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Alligatorweed; *Alternanthera philoxeroides* (Mart.) Griseb.; cattail; *Typha latifolia* L.; creeping water primrose; *Ludwigia grandiflora* (Michx.) Greuter & Burdet; parrotfeather; *Myriophyllum aquaticum* (Vell.) Verdc.; torpedograss *Panicum repens* L.; water hyacinth; *Eichhornia crassipes* (Mart.) Solms

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Simulated herbicide spray retention of commonly managed invasive emergent aquatic macrophytes

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Abstract

Invasive emergent and floating macrophytes can have detrimental impacts on aquatic ecosystems. Management of these aquatic weeds frequently relies upon foliar application of aquatic herbicides. However, there is inherent variability of overspray (herbicide loss) for foliar applications into waters within and adjacent to the targeted treatment area. The spray retention (tracer dye captured) of four invasive broadleaf emergent species (water hyacinth, alligatorweed, creeping water primrose, and parrotfeather) and two emergent grass-like weeds (cattail and torpedograss) were evaluated. For all species, spray retention was simulated using foliar applications of rhodamine WT (RWT) dye as a herbicide surrogate under controlled mesocosm conditions. Spray retention of the broadleaf species was first evaluated using a CO_2-pressurized spray chamber overtop dense vegetation growth or no plants (positive control) at a greenhouse (GH) scale. Broadleaf species and grass-like species were then evaluated in larger outdoor mesocosms (OM). These applications were made using a CO_2-pressurized backpack sprayer. Evaluation metrics included species-wise canopy cover and height influence on in-water RWT concentration using image analysis and modeling techniques. Results indicated spray retention was greatest for water hyacinth (GH, 64.7 ± 7.4; OM, 76.1 ± 3.8). Spray retention values were similar among the three sprawling marginal species alligatorweed (GH, 37.5 ± 4.5; OM, 42 ± 5.7), creeping water primrose (GH, 54.9 ± 7.2; OM, 52.7 ± 5.7), and parrotfeather (GH, 48.2 ± 2.3; OM, 47.2 ± 3.5). Canopy cover and height were strongly correlated with spray retention for broadleaf species and less strongly correlated for grass-like species. Although torpedograss and cattail were similar in percent foliar coverage, they differed in percent spray retention (OM, 8.5± 2.3 and 28.9 ±4.1, respectively). The upright leaf architecture of the grass-like species likely influenced the lower spray retention values in comparison to the broadleaf species.

Introduction

Among freshwater ecosystems, intrusion of invasive aquatic plants can have detrimental effects on water quality, wildlife habitat, invertebrate diversity and abundance, and trophic interactions (Covich et al. 2004; Engelhardt and Ritchie 2001; Gettys et al. 2014; Miranda and Hodges 2000; Nawrocki 2016; Pitlo and Dawson 1993; Stiers et al. 2011). In addition to adverse environmental impacts, invasive aquatic weeds reduce waterway utility by affecting recreation, hydroelectric power generation, flood control, property values, and human health (Anderson 1993; Gangstad and Cardarelli 1993; Gettys et al. 2014; Halstead et al. 2003). Emergent invasive aquatic weeds, either rooted in sediment or free-floating, are particularly problematic due to the dense monotypic mats they form at the water-air interface. Surface mats are associated with uniquely high levels of light interception that greatly diminish light penetration through the water column, reductions in dissolved oxygen, and increased evapotranspiration rates within invaded waterways (Getsinger et al. 2014; Miranda and Hodges 2000; Sculthorpe 1967; Villamagna and Murphy 2010). These plant growth attributes make emergent invasive weeds particularly competitive against native submersed vegetation through resource competition (Stiers et al. 2011). Additionally, emergent weed species commonly occupy irrigation canals and drainage ditches, impeding flow while increasing siltation (Anderson 1993; Pitlo and Dawson 1993). Ultimately, this can lead to a reduction in the storage capacity of these essential municipal and agricultural waterways (Getsinger et al. 2014).

The use of herbicides to control invasive aquatic vegetation can have reduced environmental impacts compared with other techniques and is often the most cost-effective management option available (Gettys et al. 2014; Hussner et al. 2017; Villamagna and Murphy 2010). Above water, foliar application of herbicides is one of the simplest forms of aquatic applications as herbicides are applied in a manner similar to terrestrial applications (Murphy and Barrett 1993). However, unlike terrestrial applications, aquatic plant treatment overspray (i.e., herbicide not retained on or absorbed by the target weed) can directly enter the water column within or adjacent to the targeted treatment zone. Once in the water column, this spray may either quickly dissociate (e.g., glyphosate) or in many cases (e.g., 2,4-D, diquat dibromide, triclopyr, flumioxazin) the herbicide could have some reduced in-water activity (Netherland 2014). While it is unlikely, in-water herbicide activity could negatively impact the growth of non-target plants and algae. More commonly, where in-water activity is minimal, foliar spray loss to the water column still has negative implications for the associated costs of lost herbicide and the potential for reduced herbicide efficacy due to limited spray retention.

