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Performance of Postemergence Herbicides Applied at Different Carrier Volume Rates

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POST weed control in soybean in the United States is difficult because weed resistance to herbicides has become more prominent. Herbicide applicators have grown accustomed to low carrier volume rates that are typical with glyphosate applications. These low carrier volumes are efficient for glyphosate applications and allow applicators to treat a large number of hectares in a timely manner. Alternative modes of action can require greater carrier volumes to effectively control weeds. Glyphosate, glufosinate, lactofen, fluazifop-P, and 2,4-D were evaluated in field and greenhouse studies using 47, 70, 94, 140, 187, and 281 L ha^{-1} carrier volumes. Spray droplet size spectra for each herbicide and carrier volume combination were also measured and used to determine their impact on herbicide efficacy. Glyphosate efficacy was maximized using 70 to 94 L ha^{-1} carrier volumes using droplets classified as medium. Glufosinate efficacy was maximized at 140 L ha^{-1} and decreased as droplet diameter decreased. For 2,4-D applications, efficacy increased when using carrier volumes equal to or greater than 94 L ha^{-1}. Lactofen was most responsive to changes in carrier volume and performed best when applied in carrier volumes of at least 187 L ha^{-1}. Carrier volume had little impact on fluazifop-P efficacy in this study and efficacy decreased when used on taller plants. Based on these data, applicators should use greater carrier volumes when using contact herbicides in order to maximize herbicide efficacy.

Nomenclature: 2,4-D; Glufosinate; glyphosate; fluazifop-P; lactofen.

Key words: Droplet size, herbicide efficacy, nozzles, soybean herbicides, spray rate.

El control de malezas POST en soya en los Estados Unidos es difícil porque la resistencia a herbicidas de las malezas se ha hecho más prominente. Los aplicadores de herbicidas se han acostumbrado a usar bajos volúmenes de aplicación que son típicos en aplicaciones con glyphosate. Estos bajos volúmenes de aplicación son eficientes para aplicaciones con glyphosate y permiten a los aplicadores tratar un gran número de hectáreas en poco tiempo. Modos de acción alternativos pueden requerir mayores volúmenes de aplicación para controlar malezas efectivamente. Glyphosate, glufosinate, lactofen, fluazifop-P, y 2,4-D fueron evaluados en estudios de campo y de invernadero usando volúmenes de aplicación de 47, 70, 94, 140, 187, y 281 L ha^{-1}. Se midió el espectro de tamaño de gota de aspersión para cada combinación de herbicida y volumen de aplicación y se determinó su impacto en la eficacia del herbicida. La eficacia de glyphosate se maximizó usando volúmenes de 70 a 94 L ha^{-1} y gotas clasificadas como medianas. La eficacia de glufosinate se maximizó a 140 L ha^{-1} y disminuyó al reducirse el diámetro de gota. Para las aplicaciones de 2,4-D, la eficacia incrementó cuando se usaron volúmenes iguales o mayores a 94 L ha^{-1}. Lactofen respondió más a los cambios en volumen de aplicación y se desempeñó mejor cuando fue aplicado con volúmenes de al menos 187 L ha^{-1}. El volumen de aplicación tuvo poco impacto sobre la eficacia de fluazifop-P en este estudio y la eficacia disminuyó cuando se usó en plantas más altas. Con base en estos datos, los aplicadores deberían usar mayores volúmenes de aplicación cuando se usan herbicidas de contacto con el objetivo de maximizar la eficacia de los herbicidas.

Weed control using foliar-applied herbicides requires impaction and retention of spray droplets on the target plant surface (Hislop 1987). Previous studies have established that herbicide spray applications are effective, yet could be more efficient because in many cases only a small fraction of the active ingredient applied is necessary to achieve the biological response desired in the targeted plants (Caseley et al. 1990; Graham-Bryce 1977; Matthews 1977). Generally, herbicide performance is directly related to the amount of active ingredient on the target plant. Thus, spray solution characteristics and application parameters are critical in

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determining the efficacy of a herbicide application. The carrier volume of a foliar-herbicide application is one of the components of a spray solution that can impact herbicide performance (Knoche 1994). The influence of carrier volume on the efficacy of foliar herbicides needs to be understood to make the most effective applications possible.

The adoption of glyphosate-resistant soybean [*Glycine max* (L.) Merr.] was extremely rapid, increasing from 17% of U.S. soybean hectares in 1997 to 68% in 2001 and 93% in 2010 (Fernandez-Cornejo et al. 2014). Reliance on this technology has reduced the use of integrated weed management practices, such as tillage and use of other mode-of-action herbicides in many crop production systems (Shaner 2000). Glyphosate-resistant technology simplified weed management and reduced herbicide expense for soybean producers by allowing application of a nonselective herbicide POST to soybean (Shaner 2000). Glyphosate-resistant weeds have since evolved at a high rate due to selection pressure applied to weed populations by the extensive use of glyphosate within corn, soybean, and cotton production systems (Johnson et al. 2009). In response to increasing glyphosate resistance, alternative weed management strategies are being incorporated that use various herbicide modes of action. This includes development of dicamba-resistant, 2,4-D–resistant, and 4-hydroxyphenylpyruvate-dioxygenase (HPPD)–inhibitor-resistant soybean that are being developed by U.S. companies and will soon be available to growers pending regulatory approval. Once approved, the dicamba-, 2,4-D-, and HPPD-resistant technology will enable the use of dicamba, 2,4-D, or HPPD-inhibitors with glyphosate tank mixtures for preplant burndown, at planting, and in-season applications (Davis 2012).

Glyphosate has developed into a global herbicide because it allows low-cost and effective weed control, while being environmentally benign (Baylis 2000). One component of glyphosate applications that increased its adoption among applicators was that plant response and subsequent control often increased as carrier volumes decreased, whereas the performance of other herbicides generally decreases as carrier volume decreases (Knoche 1994). Herbicide programs that rely primarily on glyphosate for weed control often used carrier rates as low as 50 L ha^{-1}, and in some instances less. This is a benefit to the applicator because the amount of water and time required for an application is reduced and more hectares are sprayed with each tank load. Conversely, many herbicides other than glyphosate often need a higher carrier volume for maximum efficacy. Applications that minimize carrier volumes to maximize the hectares sprayed with each tank might have a negative consequence because low volume applications usually require smaller orifice nozzles that, in turn, produce finer spray droplets and increase the potential for spray drift (van de Zande et al. 2003).

