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Efficacy of single and consecutive early-season diquat treatments on curlyleaf pondweed and associated aquatic macrophytes: A case study

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ABSTRACT

Curlyleaf pondweed (*Potamogeton crispus* L.) is an invasive aquatic macrophyte that impairs lakes throughout much of North America. Management of curlyleaf pondweed with herbicides is common with long-term control and protection of desirable native vegetation being important goals. The herbicide diquat was applied to Crystal Lake (Middletown, CT) in 2007, 2009, and 2010 to control curlyleaf pondweed prior to turion production. No herbicides were applied in 2006, 2008, or 2011. Two other invasive macrophytes, Eurasian watermilfoil (*Myriophyllum spicatum* L.) and brittleleaf naiad (*Najas minor* All.), were also present along with 14 species of native macrophytes. Aquatic vegetation surveys were performed to assess the efficacy of the single (1-yr) and consecutive (2-yr) diquat treatments on the invasive and native plant assemblages. The frequency of occurrence and abundance of curlyleaf pondweed were reduced to negligible levels in the treatment years. In the untreated year after a single treatment (2008), curlyleaf pondweed frequency was reduced slightly but the abundance was greater than in the year prior to treatment (2006). In the untreated year following two consecutive early-season diquat treatments (2011), the frequency of curlyleaf pondweed decreased by 30% and the abundance declined by 55% compared to the year prior to treatment (2006). After the first of the two consecutive years of diquat treatments (2009), Eurasian watermilfoil was eliminated. Both the frequency and abundance of brittleleaf naiad increased in the untreated years of 2008 and 2011. The response of native macrophytes to the diquat treatments was species-specific but overall native species richness was greater in years following the single and consecutive diquat treatments.

Key words: aquatic herbicide, aquatic plant management, Eurasian watermilfoil, invasive species, *Myriophyllum spicatum, Najas minor, Potamogeton crispus*.

INTRODUCTION

Curlyleaf pondweed (*Potamogeton crispus* L.) is a problematic invasive aquatic macrophyte found throughout most of North America (Stuckey 1979). In Connecticut, the plant is present in 21% of the lakes and ponds (Bugbee et al. 2012). The growth of curlyleaf pondweed peaks in late spring when the plant produces reproductive turions, rhizomes, and seeds (Nichols and Shaw 1986, Woolf 2009). Turions can survive in the hydrosoil for many years and when conditions are suitable produce new plants (Johnson et al. 2012). Information on the contribution of rhizomes to the survival and spread of curlyleaf pondweed is limited. The viability of seeds is thought to be less than 0.5% (Woolf and Madsen 2003) but under certain conditions seeds may be a source of new populations (Sastroutomo et al. 1979, Rogers and Breen 1980).

Curlyleaf pondweed has been effectively managed in treatment years with the herbicides diquat, endothall, and fluridone but such treatments have not provided sustained control in subsequent untreated years (Netherland et al. 2000, Poovey et al. 2002, Johnson et al. 2012). This is because the efficacy of herbicides on mature turions, rhizomes, and seeds is poor (Smith and Pullman 1997, Johnson et al. 2012) and long-term control cannot be obtained until these propagules are eliminated. The production of new turions and seeds may be controlled by applying herbicides early in the season prior to their formation (Netherland et al. 2000, Poovey et al. 2002, Johnson et al. 2012). In the absence of external propagule inputs, future populations of curlyleaf pondweed would need to come from the bank of old turions, rhizomes, and seeds present in the hydrosoil. Depleting this bank depends on how well the treatments control newly sprouted curlyleaf pondweed plants each year, the proportion of buried propagules that sprout each year, and the length of time propagules can remain viable in the hydrosoil.

Using herbicides without adversely affecting native macrophytes is important not only because of the benefits native plants provide the lake ecosystem but also because a robust native plant community may impart some resistance to invasion by nonnative species (Capers et al. 2007). If consecutive herbicide treatments are performed, reductions in native plant assemblages are possible but not assured as reduced competition from invasive macrophytes could favor native vegetation. In Minnesota, for instance, no substantial decline in native macrophyte assemblages were observed after four consecutive yearly curlyleaf pondweed herbicide treatments (Jones et al. 2012). One common method for reducing the risk of damage to native species is to limit the applications of herbicides to periods when the desirable vegetation is least vulnerable (Netherland et al.

