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Evaluation of very-low volume herbicide applications for giant salvinia control

ANDREW W. HOWELL, ERIKA J. HAUG, BENJAMIN P. SPERRY, AND ROBERT J. RICHARDSON*

ABSTRACT

Giant salvinia (*Salvinia molesta* D. S. Mitchell) presents numerous challenges to water resource management. Innovative chemical control methods, such as unoccupied aerial application systems (UAAS), allow for remote herbicide delivery at very-low-volume (VLV) applications. However, UAAS tank capacities (10 to 40 L) are quite limited compared to standard spray equipment (≥189 L), which ultimately confines operational functionality. A greenhouse trial investigated the efficacy of diquat, flumioxazin, and glyphosate at varying carrier volumes (23 to 935 L^{-1}) to guide UAAS treatment operations. Results indicated VLV applications (23 L ha^{-1}) were most effective with diquat, which reduced plant biomass ≥ 98% at 4 wk.

Key words: carrier volume, foliar herbicide application, diquat, drones, flumioxazin, glyphosate, invasive species, *Salvinia molesta*, water resource management

INTRODUCTION

The invasive aquatic fern, giant salvinia (*Salvinia molesta* D. S. Mitchell), continues to spread throughout the southern regions of the United States following first introduction to South Carolina in the mid-1990s (Johnson 1995, EDDMapS 2023). Waterways infested with giant salvinia generally experience negative impacts to water quality and primary production (Oliver 1993, Flores and Carlson 2006) and have limited ecological and recreational value because plants form impenetrable vegetation mats up to 1 m thick (Thomas and Room 1986, McFarland et al. 2004). As a free-floating plant, giant salvinia is highly dispersive, has the capability to thrive in almost any aquatic or wetland environment, and can double in biomass in < 3 d (Cary and Weerts 1984, Oliver 1993, Kaufman and Kaufman 2007). Therefore, giant salvinia is considered one of the most troublesome aquatic weeds (Nelson et al. 2001).

In 1984, the U.S. Department of Agriculture (USDA) classified giant salvinia as a Federally Noxious Weed (McFarland et al. 2004); thus, water resource agencies are often required to perform management operations to combat the negative ecological and economic effects of giant salvinia, while also minimizing range expansion. Although a biological control agent (e.g., salvinia weevil [*Cyrtobagous salviniae*]) has been successfully used for long-term suppression (Mudge et al. 2013, Mukherjee et al. 2014, Cozad et al. 2019), integrated management approaches with herbicides are necessary to handle giant salvinia population expansion due to the effectiveness and selectivity of chemical control (McFarland et al. 2004, Schardt and Netherland 2020). Similarly, aquatic herbicides provide more suitable opportunity for plant control under varying environmental conditions (Mudge and Sartain 2018; Sartain and Mudge 2018b, 2019) and provide early-invasion eradication prospect (Nelson et al. 2001).

There are currently nine aquatic herbicides registered by the U.S. Environmental Protection Agency (USEPA) known to be effective on the plant (Sartain and Mudge 2018a, Schardt and Netherland 2020). Of those effective herbicides, the fast-acting herbicides, diquat and flumioxazin, are often most appealing to meet resource managers' expectation of prompt visual plant control (<1 wk) while also quickly limiting the exponential growth potential of giant salvinia (Richardson et al. 2008, Mudge et al. 2016). The slow-acting herbicide glyphosate is also regularly utilized by resources managers due to its consistent control of giant salvinia across a broad range of application parameters and infestation sites (Nelson et al. 2001, 2007; Mudge et al. 2016; Howell et al. 2023a). These foliar herbicide treatments are commonly applied at a finished spray volume of 468 to 1,870 L ha^{-1} (Nelson et al. 2007), while aerially applied treatments generally target a carrier volume of (≤94 L ha^{-1}) (Sartain and Mudge 2018a).

