Invasive Plant Science and Management

www.cambridge.org/inp

Effect of carrier volume and application method on waterhyacinth (*Eichhornia crassipes*) response to 2,4-D, glyphosate, and diquat

Benjamin P. Sperry[1] and Jason A. Ferrell[2]

[1]Research Assistant Scientist, University of Florida, Center for Aquatic and Invasive Plants, Gainesville, FL, USA and [2]Professor and Director, University of Florida, Center for Aquatic and Invasive Plants, Gainesville, FL, USA

Research Article

Cite this article: Sperry BP and Ferrell JA (2021) Effect of carrier volume and application method on waterhyacinth (*Eichhornia crassipes*) response to 2,4-D, glyphosate, and diquat. Invasive Plant Sci. Manag **14**: 29–34. doi: 10.1017/inp.2021.1

Received: 5 October 2020
Revised: 7 December 2020
Accepted: 13 January 2021
First published online: 22 January 2021

Associate Editor:
Rob J. Richardson, North Carolina State University

Keywords:
Application technology; droplet size; solution concentration

Author for correspondence:
Benjamin P. Sperry, University of Florida, Center for Aquatic and Invasive Plants, 7922 NW 71st Street, Gainesville, FL 32653.
(Email: bpsperry@ufl.edu)

Abstract

Mesocosm studies were conducted in 2020 to evaluate the effects of carrier volume and application method on waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] response to 2,4-D, glyphosate, and diquat. Carrier volumes of 935, 467, and 187 L ha^{-1} were applied using either a conventional stream, conventional cone, adjustable cone, or a drizzle-stream spray pattern. Reducing carrier volume from 935 L ha^{-1} reduced spray coverage up to 60%, depending on application method. However, reducing carrier volume did not diminish efficacy of any herbicide or application method. Alternatively, *E. crassipes* control from 2,4-D increased 10% to 26% when applied using 187 L ha^{-1} compared with 935 L ha^{-1}. Likewise, *E. crassipes* biomass was reduced 91% when 2,4-D was applied using 935 L ha^{-1}; however, treatment applied at 187 L ha^{-1} resulted in 99% biomass reduction. In general, 2,4-D resulted in roughly 10% greater control when conventional or adjustable cone applications were used compared with either stream applications. *Eichhornia crassipes* control at 7 d after treatment (DAT) from diquat increased with decreasing carrier volumes; however, treatment effects in diquat experiments were not detected at other evaluation intervals. Glyphosate efficacy was highly influenced by carrier volume, as *E. crassipes* control increased up to 61% when applied using 187 L ha^{-1} compared with 935 L ha^{-1}. Moreover, *E. crassipes* biomass reduction increased from 55% in the 935 L ha^{-1} treatment to 97% in the 187 L ha^{-1} treatments. Glyphosate application methods consisting of conventional stream or conventional cone sprayers resulted in slightly increased *E. crassipes* control by 28 DAT; however, no differences among application methods were observed in *E. crassipes* biomass data. These data support further evaluations of alternative application techniques for *E. crassipes* control under field conditions and for other herbicides and aquatic plant species.

Introduction

Waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] is a rapidly growing invasive plant that has been a management challenge in Florida for more than 130 yr (Center and Spencer 1981; Penfound and Earle 1948; Pieterse 1978). In addition to impeding navigation, irrigation, and recreation, *E. crassipes* can also reduce water quality (dissolved oxygen and pH) and shelter mosquito species responsible for the spread of harmful human diseases (Holm et al. 1977; Owens and Madsen 1995; Penfound and Earle 1948; Schreiner 1980; Seabrook 1962; Ultsch 1973). Therefore, managing *E. crassipes* populations at the lowest feasible level with herbicides has become compulsory for protecting public waterways and human health (Joyce 1985; University of Florida 2011).

Control of *E. crassipes* has for decades largely relied on diquat and 2,4-D; however, glyphosate, imazapyr, triclopyr, and penoxsulam can also provide effective control (Enloe et al. 2018; Wersal and Madsen 2010). Diquat is often favored due to rapid development of symptoms and the fact that it provides simultaneous control of waterlettuce (*Pistia stratiotes* L.), which is commonly found with *E. crassipes* in mixed stands (Mudge and Netherland 2014). Rapid symptom development is important in aquatic plant management, as it provides a visual cue to the applicator to delineate which plants have been treated. This is essential, as few landmarks exist on open water to keep tabs on the spray track. Though 2,4-D does not control *P. stratiotes*, it is more selective than diquat on a number of desirable native plants and still produces herbicide symptoms within 1 to 3 d of treatment. Glyphosate and other slow-acting enzyme inhibitors are not as widely used for *E. crassipes* control, because the delayed activity makes it difficult to distinguish treated from nontreated areas (Wersal and Madsen 2010). Because these plants are free-floating and move within the lake from day to day, the delay in herbicide symptoms can result in wasted time and herbicide product, as the same plants may be sprayed multiple times as they float to different areas.