Spray retention by weed species has been shown to improve through the manipulation of abiotic factors such as the addition of surfactants, and the use of lower carrier volumes, smaller droplet sizes, lower droplet velocities, and finer spray qualities (e.g., Harbour 1997; Massinon and Lebeau 2013; Dorr et al. 2014, 2015; Silva et al. 2016). Similarly, biotic factors including increased leaf surface area, canopy density and height, as well as a more prostrate growth habit and more wettable leaf surface, could lead to an increase in spray capture (e.g., Dorr et al. 2015; Ennis et al. 1952; Massinon and Lebeau 2013; Massinon et al. 2014). However, all of these factors can interact with one another in varying ways that are not yet fully understood. To better understand the biotic factors that contribute to spray retention among commonly managed emergent aquatic weeds, research is needed to first define the inherent variability of overspray for foliar applications. In this study, we assessed spray retention for six emergent aquatic invasive species using the foliar application of an inert water tracing dye as an herbicide surrogate under controlled mesocosm conditions. Based on recent publications (e.g., Mudge et al. 2021; Sperry et al. 2022), we hypothesize that weed species with plant canopies that provide the greatest coverage of the water surface will provide the highest spray retention.

Materials and Methods

Outdoor mesocosm experiments were conducted to examine the variability of overspray in simulated foliar herbicide applications to six emergent aquatic plant species. All experiments used rhodamine WT (RWT) dye (Rhodamine WT Liquid; Keystone Aniline Corp., Chicago, IL) to approximate herbicide deposition. Doing this cost considerably less money than quantifying herbicides analytically (Mudge et al. 2021; Sperry et al. 2022). Use of RWT to follow trace aqueous herbicide movement has been used in a variety of field environments for decades (e.g., Fox et al. 1991, 1993, 2002). Applications were conducted using a CO_2-pressurized backpack sprayer with a hand-held boom. Test species included plants with varying morphology: three sprawling marginal species, alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.], creeping water primrose [*Ludwigia grandiflora* (Michx.)], and parrotfeather [*Myriophyllum aquaticum* (Vell.) Verd.]; two shoreline emergent grass-like species, cattail [*Typha latifolia* L.] and torpedograss [*Panicum repens* L.]; and one free-floating aquatic weed, water hyacinth [*Eichhornia crassipes* (Mart.) Solms]. Spray retention patterns for four of these species (alligatorweed, creeping water primrose, parrotfeather, and water hyacinth) were confirmed in a small-scale controlled environment (greenhouse) using a CO_2-pressurized calibrated spray chamber. All experiments were set up as randomized complete block designs with four replications.

Greenhouse Experiments

The small-scale greenhouse trial was completed in a controlled spray chamber. This environment reduces the potential for variability in air currents, spray angles, and plant growth and was used to bolster the more field relevant data collected in the outdoor mesocosm trials described below. In these experiments, 100% canopy cover of each species was targeted (Table 1). Six small "button" hyacinths were placed in each mesocosm. Due to the limited capacity of the spray chamber, sprawling emergent plants were not established in soil but were instead weighted down in water with lead wire. The plants we used in these experiments were greenhouse cultures with a more limited leaf area index compared with field-grown plants. As a result, we needed more plant stems to reach the targeted canopy cover. Equivalent numbers of stems of approximately equivalent length were used in each replicate for parrotfeather (28 ± 2 cm, 50 stems), creeping water primrose (33 ± 2 cm, 10 stems), and alligatorweed (33 ± 2 cm, 45 stems). All spray chamber experiments used 5-L mesocosms (20.5 cm diam) filled to capacity with dechlorinated tap water prior to treatment. Again, each trial included plant-free positive control mesocosms that were used to calculate maximum RWT concentrations. The spray chamber was equipped with a single XR11004E TeeJet® nozzle (Spraying Systems Co., Wheaton, IL) pressurized with 220 kPa CO_2 calibrated to deliver 935 L ha^{-1} of a 0.1% vol/vol RWT and 0.25% vol/vol nonionic surfactant, Cide-Kick II® (Brewer International Inc, Vero Beach, FL) solution at approximately 45 cm above the experimental units. Application parameters used in the spray chamber were estimated to produce a "medium" droplet diameter (177 to 218 µm; TeeJet Technologies 2023). However, this average spray quality was not directly measured and represents only an estimate of expected droplet sizes, because spray quality is largely dependent upon atmospheric conditions, spray solution properties, and application confines. These application parameters were selected to approximate common field scenarios. All trials included four replicates and randomized plants. All plants exhibited healthy growth at the time of treatment.