Spray applications are complex processes beginning in the spray tank with the spray solution and continue until the herbicide reaches the target. Major components of this process that impact the efficacy of the application include the tank mixtures, droplet formation, droplet travel to the plant, impaction and retention on the leaf or soil surface, uptake of the active ingredient, and the biological response (Brazes et al. 1991; Merritt et al. 1989; Reichard 1988). At any stage in the process, something could occur that has an effect on subsequent stages in the process and spray performance might be affected. In a meta-analysis of 110 previously published studies, Knoche (1994) reported that decreasing carrier volume at constant droplet size increased herbicide efficacy in 24% of the experiments, 32% were unaffected by decreasing carrier volume, and in 44% of the experiments, reduced efficacy was observed due to decreasing carrier volume. Knoche (1994) concluded that carrier volume effects are dependent upon the herbicide being applied.

The primary objective of this study was to determine the influence of carrier volume on the biological efficacy of four different POST-applied herbicides commonly used for weed control in soybean, each with a differing mode of action. The secondary objective was to evaluate the droplet size spectrum of each treatment in order to further understand efficacy data.

Materials and Methods

Spray Droplet Data Collection. The spray droplet spectrum for each herbicide and carrier-volume combination were evaluated using a low-speed wind tunnel at the Pesticide Application Technology Laboratory (PAT Lab) at the West Central Research and Extension Center in North Platte, NE. The wind tunnel uses an axial flow fan to generate air flow through the tunnel. Air moves from the fan, into an expansion chamber, through a honeycomb straightener to produce a laminar air flow, and then through eight 1.2 m by 1.2 m by 2.4 m adjoining sections. The droplet size spectrum for each treatment was measured using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc., Clausthal, Germany) positioned on the last section of the tunnel furthest from the fan. The laser was linked with WINDOX 5.7.0.0 software (Sympatec Inc.) operated on a computer adjacent to the laser. The R7 lens measured droplets in a dynamic size range from 18 to 3,750 µm. The laser consists of two main components, an emitter housing containing the optical box and the source of the laser, and a receiver housing containing the lens and detector element. The two laser housings were separated (1.3 m) on each side of the wind tunnel and mounted on an aluminum optical bench rail that connected underneath the wind tunnel to allow proper laser alignment. The spray plume was oriented perpendicular to the laser beam and was entirely traversed through the laser beam at 0.2 m s^{-1} using a mechanical linear actuator. The distance from the nozzle tip to the laser was 30 cm. A scrubber system and axial flow fan were attached to the last section to remove spray droplets and vapors from the exhausted air that passed through the wind tunnel. The laser is able to classify the spray droplet spectrum in a number of different categories to compare the spray droplet spectra of different treatments. The treatments in this study were compared using the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ parameters which represent the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively. The spray classifications used in this manuscript were derived from reference curves created from reference nozzle data at the PAT Lab as described by American Society of Agricultural Engineers (ASAE) S572.1 (ASABE 2009). The use of reference nozzles and curves allow for comparison of data obtained from other laboratories or methods (Fritz et al. 2014).

Field Studies. Field studies were conducted at sites near Brule, David City, Lexington, O'Neill, and Platte Center, NE in 2012 to demonstrate the effect of different carrier volumes on the biological efficacy of commonly used soybean herbicides. Each field location was arranged as a randomized complete block design with four replications. The Brule site (41.16°N, 102.02°W) was located on a Kuma loam soil (fine-silty, mixed, superactive, mesic Pachic Argiustolls) located approximately 16.1 km north northeast of Big Springs, NE. The David City site (41.25°N, 97.14°W) was located on a Hastings silt clay loam soil (fine, smectitic, mesic Udic Argiustolls) located approximately 0.8 km west of David City, NE. The Lexington site (40.82°N, 99.74°W) was located on a Rusco silt loam soil (fine-silty, mixed, superactive, mesic Oxyaquic Argiustoll) located approximately 3.2 km north of Lexington, NE. The O'Neill site (42.47°N, 98.59°W) was located on a O'Neill fine sandy loam soil (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplustoll) located approximately 4.8 km northeast of O'Neill, NE. The Platte Center site (41.52°N, 97.49°W) was located on a Shell silt loam soil (fine-silty, mixed, superactive, mesic Cumulic Haplustolls) located approximately 1.6 km south of Platte Center, NE.

The Brule location had a natural emerging population of kochia [*Kochia scoparia* (L.) Schrad.] that was evenly distributed across the plots (15 to 25 plants m^{-2}). The Brule site also had Russian-thistle (*Salsola tragus* L.) present at 10 to 15 plants m^{-2}. The David City site had a natural emerging population of confirmed glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) that was evenly distributed across the plots (20 to 30 plants m^{-2}). Glufosinate, glyphosate, lactofen, and 2,4-D (Table 1) were applied with five carrier volumes (Table 2) at each location. In addition, recommended adjuvants were added to each tank-mixture at the suggested labeled rates (Table 1). Treatments were applied using the operating parameters described in Table 2 using a CO_2-pressurized backpack sprayer with a six-nozzle boom having nozzles spaced 50 cm apart and boom height at approximately 50 cm above the weed canopies. Each plot was approximately 3 m wide and 6.5 m long. The Brule location was treated when kochia and Russian-thistle were 10- to 20-cm tall and the David City location was treated when giant ragweed was approximately 5- to 8-cm tall. The treatments were the same as those used at the other locations

Table 1. Source of materials used in carrier volume study.