Management Implications

Eichhornia crassipes (waterhyacinth) management relies heavily on herbicides; however, herbicide application techniques have not changed in decades. Current application techniques largely consist of high-volume applications that can appear "heavy-handed" to public stakeholders. Furthermore, these high-volume applications provide excellent spray coverage but poor overall spray retention. Consequently, we tested the effect of four application methods at three carrier volumes on 2,4-D, diquat, and glyphosate efficacy on *E. crassipes* in mesocosms. Reducing carrier volume did not reduce control in any experiment. Conversely, *E. crassipes* control increased with reduced carrier volume in 2,4-D and glyphosate. These data support field evaluation of reduced carrier volume techniques for *E. crassipes* management.

Foliar application techniques for aquatic herbicides have not changed after decades of use despite improvements in application technology in terrestrial systems. Traditionally, foliar aquatic herbicides have been applied in high carrier volumes (average of 935 L ha^{-1}) using handguns consisting of a single nozzle (Haller 2020). This application technique resembles spot-treatment methods with percent solutions in which plants are "sprayed-to-wet" or "sprayed to runoff." This procedure has proven successful with multiple herbicides and plant species over decades of use. Furthermore, this application technique is easily taught to applicators compared with standard sprayer calibration. While high carrier volumes in any application can provide excellent spray coverage, spray droplet retention and spray solution concentration are often low (Enloe et al. 2020). Additionally, applications at 935 L ha^{-1} are often conducted on public waters in full view of recreational users. As such, this water volume is highly visible and appears excessive to the public.

Previous research regarding herbicide carrier volume in aquatic plant management is limited to glyphosate on phragmites [*Phragmites australis* (Cav.) Trin. ex Steud.], *E. crassipes*, and giant salvinia (*Salvinia molesta* Mitchell) (Nelson et al. 2007; Riemer 1976; Van et al. 1986). For both *P. australis* and *E. crassipes*, control was improved when carrier volumes were decreased. This was not surprising, considering the vast amount of carrier volume data published for terrestrial systems (Ambach and Ashford 1982; Creech et al. 2015; Knoche 1994; O'Sullivan et al. 1981; Ramsdale and Messersmith 2001; Sandberg et al. 1978; Shaw et al. 2000; Stahlman and Phillips 1979; Wolf et al. 1992). Given that herbicide uptake in plants has been shown to be primarily driven by concentration gradient, it stands to reason that decreasing carrier volume (increasing herbicide concentration in each droplet) should result in greater herbicide penetration and absorption into the leaf (Devine et al. 1992). Therefore, reducing carrier volume is an ideal and efficient way to maximize efficacy of systemic herbicides. Unfortunately, efficacy of contact herbicides such as diquat generally perform worse as carrier volume is reduced (Douglas 1968; Knoche 1994). This is because contact herbicides require a balance between droplet concentration and adequate leaf coverage to be consistently effective. However, there is a tipping point between high levels of spray coverage and reductions in spray retention. Sandberg et al. (1978) reported that as much as 50% to 75% of the spray solution ran off leaf surfaces in 375 and 750 L ha^{-1} applications. Therefore, there appears to be opportunity to maintain diquat efficacy by reducing carrier volumes if application techniques can be adopted that will increase spray retention on the leaf.

In Florida, more than 72,843 hectares of floating plants received diquat in 2019 for management, while the remaining ~40,468 hectares received other herbicides or combinations (FFWCC 2019). Therefore, aquatic applicators commonly calibrate for 935 L ha^{-1}, because diquat is their primary herbicide and this methodology has proven successful for decades. The application technique is accomplished with high-pressure handguns that will commonly deliver sufficient volume for plant control at distances of more than 10 m. Unfortunately, these sprayers are prone to produce driftable fines while appearing excessive and imprecise to stakeholders. This perception has resulted in a lack of public support for aquatic plant management. It is important to determine whether advancements can be made to our current floating-plant management strategies that maintain efficacy while increasing precision. The objectives of this research are: (1) determine whether reduced carrier volumes of 2,4-D, diquat, and glyphosate alter their efficacy on *E. crassipes*; and (2) document how different spray patterns interact with carrier volume for overall efficacy.