Data Collection

Background RWT dye levels and temperature in each replicate mesocosm were measured 5 to 10 cm below the surface using a calibrated handheld fluorometer (AquaFluor Handheld Fluorometer; Turner Designs, San Jose, CA). Nadir view pretreatment imagery was collected using a 12-megapixel digital camera (iPhone 7; Apple Inc. Cupertino, CA) at a height of 46 cm above ground level. Following dye application, the solution was allowed to dry on the leaf surfaces of the plants for 1 h. Plants were then removed from the mesocosms to allow for 30 s of circulation with a glass rod. Care was taken not to allow additional dye loss during water circulation. Following circulation, a second RWT dye reading was collected for each mesocosm and the water volume remaining in the tank was measured. Biomass was harvested at the conclusion of each trial and was dried to a constant mass in an industrial drying room at 60 C for 48 h (Table 1). Canopy height was estimated by measuring the height above the water column of five random stems per replicate (Mudge et al. 2021).

Table 1. Experimental method details from studies evaluating foliar spray deposition patterns from simulated herbicide applications to emergent aquatic plant species.

Species	Study scale	Runs	n	Treatment date	Mesocosm size	Plants per meso-cosm	Supplementary material	Dry biomass[a]
					L		Stems per mesocosm	g m^{-2}
Water hyacinth	Outdoor	2	8	July 16, July 16	40	12	15	1,015.9 (61.6)
Alligatorweed	Outdoor	3	12	June 18, June 21, July 16	40	64	5	467 (35.5)
Creeping water primrose	Outdoor	3	12	June 18, June 21, July 16	40	40	30	531.6 (47.1)
Parrotfeather	Outdoor	3	12	June 18, June 21, July 16	40	64	0	583.3 (54)
Cattail	Outdoor	2	8	September 30, September 30	120	15	0	399.1 (36.4)
Torpedograss	Outdoor	2	8	September 30, September 30	5	20	0	314.0 (16.1)
Water hyacinth	Greenhouse	1	4	June 23	5	6	0	645.7 (33.2)
Alligatorweed	Greenhouse	1	4	June 23	5	45	0	362.5 (13.8)
Creeping water primrose	Greenhouse	1	4	June 23	5	10	0	623.4 (27)
Parrotfeather	Greenhouse	1	4	June 23	5	50	0	549.9 (18.2)

[a]Standard error of the mean appear in parentheses.

Outdoor Mesocosm Experiments

Larger-scale outdoor mesocosm experiments were conducted to closer mimic field conditions as compared to the greenhouse experiments described previously. Operational broadcast-foliar herbicide applications commonly target high-density plant populations. Conversely, lower density populations are frequently controlled through spray-to–wet spot treatments. Therefore, peak-density plant growth was targeted to mimic field applications that account for the largest herbicide field use patterns. Water hyacinth, alligatorweed, creeping water primrose, parrotfeather, cattail, and torpedograss plants were established in outdoor mesocosms in June, July, or August of 2021 and allowed to acclimate for 30 d prior to treatment. Water hyacinth, alligatorweed, creeping water primrose, and parrotfeather were all established and assessed in 40-L black round mesocosms (60.5 cm diam). Twelve cultivated mature hyacinth plants were placed in each mesocosm. Thirty-centimeter stems of alligatorweed (8 stems per pot), creeping water primrose (5 stems per pot), and parrotfeather (8 stems per pot) were planted in 10-cm square pots filled with topsoil amended with 3 g L^{-1} of slow-release fertilizer (Osmocote® Plus 15-9-12; Scotts Miracle-Gro, Marysville, OH) and capped with a layer of sand. Eight planted pots were established in each 40-L mesocosm and filled with pond water. Additional weighted stems were added to the mesocosms of sprawling marginal species on the day of treatment to reduce gaps in the canopy and better represent field conditions. The number of plants required to achieve these targets varied from species to species (Table 1). Cattail plants were field collected with at least 10 cm of rhizome each. Fifteen cattail plants were established in 30-L tree liners with topsoil amended with 3 g L^{-1} of slow-release fertilizer and capped with a layer of sand. Each planted tree-liner replicate was submersed in 120-L round mesocosms filled with pond water. Cultivated torpedograss plants were established in 13-cm pots at a density of 20 shoots per pot with topsoil amended with 3 g L^{-1} of slow-release fertilizer and capped with a layer of sand. Prior to treatment these pots were placed in 5-L mesocosms filled with pond water.