Over the last decade, unoccupied aerial application systems (UAAS) have gained popularity for site-specific weed management (Göktoğan et al. 2010, Lan et al. 2017, Hunter et al. 2020, Howell et al. 2023a,b). While the utilization of UAAS in aquatics has remained more limited than terrestrial weed control programs, potential is high for these technologies to deliver treatments in sites with limited access for traditional application techniques (e.g., cypress swamps with no suitable boat launch) and reducing pesticide exposure during application. However, due to current mechanical and efficiency constraints of UAAS, foliar treatments of giant salvinia delivered from UAAS require lower than standard ground- or helicopter-applied carrier volumes (i.e., ≤ 47 L ha^{-1}). Currently, herbicide efficacy

*First author: Research Scholar, Department of Crop and Soil Sciences, North Carolina State University, Campus Box 7620, Raleigh, NC 27695. Second author: Environmental Specialist, Intensive Surveys Branch, North Carolina Division of Water Resources, 4401 Reedy Creek Rd, Raleigh, NC 27607. Third author: Research Biologist, U.S. Army Engineer Research and Development Center, Gainesville, FL 32653. Fourth author: William H. Culpepper Jr. Distinguished Professor, Department of Crop and Soil Sciences, North Carolina State University, Campus Box 7620, Raleigh, NC 27695. Corresponding author's E-mail: awhowell@ncsu.edu. Received for publication April 4, 2025 and in revised form June 10, 2025.

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Table 1. Effects of carrier volume on herbicide efficacy for giant salvinia control.

Carrier Volume[3] L ha^{-1}	Herbicide Rate[4] g a.i. ha^{-1}	Weeks after Treatment[1,2] 1	2	3	4	Dry Weight[5] *g*
		% Control				
Diquat	3,136					
935		99 a	100 a	100 a	100 a	0.0 ± 0.0 a
140		96 ab	99 ab	100 a	100 a	0.0 ± 0.0 a
23		66 d	88 c	91 bc	94 ab	0.0 ± 0.1 a
Flumioxazin	210					
935		85 bc	90 c	94 ab	91 abc	0.7 ± 0.5 b
140		81 c	91 bc	92 abc	87 bc	0.8 ± 0.7 b
23		83 c	83 c	85 cd	73 d	1.6 ± 0.4 de
Glyphosate	4,539					
935		56 d	70 d	80 d	82 cd	1.1 ± 0.3 bc
140		10 e	40 e	62 e	74 d	1.3 ± 0.7 cd
23		8 e	12 f	31 f	48 e	2.0 ± 0.4 e
Nontreated	0	0 f	0 g	0 g	0 f	5.7 ± 0.3 f

[1]Visual control rated on 0 to 100% scale; 0% (no plant response) to 100% (complete necrosis).
[2]Mean responsees within a column followed by the same letter do not differ according to Fisher's Protected LSD ($P \leq 0.05$).
[3]Nonionic surfactant at 0.25% v/v included with all herbicide applications.
[4]Glyphosate is reported as g a.e. ha^{-1}.
[5]Dry weights were conducted at experiment conclusion 4 wk after treatment.

applied at very low volume (VLV) to giant salvinia is unknown. Evaluating lower carrier volumes while maintaining intended plant control would ultimately improve understanding of possible operational efficiencies and effectiveness of UAAS. The goal of this research was to evaluate how diquat, flumioxazin, and glyphosate affect giant salvinia control as application volumes decrease from conventional levels to those intended for VLV UAAS treatments.

MATERIALS AND METHODS

A small-scale mesocosm experiment at the North Carolina State University Aquatic Weed Control Labs (Raleigh, NC; 35.789°N; 78.694°W) was conducted in May and repeated in June 2022 to evaluate the influence of carrier volume on commonly utilized foliar-applied herbicides for giant salvinia control (Mudge et al. 2016). Nontreated giant salvinia was collected 4 April 2022 from a farm pond population in Columbus Co., NC (34.208°N; 78.951°W) and cultured in 121-L vessels for 2 wk in the greenhouse. Plants were then placed into each ($n = 40$) 4 to 5 L treatment mesocosm (20.5 cm dia) to achieve ca. 50% surface coverage. Mesocosms were filled with municipal tap water (pH 8.42) amended with 0.16 g of water-soluble fertilizer (24-8-16).[1] Additional tap water was added to the mesocosms as water loss occurred, and fertilizer was reapplied biweekly throughout the 4-wk experiment.