Materials and Methods

Three separate, yet concurrent experiments documenting the efficacy of glyphosate, 2,4-D, and diquat on *E. crassipes* as a function of carrier volume and application type were conducted at the University of Florida Center for Aquatic and Invasive Plants in Gainesville, FL (29.721542°N, 82.417300°W) in 2020. Methods were identical across all three experiments, and each was repeated twice with treatment dates of March 21 and May 18, 2020. In each experiment, herbicide rate was held constant while a factorial arrangement of treatments consisted of carrier volume (935, 467, and 187 L ha^{-1}) and application method (conventional stream, conventional cone, adjustable cone, and a drizzle stream). Herbicides rates for glyphosate (Roundup® Custom, Bayer CropScience LLC, Research Triangle Park, NC, USA) and 2,4-D (Alligare 2,4-D Amine, Alligare LLC, Opelika, AL, USA) were both 2.2 kg ae ha^{-1}, while diquat (Tribune™, Syngenta Crop Protection LLC, Greensboro, NC, USA) was applied at 1.1 kg cation ha^{-1}. Conventional stream and conventional cone treatments were applied using a CO_2-pressurized industry standard AA43 GunJet® (TeeJet® Technologies, Spraying Systems, Wheaton, IL, USA) equipped with a D4 orifice disk (TeeJet® Technologies) calibrated to deliver 1.7 L min^{-1} at 276 kPa. Conventional stream treatments were achieved on the AA43 GunJet® by utilizing setting "C" by depressing the trigger fully. Likewise, conventional cone applications were achieved on the GunJet utilizing setting "A" by depressing the trigger 50% to maintain a wide-angle cone. Adjustable cone treatments were applied using a CO_2-pressurized FIMCO Deluxe Pistol Grip Handgun (FIMCO Industries, North Sioux City, SD, USA) equipped with an adjustable cone nozzle (FIMCO Industries) calibrated to deliver 0.53 L min^{-1} at 138 kPa. Drizzle applications were made with a CO_2-pressurized JD9-C High Pressure Spray Gun (H.D. Hudson Manufacturing, Lowell, MI, USA) equipped with a J9 (H.D. Hudson Manufacturing) nozzle calibrated to deliver 3.4 L min^{-1} at 69 kPa. To ensure that each experimental unit received the desired carrier volume without changing the spray droplet spectrum, travel speed was the only parameter manipulated.

Eichhornia crassipes plants were collected from the Rodman Reservoir in Florida (29.515923°N, 81.877916°W) in the summer of 2019 and transferred to 1,000-L concrete vaults. Vaults were amended with soluble fertilizer (24-8-16, Miracle-Gro® All Purpose Plant Food, Scotts Company, Marysville, OH, USA) at 0.2 g L^{-1} and chelated iron (Grow More Iron Chelate 10%, Grow More, Gardena, CA, USA) at 0.02 g L^{-1} to ensure sufficient growth of ramets. Likewise, plants were treated as needed with zeta-cypermethrin (GardenTech Sevin Insect Killer Concentrate, TechPac, Atlanta, GA, USA) for insect control. Experiments were set up in a completely randomized design with four replications per experimental run. Experimental units were established as 20 individual plants of similar size in 95-L plastic tubs maintained with the same fertilizer and insect control regime described for concrete vaults. Plants were left to acclimate in tubs for 2 wk before treatment initiation.

In addition to herbicides in each experiment, all treatment solutions contained a nonionic surfactant (Induce®, Helena Agri-Enterprises, Collierville, TN, USA) at 0.25% v/v. Likewise, all solutions contained rhodamine WT tracer dye (Rhodamine WT Liquid, Keystone Aniline, Chicago, IL, USA) at 0.25% v/v to stain spray cards for coverage analysis.

On the day of treatment, pretreatment biomass from four mesocosms per experiment was harvested, dried in a forced-air oven at 60 C for 5 d, and weighed for biomass. Also, two photo cards (Kromekote® Photo Paper, CTI Paper USA, Sun Prairie, WI, USA) per experimental unit were set at canopy height on ring stands set adjacent to experimental units (Ferguson et al. 2016; Hewitt and Meganasa 1993; Higgins 1967; Roten et al. 2015). After cards were dry (~15 min), spray cards were collected into envelopes. Visual estimates of percent control were conducted at 7, 14, 21, and 28 d after treatment (DAT) on a 0% to 100% scale, with zero being similar to the nontreated control (NTC) and 100% being complete plant death. At 6 wk after treatment (WAT), all viable biomass in each mesocosm was harvested, dried in a forced-air oven at 60 C until constant moisture level, and weighed for biomass.