Common name	Trade name	Treatment rate	Manufacturer
Fluazifop-P	Fusilade DX®	0.07 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC 27419
Glufosinate	Liberty®	0.59 kg ai ha^{-1}	Bayer Crop Science LP, Durham, NC 27709
Glyphosate	Roundup PowerMax®	0.87 or 1.26 kg ae ha^{-1}[a]	Monsanto Corporation, St. Louis, MO 63141
Lactofen	Cobra®	0.11 kg ai ha^{-1}	Valent USA Corporation, Walnut Creek, CA 94596
2,4-D	Weedone®	0.20 kg ae ha^{-1}	Nufarm Americas, Alsip, IL 60803
Ammonium sulfate	Bronc®	5.0 or 2.5% v/v[b]	Wilbur-Ellis Company, Fresno, CA 94596
Crop oil concentrate	R.O.C.®	1.0% v/v[c]	Wilbur-Ellis Company, Fresno, CA 94596
Nonionic surfactant	R-11®	0.25% v/v[d]	Wilbur-Ellis Company, Fresno, CA 94596

[a] Brule and David City were treated with 1.26 kg ae ha^{-1} glyphosate; Lexington, O'Neill, Platte Center were treated with 0.87 kg ae ha^{-1} glyphosate.

[b] Ammonium sulfate was added to glufosinate and glyphosate at 5% v/v and to lactofen and 2,4-D at 2.5% v/v.

[c] Crop oil concentrate was added to fluazifop-P and lactofen.

[d] Nonionic surfactant was added to 2,4-D.

described hereafter, with the exception of the rate of glyphosate used (1.26 kg ae ha^{-1} in Brule and David City; 0.87 kg ae ha^{-1} in Lexington, O'Neill, and Platte Center) (Table 1). Visual estimations of control were collected at 14 and 28 d after treatment (DAT) using a scale of 0 to 100 where 0 = no control and 100 = plant death.

Plots at Lexington, O'Neill, and Platte Center were established by seeding glyphosate-susceptible volunteer corn (*Zea mays* L.) and soybean, grain-type amaranth (*Amaranthus hypochondriacus* L.), and velvetleaf (*Abutilon theophrasti* Medik.), in rows spaced 76 cm apart, on July 23, 20, and 19, respectively. These species were chosen because of seed availability, ease to germinate and grow in an uncontrolled field setting, wide range of physiological characteristics, and low disposition to persist in the field long-term. These species are also representative in morphology and biology of other weedy species that can be found in Nebraska soybean fields. Plots at these locations were irrigated as needed using a center pivot irrigation system to ensure uniform germination and growth. Treatments were applied (as described previously) on August 3 at the Platte Center and O'Neill sites and August 10 at Lexington site when the corn was approximately 20-cm tall and the other seeded species averaged 10- to 15-cm tall. Although corn and soybean were in treated plots, herbicide phytotoxicity to corn in 2,4-D plots and soybean in lactofen plots were not recorded. Plots were rated in the same manner as the Brule and David City locations.

Greenhouse Study. A greenhouse study was conducted at the PAT Lab using the same treatments and application parameters that were used in the field studies (Tables 1 and 2). In addition to the field treatments, fluazifop-P, and another carrier volume, 280 L ha^{-1}, were used in the greenhouse study and noted in Tables 1 and 2. Fluazifop-P treatments were only applied to grass species and 2,4-D was only applied to broadleaf species. Volunteer corn, common flax (*Linum usitatissimum* L.), grain amaranth, shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet and Harlan], soybean, tomato (*Solanum lycopersicum* L.), and velvetleaf were grown in SC10 cone-tainer cells (Stuewe and Sons Inc., Corvallis, OR 97389) filled with potting mix (Baccto Professional Grower's Mix; Michigan Peat Company, Houston, TX 77098) consisting of 75 to 85% sphagnum peat moss and 15 to 25% perlite with a pH of 5.5 to 6.5. Although flax and tomatoes

Table 2. Application parameters used to achieve different carrier volumes.

Carrier volume	Nozzle type	Pressure	Application speed
L ha^{-1}		kPa	km h^{-1}
47	XR11001[a]	103	7.7
70	XR11001	138	6.4
94	XR11001	276	6.4
140	XR110015	276	6.4
187	XR11002	276	6.4
280[b]	XR11003	276	3.2

[a] Teejet Technologies, Spraying Systems Co., Springfield, IL 62703.

[b] Only used in the greenhouse study.

Table 3. Spray droplet diameters generated from reference nozzles as described in American Society of Agricultural Engineers (ASAE) 572.1 volume diameters used to determine spray droplet classifications.

Nozzle	Droplet size[a] $D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$
	μm		
11,001	61	135	1,061
11,003	117	260	422
11,006	168	369	608
8,008	200	442	740
6,510	239	526	865
6,515	314	663	1,061

[a] Parameters representing the droplet size such that 10, 50, and 90% of the spray volume is contained in droplets of equal or smaller values, respectively.

are not considered weedy species, they were included because tomatoes are highly responsive to herbicides and flax has small leaves similar in morphology and biology to other weeds that can be found in Nebraska soybean fields. Plants were seeded at different intervals beginning in August through September of 2013 and were watered as needed. Plants received supplemental nutrition (Scotts Miracle-Gro® LiquaFeed® All Purpose; The Scotts Company, Marysville, OH, 43041) once per week. Supplemental lighting (NeoSol™ DS 300W; Illumitex, Austin, TX, 78735) was provided to ensure 14-h d. Herbicide treatments were applied at two growth stages when plants from each species were either 15- or 30-cm tall. The experiment was conducted twice, separated temporally; therefore, each species had two experimental runs for each height or four runs for each species. Treatments were applied throughout October and November using a single-nozzle track sprayer (Generation III Research Track Sprayer; DeVries Manufacturing, Hollandale, MN 56045). An individual plant in a cone-tainer was an experimental unit. Visual estimations of control were collected at 7, 14, and 28 DAT using the aforementioned scale of 0 to 100%. At 28 DAT, plants were destructively sampled by clipping the plant at the soil surface and recording the fresh weights. These samples were then dried at 40 C for 7 d, following which dry weights were recorded.

Statistical Analysis. The droplet size spectrum analysis was conducted as a factorial arrangement of treatments within a randomized complete block design with three replications for each treatment combination. Each traverse of the spray pattern through the laser beam represented a replication and produced data for the droplet size parameters $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ in accordance to ASAE S572.1 (ASABE 2009) (Tables 3 and 4). Droplet-size spectrum data were analyzed using the PROC Mixed procedure (method = REML) (Littell et al. 2006) in SAS v9.3 (SAS Institute Inc., Cary, NC, 27513) with replication as the random variable. Mean treatment effects were compared using Tukey's studentized range test (HSD) at the 0.05 significance level. Tukey's HSD was used to reduce the chance of type I errors (Steel and Torrie 1980).