Herbicide applications were conducted 10 days after placement in treatment mesocosms when plants completely covered (100% coverage) the water's surface with single-layer tertiary growth. The experiment was set up as a randomized complete block design with a factorial arrangement of treatments and four replications. Factors consisted of herbicide (diquat[2] [3136 g a.i. ha^{-1}], flumioxazin[3] [210 g a.i. ha^{-1}], and glyphosate[4] [4539 g a.e. ha^{-1}]) and carrier volume (23, 140, and 935 L^{-1}). A nonionic surfactant[5] was included in all herbicide treatments at 0.25% v v^{-1}. A nontreated control was included for reference. Treatments were applied using a controlled droplet application (CDA) sprayer[6] or a CO_2 pressurized backpack sprayer with a handheld boom equipped with XR11002-VP or XR11008-VP nozzles[7] for 23, 140, and 935 L^{-1} treatments, respectively. At treatment application, mesocosm water pH was 5.7 (SD ± 0.15) and temperature was 25.3°C (SD ± 1.98). Giant salvinia response was evaluated weekly using visual estimations of plant control (0 to 100%; no plant injury to complete necrosis) to determine the effect of carrier volume with evaluated herbicides. All viable giant salvinia was harvested 4 WAT and dried at 70 C for 48 hr to record dry biomass. Plant response data were subjected to analysis of variance (ANOVA), and means were separated using Fisher's protected LSD ($\alpha = 0.05$) in RStudio (v. 4.0.3; R Core Team 2020) using the *agricolae* (de Mendiburu 2020) and *dplyr* packages (Wickham et al. 2021).

RESULTS AND DISCUSSION

No significant interaction occurred between experimental runs; therefore, data from both runs were pooled. Nontreated reference plant biomass increased by twofold over the 4-wk trial duration, indicating conditions were adequate for plant growth throughout experimentation. All diquat-treated plants displayed rapid injury symptoms, with necrotic fronds appearing within 1 d after treatment (DAT) (data not shown). At 1 WAT, diquat applied at 935 and 140 L ha^{-1} resulted in 99 and 96% control, respectively (Table 1). However, when diquat was applied at 23 L ha^{-1}, giant salvinia control was reduced to 66% at 1 WAT. Likewise, giant salvinia control was at least 99% at 2 through 4 WAT among diquat treatments applied at 935 and 140 L ha^{-1}. Similarly high levels of giant salvinia control were not observed in diquat treatments applied at 23 L ha^{-1} until 4 WAT (94%). Despite initial differences in visual control, by 4 WAT, no differences in biomass were detected for diquat treatments regardless of carrier volume. Sperry et al. (2022) indicated spray applications at 93 L ha^{-1} provided greater retention of rhodamine WT dye to plants than conventional volumes of ≥ 935 L ha^{-1} to giant salvinia. Further, Mudge et al. (2021) found foliar spray loss was undetectable when giant salvinia was at 100% coverage under mesocosm settings. The slower injury response of 23 L ha^{-1} application in the present study may, in part, be due to no-to-minimal overspray (i.e., in-water deposition) as compared to the higher carrier volumes tested. Brown et al. (2022) discovered waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] was injured >90% when field maximum diquat rates (0.36 kg ai ha^{-1}) were applied in water to simulate complete foliar spray loss to a 30-cm water column. Although the relative herbicide sensitives between waterhyacinth and giant salvinia likely differ by carrier volume, any in-water-deposited diquat from the > 140 L ha^{-1} treatments could have contributed to the faster injury observed from the 23 L ha^{-1} applications made to the 17-cm water columns in the present experiment. Nevertheless, these data suggest the utility of diquat foliar applications for giant salvinia control across a broad range of carrier volumes and provide data supporting UAAS VLV deployment as all spray applications reduced plant biomass ≥ 98%.