Spray cards were scanned into JPEG files, converted to 8-bit format, threshold adjusted, and analyzed for percent coverage using ImageJ software (Schneider et al. 2012). All percent data were arcsine-square-root transformed to improved homogeneity of variance before analysis to meet model assumptions; however, back-transformed means are presented for clarity. All data were subject to mixed-model ANOVA under the LME4 package in R (v. 3.6.1; Bates et al. 2015; Mendiburu 2019; R Core Team 2019), where carrier volume and application method were considered fixed effects and experimental run and replicate (nested in experimental run) were considered random effects (Blouin et al. 2011). Where significant effects were detected, means were separated using Fisher's LSD test ($\alpha = 0.05$) under the EMMEANS package in R (Lenth 2020). Additionally, a *t*-test was conducted at $\alpha = 0.05$ to determine significant differences among treated and nontreated biomass.

Results and Discussion

2,4-D

All visual evaluations of *E. crassipes* control and biomass reductions from 2,4-D treatments were affected independently by the main effects of carrier volume and application method (Table 1). As the interaction between carrier volume and application methods was not significant, only the main effects will be shown. *Eichhornia crassipes* control at 7 and 14 DAT increased with decreasing carrier volume, and by 21 and 28 DAT applications at 467 and 935 L ha^{-1} performed similarly. However, reducing carrier volume to 187 L ha^{-1} resulted in 14% and 10% greater *E. crassipes* control compared with treatment at 935 L ha^{-1} at 21 and 28 DAT. Biomass reduction improved by 8% when reducing carrier volume from 935 to 187 L ha^{-1}. Conventional cone and adjustable cone treatments resulted in greater *E. crassipes* control (97%) than conventional stream and drizzle-stream methods (83% to 85% control) regardless of carrier volume across all evaluation intervals. These control estimations translated into a similar trend in biomass reduction, with conventional cone and adjustable cone methods reducing biomass 8% to 9% more than either stream method. Additionally, all treatments reduced biomass compared with the NTC.

Table 1. *Eichhornia crassipes* control and biomass reduction as affected by the main effects of carrier volume and application method from 2,4-D (2.2 kg ae ha^{-1}) treatments in mesocosms.[a]

Carrier volume	Control[b] 7 DAT	14 DAT	21 DAT	28 DAT	Biomass reduction[c]
L ha^{-1}	——————	———	%———	———	
935	50 c	74 c	82 b	86 b	91 b*
467	61 b	84 b	86 b	90 ab	93 ab*
187	76 a	92 a	96 a	96 a	99 a*
Application method					
Conventional stream	60 bc	78 b	81 b	83 b	90 b*
Conventional cone	68 a	89 a	93 a	97 a	98 a*
Adjustable cone	64 ab	86 a	95 a	97 a	99 a*
Drizzle stream	57 c	80 b	82 b	85 b	90 b*

[a]Means within a column and main effect (carrier volume or application method) followed by the same letter are not different according to Fisher's LSD test ($\alpha = 0.05$).
[b]DAT, days after treatment.
[c]Pretreatment dry biomass was 1,776 and 1,344 kg ha^{-1} in experimental runs 1 and 2, respectively. Mean dry biomass of nontreated control was 3,548 and 3,860 kg ha^{-1} in experimental runs 1 and 2, respectively. Asterisks signify significant difference compared with the nontreated control according to *t*-test ($\alpha = 0.05$).

The stream application methods are commonly desired, because these spray patterns largely minimize production of fine spray droplets with high drift potential. Without the nozzle atomizing spray solution, the stream either fractures as it falls through the air or shatters into droplets upon impact with plant leaves. The stream technologies tested in this small-scale experiment study did not provide adequate coverage to achieve optimum activity with 2,4-D. This limitation could potentially be avoided if the herbicide possessed in-water activity at potential concentrations, thus providing two routes of entry into the plant (roots and leaves). Though 2,4-D is used as an in-water treatment of Eurasian watermilfoil (*Myriophyllum spicatum* L.) (Elliston and Steward 1972; Getsinger et al. 1982; Green and Westerdahl 1990), these data lead us to suggest that in-water activity of 2,4-D on *E. crassipes* is limited at the resultant concentrations in the current study. However, additional research should investigate the dose–response relationship between *E. crassipes* and in-water 2,4-D exposure.

Diquat

Eichhornia crassipes response to diquat was not affected by application method at any evaluation timing, but control ranged from 93% to 96% at 7 DAT and quickly approached 99% to 100% control by 14 DAT (data not shown). However, early *E. crassipes* control evaluations (7 and 14 DAT) revealed that decreased carrier volume to 187 L ha^{-1} increased control 3% to 9% (Table 2). By 28 DAT, all

https://doi.org/10.1017/inp.2021.1 Published online by Cambridge University Press

Table 2. *Eichhornia crassipes* control and biomass reduction as affected by the main effect of carrier volume from diquat (1.1 kg cation ha^{-1}) treatments in mesocosms.[a]

	Control[b]				
Carrier volume	7 DAT	14 DAT	21 DAT	28 DAT	Biomass reduction[c]
L ha^{-1}	————————————	———	%———	———	————————————
935	91 c	97 b	98 a	100 a	100 a*
467	93 b	100 a	100 a	100 a	100 a*
187	100 a	100 a	100 a	100 a	100 a*

[a]Means within a column followed by the same letter are not different according to Fisher's LSD test (α = 0.05).
[b]DAT, days after treatment.
[c]Pretreatment dry biomass was 1,652 and 1,227 kg ha^{-1} in experimental runs 1 and 2, respectively. Mean dry biomass of nontreated control was 3,353 and 3,270 kg ha^{-1} in experimental runs 1 and 2, respectively. Asterisks signify significant difference compared with the nontreated control according to *t*-test (α = 0.05).