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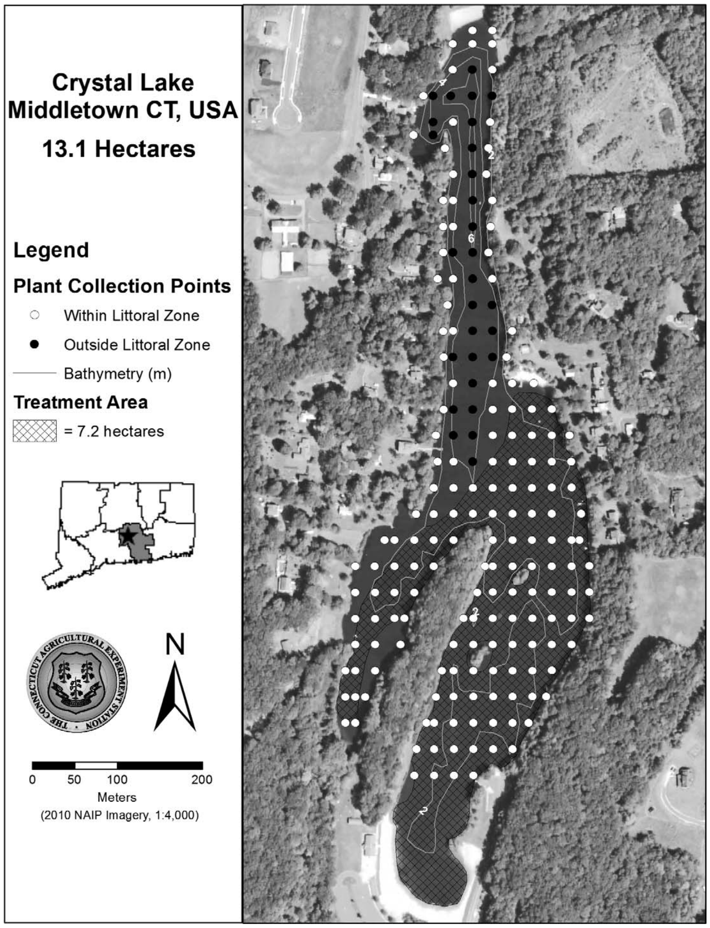

Figure 1. Plant sampling points, bathymetry, and treatment area in Crystal Lake, Middletown, CT. Solid white points are within the littoral zone and used for statistical analysis. White points with an X are not in the littoral zone and removed from statistical analysis. Crosshatching indicates area treated with diquat.

2000, Poovey et al. 2002). This strategy is particularly attractive for controlling curlyleaf pondweed because its peak period of growth and turion and seed production occurs before that of most native macrophytes (Bolduan et al. 1994).

Crystal Lake is a 13.1-ha man-made impoundment located in Middletown, CT (Figure 1). The southern half of the lake is generally less than 3 m deep and supports abundant stands of curlyleaf pondweed and other macrophytes, while the northern half is generally greater than 3 m deep and is sparsely vegetated (Jacobs and O'Donnell 2002). In the summertime, the lake has Secchi transparencies of 2 to 3 m and the surface water has dissolved oxygen of 7 to 10 mg L^{-1}, alkalinities of 25 to 45 mg L^{-1} $CaCO_3$, and total phosphorus of 9 to 36 μg L^{-1}. A summer thermocline develops at 2 to 5 m with the hypo-limnetic water typically having dissolved oxygen concentrations of 0 to 2 mg L^{-1}, alkalinities of 30 to 80 mg L^{-1} $CaCO_3$, and total phosphorus of 30 to 90 μg L^{-1} (CAES IAPP 2014, Robb et al. 2014). Dense stands of curlyleaf pondweed in the southern half of Crystal Lake reach the surface each spring, disrupting the native ecosystem and interfering with recreational activities. Other aquatic macrophytes in the lake include two invasive species, Eurasian watermilfoil (*Myriophyllum spicatum* L.) and brittleleaf naiad (*Najas minor* All.), and 14 native species (Table 1) (CAES IAPP 2014). In 2006, stakeholders decided that a herbicide treatment was needed. State permits were obtained for an application of diquat in 2007. Diquat is a herbicide that is effective for controlling curlyleaf pondweed in the spring when water temperatures are cool (Netherland et al. 2000, Poovey et al. 2002). In addition, it is a nonsystemic product with relatively short persistence (Funderburk and Lawrence 1964, Robb et al. 2014). These characteristics may make it particularly attractive for use in the early season, when protection of native species can be achieved. The following study explores the efficacy of single (1 yr) and consecutive (2 yr) early-season diquat applications on curlyleaf pondweed and associated invasive and native macrophytes.