Prior to treatment, all mesocosms were filled to capacity with unfiltered pond water. Experiments used different sized mesocosms to accommodate varying plant habits (Table 1). Each trial included plant-free control mesocosms that were used to calculate the mesocosm-specific maximum RWT concentrations. All trials included four replications and were repeated in space and time (Table 1). All plants exhibited healthy growth at time of treatment. Applications were made with a CO_2-pressurized backpack sprayer fitted with a four-nozzle boom and three XR11008 flat-fan TeeJet® nozzles (Spraying Systems Co.). The fourth nozzle head was blocked using a blank nozzle (no orifice). The spray system was calibrated to deliver 935 L ha^{-1} of a 0.1% vol/vol RWT and 0.25% vol/vol nonionic surfactant, Cide-Kick II® (Brewer International Inc.) solution at approximately 60 cm above experimental units. Application parameters used in outdoor experiments were estimated to produce a “course” droplet diameter (218 to 349 µm) at the 138 kPa pressure used in this study (TeeJet Technologies 2023). As with the greenhouse study, average spray quality was not directly measured and represents only an estimate of expected droplet sizes. Applications were performed when wind speeds were less than or equal to 5 km h^{-1} to minimize interference. These application parameters were selected to approximate common field application scenarios. Following application, the solution was allowed to dry on the leaf surfaces of the plants for 1 h. After this drying period concluded, submersible pumps (PL-118 mini submersible pump; PULACO Purelake Group LTD, Guangzhou, China) were inserted halfway into the water column and water was circulated for 3 min to allow the dye to reach equilibrium. Given container size limitations, a small glass rod was used to manually circulate the water and dye for 30 s for the torpedograss trial. Care was taken not to disturb the plants during water circulation.

Data Collection

Prior to treatment, background RWT dye levels in each replicate mesocosm were measured 15 to 20 cm below the surface using either a calibrated multiparameter data sonde (Trimeter; Eureka

Water Probes, Austin, TX) or a handheld fluorometer (AquaFluor; Turner Designs, San Jose, CA). Nadir view pretreatment imagery was collected using a DJI Phantom 4 drone (SZ DJI Technology Co., Ltd. Shenzhen China) with a camera height of 6 to 9 m above ground level. Following dye application, drying, and circulation, a second RWT dye reading was collected for each mesocosm. Plants were then removed and the water volume remaining in the tank was measured. To estimate uniformity in plant growth between replicates of the same species, biomass measurements for rooted species (shoot tissue above the soil level) and water hyacinth (shoot and root tissue) were collected (Table 1). Biomass was harvested at the conclusion of each experiment and was dried to a constant mass in an industrial drying room at 60 C for 48 h. Measurements of percent canopy coverage and canopy height were collected because other studies have found these parameters to affect spray retention (Don Wauchope and Street 1987; Mudge et al. 2021). Canopy height was estimated by measuring the height above the water column of five random stems per replicate.

Data Analysis

Imagery Analysis

Collected images were subjected to a series of digital processing techniques to develop binary classification statistics. These statistics were used to calculate the percentage of plant foliage cover for each representative plant treatment mesocosm using ImageJ software (National Institutes of Health, Bethesda, MD). Processing of individual images followed similar methods as described by Ali et al. (2013) to segment plant foliage from the water surface. Images were first cropped to the circular extent of the treatment mesocosms, with hue, saturation, and brightness color thresholding calibrated to detect the plant material of each respective plant species. Following the conversion of selected plant material, misclassified data (i.e., nonvegetated pixels) were manually removed from the canopy selection. Plant canopy cover was then measured using the *Analyze* tool in ImageJ and recorded for further statistical measures.

Statistical Analysis

Data were processed to account for differences in water volumes and pretreatment dye readings. The percentage of the applied spray solution that reached the water column was calculated following the methods described by Sperry et al. (2022) and Mudge et al. (2021) using the following formula:

$$Y = 100 - \left[\frac{(x-p)}{(c-p)}\right] * 100 \qquad [1]$$

where Y is the % spray retention, x is the posttreatment dye concentration in experimental units, c is the posttreatment dye concentration in the blank reference units, and p is the pretreatment background fluorescence.

A correlation analysis was performed for all species to compare the percent spray retention to the calculated percent canopy cover and to compare the percent spray retention to the canopy height measurements. It is worth noting that these correlation analyses included canopy cover endpoints only (i.e., no plants or high-density growth), which likely impacted the resulting Pearson correlation coefficient, r, values. Where appropriate, data were subjected to ANOVA followed by a Tukey-Kramer honestly significant difference test to separate means using the AGRICOLAE package with RStudio software (de Mendiburu 2020; R Core Team 2020).

