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Evaluation of aquatic herbicide activity against crested floating heart

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ABSTRACT

Crested floating heart [*Nymphoides cristata* (Roxb.) Kuntze] is a rapidly spreading invasive aquatic plant found in the southeastern United States. This plant exhibits a nymphaeid growth form producing dense mats of overlapping, floating leaves at the end of long stems in water up to 3 m in depth. To date, most operational strategies have relied on aquatic herbicides; however, results have been inconsistent and anecdotal. The objective of this research was to evaluate the majority of registered aquatic herbicides for activity against crested floating heart. A series of small-scale tank experiments was conducted to determine efficacy of the active ingredients: (2,4-dichlorophenoxy)acetic acid (2,4-D), [(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid (triclopyr), 7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid (endothall), 6,7-dihydrodipyrido[1,2-α:2′,1′-*c*]pyrazinediium ion (diquat), X,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid (carfentrazone), 2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propanyl)-2*H*-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1*H*-isoindole-1,3(2*H*)-dione (flumioxazin), 2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]benzoic acid (bispyribac-sodium), *N*-(phosphonomethyl)glycine (glyphosate), 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid (imazamox), (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid (imazapyr), and 2-(2,2-difluoroethoxy)-*N*-(5,8-dimethoxy[1,2,4]triazolo[1,5-*c*]pyrimidin-2-yl)-6-(trifluoromethyl)benzenesulfonamide (penoxsulam) applied via foliar and subsurface applications. Herbicides were applied at concentrations near maximum and half-maximum label use rates in the late spring through summer on plants that had formed a surface canopy. The submersed treatments were evaluated at 24 and 96-h exposure periods. Harvest at 4 wk after treatment indicated that most of the herbicides were not active after either the 24 or 96-h exposure at the highest test rate. In contrast, the liquid subsurface treatments of endothall at 0.25 and 0.5 mg ae L^{-1} provided complete control after 24 and 96-h exposures, whereas diquat at 0.18 and 0.37 mg ai L^{-1} provided 91 to 95% control after a 96-h exposure. Endothall also provided 24 to 60% biomass reductions after granular applications of 3 mg ae L^{-1} for a 96-h exposure. Foliar-applied imazamox and imazapyr at 1.2 kg ai ha^{-1} provided similar levels of control ranging from 81 to 83% control respectively. The other foliar-applied herbicides, including 2,4-D, triclopyr, and glyphosate, were not effective. For herbicides tested as both foliar and submersed applications, it was found that method of application had limited impact on activity and efficacy. Furthermore, aside from the amine salt of endothall, we did not detect a difference between liquid and granular formulations for submersed applications. These data indicate that most of the herbicides tested had limited activity on crested floating heart in our experimental system. These results suggest the amine salt of endothall and diquat as submersed applications and imazapyr and imazamox as foliar applications were the most effective. Further testing is needed to determine optimal timing, use rates, and products for efficacy under field conditions.

Key words: endothall, foliar, imazapyr, imazamox, *Nymphoides*, subsurface.

INTRODUCTION

Crested floating heart [*Nymphoides cristata* (Roxb.) Kuntze] is a floating leaf aquatic plant native to Southeast Asia (Vietnam, Thailand, India, Sri Lanka, and southern provinces of the People's Republic of China). Despite the native status in Asia, the plant is often considered to be a pest in rice fields (Burks 2002a). It was introduced to North America through the water garden trade where it is readily available for purchase from a multitude of online aquatic plant distributors and aquarium stores. It is often marketed as water snowflake because it can cover a water surface in tiny white flowers, giving the appearance of snow throughout the long flowering season. The plant was first confirmed outside of ornamental culture in 1996 in Horseshoe Lake, Collier County, FL (Burks 2002a). Crested floating heart now exists in expanding, invasive populations in many waterways in Florida as well as South Carolina, Texas (Center for Invasive Species and Ecosystem Health 2010), and Louisiana (A. Perret, pers. comm.). The Florida Exotic Pest Plant Council (FLEPPC) listed crested floating heart as a category 1 invasive species, meaning it is a nonnative species that has been observed altering native plant community structures and ecological functions and is present in natural areas (FLEPPC 2009).

One of the most significant infestations currently known has occurred in the 64,750-ha Santee Cooper reservoir system in South Carolina where ~2,400 ha of water are currently impaired by dense crested floating heart growth

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(Westbrooks et al. 2012). The Santee Cooper infestation suggests that all water bodies in Florida and in much of the Southeast United States are within a climate zone favorable for sustaining invasive growth of the plant. Crested floating heart has been observed forming dense mats in water from 0.6 to 3 m deep in the Santee Cooper system (C. Davis, pers. comm.). This would suggest the potential for crested floating heart to infest significant areas of numerous shallow water bodies throughout the Southeast. It can also survive extended periods in moist soil, suggesting that the plant can persist through periods of low water levels and drawdowns (Willey and Langeland 2011).

In areas where crested floating heart has become established, overlapping, floating leaves form dense mats that interfere with boat traffic and recreational water uses. The mats also shade the water column below, reducing light availability to submersed native vegetation and phytoplankton, lowering dissolved oxygen levels, and reducing water flow and aeration (Burks 2002a). Studies on similar mat-forming floating leaf vegetation have shown that submersed macrophyte growth beneath these mats is significantly reduced (Janes et al. 1996).

Despite prolific production of flowers, viable seeds are not produced. Reproduction and spread of the plant is facilitated via fragmentation, which can be caused by contact with boat motors, wave action, and mechanical harvesting (Burks 2002a). Spread is also facilitated through the production of clonal reproductive structures called ramets, commonly referred to as daughter plants, which develop beneath the floating leaves and protrude from the stems of the plant as a tuber cluster with several small leaves. These propagules easily separate from the parent plant and form new colonies or expand the parent colony (Burks 2002a).