Control rating data from the field studies were compared using a generalized linear mixed model analysis of variance in the GLIMMIX procedure of SAS v9.3 (SAS Institute). Nontreated controls were included in each field study for visual rating reference only and were not included in analysis of data. David City and Brule sites were each analyzed separately because each site had different weed species. Analysis for each site had replication designated as a random effect in the model. Lexington, O'Neill, and Platte Center control rating data were analyzed together with replication nested within location and considered a random effect as suggested by Carmer et al. (1989). The analysis was performed using repeated measures, which allowed for pooling of means over rating intervals. The Akaike information criterion with a correction for finite sample sizes (AICc) was used, as suggested by Burnham and Anderson (2002), to select the appropriate covariance model to use in the repeated-measure analysis. The AICc indicated the default covariance model used by GLIMMIX best fit the data and was used for repeated measure analysis conducted for both field and greenhouse studies. The Kenward-Rogers degree-of-freedom approximation procedure was used for the Lexington, O'Neill, and Platte Center analysis due to some instances of missing data. Pearson's correlation coefficient (*r*) was used to evaluate relationships between the response variables carrier volume and droplet size.

For the greenhouse study, treatments were applied to each weed species and size separately. Therefore, each species and size was analyzed separately. Each experiment was arranged as a randomized complete

Table 4. Volume diameters below which droplets of equal or smaller size constitute 10, 50, and 90% ($D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$) of the total spray volume for each herbicide and carrier volume combination used. Spray classification determined in accordance with American Society of Agricultural Engineers (ASAE) 572.1 standards from reference curves created using the same methods to determine treatment droplet data.

		Droplet size			
Herbicide	Volume	$D_{v0.1}$	$D_{v0.5}$	$D_{v0.9}$	Spray classification
	L ha^{-1}		———μm^{a}———		
2,4-D	47	114 b	229 b	367 b	fine
	70	104 c	206 d	343 c	fine
	94	90 d	172 e	281 d	fine
	140	103 c	204 d	354 c	fine
	187	114 b	221 c	352 c	fine
	281	129 a	251 a	407 a	medium
Fluazifop-P	47	136 b	252 b	379 b	medium
	70	122 c	227 d	351 d	medium
	94	93 e	178 f	283 e	fine
	140	111 d	212 e	350 d	fine
	187	125 c	237 c	364 c	medium
	281	143 a	275 a	423 a	medium
Lactofen	47	89 a	202 a	358 a	fine
	70	75 b	176 b	323 b	fine
	94	62 c	144 d	270 c	fine
	140	67 c	160 c	325 b	fine
	187	76 b	178 b	317 b	fine
	281	87 a	205 a	366 a	fine
Glufosinate	47	98 ab	227 a	378 b	fine
	70	95 b	201 b	352 c	fine
	94	77 d	159 d	281 e	fine
	140	89 c	187 c	352 c	fine
	187	95 b	200 b	341 d	fine
	281	102 a	227 a	392 a	fine
Glyphosate	47	127 b	243 b	372 b	medium
	70	118 c	222 d	348 c	medium
	94	93 e	176 f	281 d	fine
	140	109 d	210 e	350 c	fine
	187	122 bc	233 c	358 c	medium
	281	140 a	271 a	420 a	medium

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

block design with five replications. Estimation of visual control data for the greenhouse studies had replication nested within run designated as a random effect in the model. Percent biomass reduction for treated experimental units was calculated using both the fresh and dry weights relative to the average biomass of the nontreated control plants in each study as (Equation 1):

$$\textit{Percent biomass reduction} = [(\bar{C} - B/\bar{C})]100 \quad [1]$$

where $\bar{C}$ is the mean biomass of the nontreated control replicates, and B is the biomass of an individual experimental unit after being treated. Values for biomass reduction were compared using a generalized linear mixed model analysis of variance (GLIMMIX) procedure of SAS (Littell et al. 2006). Least-squares (LS) means were compared for significant fixed effects at an alpha level of 0.05.

Results and Discussion

Droplet Size. A significant herbicide by carrier volume interaction of spray droplet size was present ($P < 0.001$) for the $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ droplet size parameters. Estimated means from each of the droplet size parameters were sorted by herbicide to simplify the presentation of results (Table 4). The greatest $D_{v0.5}$ values were observed at the highest application volume rate (281 L ha^{-1}) for all herbicides tested except lactofen and glufosinate which had similar $D_{v0.5}$ values at 47 L ha^{-1} (Table 4). As carrier volume increased from 47 to 94 L ha^{-1}, the $D_{v0.5}$ values of 2,4-D and lactofen decreased almost 60 μm yet remained within the fine spray classification (Table 4). The droplet classification of glufosinate and glyphosate also stayed at a fine classification as $D_{v0.5}$ values decreased 68 and 67 μm, respectively, and fluazifop-P had the greatest decrease at 74 μm, keeping it at a fine classification (Table 4). $D_{v0.5}$ values then increased as carrier volumes increased from 94 to 281 L ha^{-1}, maintaining the fine spray classification for 2,4-D, lactofen, and glufosinate, and moving droplet classification to medium for fluazifop-P. The $D_{v0.1}$ and $D_{v0.9}$ values followed a similar pattern as the $D_{v0.5}$ values, initially decreasing, and then increasing as carrier volume increased (Table 4). The changes in droplet size resulted from the application parameters used to achieve each carrier volume (Table 2) and how these parameters interacted with each herbicide and carrier volume. The objective of collecting and analyzing of the spray droplet data in this study was not to describe the effects of carrier volume on droplet size. Rather the objective was to describe how the operating parameters impacted spray droplet size and provide insight into some instances where differences in results cannot be explained by the simple change in carrier volume. Droplet size has been shown to increase as herbicide concentra-

Table 5. Estimation of visual control values derived from a repeated measures analysis using ratings conducted at 14 and 28 d after treatment (DAT) of Russian-thistle and glyphosate-resistant kochia with various herbicides and carrier volumes near Brule, NE.