Table 3. *Eichhornia crassipes* control at 7 and 14 d after treatment (DAT) with glyphosate (2.2 kg ae ha^{-1}) as affected by the interaction between application method and carrier volume in mesocosm experiments.

Application method	Carrier volume	7 DAT[a]	14 DAT[a]
	L ha^{-1}	————	%————
Conventional stream	935	20 f	46 e
	467	48 cd	85 bc
	187	59 ab	93 ab
Conventional cone	935	9 gh	29 f
	467	48 cd	76 c
	187	69 a	96 a
Adjustable cone	935	6 h	28 f
	467	39 de	75 c
	187	65 ab	94 ab
Drizzle stream	935	19 fg	35 f
	467	29 ef	60 d
	187	56 bc	80 c

[a]Means within a column followed by the same letter are not different according to Fisher's LSD test (α = 0.05).

treatments resulted in 100% control, and no viable plant tissue was present for biomass harvest.

Diquat is a fast-acting contact herbicide that is highly effective on *E. crassipes* and has in-water activity (Langeland et al. 2002). Consequently, the rate used in this study may have been too high to observe the application technique effects. Additionally, these data in combination with herbicide use records in Florida suggest that diquat is highly versatile and can be forgiving when application technique is not optimal (FFWCC 2019). Future work will evaluate these application effects at lower rates.

Glyphosate

Eichhornia crassipes control at 7 and 14 DAT with glyphosate was affected by an interaction between application method and carrier volume (Table 3). At 7 DAT, decreasing carrier volume resulted in greater *E. crassipes* control in every application method except for the drizzle stream. In the drizzle-stream treatments, carrier volumes of 935 and 467 L ha^{-1} performed similarly; however, when carrier volume was reduced to 187 L ha^{-1}, control increased 27% to 37%. Additionally, *E. crassipes* control was greatest, independent of application method, at 7 DAT when a carrier volume of 187 L ha^{-1} was used. This suggests that reduced carrier volume applications of glyphosate may compensate for spray coverage deficiencies of certain application methods. By 14 DAT, all

Table 4. *Eichhornia crassipes* control at 21 and 28 d after treatment (DAT) and biomass reduction as affected by the main effects of carrier volume and application method from glyphosate (2.2 kg ae ha^{-1}) treatments in mesocosms.[a]

	Control		
Carrier volume	21 DAT	28 DAT	Biomass reduction[b]
L ha^{-1}	————————	%————	————————
935	32 c	62 c	55 c*
467	78 b	84 b	82 b*
187	93 a	93 a	97 a*
Application method			
Conventional stream	76 a	87 a	81 a*
Conventional cone	72 ab	84 a	82 a*
Adjustable cone	68 b	75 b	78 a*
Drizzle stream	54 c	72 b	72 a*

[a]Means within a column and main effect (carrier volume or application method) followed by the same letter are not different according to Fisher's LSD test (α = 0.05).
[b]Pretreatment dry biomass was 2,136 and 1,073 kg ha^{-1} in experimental runs 1 and 2, respectively. Mean dry biomass of nontreated control was 3,719 and 3,377 kg ha^{-1} in experimental runs 1 and 2, respectively. Asterisks signify significant difference compared with the nontreated control according to *t*-test (α = 0.05).

reductions in carrier volume resulted in increased *E. crassipes* control, except in the conventional stream treatments. In the conventional stream treatments, carrier volumes of 467 and 187 L ha^{-1} resulted in similar *E. crassipes* control; however, carrier volumes of 935 L ha^{-1} decreased control 39% to 47%. Despite the conventional stream at 935 L h^{-1} treatment resulting in the lowest *E. crassipes* control of the conventional stream treatments, this treatment resulted in the greatest *E. crassipes* control of all 935 L ha^{-1} treatments.