Results and Discussion

Greenhouse Experiments

Greenhouse experiments were carried out to understand the differences among sprawling marginal species in spray retention where conditions could be closely controlled. Water hyacinth was included in this experiment to compare results with those previously reported (Sperry et al. 2022). Canopy coverage was similar among all species tested (Table 2). All correlation analyses for the greenhouse experiments indicated that the percent retention and percent cover were highly positively correlated for broadleaf weed species ($r > 0.97$; Table 3). Similarly, canopy height was highly positively correlated with spray retention for these species, with parrotfeather demonstrating the weakest correlation ($r > 0.82$; Table 3). Spray retention was significantly higher for water hyacinth compared with that for alligatorweed, despite similar canopy coverage and canopy height measurements. Less mature water hyacinth plants were used in the greenhouse studies compared to the outdoor studies. Immature water hyacinth plants tend to have shorter petioles with a larger proportion of the petioles inflated and thus display more prostrate and compact growth compared with mature water hyacinth. Although the alligatorweed canopy has more leaves lower in the canopy to catch secondary droplets, the leaves are smaller and less compact than immature water hyacinth leaves. These biotic attributes may have contributed to the increased spray retention observed for water hyacinth compared to that of alligatorweed. Creeping water primrose experimental plants showed significantly greater heights compared to the other broadleaf species, yet no difference in spray retention was detected (Table 2).

Outdoor Mesocosm Experiments

Plants used for outdoor experiments were targeted for treatment when visual canopy cover was at its peak, which resulted in 33.6% to 70.1% area covered based on posttreatment image analysis (Tables 1 and 2). No treatment-by-experimental run interaction was detected among the outdoor mesocosm experiments. Therefore, data from outdoor mesocosm experiments were pooled across experimental runs to compare calculated spray retention interactions to canopy cover and canopy height metrics (Tables 2 and 3).

Water hyacinth showed the greatest spray retention (76.1%) of all species tested in the outdoor mesocosm experiment (Table 2). Although water hyacinth showed greater percent retention than any of the sprawling marginal species, the calculated percent cover for water hyacinth (70.1%) did not statistically differ from that of either alligatorweed (62.4%) or creeping water primrose (66.1%). Canopy heights were also similar among broadleaf weeds apart from parrotfeather, which showed reduced canopy height. Given these similarities in canopy cover and height, the improved spray retention observed with water hyacinth was unexpected. Differences in plant morphology have been shown to influence spray retention (e.g., Dorr et al. 2014; Massinon et al. 2014). For example, the sprawling marginal species in this study have more leaves lower in the canopy to catch secondary spray droplets. Additionally, water hyacinth leaves are glabrous, upright, and on a long-inflated petiole, which differs from the sprawling marginal species (Godfrey and Wooton 1981; Radford et al. 1968). However,

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Table 2. Spray retention and canopy characteristics from experiments evaluating foliar spray deposition patterns in applications to emergent aquatic plants.

Species	Study scale[a]	Canopy coverage[b,c]	Canopy height	Spray retention
		%	cm	%
Water hyacinth	Outdoor	70.1 (1.0) A	25.7 (1.9) C	76.1 (3.8) A
Alligatorweed	Outdoor	62.4 (3.3) AB	22.4 (0.8) C	42.0 (5.7) BC
Creeping water primrose	Outdoor	66.1 (2.1) AB	27.7 (1.2) C	52.7 (5.7) BC
Parrotfeather	Outdoor	58.9 (1.8) B	12.0 (0.7) D	47.2 (3.5) BC
Cattail	Outdoor	39.8 (2.4) C	124.9 (2.8) A	28.9 (4.1) C
Torpedograss	Outdoor	33.6 (2.9) C	50.1 (1.7) B	8.5 (2.3) D
Water hyacinth	Greenhouse	69.9 (2.5) a	6.3 (0.4) b	64.7 (7.4) a
Alligatorweed	Greenhouse	71.6 (2.2) a	8.9 (0.8) b	37.2 (4.5) b
Creeping water primrose	Greenhouse	83.0 (5.1) a	13.8 (1.0) a	54.9 (7.2) ab
Parrotfeather	Greenhouse	80.4 (3.1) a	5.8 (1.8) b	48.2 (2.3) ab

[a]Means within columns for a particular study scale followed by the same letter do not differ according to Tukey's honestly significant difference test ($P \leq 0.05$).
[b]Standard error of the mean appears in parentheses.
[c]Values are not inclusive of plant-free control units.

Table 3. Pearson correlation coefficients and their significance for calculated percent cover and canopy height as factors for emergent aquatic plant spray retention.

		Spray retention			
		Canopy cover		Canopy height	
		%		cm	
Species	Study scale	Pearson's coefficient	P[a]	Pearson's coefficient	P[a]
Water hyacinth	Outdoor	0.99	**<0.001**	0.95	**<0.001**
Alligatorweed	Outdoor	0.94	**<0.001**	0.91	**<0.001**
Creeping water primrose	Outdoor	0.91	**<0.001**	0.87	**<0.001**
Parrotfeather	Outdoor	0.97	**<0.001**	0.96	**<0.001**
Cattail	Outdoor	0.86	**<0.001**	0.88	**<0.001**
Torpedograss	Outdoor	0.67	**0.009**	0.75	**0.003**
Water hyacinth	Greenhouse	0.97	**<0.001**	0.99	**<0.001**
Alligatorweed	Greenhouse	0.97	**<0.001**	0.98	**<0.001**
Creeping water primrose	Greenhouse	0.97	**<0.001**	0.95	**<0.001**
Parrotfeather	Greenhouse	0.99	**<0.001**	0.82	**0.0136**