	Control			
Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
L ha^{-1}		$\%^{a,b}$		
47	32	15 c	50 b	95 a
70	32	17 c	59 ab	93 ab
94	31	18 c	51 ab	86 b
140	33	28 b	62 a	92 ab
187	27	42 a	49 b	94 a

[a] Treatments applied to 10- to 20-cm-tall kochia and Russian-thistle.

[b] Means within a column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 6. Estimation of visual control for glyphosate-resistant giant ragweed 28 d after treatment (DAT) with various herbicides and carrier volumes near David City, NE.

	Control			
Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
L ha^{-1}		$\%^{a,b}$		
47	70	34 c	63	63
70	68	73 ab	48	68
94	86	59 b	58	51
140	77	61 b	41	68
187	76	82 a	54	55

[a] Treatments applied to 5- to 8-cm-tall giant ragweed.

[b] Means within a column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

tion was diluted by increasing carrier volumes (Creech et al. 2015). When averaged over different herbicides, nozzles, nozzle tip sizes, and pressures, increasing carrier volume from 47 to 187 L ha^{-1} increased the $D_{v0.5}$ value 5% from 383 to 404 µm (Creech et al. 2015).

Field Studies. Weed species was removed from the model used to analyze the Brule location because it did not have any significant interactions ($P = 0.6574$). Means from the Brule data presented in Table 5 were estimated using the herbicide by carrier volume interaction ($P < 0.0001$) and were sorted by herbicide. No differences were observed among treatments as carrier volume increased using 2,4-D at the Brule location (Table 5). Glyphosate treatments at Brule provided the greatest control when applied at 47, 70, 140, and 187 L ha^{-1} with 95, 93, 92, and 94% control, respectively (Table 5). The least control was observed when applications were made at 94 L ha^{-1} (86%) although observed control was not different from control following application volumes of 70 and 140 L ha^{-1} (Table 5). Weed control from glufosinate was greatest at 140 L ha^{-1} (62%) followed by control following application at 47 and 187 L ha^{-1} (50 and 49%, respectively); although observed control was not different than that observed following applications made at 70 and 94 L ha^{-1} (59 and 51% respectively; (Table 5). Control of kochia and Russian-thistle increased from 18 to 42% as carrier volume increased from 94 to 187 L ha^{-1}, respectively, when using lactofen (Table 5).

A herbicide by carrier volume interaction ($P = 0.0086$) was present at David City. Therefore, means were calculated using the herbicide by carrier volume interaction and the resulting estimated means were sorted by herbicide (Table 6). No difference in control was observed among carrier volumes when using 2,4-D, glufosinate, or glyphosate when applied to glyphosate-resistant giant ragweed (Table 6). Visual estimations of control from lactofen treatments increased from 59 to 82% when increasing carrier volume from 94 to 187 L ha^{-1}, respectively. Control following lactofen application at 187 L ha^{-1} (82%) was not different than control observed following application at 70 L ha^{-1} (73%; Table 6). Increasing the carrier volume when using lactofen from 47 to 187 L ha^{-1} resulted in 141% increase in control from 34 to 82%, respectively (Table 6).

The Lexington, O'Neill, and Platte Center data were pooled across location because no significant interactions with location were present. A significant herbicide by carrier volume by species interaction was present ($P = 0.0243$). Estimated means were sorted by herbicide and species in Table 7 to simplify the presentation of the results. Results from 2,4-D on corn and lactofen on soybean were omitted from the analysis due to lack of control based on visual estimates. The only species to respond to changes in carrier volume when using glyphosate at these locations was the grain-type amaranth. The least control at 88% was observed

Table 7. Estimation of visual control derived from a repeated measures analysis using ratings conducted at 14 and 28 d after treatment (DAT) with various herbicides and carrier volumes pooled across studies conducted near Lexington, O'Neill, and Platte Center, NE.

		Herbicide			
Species	Volume	2,4-D	Lactofen	Glufosinate	Glyphosate
	L ha^{-1}	$\%^{a,b}$			
Amaranth	47	83 b	84 b	71 bc	88 b
	70	82 b	92 b	70 c	95 a
	94	84 ab	99 a	82 ab	92 ab
	140	93 a	99 a	88 a	93 ab
	187	89 ab	100 a	87 a	92 ab
Corn	47	—	24 b	79 bc	98
	70	—	23 b	76 c	98
	94	—	29 b	88 a	98
	140	—	32 b	87 ab	97
	187	—	44 a	85 abc	97
Soybean	47	46 c	—	86 abc	96
	70	52 bc	—	81 c	98
	94	68 a	—	95 a	96
	140	65 ab	—	93 ab	97
	187	61 abc	—	88 abc	98
Velvetleaf	47	55	52 b	69 b	95
	70	59	57 b	74 b	94
	94	59	76 a	77 b	96
	140	58	84 a	90 a	93
	187	63	85 a	89 a	95

[a] Treatments applied to 10- to 15-cm-tall plants.

[b] Means within each species and herbicide followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

following application at 47 L ha^{-1} which was less than control following application at 70 L ha^{-1} (95%; Table 7). The greatest control of grain amaranth when using 2,4-D was observed when applications were made at a 140 L ha^{-1} (93%; Table 7). This observed control of 93% following 2,4-D application was not different from 94 or 187 L ha^{-1} which resulted in 84 and 89% control, respectively (Table 7). Soybean control increased to 68% when applying 2,4-D at 94 L ha^{-1}; however, control was not different than that observed following 2,4-D applied at 140 or 187 L ha^{-1} which resulted in 65 and 61% control, respectively (Table 7). No differences in velvetleaf control were observed due to changing carrier volumes when using 2,4-D (Table 7). Visual estimation of control was generally greatest when applying glufosinate using carrier volumes greater than 94 L ha^{-1} for the four species (Table 7). Amaranth, corn, and soybean control was highest when applying glufosinate at 94, 140, and 187 L ha^{-1} (82, 88, and 87%; 88, 87, and 85%; and 95, 93, and 88%, respectively), although soybean control following application at higher carrier volumes were not different than control observed following applications at 47 L ha^{-1} (86%). Velvetleaf control was greatest when applying glufosinate in 140 and 187 L ha^{-1} carrier volumes (90 and 89%, respectively). Greater control was observed at these locations generally when lactofen was applied at 94, 140, and 187 L ha^{-1} to amaranth, corn, and velvetleaf (Table 7). Grain amaranth and velvetleaf control was greatest when application were made at 94, 140, and 187 L ha^{-1} (99, 99, and 100%; and 76, 84, and 85%, respectively) and corn control was greatest at 187 L ha^{-1} (44%) (Table 7).