In terms of potential management options, triploid grass carp (*Ctenopharyngodon idella*) did not consume this plant even when provided no other option (Van Dyke et al. 1984, Singh et al. 1966). Many lakes in Florida and other southeastern reservoirs are stocked with grass carp for hydrilla [*Hydrilla verticillata* (L.f.) Royle] control and these systems could create an environment where crested floating heart could thrive in areas previously dominated by hydrilla. For example, the Santee Cooper system is stocked with grass carp (109,000 in 2012 in addition to 750,000 previously stocked) to control hydrilla and many of these areas are now experiencing dense infestations of floating heart (C. Davis, pers. comm.). Drawdowns on Santee Cooper that exposed the plants to desiccation and potentially short-term freezing temperatures did not prevent recovery the following spring (Page 2010). Data from a study in India showed that crested floating heart was able to recover quickly from mechanical cutting (Middleton, 1990, Burks 2002a). At this point, no classical biological control organisms have been identified for crested floating heart.

Herbicides are the best current option for managing this species; however, herbicide activity is not well documented and reports from managers tend to be anecdotal and often conflicting. Current literature from Burks (2002b) states that a maximum of 4 mo of control has been achieved when using foliar applications of a 2% *N*-(phosphonomethyl)glycine (glyphosate) solution combined with (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid (imazapyr) (amount not stated) and a surfactant. Other research performed by Puri and Haller (2010) stated that 98 to 100% control was achieved with 6-wk static exposures to the dipotassium salt of 7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid (endothall). There are several published articles reporting herbicide efficacy on nymphaeid plants with similar morphology to crested floating heart (Seddon 1981, Baird et al. 1983, Hanlon and Haller 1990, Langeland et al. 1993, Skogerboe and Getsinger 2001, Glomski and Nelson 2008), which suggests that a broad array of herbicides should be evaluated for activity on crested floating heart. It has also been hypothesized that different herbicide formulations (e.g., liquid vs. granular) or methods of application (e.g., foliar vs. submersed) may also influence efficacy on floating leaf plants (Wersal and Madsen 2010).

The lack of published information for managing crested floating heart suggests that additional studies would be of value to aquatic managers. The objectives of this study were to comparatively evaluate selected aquatic herbicides for activity on crested floating heart, determine if method of application influences efficacy, and to determine if herbicide formulation has an influence on efficacy.

MATERIALS AND METHODS

Subsurface herbicide applications

Experiments were conducted at the University of Florida, Center for Aquatic and Invasive Plants in Gainesville, FL in 2011. Entire plants and ramets used for establishing the initial stock were collected in January 2011 from a canal near Storm Water Treatment Area 1 East in South Florida. Ramets were planted in 1-L plastic containers that were filled with Margo Professional Topsoil[1] (92% sand, 4% silt, 4% clay) amended with fertilizer (Osmocote® 15–9–12)[2] at 1g kg^{-1} of soil. Plants were cultured in 95-L tanks in a greenhouse from January 2011 until early March 2011, then moved into outdoor 1,000-L mesocosm tanks until ramets were produced. Ramets were collected from this culture and planted in 1-L pots filled with the previously described potting soil and fertilizer addition to conduct herbicide studies. After planting, ramets were transferred to 95-L tanks and allowed to grow until leaves emerged at the surface and flower production was observed. Herbicide application took place when flower production was observed on all plants. A pretreatment biomass sample was collected at the time of treatment. Herbicides applied subsurface were evaluated using liquid and granular formulations (Table 1). To evaluate the impact of herbicide exposure time, plants were exposed to all submersed treatments for periods of 24 and 96 h. Current literature suggests that, depending on the rate of water exchange and size of treatment area in relation to water body size and other characteristics in a natural system, the half-life of the herbicide concentration may range from as low as a few hours (Poovey et al. 2004) to as long as a few weeks (Simsiman and Chesters 1975, Langeland and Warner 1986,

TABLE 1. TREATMENT RESULTS COMPARED WITH UNTREATED CONTROL FOR SUBMERSED APPLICATIONS AT HIGHEST CONCENTRATION USED AND 96-H EXPOSURE[1].

Herbicide	Treatment method[2]	Concentration[3] mg L^{-1}	*P*-Value Study 1	Study 2
Triclopyr	S	2.5	0.987	0.051
2,4-D amine[4]	S	2.5	0.400	<0.001[5]
Endothall dipotassium[4]	S	3.0	< 0.001	0.136
Endothall amine[4]	S	0.5	< 0.001	0.001
Diquat	S	0.37	< 0.001	< 0.001
Flumioxazin	S	0.4	0.128	0.452
Carfentrazone	S	0.2	0.755	0.326
Bispyribac	S	0.03	0.061	0.176
Triclopyr	G	2.5	0.105	0.028[5]
2,4-D ester[4]	G	2.5	0.100	< 0.001[5]
Endothall dipotassium[4]	G	3.0	< 0.001	0.001
Endothall amine[4]	G	0.5	0.168	< 0.001

[1]Data only shown for highest evaluated concentration and 96-h exposure. In cases where the high concentration and exposure weren't effective, analysis found that the lower concentration and shorter exposures were also ineffective.
[2]Abbreviations: S = subsurface, G = granular.
[3]Concentration listed is highest concentration tested; all lower concentrations tested were 50% of this value. Carfentrazone and bispyribac were only tested at the concentration listed.
[4]Herbicide treatment concentration and rate are acid equivalence; all others are active ingredient.
[5]Significant *P*-values are due to treatment biomass being greater than the control.

Green et al. 1989). As a key objective of this screening was to evaluate comparative efficacy, we decided to focus on one short-term exposure time (24 h) and one moderate exposure (96 h) for submersed herbicide applications. All trials were conducted in 95-L tanks.

