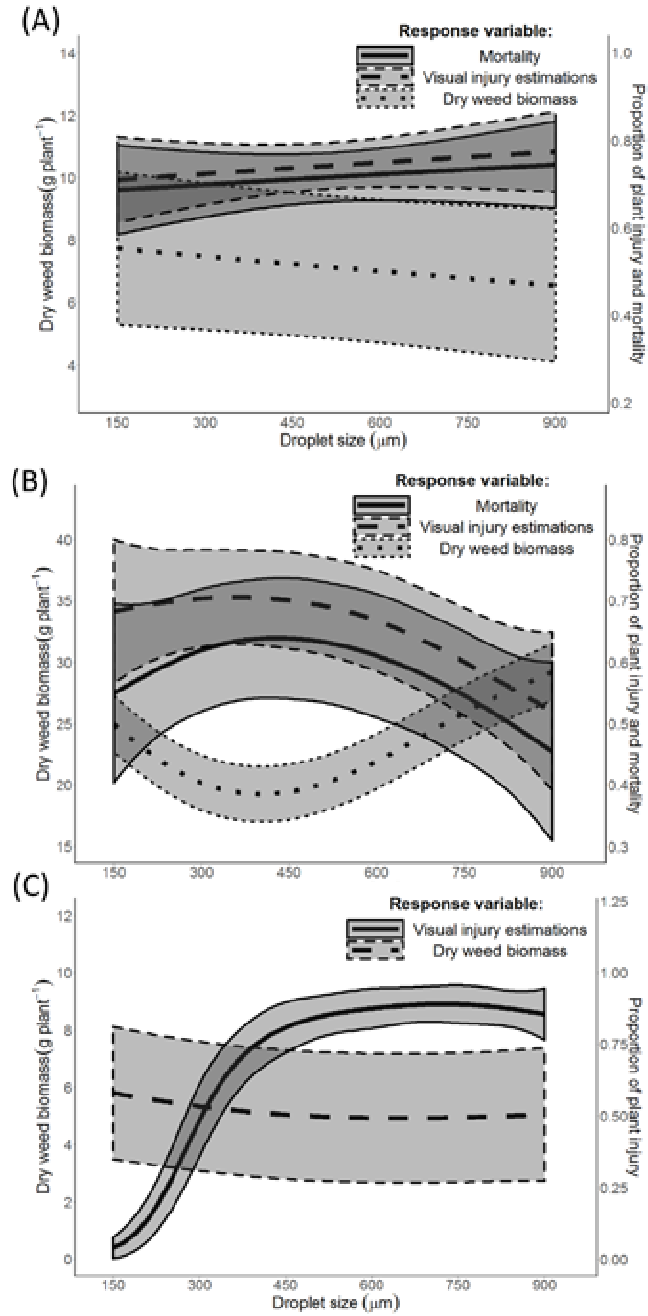

Fig. 2. Weed dry biomass per plant, visual injury estimation proportion, and plant mortality proportion generalized additive models for the 2017 Dundee, MS (A), 2017 Brule, NE (B), and 2017 Fargo, ND (C) site-years as representative examples to assess the plausibility of site-specific weed management strategies. The shaded area indicates the 95% confidence limits.

weed control were observed as droplet size increased greater than those critical sizes (Table 5; Fig. 2). Therefore, alternative particle drift reduction practices must be identified and implemented; otherwise, losses in weed control will be observed.

This difference in optimum droplet sizes across sites may be partially attributed to the weed species evaluated. The primary weed species in Mississippi and North Dakota were Palmer amaranth (*Amaranthus palmeri* S. Wats) and common lambsquarters (*Chenopodium album* L.), respectively. Spillman (1984) reported that coarser droplets had greater impaction and retention efficiency on horizontal leaf surfaces. Both Palmer

Table 5. Predicted droplet sizes based on a generalized additive model to achieve maximum weed control and 90% of maximum weed control to enhance drift mitigation efforts within individual site-years from applications in Mississippi, Nebraska, and North Dakota from 2016 to 2018 for each response variable to investigate the plausibility of site-specific weed management.

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

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

‡ Spray classifications determined using ASABE S572.1. F, Fine; M, Medium; C, Coarse; VC, Very Coarse; EC, Extremely Coarse; UC, Ultra Coarse.

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

amaranth and common lambsquarters have flat, horizontal leaf surfaces in which coarser droplets may have had increased retention, leading to the minimal droplet size effect on herbicidal efficacy. Conversely, the primary weed species in Nebraska were kochia [*Bassia scoparia* (L.) A.J. Scott] and horseweed (*Erigeron canadensis* L.), and they had similar trends in herbicide efficacy across droplet size treatments within the same site-year (Table 5; Fig. 3). Typically, maximum kochia and horseweed control was achieved with a 150-µm (Fine) droplet size, but 90% of the maximum control was achieved with 565- to 690-µm (Extremely Coarse) droplet sizes. This is likely due to kochia and horseweed having a much smaller and narrower leaf structure paired with relatively vertical plant architecture compared with Palmer amaranth and common lambsquarters. Previous research showed finer droplets paired with horizontal winds resulted in greater impaction and retention efficiency on vertical leaf surfaces (Lake, 1977). Further research observed an effect of plant architecture and leaf surface composition on droplet impaction and retention and thereby herbicidal efficacy (Massinon et al., 2017; Nairn et al., 2013). Therefore, due to the structure of the kochia and horseweed plants, smaller droplet sizes may have been required to achieve the necessary droplet retention and coverage to maximize the efficacy of 2,4-D choline plus glyphosate pre-mixture.

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

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

CONCLUSIONS

The need for environmentally safe, efficacious, and more economical herbicide applications is a major concern in today's agricultural industry, and optimizing each application is critical for proper herbicide stewardship. This research identified, across

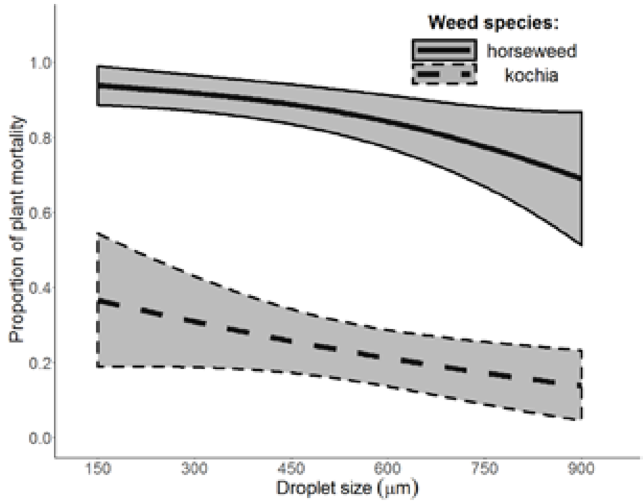

Fig. 3. Mortality proportion generalized additive models for the horseweed (*Erigeron canadensis* L.) and kochia [*Bassia scoparia* (L.) A.J. Scott] weed species at the 2018 North Platte, NE, site-year. The shaded area indicates the 95% confidence limits.

a broad geographic setting and diverse weed spectrum, that efficacy of 2,4-D choline plus glyphosate pre-mixture applied with a carrier volume of 94 L ha^{-1} could only be predicted with less than 5% accuracy when analyzed in a pooled site-year approach.

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

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

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