[a]Bold type indicates metrics significant at $\alpha \leq 0.05$.

these morphological differences would be expected to contribute to a reduced spray retention for water hyacinth. Perhaps the larger, more curved leaf shape of water hyacinth leaves contributed to the increase in spray retention observed. Canopy cover and height were strongly correlated with percent spray retention for all broadleaf weeds (Table 3). These results are consistent with those of other studies that suggested canopy height and structure influence spray interception among floating plant species (Mudge et al. 2021; Sperry et al. 2022).

In field scenarios, alligatorweed typically displays a lower plant architecture than the other two sprawling marginal plants tested, creeping water primrose and parrotfeather. Though they are depth-dependent, both alligatorweed and parrotfeather plants can have a notable proportion of biomass below the water surface. This submersed biomass is often not targeted when conducting foliar spray operations nor can it retain spray solution (Emerine et al. 2010). Despite the architectural variation, calculated canopy cover estimates in this study showed no statistical difference between any of the sprawling marginal plant species tested ($P > 0.05$; Table 2). Similarly, no difference was observed in spray retention between the evaluated sprawling marginal plant species ($P > 0.05$; Table 2). Parrotfeather did show statistically lower canopy height than the other two species; however, this difference in canopy height did not appear to affect spray retention (Table 2). Of these species the correlation between calculated canopy cover and calculated percent retention was weakest for creeping water primrose ($r = 0.91$) followed by alligatorweed ($r = 0.94$). Parrotfeather showed the strongest correlation with a Pearson correlation coefficient of 0.97 (Table 3). Results of canopy height and spray retention analyses largely followed the same patterns with all three species showing a high degree of positive correlation (Table 3). Again, the strongest relationship was observed for parrotfeather ($r = 0.96$), followed by alligatorweed ($r = 0.91$), followed by creeping water primrose ($r = 0.87$; Table 3).

Image analysis indicated that torpedograss (33.6% ± 2.9%) and cattail (39.8% ± 2.4%), had the lowest canopy cover of all species evaluated (Table 2; Figure 1). Brecke et al. (2001) noted a similarly limited canopy surface area for torpedograss in terrestrial environments. Previous research suggests that grass-like species with minimal leaf surface area and canopy overlap perpendicular to the spray pattern are hard to wet, which limits spray retention, in part, due to spray droplet shatter and bounce (Zabkiewicz et al. 2020). While no significant difference in percent canopy cover was observed between these two species, torpedograss did exhibit lower spray retention (8.5% ± 2.3%) compared to cattail (28.9% ± 4.1%). Correlation analyses between spray retention and canopy cover indicated that for torpedograss ($r = 0.67$) the association is much weaker than for cattail ($r = 0.86$). Similarly, the association between canopy height and spray retention was weaker for torpedograss ($r = 0.75$) than for cattail ($r = 0.88$). Cattail canopies (124.9 ± 2.8 cm) were 2.5 times taller than torpedograss canopies (50.1 ± 1.7 cm). It is likely that this increase in surface area,