Herbicides were tested at concentrations near the maximum and half-maximum label rates. For the submersed applications we did not evaluate the herbicides 1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone (fluridone), 2-(2,2-difluoroethoxy)-*N*-(5,8-dimethoxy[1,2,4]-triazolo[1,5-*c*]pyrimidin-2-yl)-6-(trifluoromethyl)benzene-sulfonamide (penoxsulam), and 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid (imazamox) as part of this trial because of their requirement for a long-term aqueous exposure. Both imazamox and penoxsulam were evaluated as foliar applications (treatments described below). Two herbicides, X,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid (carfentrazone-ethyl) and 2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]benzoic acid (bispyribac-sodium), were tested only at the maximum label rate. Although bispyribac-sodium has an acetolactate synthase (ALS) mode of action and typically requires long-term exposures for submersed plant control, it was selected to be evaluated under these shorter-term exposures. Liquid herbicides were applied using an adjustable pipette and the water was gently stirred to enhance mixing. Granular herbicides were weighed to within ± 0.02 g needed to achieve the target concentration using a digital scale (Denver Instrument APX-203)[3], then dropped into the water over the root crown. Granules that remained atop surface leaves were placed back into the water. Water samples were collected 1 d after treatment from all treatments of (2,4-dichlorophenoxy)acetic acid (2,4-D) ester and amine, [(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid (triclopyr) amine, and both formulations of endothall, and analyzed using an enzyme-linked immunosorbent assay (ELISA) (SDIX RaPID Assay)[4] to confirm that nominal herbicide concentrations were achieved. A small electric pump was used 24 and 96 h after treatment (HAT) to remove the treated water from each tank and the tanks were refilled with untreated well water as described by Wersal and Madsen (2010). Visual observations of phytotoxicity were recorded weekly. The first trial for 2,4-D and triclopyr was initiated 17 June 2011 and repeated 12 July 2011. The first trial for endothall, diquat, and bispyribac was initiated on 7 July 2011 and repeated 5 August 2011. Trials using bispyribac-sodium, carfentrazone, and 2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propanyl)-2*H*-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1*H*-isoindole-1,3(2*H*)-dione (flumioxazin) were initiated on 24 June 2011 and repeated on 25 July 2011.

For each trial and herbicide evaluated, methods of harvest and data collected were consistent. Entire plants, including all live roots and foliage, were harvested 4 wk after treatment (WAT) and rinsed to remove algae, sediment, and dead tissue. Harvested plants were dried in a forced-air oven (76 C) for 1 wk. Treatment dry weight was compared with an untreated reference to determine percent control on the basis of mean dry weight.

TABLE 2. TREATMENT RESULTS COMPARED WITH UNTREATED CONTROL FOR FOLIAR HERBICIDE APPLICATIONS

Herbicide	Rate kg ha^{-1}	*P*-value Study 1	Study 2
Triclopyr	3.5	0.029[1]	0.748
2,4-D amine	2.2	0.700	0.039[1]
Endothall dipotassium	2.5	< 0.001	0.439
Diquat	2.2	< 0.001	0.001
Imazapyr	1.2	< 0.001	< 0.001
Imazamox	1.2	< 0.001	< 0.001
Penoxsulam	0.1	0.035	0.019
Glyphosate	2.4	0.669	0.454

[1]Significant *P*-values are due to treatment biomass being greater than the control.

Foliar herbicide application

Foliar applications were made using a CO_2-pressurized, single-nozzle spray system at the time of flowering. A spray volume equivalent to 934 L ha^{-1} (100 gal ac^{-1}) was used for all foliar treatments over an area of 0.185 m^2. Output pressure was regulated at 83 to 103 kPa, which allowed for a consistent spray with minimal misting of droplets. Foliar application use rates are listed in Table 2. Herbicides were applied with methylated seed-oil-type surfactant, except for glyphosate, which was used with a nonionic surfactant. All surfactants were applied at a rate of 0.25%. Tanks were drained 24 HAT following the foliar treatments and refilled with untreated well water to reduce confounding issues associated with herbicide concentrations remaining in the water column. Foliage was not rinsed during this process. Triclopyr, 2,4-D, 6,7-dihydrodipyrido[1,2-α:2′,1′-*c*]pyrazinediium ion (diquat), and endothall applications were performed at the same time as the respective submersed applications to allow for comparison by application method. The first trials for the amino acid-inhibiting herbicides were initiated on 21 June 2011 and repeated on 19 July 2011. Visual observations, harvest methods, and data collection followed the same procedure described previously for the submersed applications.

All studies were arranged in a complete randomized design with three replications of each treatment. Treatment effects on dry weight were analyzed using ANOVA ($P \leq 0.05$) with a post hoc Fisher's LSD test to compare treatments with the untreated control. Statistical analysis and graphical presentations of data were performed using SigmaPlot 11.0[5]. Data from each trial are reported separately for each herbicide tested.

RESULTS AND DISCUSSION

Subsurface herbicide application

Differences in activity were noted between herbicide active ingredients (Table 1). Only diquat and both formulations of endothall reduced crested floating heart biomass at the highest concentration tested after a 96-h exposure (Table 1, Figures 1 and 2). After the 24-h exposure, only plants treated with diquat and the amine salt of endothall at both tested concentrations reduced biomass compared with the untreated controls ($P < 0.001$). Diquat-treated plants rapidly developed symptoms. By 1 WAT, foliage was necrotic and stems had dropped away from the water surface; however, new leaves began to emerge by 2 WAT. During regrowth, this new foliage would become chlorotic, and then would either become necrotic or very slowly recover. Plants started to recover between 3 and 4 WAT, but regrowth remained limited, with some new foliage remaining chlorotic near the midvein of the leaf. The high water clarity associated with these applications (nephelometric turbidity units < 1) would strongly favor diquat activity in these trials. In field situations where higher turbidity is likely, the performance of diquat could be negatively affected due to the tendency of diquat to adsorb to inorganic suspended sediments (Hofstra et al. 2001; Poovey and Getsinger, 2002).