Similar to diquat, injury symptoms from all flumioxazin treatments were quick to develop (Table 1). Yellowing of fronds was observed on 30 to 90% of plant material within 1 to 2 DAT, with some plants sinking at the 935 L ha^{-1} carrier volume by 3 DAT (data not shown). Giant salvinia control from flumioxazin ranged from 81 to 91% at 1 to 2 WAT, but no differences among carrier volumes were detected. By 3 WAT, flumioxazin applied at 935 L ha^{-1} resulted in 9% greater giant salvinia control compared to application at 23 L ha^{-1}. By 4 WAT, some plant recovery was apparent across all carrier volumes evaluated, which is not uncommon with single applications of flumioxazin on giant salvinia (Sartain and Mudge 2019). Flumioxazin applied at 935 and 140 L ha^{-1} provided 14 to 18% greater giant salvinia control than 23 L ha^{-1} applications at 4 WAT. All flumioxazin treatments reduced giant salvinia biomass 72 to 88% (Table 1); however, increasing carrier volume from 23 L ha^{-1} to either 140 or 935 L ha^{-1} improved biomass reduction by 14 and 16%, respectively. Much like the diquat-treated plants, possible overspray entering the water at the > 23 L ha^{-1} carrier volumes could have contributed to improved plant control, as flumioxazin has high in-water activity on giant salvinia. However, any flumioxazin spray solution entering the water column would likely hydrolyze rapidly (Katagi 2003, Mudge et al. 2010), especially in operational field conditions having minimal water exchange. Any measurable in-water flumioxazin concentration or effect of this hypothesis remains largely unknown, and future carrier volume experiments should consider collecting herbicide residue samples to clarify possible overspray activity.

As anticipated, injury from glyphosate treatments was more limited compared to the fast-acting herbicides diquat and flumioxazin. Plants treated with glyphosate typically show a phytotoxic response within 4 to 7 DAT (Shaner 2014), which supports initial injury response observations in the present experiment. Giant salvinia displayed chlorosis and browning of frond margins by 2 to 3 DAT on 10 to 30% of plant tissues irrespective of carrier volume (data not shown). Glyphosate-treated plants at the 935 L ha^{-1} carrier volume at 1 to 3 WAT ranged 56 to 80% and displayed significantly greater control than the lower application volumes, which ranged 8 to 62% control during the same evaluations. By 4 WAT, the 140 and 935 L ha^{-1} carrier volumes performed similarly; however, when carrier volume was reduced to 23 L ha^{-1} control was decreased by 26 to 34%. In previous carrier volume research on waterhyacinth, glyphosate efficacy significantly increased by 61% when applied at 187 L ha^{-1} compared with applications made at 935 L ha^{-1} (Sperry and Ferrell 2021). However, the present experiment on giant salvinia did not demonstrate improved control between glyphosate evaluated at 140 and 935 L ha^{-1} application volumes, and several biotic and abiotic factors could help explain these differences.

Influences of plant architecture (e.g., erect vs. prostrate), spray quality and retention (e.g., droplet size, distribution, and plant capture of spray), and leaf-surface morphology (i.e., pubescent vs. glabrous leaf surfaces; giant salvinia and waterhyacinth, respectively) can greatly influence the performance of herbicides on floating plant species (Mudge et al. 2021, Sperry and Ferrell 2021, Sperry et al. 2022, Haug et al. 2023). There are also physiological differences between ferns (e.g., giant salvinia) and angiosperms (e.g., water hyacinth), with angiosperms having a more advanced vascular structure that allows for faster and more efficient translocation of resources and compounds (Cronk and Fennessy 2001). This difference could help explain the contradictory findings regarding lower herbicide efficacy when glyphosate is applied with reduced carrier volume to giant salvinia. Nevertheless, biomass closely supported the findings from visual control ratings at harvest, indicating glyphosate reduced giant salvinia biomass by 65, 77, and 80% of the nontreated control (23, 140, and 935 L ha^{-1}, respectively). The timing of glyphosate treatments can also influence the performance of lower volume applications (94 L ha^{-1}) since winter temperatures may result in freeze damage that further limits herbicide mobility and resultant efficacy (Sartain and Mudge 2018a). Additional research assessing appropriate spray adjuvants, treatment rates, and specific spray deposition requirements to improve glyphosate's effectiveness at the lowest carrier volume (23 L ha^{-1}) for UAAS spray operations is needed to improve control opportunity of giant salvinia.