Greenhouse Study. The greenhouse data, as described previously, were analyzed separately by species and size. A significant ($P < 0.05$) herbicide by carrier volume interaction was present for each of the species. Therefore, data were sorted by herbicide as previously described in the field components of this experiment. In addition, results from the 15-cm-tall weed species were not presented in table form to simplify the presentation of the results. Nearly all the results from the 15-cm-tall species were similar to the 30-cm-tall results and any differences worth noting will be mentioned in the following text.

Control of corn with glyphosate according to the dry weight reduction (DWR) was less at the two smallest carrier volumes than the greater volumes (Table 8). Conversely, shattercane wet weight reduction (WWR) and DWR was lower when using higher carrier volumes. The response of other species to glyphosate when increasing carrier volume was more variable and no clear trend was observed (Table 8).

Soybean control and weight reduction was generally greatest when 2,4-D was applied at the highest carrier volume, 281 L ha^{-1} (Table 9). In contrast, velvetleaf was not impacted by changes in carrier volume at the field locations or consistently in the greenhouse (Tables 7 and 8). Grain amaranth displayed little response to changes in carrier volume in the greenhouse (Table 9). Tomato control ratings decreased dramatically at 281 L ha^{-1} when using 2,4-D. Runoff likely decreased the amount of 2,4-D on the leaf surface due to the

Table 8. Estimation of visual control ratings, wet-weight reductions (WWR), and dry-weight reductions (DWR) of 30-cm-tall plant species to glyphosate applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Glyphosate[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	49 a	91 a	67 b
	70	45 ab	88 ab	69 b
	94	40 ab	87 ab	70 ab
	140	31 b	84 b	73 ab
	187	34 ab	88 ab	76 a
	281	36 ab	88 ab	77 a
Flax	47	70 ab	54 c	47 c
	70	68 ab	62 abc	55 bc
	94	62 b	49 c	44 c
	140	81 a	71 ab	69 c
	187	79 a	80 a	82 a
	281	72 ab	60 bc	61 ab
Grain amaranth	47	21 bc	87 b	82 ab
	70	11 cd	96 a	91 a
	94	29 ab	88 b	81 b
	140	32 ab	93 ab	89 ab
	187	10 d	94 ab	91 a
	281	37 a	96 a	91 a
Shattercane	47	77 a	81 a	78 a
	70	73 ab	76 ab	72 ab
	94	72 ab	73 abc	75 a
	140	59 ab	57 c	60 bc
	187	55 b	57 c	53 c
	281	64 ab	63 bc	65 abc
Soybean	47	25 a	25	38
	70	18 b	23	25
	94	16 b	22	18
	140	17 b	18	20
	187	11 c	23	16
	281	20 ab	21	18
Tomato	47	54 a	64	56 ab
	70	67 a	71	61 a
	94	55 a	53	48 ab
	140	61 a	57	39 b
	187	54 a	59	53 ab
	281	28 b	49	39 ab
Velvetleaf	47	17 ab	67 a	71 a
	70	14 ab	26 abc	48 ab
	94	8 b	5 bc	29 ab
	140	12 ab	2 c	12 b
	187	22 a	40 abc	41 ab
	281	17 ab	51 abc	63 ab

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 9. Estimation of visual control ratings, wet-weight reductions (WWR), and dry-weight reductions (DWR) of 30-cm-tall plant species to 2,4-D applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		2,4-D[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Flax	47	57 a	53 a	58 a
	70	40 b	48 a	43 abc
	94	45 ab	47 a	55 a
	140	36 b	25 b	38 abc
	187	37 b	32 ab	30 c
	281	40 ab	37 ab	34 bc
Grain amaranth	47	56 ab	99	92
	70	59 ab	99	94
	94	44 b	99	94
	140	55 ab	99	94
	187	43 b	99	92
	281	69 a	99	92
Soybean	47	49 bcd	40 b	42 b
	70	43 cd	47 b	42 b
	94	40 d	31 b	34 b
	140	51 bc	45 b	46 b
	187	54 b	44 b	38 b
	281	76 a	78 a	69 a
Tomato	47	77 ab	72 ab	48 bc
	70	63 b	58 b	39 c
	94	79 a	81 a	67 a
	140	79 a	74 ab	62 ab
	187	79 a	70 ab	44 bc
	281	38 c	83 a	70 a
Velvetleaf	47	71 ab	74 ab	58
	70	73 a	71 ab	47
	94	75 a	77 a	58
	140	75 a	76 a	54
	187	56 b	59 ab	44
	281	84 a	50 b	44

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

morphology of tomato plants. Although both the wet- and dry-weight reductions for tomato in Table 9 fail to corroborate the control ratings, it should be noted that elongation and swelling of the stems was observed on both tomato and velvetleaf. Therefore, weight often increased as a result of the 2,4-D application, and the visual control rating might be a better measure of the effectiveness of 2,4-D for some plant species. Flax control was also generally greater at lower carrier volumes as illustrated by the DWR (Table 9). Pearson's correlation coefficients were not significant ($P < 0.05$) for droplet size and