The amine salt formulation of endothall was the most effective liquid subsurface herbicide evaluated. These treatments resulted in 100% control in both trials at the rates tested for 24 and 96 HAT (Table 1; Figures 2A and 2B). Treated plants showed necrosis by 24 HAT. One WAT all plant material had dropped away from the water surface and by 4 WAT there was no observed regrowth. In this case, the granular applications of endothall were variable and less effective than liquid applications ($P \leq 0.001$) (Table 1). ELISAs indicated that endothall concentrations for both the granular and liquid treatments were within 10% of nominal treatment concentrations at 24 HAT.

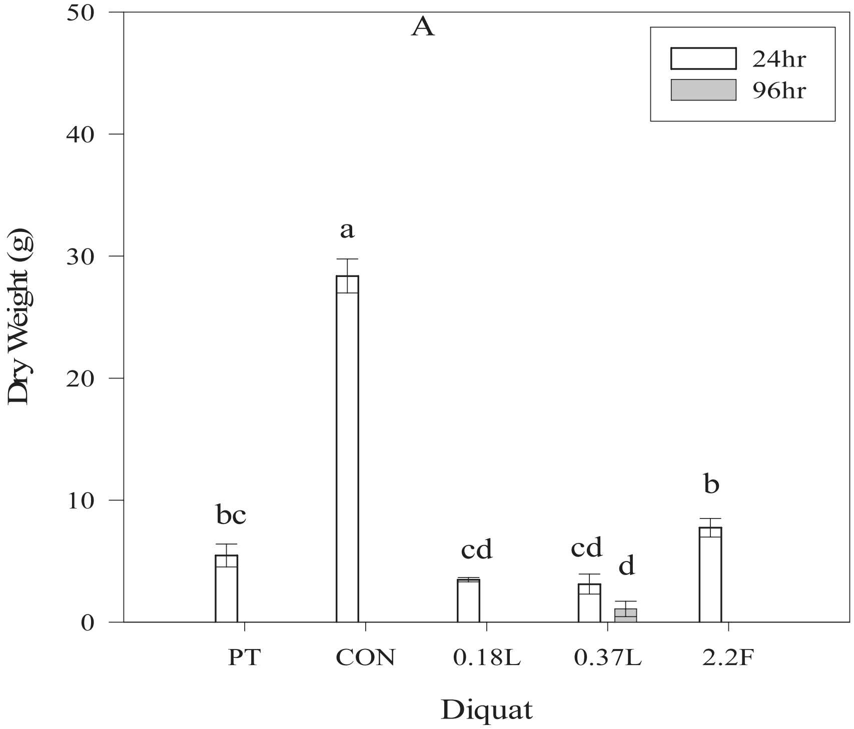
Given the shallow nature of our treatment tanks, granules were not highly concentrated near the basal portions of the plant at the label rates tested. These root crowns support multiple shoots and it has been speculated that granules may be more effective in deeper water where the total amount of granular product applied is greater and short-term herbicide concentrations are much higher near the basal crown of the plant. Additional trials would be necessary to test this hypothesis.

The dipotassium salt of endothall also resulted in variable control depending on application method. Symptoms developed slowly after treatment. One WAT isolated spots of foliar desiccation were observed. Two WAT foliage and stems began to show signs of necrosis and dropped off the water surface; however, regrowth began between 2 and 3 WAT. In the first trial, the highest rate of liquid herbicide resulted in 57% reduction in biomass compared with the untreated control; however, the remaining biomass was still greater than the pretreatment reference. Moreover, this treatment was not different from the untreated reference in the repeated trial. Granular applications resulted in 60 and 24% reductions in biomass from the untreated control in both trials after 96-h exposures (Figure 3). The granular applications of dipotassium endothall were more effective than the liquid in the second trial. The 24-h exposures were much less effective than 96-h exposures, with plants recovering quickly and resulting in greater biomass than the untreated control. Early research on crested floating heart showed that dipotassium endothall was most effective after static exposures and 98 to 100% control was achieved using rates of 1.5 and 2.5 mg ai L^{-1} respectively at 6 WAT (Puri and Haller 2010). This high percentage of control could be due more in part to the exposure time than to the herbicide concentration.

To address the discrepancies between the findings of Puri and Haller (2010) and the findings of the current endothall trials, an additional trial was initiated 5 August 2011 to assess the efficacy of dipotassium endothall at 4.3 mg ae L^{-1} under a 4-wk static exposure. Dry weight of the plant was reduced below the untreated control by 80 and 83% after liquid and granular treatments respectively; however, regrowth was observed beginning 3 WAT. On the basis of these results, control could potentially be increased in systems where extended exposure times are possible; however, the observations of regrowth indicate that crested floating heart may tolerate even extended exposures to the dipotassium salt of endothall.

Five compounds, triclopyr, 2,4-D, bispyribac-sodium, carfentrazone, and flumioxazin, resulted in no reduction compared with the untreated control (or in some cases an actual increase in biomass) at 4 WAT regardless of application method or exposure time (Tables 1 and 2). Although initial injury was often noted after application, there was no evidence of sustained herbicide injury at the time of harvest. ELISAs indicated that 2,4-D and triclopyr concentrations were within 10% of nominal treatment concentrations at 24 HAT after both liquid and granular applications.