While not directly measured in the present experiments, effects of spray coverage and quality likely contributed to carrier volume performance on giant salvinia. To achieve a broad range of application volumes, spray equipment and nozzles were not consistent among evaluated treatments, thus differences in droplet size and deposition patterns occurred. For example, the lowest application volume (23 L ha^{-1}) used a CDA sprayer, which produces a volume median diameter (VMD) of 200–300 µm (fine to medium quality). Conversely, the higher application volumes were achieved using XR11002 and XR11008 nozzles that produce VMD spray droplets of 106 to 340 µm (fine to medium quality) and 341 to 403 µm (coarse quality), respectively. Likewise, diluent concentration increases inversely with carrier volume such that smaller droplets used for VLV contain more herbicide per unit volume than larger droplets from high volume applications (Jordan 1981). While decreasing droplet size generally results in higher plant retention (Knoche

1994, Feng et al. 2003) and greater herbicide phytotoxicity (Ennis and Williamson 1963, McKinlay et al. 1972), reducing VMD spray quality can produce sprays more prone to drift and faster evaporation rates (Hilz and Vermeer 2013). Ultimately, these spray quality factors may lead to decreased target plant interception and increasing risk of non-target injury in field settings. Given the unique trichome structure of giant salvinia, the resultant droplet size likely further influences herbicide interception and uptake. Feng et al. (2003) evaluated the effect of droplet size on glyphosate retention, absorption, and translocation in corn (*Zea mays* L.) and discovered glyphosate increased cuticle disruption and leaf absorption as droplet VMD increased from 180 µm (fine) to 490 µm (coarse). Additional studies are needed to understand the influence of spray droplet size specific to improving giant salvinia control with foliarly applied systemic herbicides at VLV since a significant effect on plant efficiency likely exists.

This research provides the first published data to describe carrier volume influence on the efficacy of diquat, flumioxazin, and glyphosate directed at guiding potential VLV operations (e.g., UAAS; knapsack sprayer) for giant salvinia management. Data from these greenhouse experiments suggest low carrier volume foliar applications (140 L ha^{-1}) of diquat and flumioxazin can provide an effective alternative to the more commonly delivered spray volumes of 935 L ha^{-1} for floating plant control (Nelson et al. 2007, Sartain and Mudge 2018a, Haller 2020). Additionally, this small-scale experiment supports further research and development of VLV applications (23 L ha^{-1}) of diquat for foliarly applied management operations on giant salvinia. Field verification of this technique is required to verify the present findings prior to operational adoption.

In conclusion, resource managers wishing to implement similar application methods would benefit from further research evaluating integrated strategies with tank-mix partners (i.e., herbicide combinations; suitable surfactants) or management techniques (e.g., biological control operations) to improve giant salvinia control with VLV applications of flumioxazin or glyphosate. Similarly, studies investigating the impact of VLV and ultra-low volume ($\leq$ 9.4 L ha^{-1}) methods on giant salvinia growth stage (e.g., early invasion primary- and secondary-growth vs. well-established multilayered tertiary growth) would additionally guide appropriate management action since mat thickness would expectedly dictate low-volume herbicide application performance under field conditions. Herbicides evaluated at VLV (23 L ha^{-1}) applications in the present experiment were below the product labeled carrier volumes for aerial application (28 to 46.8 L ha^{-1}), therefore current labeling language ultimately regulates UAAS operational utility based upon current aerial application guidelines. Consequently, research investigating common product label minimum aerial application volumes of $\geq$46.8 L ha^{-1} are warranted for immediate field implications. Further research on herbicide rates above those used in the present experiments is also needed to determine rate response impacts on the efficacy of controlling giant salvinia at VLV applications.

SOURCES OF MATERIALS

[1]Miracle-Gro® All Purpose Plant Food, Scotts Company, Marysville, OH 43040.

[2]Reward®, Syngenta, Greensboro, NC 27409.

[3]Clipper® SC, NuFarm, Alsip, IL 60803.