Table 10. Estimation of visual control rating, wet-weight reductions (WWR) and dry-weight reductions (DWR) of 30-cm-tall plant species to glufosinate applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Glufosinate[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	——————%	——————	
Corn	47	20 bc	45 b	17 d
	70	22 bc	34 b	28 cd
	94	21 bc	21 c	36 bc
	140	23 b	43 b	43 b
	187	17 c	19 c	45 b
	281	30 a	59 a	60 a
Flax	47	61 ab	46 b	62 ab
	70	71 a	64 a	66 ab
	94	49 b	31 b	51 b
	140	61 ab	50 ab	71 a
	187	68 a	68 a	72 a
	281	69 a	69 a	63 ab
Grain amaranth	47	90 a	99 a	96 a
	70	87 ab	98 a	95 ab
	94	70 c	95 b	90 b
	140	73 c	98 a	93 ab
	187	76 bc	98 a	96 a
	281	93 a	99 a	97 a
Shattercane	47	65 a	62 a	75
	70	50 b	40 b	66
	94	40 b	53 ab	66
	140	45 b	49 ab	69
	187	47 b	60 ab	63
	281	64 a	56 ab	75
Soybean	47	79 ab	76 a	77 a
	70	64 cd	63 abc	64 abc
	94	60 d	52 bc	57 bc
	140	67 bcd	67 ab	70 ab
	187	63 cd	47 c	50 c
	281	81 a	75 a	76 a
Tomato	47	91 a	90 a	76 a
	70	71 bc	54 c	58 b
	94	79 abc	81 ab	67 ab
	140	64 c	68 bc	54 b
	187	86 a	77 ab	73 a
	281	41 d	78 ab	68 ab
Velvetleaf	47	76 a	73 a	71
	70	66 b	68 ab	68
	94	50 c	42 b	63
	140	47 c	55 ab	51
	187	63 bc	50 ab	60
	281	89 a	71 a	51

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

any of the response variables related to 2,4-D, indicating that droplet size is not as important as other factors in the application process.

When applying glufosinate treatments, the highest carrier volume (281 ha^{-1}) provided the best control of corn in the greenhouse (60% DWR; Table 10). Although other species in the greenhouse were adequately controlled with higher application volumes, no obvious correlation was observed (Table 10). Pearson's correlation revealed that a number of the species responded more to the changes in droplet size than changes in carrier volume (data not shown). Nearly all the glufosinate response variables had significant ($P < 0.05$) r values (0.86 to 0.99) when the correlation between control and droplet size was evaulated. Therefore, these results suggest glufosinate efficacy increases as droplets size increases.

Wet- and dry-weight reductions of 15-cm-tall corn and shattercane were greatest when lactofen applications were made at 281 L ha^{-1} (data not shown). Velvetleaf also responded to high carrier volumes in the greenhouse with greatest control being observed most often following applications at 187 and 281 L ha^{-1} (Table 11). Grain amaranth did not show a similar response to the field studies because a high level of control was achieved across carrier volumes in the greenhouse (Table 11). The greatest control of flax was when applications were made at 94 to 281 L ha^{-1}. Tomato control was inconsistent and did not produce an increasing pattern of control as carrier volume increased (Table 11). In addition, WWR and DWR were generally lower for the 30-cm-tall plants compared to 15-cm-tall plants (data not shown).

Fluazifop-P ratings, WWR, and DWR were nearly all greater than 90% for 15-cm corn and shattercane except for some of the corn results (data not shown). Hence, little difference was observed when using fluazifop-P to control corn and shattercane, although corn DWR following applications at 47 L ha^{-1} was lower than most carrier volumes (Table 12). Corn DWR following applications to 30-cm plants was greatest when applications were made at 187 and 281 L ha^{-1} which resulted in 78 and 79% reductions, respectively (Table 12).

Results from the Brule location showed no correlation to changes in carrier volume. Glyphosate control was highly related to $D_{v0.5}$ values ($r = 0.98$, $P < 0.0001$). Other studies have evaluated droplet

Table 11. Estimation of visual control ratings, wet-weight reductions (WWR) and dry-weight reductions (DWR) of 30-cm-tall plant species to lactofen applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Lactofen[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	13	12 bc	11
	70	13	7 c	12
	94	14	9 bc	18
	140	14	13 bc	18
	187	16	24 a	21
	281	15	18 abc	22
Flax	47	82 bc	58 b	54 b
	70	80 c	54 b	53 b
	94	87 ab	65 ab	61 ab
	140	87 ab	63 ab	57 b
	187	88 ab	61 ab	75 a
	281	94 a	78 a	77 a
Grain amaranth	47	95 ab	99	96
	70	96 ab	98	95
	94	93 ab	99	95
	140	89 b	98	94
	187	95 ab	99	96
	281	98 a	99	96
Shattercane	47	23 b	20 bc	25 b
	70	25 ab	17 c	24 b
	94	28 ab	43 a	37 ab
	140	26 ab	33 ab	44 a
	187	35 a	30 abc	44 a
	281	36 a	39 a	44 a
Tomato	47	68 b	53 b	59 ab
	70	75 ab	64 ab	52 b
	94	66 b	54 b	50 b
	140	63 b	60 ab	58 ab
	187	84 a	57 ab	58 ab
	281	42 d	81 a	76 a
Velvetleaf	47	64 c	56 ab	72 a
	70	69 bc	49 b	53 b
	94	71 bc	52 b	55 ab
	140	77 b	61 ab	60 ab
	187	70 bc	74 ab	65 ab
	281	93 a	76 a	69 ab

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

Table 12. Estimation of visual control ratings, wet-weight reductions (WWR), and dry-weight reductions (DWR) of 30-cm-tall plant species to fluazifop-P applied at different carrier volumes conducted in a greenhouse experiment in North Platte, NE.

		Fluazifop-P[a]		
Species	Volume	Rating	WWR	DWR
	L ha^{-1}	%		
Corn	47	49	92 ab	64 d
	70	46	90 b	70 cd
	94	51	91 ab	71 cd
	140	58	95 a	72 bc
	187	42	90 ab	78 ab
	281	54	95 ab	79 a
Shattercane	47	59	62 ab	57 abc
	70	55	62 ab	58 abc
	94	58	67 ab	65 a
	140	50	57 ab	50 bc
	187	50	51 b	48 c
	281	57	70 a	60 abc

[a] Means within each herbicide and column followed by the same letter are not significantly different at the $P \leq 0.05$ level using least-squares means.

size effects on glyphosate efficacy and concluded that larger droplets increase absorption and translocation of glyphosate (Feng et al. 2003; Liu et al. 1996). In contrast, Ramsdale et al. (2003) found that grasses were controlled equally following applications using a standard flat-fan nozzle that produce small droplets and drift-reducing nozzles that produce larger droplets. Greenhouse results for glyphosate summarized in Table 8 and in the data not shown of the 15-cm-tall plants shows applications made to 30-cm plants resulted in reduced control and greater response to changes in carrier volume. Applications to tomato resulted in decreased efficacy when applications were made at 281 L ha^{-1} (Table 8). Sandberg et al. (1978) reported that reduced glyphosate efficacy caused by spray runoff can occur at spray volumes above 190 L ha^{-1}. Similarly, runoff was observed from tomato plants after the glyphosate application at 281 L ha^{-1}, which is likely related to the morphology of the tomato plants. Moreover, Ramsdale et al. (2003) concluded the amount of surfactant in formulated glyphosate was insufficient when applied in volumes of 94 L ha^{-1} or greater, and that additional surfactant enhanced glyphosate efficacy. Thus, spraying glyphosate at rates of 94 L ha^{-1} or greater provides little additional benefit and is not recommended because reductions in efficacy could occur.