For triclopyr and 2,4-D, auxin-mimic-type symptoms began to develop by 1 WAT, with noticeable epinasty of the stems, elongated flower stalks, and leaf curling. These symptoms were transient and did not persist; by 2 WAT and 3 WAT the plants had completely recovered (no visible symptoms). Typically, broad-leaved aquatic plants of similar morphology to crested floating heart are susceptible to auxin-mimic herbicides. Previous studies have found that subsurface applications of 2,4-D ester at 1.5 and 2.5 mg ae L^{-1} to fragrant waterlily (*Nymphaea odorata* Aiton) resulted in less dry weight than the untreated controls (Glomski and



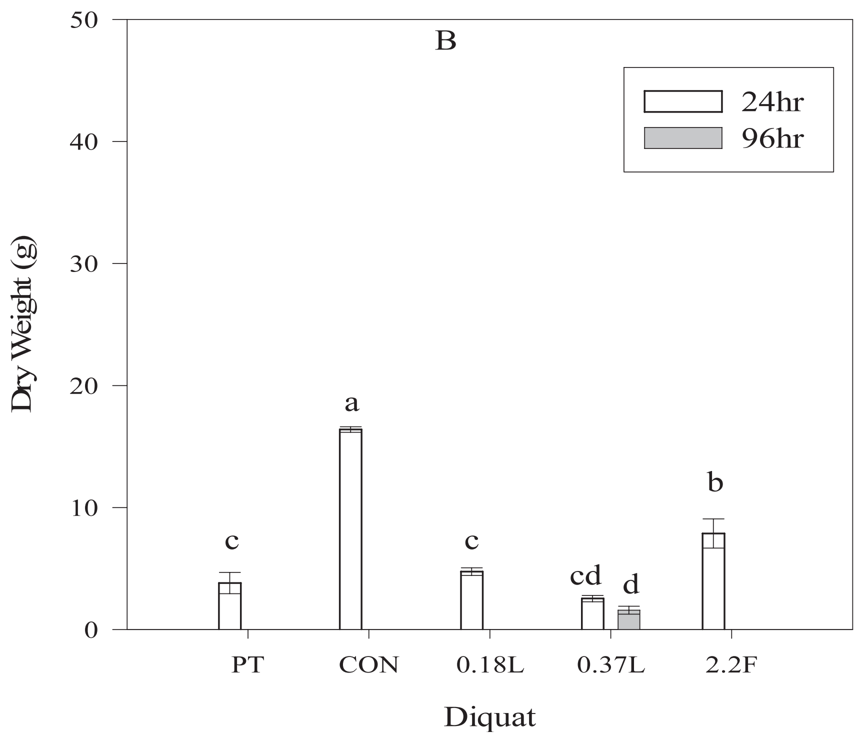


Figure 1. Combined dry weight of roots and foliage of crested floating heart 4 wk after treatment (WAT) in response to diquat at 24- and 96-h exposures in trial 1 (A) and in trial 2 (B). PT = pretreatment reference, CON = untreated control, L = liquid subsurface, and F = foliar rate in kg ae ha^{-1}. Liquid subsurface concentrations are in mg ai L^{-1}. Each bar represents the average of three replicates ± standard error.