[4]Rodeo®, Corteva, Indianapolis, IN 46268.

[5]Induce®, Helena Agri-Enterprises, Collierville, TN 38017.

[6]Herbi Handheld Sprayer, Micron Group, Bromyard, Herefordshire, UK.

[7]TeeJet®, Spraying Systems Co., Wheaton, IL 60187.

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LITERATURE CITED

Brown H, Sperry B, Prince C, Ferrell J. 2022. In-water activity of glyphosate, 2,4-D, and diquat on waterhyacinth (*Eichhornia crassipes*). J. Aquat. Plant Manag. 60:75–78.

Cary PR, Weerts PGJ. 1984. Growth of *Salvinia molesta* as affected by water temperature and nutrition. III. Nitrogen-phosphorus interactions and effect of pH. Aquat. Bot. 19:171–182.

Cozad LA, Mudge CR, Rodrigo D. 2019. Integrated management of giant salvinia using herbicides and the salvinia weevil. J. Aquat. Plant Manag. 57:62–68.

Cronk JK, Fennessy MS. 2001. Wetland Plants: Biology and ecology. Lewis, Boca Raton, FL. 462 pp.

de Mendiburu F. 2020. agricolae: Statistical procedures for agricultural research. R package version 1.3-3. https://CRAN.R-project.org/ package agricolae.

EDDMapS. 2023. Early detection & distribution mapping system. University of Georgia, Center for Invasive Species and Ecosystem Health. http://www.eddmaps.org/. Accessed July 6, 2023.

Ennis WB, Williamson RE. 1963. Influence of droplet size on effectiveness of low-volume herbicidal sprays. Weeds 11(1):67–72.

Feng PCC, Sammons TCRD, Ryerse JS. 2003. Droplet size affects glyphosate retention, absorption, and translocation in corn. Weed Sci. 51:443–448.

Flores D, Carlson JW. 2006. Biological control of giant salvinia in East Texas waterways and the impact on dissolved oxygen levels. J. Aquat. Plant Manage. 44:115–121.

Göktoğan AH, Sukkarieh S, Bryson M, Randle J, Lupton T, Hung C. 2010. A rotary-wing unmanned air vehicle for aquatic weed surveillance and management. J. Intell. Robot. Syst. 57:467–484.

Haller WT. 2020. Aquatic herbicide application methods, pp. 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.

Haug JE, Howell AW, Sperry BP, Mudge CR, Richardson RJ, Getsinger KD. 2023. Simulated herbicide spray retention of commonly managed invasive emergent aquatic macrophytes. Weed Technol. 37:243–250.

Hilz E, Vermeer AWP. 2013. Spray drift review: The extent to which a formulation can contribute to spray drift reduction. Crop Protect. 44:75–83.

Howell AW, Haug EJ, Everman WJ, Leon RG, Richardson RJ. 2023a. Low carrier volume herbicide trials and UAAS support management efforts of giant salvinia (*Salvinia molesta*): A case study. Invasive Plant Sci. Manag. 16:130–138.

Howell AW, Leon RG, Everman WJ, Mitasova H, Nelson SAC, Richardson RJ. 2023b. Performance of unoccupied aerial application systems for aquatic weed management: Two novel case studies. Weed Technol. 37:277–286.

Hunter JE, Gannon TW, Richardson RJ, Yelverton FH, Leon RG. 2020. Integration of remote-weed mapping and an autonomous spraying unmanned aerial vehicle for site-specific weed management. Pest Manage. Sci. 76(4):1386–1392.

Johnson D. 1995. Giant salvinia found in South Carolina. Aquatics 17(4):22.

Jordan TN. 1981. Effects of diluent volumes and surfactant on the phytotoxicity of glyphosate to bermudagrass (*Cynodon dactylon*). Weed Sci. 29(1):79–83.

Katagi T. 2003. Hydrolysis of *n*-phenylimide herbicide flumioxazin and its anilic acid derivative in aqueous solutions. J. Pest Sci. 28:44–50.

Kaufman SR, Kaufman W. 2007. Invasive plants: Guide to identification and the impacts and control of common North American species. Stackpole Books, Mechanicsburg, PA. 458 p.