Eichhornia crassipes control from glyphosate at 21 and 28 DAT and biomass reduction data were independently affected by the main effects of application method and carrier volume, and no interactions were detected (Table 4). At 21 DAT, the conventional stream method provided 8% and 22% greater *E. crassipes* control compared with the adjustable cone and drizzle-stream methods, respectively. By 28 DAT, conventional stream and cone methods performed similarly, yet resulted in 9% to 15% greater *E. crassipes* control compared with adjustable cone or drizzle-stream methods. Biomass reductions ranged from 72% to 81%, with no differences observed among application methods. Reducing carrier volume in glyphosate treatments resulted in greater *E. crassipes* control at 21 and 28 DAT and greater biomass reduction. Likewise, biomass reduction was 42% greater when glyphosate was applied at 187 L ha^{-1} compared with 935 L ha^{-1}.

Reducing carrier volumes in glyphosate applications has been shown to increase efficacy on several terrestrial species (Ambach and Ashford 1982; O'Sullivan et al. 1981; Sandberg et al. 1978). Similar to the current study, Van et al. (1986) observed greater *E. crassipes* control with 1.7 kg ae ha^{-1} glyphosate when treatment was applied at 187 L ha^{-1} compared with 468 or 935 L ha^{-1}. However, Van et al. (1986) also reported that increasing glyphosate rate eliminated any increased activity from lower carrier volumes. Despite the same rate of herbicide being applied to a given surface area (e.g., 1 kg ai ha^{-1}), glyphosate efficacy can be increased by manipulating application technique. While we did not test the concept directly in the current study, these data suggest that the same level of *E. crassipes* control may be obtained with a reduced herbicide rate simply by reducing carrier volume and promoting greater absorption and translocation in the target plant. However, further research is needed to test this hypothesis.

Although the speed of herbicide activity was not statistically evaluated in these experiments, trends in early control evaluations

https://doi.org/10.1017/inp.2021.1 Published online by Cambridge University Press

Table 5. Quantified spray coverage from herbicide applications made to *Eichhornia crassipes* as affected by the interaction between carrier volume and application method.

Application method	Carrier volume	Herbicide[a]		
		Glyphosate	2,4-D	Diquat
	$L\ ha^{-1}$	Spray coverage —%—		
Conventional stream	935	92 b	90 ab	93 ab
	467	84 c	89 b	88 bc
	187	75 d	63 c	61 d
Conventional cone	935	99 a	99 ab	100 a
	467	97 ab	99 ab	100 a
	187	92 b	98 ab	99 a
Adjustable cone	935	100 a	100 a	100 a
	467	100 a	99 ab	100 a
	187	99 a	99 ab	100 a
Drizzle stream	935	100 a	96 ab	95 ab
	467	98 ab	92 ab	82 c
	187	40 e	63 c	59 d

[a]Means within a column followed by the same letter are not different according to Fisher's LSD test ($\alpha = 0.05$).

(7 DAT) suggest that reduced carrier volume may decrease time to observable symptoms. Therefore, applicators and resource managers may be more open to glyphosate use for *E. crassipes* if lower carrier volumes are utilized.

Eichhornia crassipes Spray Deposition

For each herbicide experiment, an interaction between carrier volume and sprayer type was detected in spray coverage data (Table 5). For glyphosate experiments, all 935 and 467 $L\ ha^{-1}$ treatments resulted in spray coverage >90% regardless of sprayer type, except for the 467 $L\ ha^{-1}$ conventional stream treatment. Conventional cone and adjustable cone 187 $L\ ha^{-1}$ treatments resulted in spray coverage of 92% and 99%, respectively. However, the conventional stream and drizzle spray types resulted in 75% and 40% spray coverage when carrier volume was reduced to 187 $L\ ha^{-1}$. In 2,4-D and diquat treatments, spray coverage consistently decreased with decreasing carrier volume in the conventional stream and drizzle sprayers only. Conversely, conventional cone and adjustable cone sprayers produced excellent spray coverage (>97%) across all carrier volumes, likely due to atomization of finer droplets.

The systemic herbicides tested in these experiments provided greater *E. crassipes* control when carrier volume was reduced from 935 $L\ ha^{-1}$. However, little difference was observed among diquat treatments. This suggests that the diquat rate tested was likely too high and could have prevented observation of the treatment effects. However, for the given rate tested, these data indicate that diquat does not require as much spray coverage as many applicators believe. Alternatively, foliar applications of diquat may simply be more forgiving due to its in-water activity under nonturbid conditions (Hofstra et al. 2001). Sandberg et al. (1978) reported that 50% to 75% of spray solution ran off leaf surfaces in 375 and 750 $L\ ha^{-1}$ spray applications. Therefore, the efficacy of diquat on *E. crassipes* may require a combination of foliar and in-water absorption, as the *E. crassipes* meristem is usually found just below the water surface (Penfound and Earle 1948). However, in-water activity of diquat under field conditions may be reduced by turbidity of both source water and site water around *E. crassipes* plants. Conversely, glyphosate is largely inactive in water due to adsorption and rapid microbial degradation (Borggaard and Gimsing 2008; Zaranyika and Nyandoro 1993). Likewise, 2,4-D is applied in-water to control some submersed species such as *M. spicatum*; however, it has not exhibited in-water activity on *E. crassipes* in preliminary studies (Getsinger et al. 1982; unpublished data). Therefore, the greater increases in 2,4-D and glyphosate efficacy from reduced carrier volumes compared with diquat in the current study may be related to in-water activity. However, further research is needed to test these hypotheses.