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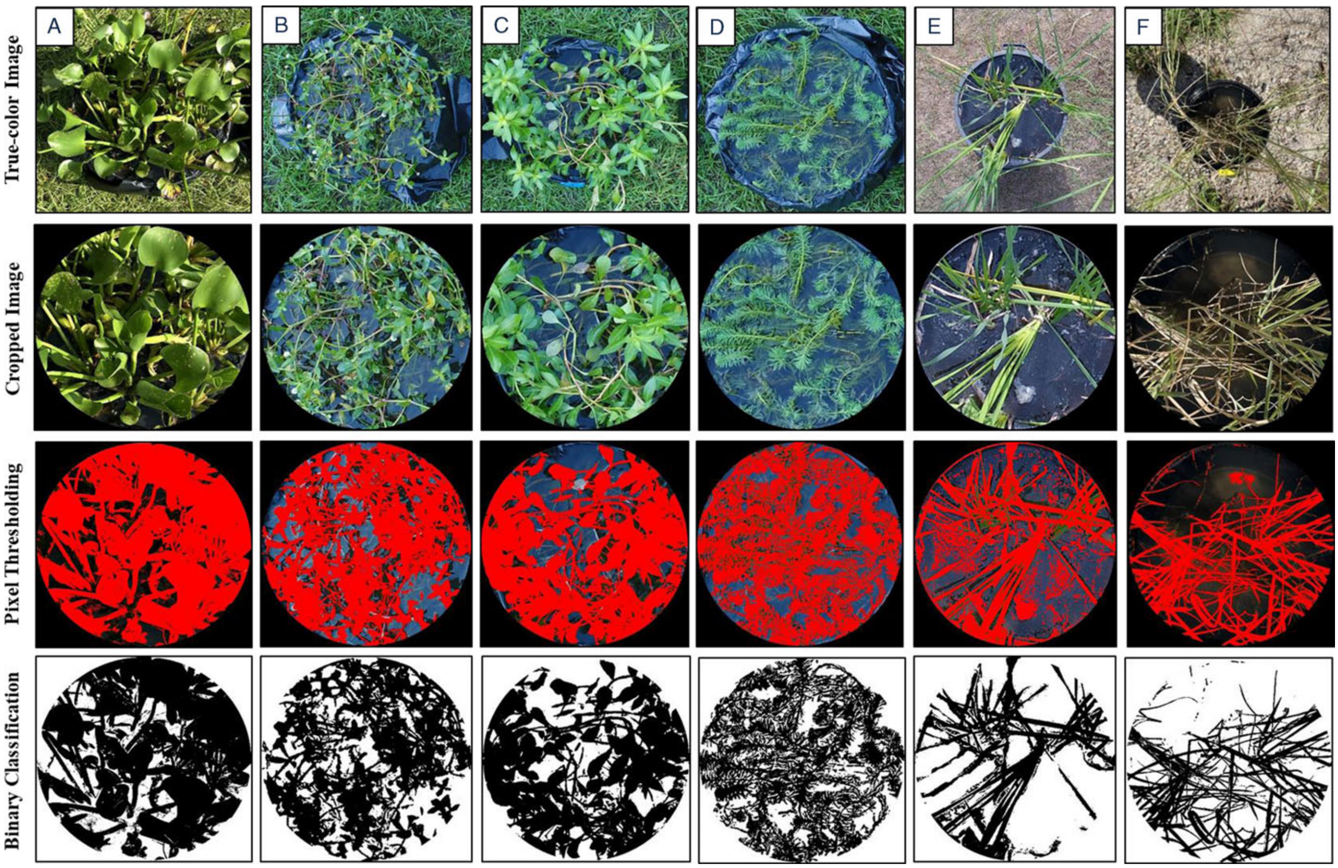

Figure 1. Example of the image processing techniques used to quantify the percentage of plant canopy cover for each respective emergent species evaluated for the backpack spray retention trial. To quantify canopy cover using ImageJ software, an original true-color image was 1) cropped to the surface area extent of the mesocosm to set a region of interest (ROI) using the *ROI Manager* tool, 2) filtered using the *Color Threshold* tool to select the plant canopy pixels from nonvegetative background, 3) converted to a binary selection using the *Make Binary* tool where only plant material pixels (black) were retained, 4) nonvegetated artifacts were manually removed using the *Paintbrush* tool, 5 the ROI was recalled so that resultant plant canopy pixels represented the extent of the mesocosm, and 6) pixels were quantified using the *Measure* tool to achieve a percent canopy cover value. Example canopy cover results for each experimental unit displayed were (A) water hyacinth, 76.60%; (B) alligatorweed, 64.82%; (C) creeping water primrose, 68.09%; (D) parrotfeather, 62.59%; (E) cattail, 37.93%; and torpedograss, 36.44%.

although not perpendicular to the spray trajectory, led to an increase in spray capture for cattails as compared to torpedograss. Additionally, while torpedograss blades are more prostrate than cattail leaf blades, torpedograss blades are much narrower and shorter than cattail leaf blades (Godfrey and Wooton 1981; Radford et al 1968). Torpedograss plants have more leaves deeper in the canopy compared to cattails, which can capture secondary spray droplets (Godfrey and Wooton 1981); however, this difference appeared to have limited impact in the present experiment.

Leaf surface architecture, angles, roughness, and growth habit may explain some of the differences in retention among species in this study (e.g., Huet et al. 2020; Zabkiewicz et al. 2020). Canopy cover and height were positively correlated with spray retention for water hyacinth and sprawling marginal species. These canopy cover results are consistent with those reported by Mudge et al. (2021) for the floating aquatic species water hyacinth, water lettuce (*Pistia stratiotes* L.), and giant salvinia (*Salvinia molesta* D.S. Mitchell). Furthermore, terrestrial studies have observed that canopy volume (i.e., product of coverage and height) is more indicative of spray retention rather than coverage alone (Don Wauchope and Street 1987). However, neither canopy cover nor height were strongly correlated with torpedograss spray retention in the present study. As previously mentioned, the lowest percent spray retention was noted for grass-like species. This phenomenon may be best explained by the direction of the spray application for the erect canopy architecture of grass-like species. A spray application directly perpendicular to the water level should allow for higher spray interception by the more prostrate leaves of sprawling marginal species as compared to the more vertical habit of the grass-like species tested (e.g., Dorr et al. 2014, 2015; Ennis et al. 1952; Massinon et al. 2014). Managers seeking to control erect, grass-like species should consider alternative spray methods to potentially improve spray retention. One previous study (Massinon et al. 2014) suggested that lowering the spray angles can improve the impact and leaf interception for highly hydrophobic vertical leaves. Another study (Spillman 1984) proposed that droplet deposition can be improved with the use of finer droplets for species with a vertical growth habit. It is additionally possible that the adjuvant type could increase spray retention for grass-like species (Huet et al. 2020). Previous laboratory-based research (Harbour 1997; Silva et al. 2016) reported the addition of a nonionic surfactant, such as that used in the present study, significantly improved spray retention and uniformity of spray droplet distribution on cattail leaves, whereas the use of a drift control agent did not significantly improve spray retention. In a mesocosm study, Sperry et al. (2022) also observed an improvement in spray retention for free-floating species with the addition