Knoche M. 1994. Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Protect. 13(3):163–178.

Lan Y, Shengde C, Fritz B. 2017. Current status and future trends of precision agricultural aviation technologies. Int. J. Agric. Biol. Eng. 10:1–17.

McFarland DG, Nelson LS, Grodowitz MJ, Smart RM, Owens CS. 2004. *Salvinia molesta* D. S. Mitchell (giant salvinia) in the United States: A review of species ecology and approaches to management. ERDC/EL SR-04-2. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

McKinlay KS, Brandt SA, Morse P, Ashford R. 1972. Droplet size and phytotoxicity of herbicides. Weed Sci. 20(5):450–452.

Mudge CR, Haller WT, Netherland MD, Kowalsky JK. 2010. Evaluating the influence of pH-dependent hydrolysis on the efficacy of flumioxazin for hydrilla control. J. Aquat. Plant Manage. 48:25–30.

Mudge CR, Harms NE, Nachtrieb JG. 2013. Interactions of herbicides, surfactants, and the giant salvinia weevil (*Cyrtobagous salviniae*) for control of giant salvinia (*Salvinia molesta*). J. Aquat. Plant Manage. 51:77–83.

Mudge CR, Perret AJ, Winslow JR. 2016. Evaluation of foliar herbicide and surfactant combinations for control of giant salvinia at three application timings. J. Aquat. Plant Manag. 54:32–36.

Mudge CR, Sartain BT. 2018. Influence of winter on herbicide efficacy for control of giant salvinia (*Salvinia molesta*). J. Aquat. Plant Manag. 56:68–67.

Mudge CR, Sperry BP, Getsinger KD. 2021. Influence of floating plant density on potential herbicide spray loss. Pest Manag. Sci. 77:4447–4452.

Mukherjee A, Knutson A, Hahn DA, Heinz KM. 2014. Biological control of giant salvinia (*Salvinia molesta*) in a temperate region: Cold tolerance and low temperature oviposition of *Cyrtobagous salviniae*. BioControl 59:781–790.

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.

Nelson LS, Skogerboe JG, Getsinger KD. 2001. Herbicide evaluation against giant salvinia. J. Aquat. Plant Manag. 39:48–53.

Oliver JD. 1993. A review of the biology of giant salvinia (*Salvinia molesta* Mitchell). J. Aquat. Plant Manag. 31:227–231.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. Accessed 20 April 2020.

Richardson RJ, Roten RL, West AM, True SL, Gardner AP. 2008. Response of selected aquatic invasive weeds to flumioxazin and carfentrazone-ethyl. J. Aquat. Plant Manag. 46:144–158.

Sartain BT, Mudge CR. 2018a. Effect of winter herbicide applications on bald cypress (*Taxodium distichum*) and giant salvinia (*Salvinia molesta*). Invasive Plant Sci. Manag. 11:136–142.

Sartain BT, Mudge CR. 2018b. Evaluation of 12 foliar applied non-aquatic herbicides for efficacy against giant salvinia (*Salvinia molesta*). J. Aquat. Plant Manag. 56:107–112.

Sartain BT, Mudge CR. 2019. The response of giant salvinia to foliar herbicide applications at three winter timings. J. Aquat. Plant Manag. 57:1–6.

Schardt J, Netherland MD. 2020. Chemical control of aquatic weeds, pp. 163–178. 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.

Shaner DL. 2014. Herbicide handbook. 10th ed. Weed Science Society of America, Lawrence, KS. 513 p.

Sperry BP, 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.

Sperry BP, Mudge CR, Getsinger KD. 2022. Simulated herbicide spray retention on floating aquatic plants as affected by carrier volume and adjuvant type. Weed Technol. 36(1):56–63.

Thomas PA, Room PM. 1986. Taxonomy and control of *Salvinia molesta*. Nature 320(17):581–584.

Wickham H, Francois R, Henry L, Muller K. 2021. dplyr: A grammar of data manipulation. R package version 1.0.4. https://cran.r-project.org/web/packages/dplyr/index.html.