Overall, these data suggest that lower carrier volume herbicide applications made to *E. crassipes* provided high levels of efficacy with reduced spray coverage. In fact, there were several accounts of increased efficacy and rate of symptom development from reduced carrier volumes. Likewise, these data also support the evaluation of alternative application equipment and techniques that may be more discrete. While spray coverage was reduced by some application types, these data indicate that complete coverage is not a requirement for optimal *E. crassipes* control. Future research will investigate alternative application techniques with other herbicides and plant species as well as field verification of these techniques.

Acknowledgments. The authors extend their appreciation to the Florida Fish and Wildlife Conservation Commission for partial funding of the research. Additionally, we thank J. P. Keller and Jake Myers for assistance in conducting this work. No conflicts of interest have been declared.

References

Ambach RM, Ashford R (1982) Effects of variation in drop makeup on the phytotoxicity of glyphosate. Weed Sci 30:221–224
Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48
Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol 25:165–169
Borggaard OK, Gimsing AL (2008) Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: a review. Pest Manag Sci 64: 441–456
Center TD, Spencer NR (1981) The phenology and growth of waterhyacinth (*Eichhornia crassipes* (Mart.) Solms) in a eutrophic north-central Florida lake. Aquat Bot 10:1–32
Creech CF, Henry RS, Werle R, Sandell LD, Hewitt AJ, Kruger GR (2015) Performance of postemergence herbicides applied at different carrier volume rates. Weed Technol 29:611–624
Devine M, Duke SO, Fedtke C, eds (1992) Physiology of Herbicide Action. Englewood Cliffs, NJ: Prentice Hall. 441 p
Douglas G (1968) A comparison of the 'Vibrajet' nozzle and a fan jet for overall application of bipyridyl herbicides. Weed Res 8:14–27
Elliston RA, Steward KK (1972) The response of Eurasian watermilfoil to various concentrations and exposure periods of 2,4-D. Hyacinth Contr J 10:38–40
Enloe SF, Leary JK, Prince CM, Sperry BP, Lauer DK (2020) Brazilian peppertree and mangrove species response to foliar-applied novel auxin-type herbicides. Invasive Plant Sci Manag 13:102–107
Enloe SF, Netherland MD, Haller W, Langeland K (2018) Efficacy of Herbicide Active Ingredients against Aquatic Weeds. SS-AGR-44. https://edis.ifas.ufl.edu/ag262. Accessed: August 11, 2020
Ferguson JC, Cheschetto RG, Hewitt AJ, Chauhan BS, Adkins SW, Kruger GR, O'Donnell CC (2016) Assessing the deposition and canopy penetration of nozzles with different spray qualities in an oat (*Avena sativa* L.) canopy. Crop Prot 81:14–19
[FFWCC] Florida Fish and Wildlife Conservation Commission (2019) Annual Report of Pollutant Discharges to the Surface Waters of the State from the Application of Pesticides. NPDES Generic Permit Coverage Number: FLG510039-IWPG. Tallahassee, FL: FFWCC. 52 p