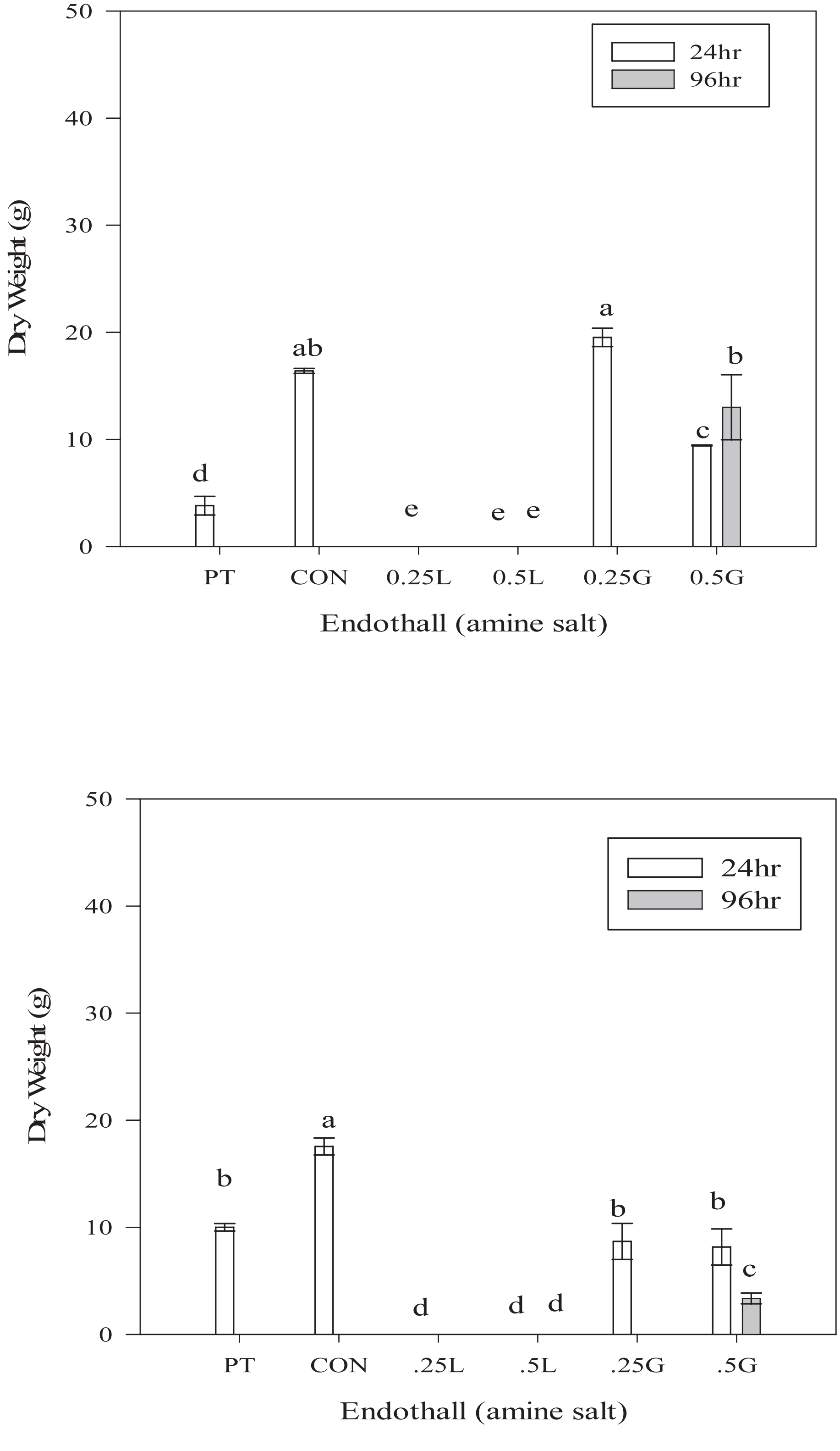


Figure 2. Combined dry weight of roots and foliage of crested floating heart 4 wk after treatment (WAT) in response to endothall (amine salt) for 24- and 96-h exposures in trial 1 (A) and in trial 2 (B). PT = pretreatment reference, CON = untreated control, L = liquid subsurface, G = granular subsurface. L and G subsurface concentrations are in mg ae L^{-1}. Each bar represents the average of three replicates ± standard error.

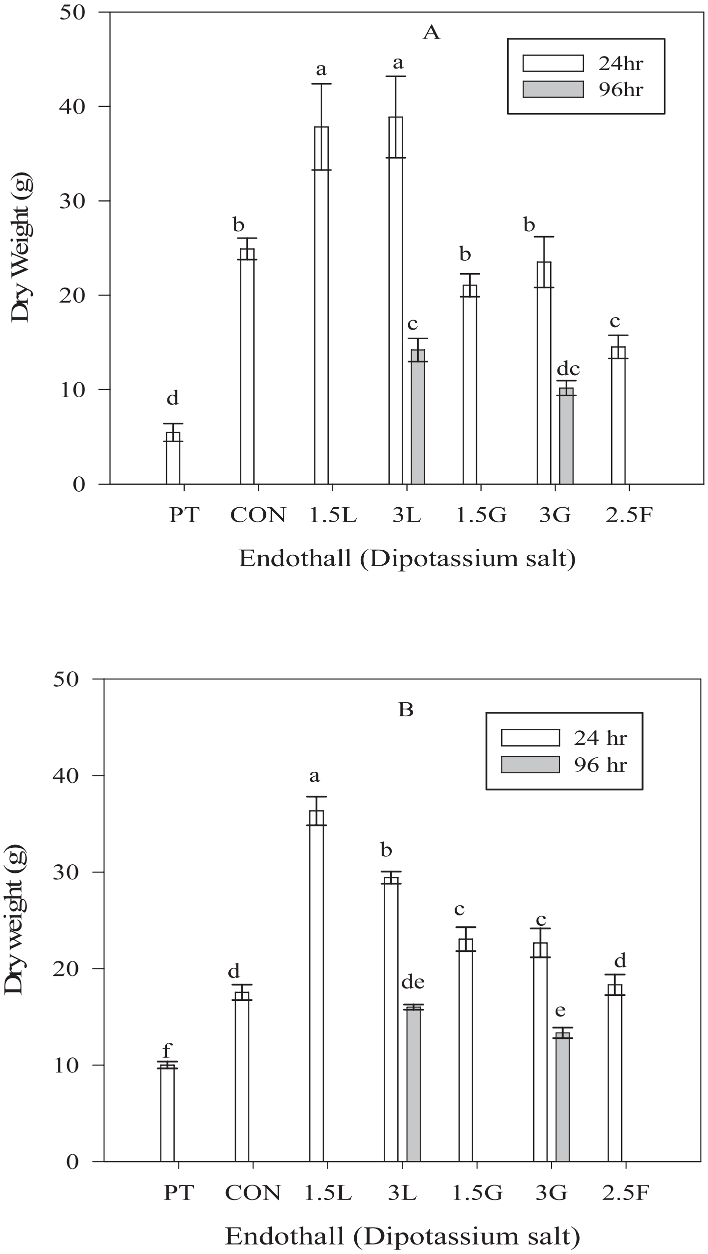


Figure 3. Combined dry weight of roots and foliage of crested floating heart 4 wk after treatment (WAT) in response to endothall (dipotassium salt) for 24- and 96-h exposures in trial 1 (A) and in trial 2 (B). PT = pretreatment reference, CON = untreated control, L = liquid subsurface, G = granular subsurface. L and G concentrations are in mg ae L^{-1}. Each bar represent the average of three replicates ± 1 standard error.

Nelson 2008). Spatterdock (*Nuphar advena* Aiton) dry weight was also reduced by the same rates of 2,4-D ester, as well as 2.0 mg ae L^{-1} triclopyr amine by 6 WAT (Glomski and Nelson 2008).

Symptoms were observed after the bispyribac exposures and flower production ceased at 1 WAT. By 2 WAT foliage began to turn red in color; however, plants quickly recovered and new growth was visible by 3 WAT. Bispyribac-sodium has been found to have activity on several emergent aquatic plants (Koschnick et al. 2007); however, extended exposure periods are usually needed. Under these short-term exposures, bispyribac resulted in initial injury symptoms, but rapid recovery.

Carfentrazone and flumioxazin are fast-acting protoporphyrinogen oxidase inhibitors that affect chlorophyll synthesis and cause cell membrane leakage in sensitive species (Senseman 2007). The pH of the water at the time of application was 6.8 and this should have provided in the range of a 24-h product half-life on the basis of estimation of pH-dependent hydrolysis. Neither of these herbicides reduced biomass below the untreated control by 4 WAT (Table 1). One WAT the foliage of the flumioxazin- and carfentrazone-treated plants had turned necrotic and had begun to drop away from the surface; however, rapid regrowth was observed 2 WAT. This result is in contrast to flumioxazin activity on several other nymphaeid species (e.g., American lotus, *Nuphar advena*, *Nymphaea odorata*) that have proven to be very sensitive to submersed applications of flumioxazin.