A previously conducted study evaluating droplet size effects on 2,4-D efficacy concluded that greater control of common beet (*Beta vulgaris* L.) is achieved when using smaller droplets (65 µm) as compared to larger droplets (411 or 530 µm) (Ennis and Williamson 1963). Similarly, McKinlay et al.

(1972) reported decreasing control of common sunflower (*Helianthus annuus* L.) as droplet size increased from 100, 200, and 400 µm. McKinlay et al. (1972) observed that leaf cells collapse and eventually die following applications using 400-µm droplets and hypothesized the collapsed leaf cells limited the amount of translocation of 2,4-D into the plant. McKinlay et al. (1972) did use diesel fuel as a carrier and it is likely that the phytotoxicity of the diesel injured the plant cells and not the 2,4-D itself. 2,4-D treatments used in this study were similar in droplet size, with $D_{v0.5}$ values ranging from 172 to 251 µm (Table 4). Large differences in droplet size were noted in studies by Ennis and Williamson (1963) and McKinlay et al. (1972), and differences in 2,4-D efficacy were observed. Similar to the increase in amaranth and soybean control observed using 2,4-D at the Lexington, O'Neill, and Platte Center locations as carrier volume increased, Smith (1946) concluded carrier volumes between 122 and 234 L ha^{-1} and medium to coarse droplets provided the best control for 2,4-D. Because no droplet size and efficacy correlation was observed in this work, 2,4-D applications should be made using carrier volumes between 94 and 281 L ha^{-1} using medium to coarse droplets to deliver the 2,4-D to the intended target as recommended by (Smith 1946). Moreover, care should be given to ensure few droplets above 400 µm are produced because previous work has shown decreases in 2,4-D efficacy with larger droplets (Ennis and Williamson 1963; McKinlay et al. 1972).

Glufosinate is a nonselective herbicide normally characterized as a contact herbicide due to its limited translocation within a plant. Although glyphosate and glufosinate have similar chemical properties, glufosinate translocation is minimal compared to glyphosate (Beriault et al. 1999). Etheridge et al. (2001) observed increased glufosinate efficacy on common cocklebur (*Xanthium strumarium* L.) when increasing carrier volumes from 50 to 100 L ha^{-1}. In the same study, Etheridge et al. (2001) found droplet size to be negatively correlated with glufosinate and paraquat performance. Other research has found environmental factors, namely humidity, to affect the amount of glufosinate translocated within plants (Anderson et al. 1993; Coetzer et al. 2009). They found glufosinate efficacy increased as humidity increased. How this relates to carrier volume and droplet size has yet to be studied and could be important when choosing a droplet classification to use to apply glufosinate. The results from our study generally support using a carrier volume of 140 L ha^{-1} and making application with medium to coarse spray droplets.

Visual control resulting from lactofen applications increased at the field locations as carrier volume increased. Similarly, Berger et al. (2014) found applications of lactofen to 15- to 20-cm Palmer amaranth (*Amaranthus palmeri* S. Wats.) provided less control than when lactofen was applied to 5- to 10-cm-tall plants. In addition, they observed less control of 15- to 20-cm Palmer amaranth when making applications at 94 L ha^{-1} as compared to applications made at 187 or 281 L ha^{-1}. Moreover, they evaluated both extended-range (XR) and air-induction (AI) nozzles and discovered that although the XR nozzle provided greater coverage, no difference in lactofen efficacy was observed. Our research results agree with the findings of Berger et al. (2014) in that lactofen provides best control when the target species are smaller than 15 cm and when using carrier volumes greater than 187 L ha^{-1}. Likewise, we observed no impact of droplet size on lactofen efficacy.

Chandrasena and Sagar (1989) found applications volumes of 100 and 200 L ha^{-1} provided similar efficacy when applying fluazifop-P, and efficacy decreased as carrier volume increased to 400 and 800 L ha^{-1}. Similarly, Smeda and Putnam (1989) concluded application volumes of 187 L ha^{-1} provided better control than application volumes of 374 L ha^{-1}. Fluazifop-P efficacy increased as carrier volume increased in a low carrier volume study using volumes of 10, 30, 50, and 100 L ha^{-1} (Rogers 1989). Chandrasena and Sagar (1989) also evaluated the impact of droplet size on fluazifop-P efficacy and concluded that 780-µm droplets resulted in greater efficacy than 990- or 1,240-µm droplets. Our operating parameters created much smaller droplets with modest variations among treatments, compared to those used by Chandrasena and Sagar (1989), and we observed no droplet size effect on efficacy.

The impacts of carrier volume and to lesser extent, droplet size, on the performance of foliar-applied herbicides were evaluated in this study to provide a better understanding of the influence of spray application factors on herbicide efficacy. Carrier volume requirements depend on the mode of action of the herbicide being applied and is impacted by the size and structure of the intended weed target. When applicators use products other than glyphosate for weed control, it is important to understand the application requirements of the products that are being applied and what can be done to maximize efficacy. The herbicides evaluated in this study responded to changes in carrier volume and the response observed was often herbicide specific as well as plant species-specific. Increased application volumes result in more being transported and sprayer tanks filled more often to spray fewer hectares; however, the increase in herbicide efficacy can have a positive impact on crop yield and help reduce the rate of spread of herbicide-resistant weeds because of reduced selection pressure from greater weed control.

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