Getsinger KD, Davis GJ, Brinson MM (1982) Changes in a *Myriophyllum spicatum* L. community following 2,4-D treatment. J Aquat Plant Manag 20:4–8
Green WR, Westerdahl HE (1990) Response of Eurasian watermilfoil to 2,4-D concentrations and exposure times. J Aquat Plant Manag 28:27–32
Haller WT (2020) Aquatic herbicide application methods. Pages 191–196 *in* Gettys LA, Haller WT, Petty DG, eds. Biology and Control of Aquatic Plants: A Best Management Practices Handbook. 4th ed. Aquatic Ecosystem Restoration Foundation, Marietta, GA
Hewitt AJ, Meganasa T (1993) Droplet distribution densities of a pyrethroid insecticide within grass and maize canopies for the control of *Spodoptera exempta* larvae. Crop Prot 12:59–62
Higgins AH (1967) Spread factors for technical malathion spray. J Econ Entomol 60:280–281
Hofstra DE, Clayton JS, Getsinger KD (2001) Evaluation of selected herbicides for the control of exotic submerged weeds in New Zealand: II. The effects of turbidity on diquat and endothall efficacy. J Aquat Plant Manag 39:25–27
Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The World's Worst Weeds: Distribution and Biology. 18th ed. University Press Publications, Honolulu, HI. P 609
Joyce JC (1985) Benefits of maintenance control of waterhyacinth. Aquatics 7(4):11–13
Knoche M (1994) Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot 13:163–178
Langeland KA, Hill ON, Koschnick TJ, Haller WT (2002) Evaluation of a new formulation of Reward Landscape and Aquatic Herbicide for control of duckweed, waterhyacinth, waterlettuce, and hydrilla. J Aquat Plant Manag 40:51–53
Lenth R (2020) emmeans: Estimated Marginal Means, aka Least-Squares Means. R Package v. 1.4.6. https://CRAN.R-project.org/package=emmeans. Accessed: September 5, 2020
Mendiburu F (2019) agricolae: Statistical Procedures for Agricultural Research. R Package v. 1.3-1. https://CRAN.R-project.org/package=agricolae. Accessed: September 5, 2020
Mudge CR, Netherland MD (2014) Response of giant bulrush, water hyacinth, and water lettuce to foliar herbicide applications. J Aquat Plant Manag 52:75–80
Nelson LS, Glomski LM, Gladwin DN (2007) Effect of glyphosate rate and spray volume on control of giant salvinia. J Aquat Plant Manag 45:58–61
O'Sullivan PA, O'Donovan JT, Hamman WM (1981) Influence of non-ionic surfactants, ammonium sulfate, water quality and spray volume on the phytotoxicity of glyphosate. Can J Plant Sci 61:391–400
Owens CS, Madsen JD (1995) Low temperature limits of waterhyacinth. J Aquat Plant Manag 33:63–68
Penfound WT, Earle TT (1948) The biology of the waterhyacinth. Ecol Monogr 18:447–472
Pieterse AH (1978) The waterhyacinth (*Eichhornia crassipes*)—a review. Abst Trop Agric 4:9–12
Ramsdale BK, Messersmith CG (2001) Nozzle, spray volume, and adjuvant effects on carfentrazone and imazamox efficacy. Weed Technol 15:485–491
R Core Team (2019) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org. Accessed: September 5, 2020
Riemer DN (1976) Long-term effects of glyphosate applications to phragmites. J Aquat Plant Manag 14:39–43
Roten RL, Connell RJ, Hewitt AJ, Woodward SJR (2015) Comparison of spray dose measured on leaf surfaces with spray coverage estimated from Kromekote® paper. NZ Plant Prot 68:38–43
Sandberg CL, Meggit WF, Penner D (1978) Effect of diluent volume and calcium on glyphosate phytotoxicity. Weed Sci 26:476–479
Schneider CA, Rasband WS, Eliceiri KW (2012) NIH image to ImageJ: 25 years of image analysis. Nature Methods 9:671–675
Schreiner SP (1980) Effects of waterhyacinth on the physiochemistry of a south Georgia pond. J Aquat Plant Manag 18:9–12
Seabrook EL (1962) The correlation of mosquito breeding to hyacinth plants. Hyacinth Contr J 1:18–19
Shaw DR, Morris WH, Webster EP, Smith DB (2000) Effects of spray volume and droplet size on herbicide deposition and common cocklebur (*Xanthium strumarium*) control. Weed Technol 14:321–326
Stahlman PW, Phillips WM (1979) Effects of water quality and spray volume on glyphosate phytotoxicity. Weed Sci 27:38–41
Ultsch GR (1973) The effects of waterhyacinth on the microenvironment of aquatic communities. Arch Hydrobiol 72:460–473
University of Florida (2011) Plant Management in Florida Waters: 2,4-D Considerations. https://plants-archive.ifas.ufl.edu/manage/developing-management-plans/chemical-control-considerations/24-d-considerations. Accessed: August 11, 2020
Van TK, Vandiver VV, Conant RD (1986) Effect of herbicide rate and carrier volume on glyphosate phytotoxicity. J Aquat Plant Manag 24:66–69
Wersal RM, Madsen JD (2010) Combinations of penoxsulam and diquat as foliar applications for control of waterhyacinth and common salvinia: evidence of herbicide antagonism. J Aquat Plant Manag 48:21–25
Wolf TM, Caldwell BC, Mcintyre GI, Hsiao AI (1992) Effect of droplet size and herbicide concentration on absorption and translocation of ^{14}C-2,4-D in Oriental mustard (*Sisymbrium orientale*). Weed Sci 40:568–575
Zaranyika MF, Nyandoro MG (1993) Degradation of glyphosate in the aquatic environment: an enzymatic kinetic model that takes into account microbial degradation of both free and colloidal (or sediment) particle adsorbed glyphosate. J Agric Food Chem 41:838–842