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of various adjuvants in the spray solution but found no spray retention difference between adjuvants for the species tested. Results from these past studies should be confirmed for the sprawling marginal and grass-like species in the present study among mesocosm and field settings.

Spray quality (fine to course) can affect penetration into the canopy and influence adhesion on plant surfaces (Spillman 1984). Estimated spray quality values were less coarse in the greenhouse experiments compared to the outdoor mesocosm experiments. A prior study (Bowmer et al. 1993) suggested that alligatorweed has improved spray coverage and uptake of glyphosate as droplet size decreases. As such, a difference in applied droplet diameters could have been partially responsible for the increased spray retention noted in the greenhouse experiments compared to the outdoor mesocosm experiments (Knoche 1994).

Another important factor in spray retention is the carrier volume used. In aquatics, herbicides are typically delivered at total carrier volumes of between 468 to 1,870 L water ha^{-1} (Haller 2020; Nelson et al. 2007). However, "high" spray volume applications may prove undesirable for prevailing management approaches. Sperry et al. (2022) found a decline in spray retention with increasing carrier volumes from 187 to 935 L ha^{-1} for the free-floating aquatic species water hyacinth, giant salvinia, and water lettuce. However, Katovich et al. (1996) observed slightly improved retention when a 10× higher carrier volume was applied to purple loosestrife (*Lythrum salicaria* L.). Regardless, care should be taken not to reduce or increase the carrier volume too drastically, because herbicide efficacy may be compromised. With low carrier volume applications, targets generally receive more limited spray coverage and droplet penetration into the canopy is limited (Katovich et al. 1996; Knoche 1994). Similarly, if the carrier volume is too high, the dilute concentration of herbicide may reduce its efficacy and increased droplet size velocity at these carrier volumes may reduce retention (Dorr et al. 2014, 2015). Further testing with herbicide included in the spray solution is required to confirm similar impacts to the species tested in this study. Additionally, future studies should determine whether lower canopy coverages (e.g., 25% to 50% cover) produce similar spray retention responses for species that were tested in the present studies.

In conclusion, these studies indicate that as canopy cover increases, overspray decreases for water hyacinth and the sprawling marginal species tested. When canopy cover is reduced, managers should be mindful of herbicide selection, spray volume, spray angle, and the potential impacts that these factors may cause with overspray to the water column. Conversely, a low canopy cover may indicate the need for an herbicide with in-water activity to achieve secondary uptake through submersed plant tissue or roots by the target weed.

Practical Implications

Intrusion by emergent aquatic weeds can have detrimental impacts to the environment and utility of a waterway, including deterioration of water quality, wildlife habitat, swimming, navigation, flood water storage, and hydroelectric power generation. One of the most cost-effective and least disruptive methods of management includes the use of aquatic herbicides registered by the Environmental Protection Agency to selectively control these invasive weeds. However, there is often a measure of negative public perception regarding the amount of herbicide entering the waterway in which the target weeds are growing. Additionally, water resources managers may have concerns regarding spray retention and the associated influence on herbicide efficacy. To date, studies have not examined the amount of herbicide retained in the canopy of commonly managed emergent aquatic weeds. This simulated herbicide study was conducted to measure the influence of weed canopy cover and height on spray retention for water hyacinth, alligatorweed, creeping water primrose, parrotfeather, cattails, and torpedograss. Greenhouse and outdoor mesocosm trials indicated that water hyacinth produced the greatest spray retention of all the species that were evaluated. Conversely, grass-like species, torpedograss, and cattails, were observed to have reduced canopy cover that contributed to reduced spray retention with overtop application. When formulating herbicide application strategies, managers should consider the increased overspray potential associated with weed species having limited canopy cover and vertical leaf angles. To improve spray retention in these species, additional spray strategies such as lowering the carrier volume, lowering the spray angle, and adding appropriate adjuvants, should be considered.

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