Foliar herbicide application

Foliar applications also resulted in strong differences in activity between herbicide active ingredients. The products diquat, imazapyr, and imazamox resulted in consistent biomass reduction after foliar treatment. Foliar applications of diquat resulted in 73 and 52% reductions in biomass below the control in trials 1 and 2 respectively (Table 2) (Figures 1A and 1B). Diquat-treated foliage died back from the surface quickly but began to recover within 2 WAT. Some of the foliage that reached the surface continued to show symptoms of chlorosis. A possible confounding factor regarding activity of diquat from a foliar application is the fact that aqueous concentrations resulting from treatment of shallow tanks resulted in nearly doubling the submersed label rate (0.65 mg ai L^{-1}) for a 24-h period. The combination of the rapid submersed activity of diquat and the near doubling of the label concentration in the water after a foliar application was unique to diquat. None of the other foliar-applied herbicides (auxin mimics, amino acid inhibitors) were subject to this potentially confounding issue.

Four amino acid-inhibiting herbicides were screened for foliar application (Table 2). Three of the herbicides (imazamox, imazapyr, and penoxsulam) are ALS inhibitors, whereas the fourth (glyphosate) is a 5-enolpyruvylshikimate-3-phosphate synthase inhibitor. Glyphosate was not different from the untreated control at 4 WAT. Imazamox and imazapyr resulted in 83 and 81% biomass reductions compared with the control, respectively (Figure 4). Penoxsulam also resulted in less biomass than the control, but was less effective than imazamox and imazapyr. The ALS herbicides resulted in cessation of growth by 1 WAT. Two WAT foliage from imazamox- and imazapyr-treated plants was not present on the surface, whereas foliage was still present on glyphosate- and penoxsulam-treated plants. No regrowth had occurred 4 WAT on imazamox- and imazapyr-treated plants, but the root systems were still intact upon harvesting. When penoxsulam-treated plants were harvested, it was noticed that even though shoot material was

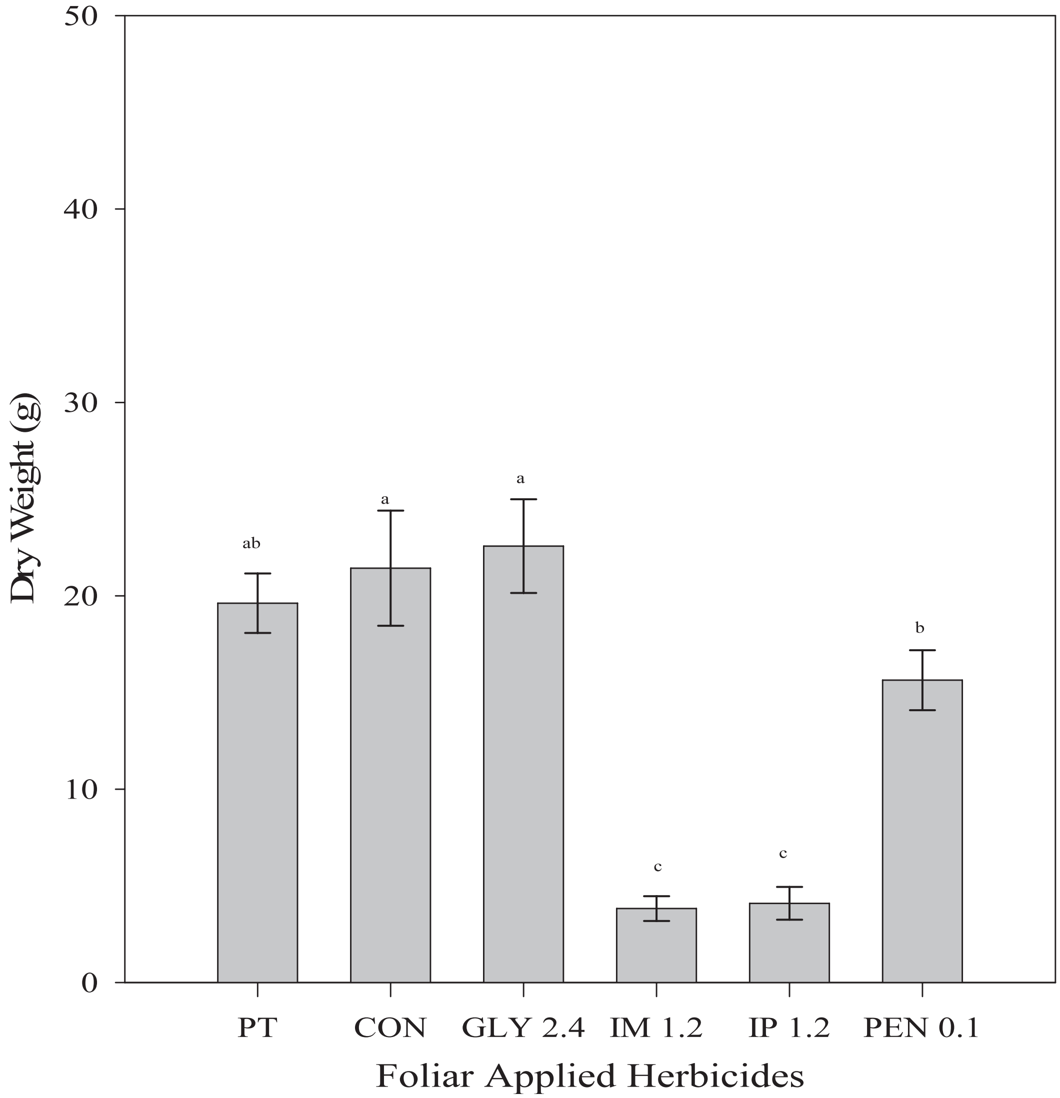


Figure 4. Combined dry weight of roots and foliage of crested floating heart 4 wk after treatment (WAT) in response to foliar-applied amino acid-inhibiting herbicides. PT = pretreatment reference. CON = untreated control. GLY = glyphosate, IM = imazamox, IP = imazapyr, PEN = penoxsulam. Numbers represent treatment rate in kg ai ha^{-1}. Each bar represents the average of three replicates ± standard error.

largely intact and green in color, the root system sustained severe damage with almost no viable root tissue recovered during the harvest. This observation suggests that further evaluation of foliar penoxsulam treatments is warranted.

Glyphosate-treated plants began to show signs of recovery 4 WAT with appearance of new flowers. The results for glyphosate were unexpected, as it is often suggested in crested floating heart control programs. Although we did not test the various surfactants available for aquatic applications, the general lack of activity in repeated trials would suggest that crested floating heart is not inherently sensitive to glyphosate. Other emergent plants such as fragrant waterlily and spatterdock are effectively controlled with glyphosate at rates of 2.5 kg ai ha^{-1}(Seddon 1981, Baird et al. 1983). Numerous applicators include glyphosate in combination with imazapyr as part of their current treatment regime for crested floating heart (Burks 2002b), but the results of this study show that glyphosate may have limited activity on this plant. Reported efficacy in the field with this combination suggests that further evaluation of herbicide combinations may be warranted.

Foliar applications of triclopyr and 2,4-D were ineffective (Table 2). Typical symptoms of these herbicides began to develop within 1 WAT but the plants quickly recovered by 2 WAT and continued growing until the study was harvested. Other studies examining effects of foliar applications have shown that rates of 2,4-D amine up to 4.48 kg ha^{-1} caused symptom development in spatterdock, but did not result in death of the plant tissue (Hanlon and Haller 1990). Waterlily has also been reported to be sensitive to triclopyr amine via foliar application, but no details were given pertaining to rates (Langeland et al. 1993, Glomski and Nelson 2008).

Dipotassium endothall applied to foliage resulted in symptom development of spotty foliar desiccation by

1 WAT, followed by quick recovery and emergence of new healthy leaves by 2 WAT. This treatment did not reduce biomass.

The screening of foliar-applied herbicides has identified imazamox and imazapyr as having good activity on crested floating heart. When making foliar applications of herbicides for crested floating heart, translocation likely plays a critical role in treatment efficacy. In the Santee Cooper system, it has been noted that posttreatment regrowth is slower at depths less than 1.5 m (C. Davis, pers. comm.). Furthermore, managers in South Florida have reported better control in shallower, quiescent areas (Burks 2002b). As a result of these observations, it is hypothesized that water depth may affect the ability of herbicides to translocate from foliage to roots (C. Davis, pers. comm.). The plant has been found to grow in up to 3 m of water. If water depth (stem length) has an impact on the ability of a herbicide to translocate, it may be difficult to control the root crowns of this plant in deep water when using foliar treatment strategies.

In-field observations have indicated that even the slightest water disturbance by wind, boat wake, etc. can result in the surface leaves of crested floating heart dipping momentarily below the water. This suggests that foliar applications may be subject to rapid wash-off. Although rainfastness is typically a consideration with emergent treatments, the somewhat unique tendency of crested floating heart leaves to dip below the water surface with limited disturbance could have a significant influence on emergent applications under sunny conditions. The plants treated in our tanks were not subject to potential wash-off from leaves dipping below the water surface.

On the basis of these evaluations, submersed applications of liquid endothall (amine salt) or diquat and foliar applications of imazamox or imazapyr had the most activity. There were few differences between liquid and granular formulations in the study system and results were variable. The findings of this study also suggest that in most cases foliar or subsurface applications have no strong influence on herbicide activity or efficacy. This result is similar to that reported by Wersal and Madsen (2010). It is important to note that not all treatment methods available were evaluated in this study. For example, using combinations of herbicides with different modes of action (e.g., diquat combined with dipotassium endothall) may increase activity. Moreover, we did not attempt to compare the vast range of surfactants available for foliar applications.

These small-scale trials can provide valuable information regarding the comparative activity of various herbicides on newly established crested floating heart. Subsequent field trials will help determine use patterns and optimal timing of various treatment strategies. These preliminary trials show that several of the herbicides can result in initial injury symptoms on crested floating heart; however, in many cases these plants rapidly recovered in our small-scale systems. The ability of larger and more robust field specimens to recover under less favorable environmental conditions (e.g., greater depth, turbidity, herbivory, etc.) remains difficult to predict using data from small-scale studies. Nonetheless, the results of these trials provide information for us to identify several products that are unlikely to provide a level of initial control or injury that would allow for environmental conditions to further reduce or limit growth of crested floating heart.

Management of crested floating heart will continue to remain a challenge because of the small number of herbicides that provide strong activity. The potential cost differential between submersed treatments and foliar applications will need to be weighed as managers evaluate product costs, application logistics, and treatment longevity. We did not evaluate the sensitivity of quiescent ramets, and the response of these propagules to submersed applications would be of significant interest to managers. The propensity of the surface leaves to dip below the water surface under minimal disturbance may create a unique challenge when using foliar applications to manage crested floating heart. The herbicides that have resulted in good efficacy during these trials are being further evaluated over a wider range of exposure times, concentrations, and environmental conditions to further develop an optimal treatment strategy.

SOURCES OF MATERIALS

[1]Margo Professional Topsoil, Margo Garden Products, Folkston, GA 31537.
[2]The Scotts Company, Marysville, OH 4304.
[3]Denver Instruments, Arvada, CO 80004.
[4]Strategic Diagnostics Inc., Newark, DE 19713.
[5]Systat Software Inc., San Jose, CA 95110,

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