MATERIALS AND METHODS

Diquat[1] was applied to the southern half of the lake at the maximum suggested label rate of 7.8 kg ai ha^{-1} (U.S. Environmental Protection Agency [USEPA] registration no. 100-1091) on 23 April 2007, 6 May 2009, and 30 April 2010. This equates to an active ingredient concentration (diquat cation) of 224 μg L^{-1} in the treatment area. A 1 : 1 ratio of diquat formulation : water was injected 0.5 m beneath the surface with a 95-L electric sprayer using a boat powered by an outboard motor. An onboard global positioning system[2] was used to assure the boat paths were approximately 15 m apart. Water temperatures were measured prior to each diquat application, 0.5 m below the surface, at 1-m depth intervals, and 0.5 m above the bottom (data not shown). Herbicides were not applied in 2006, 2008, or 2011. No herbicides were applied prior to 2006.

To determine if turions and seeds were present prior to each diquat application, curlyleaf pondweed plants were collected from four 2-m-deep sites within the treatment area by tossing a weighted 20-cm by 14-cm double-sided grapple with 11 tines per side. The grapple came into contact with the bottom for approximately 1 m per toss. All plants collected with the grapple were inspected. Not all of the plants were intact, so nine of the largest fully intact plants per site were separated and the presence or absence of new (current-year) turions, old (past years) turions, seeds, and rhizomes were recorded (Figure 2; Table 2). The length of each plant was measured to compare the plant maturity from year to year. In addition, the plant length documented if weed growth had "reached the water surface" and if subsurface injection with weighted hoses was necessary in accordance with diquat labeling (USEPA registration no. 100-1091).

To determine the efficacy of diquat on curlyleaf pondweed, yearly surveys were conducted during the period of peak growth in late May or early June, prior to the plant's natural senescence in early summer. To assess differences in the composition of the aquatic plant assemblages between treatment and nontreatment years, surveys were also conducted in late August or early September for all aquatic macrophytes. Plants were collected from 194 points that

Table 1. Aquatic macrophytes found in Crystal Lake on georeferenced points (○ = untreated years, ● = treated years). Invasive species in bold.

Common Name	Scientific Name	2006	**2007**	2008	**2009**	**2010**	2011
Curlyleaf pondweed	***Potamogeton crispus* L.**	○*		○	●		○
Eurasian watermilfoil	***Myriophyllum spicatum* L.**	○		○			
Brittleleaf naiad	***Najas minor* All.**	○	●	○	●	●	○
Coontail	*Ceratophyllum demersum* L.	○	●	○	●	●	○
Golden hedge-hyssop	*Gratiola aurea* Pursh	○	●	○	●	●	○
Marsh primrose-willow	*Ludwigia palustrus* (L.) Elliott		●				○
Needle spikerush	*Eleocharis acicularis* (L.) Roem. & Schult		●	○	●	●	○
Robbins pondweed	*Potamogeton robbinsii* Oakes	○	●	○	●	●	○
Slender naiad	*Najas flexilis* (Willd.) Rostk. & Schmidt	○	●	○	●	●	○
Small pondweed	*Potamogeton pusillus* L.		●	○	●	●	○
Snailseed pondweed	*Potamogeton bicupulatus* Fernald		●		●	●	○
Waterweed	*Elodea nuttallii* (Planch.) H. St. John	○	●	○			
White water lily	*Nymphaea odorata* Aiton					●	○
Invasive Species Richness	3**	3	1	3	2	1	2
Native Species Richness	10**	5	6	7	7	8	9
Total Species Richness	13**	8	7	10	9	9	11

*Curlyleaf pondweed- spring survey, Others - summer survey
**All years

were established with a global positioning system[3] at 1-s latitudinal and longitudinal intervals (approximately 25 m apart) throughout the lake. Points deeper than 4 m were outside the littoral zone (28 of the 194 points) and were not included in data analysis (Figure 1). Depth was measured at each point with a drop line and the bathymetry was interpolated using a geographic information system.[4] All plants and plant parts retrieved at each point were separated by species, dried at 70 C for 1 wk, and weighed. Surveys began in 2006, 1 yr prior to the first treatment. These surveys served as the control conditions to which the following years in this case study were compared (2007 to 2011).

The effects of the diquat treatments on each plant species were determined using the point intercept method from the georeferenced point data (Madsen 1999). Frequency of occurrence (hereafter referred to as frequency) was calculated by the percentage of sampled littoral zone points where each species was found. Species abundance was calculated as the mean dry weight of each species at all sampled littoral zone points. Multivariate ANOVA was used to evaluate if overall differences in plant assemblages were significant among years. ANOVA was used to determine if there were yearly differences for each species. If effects were significant ($P \leq 0.05$), years were compared using Tukey's honestly significant difference *post hoc* analysis. SYSTAT® software[5] was used for all statistical analyses.

RESULTS AND DISCUSSION

In the pretreatment year of 2006, the plant community of Crystal Lake was dominated by curlyleaf pondweed (84%

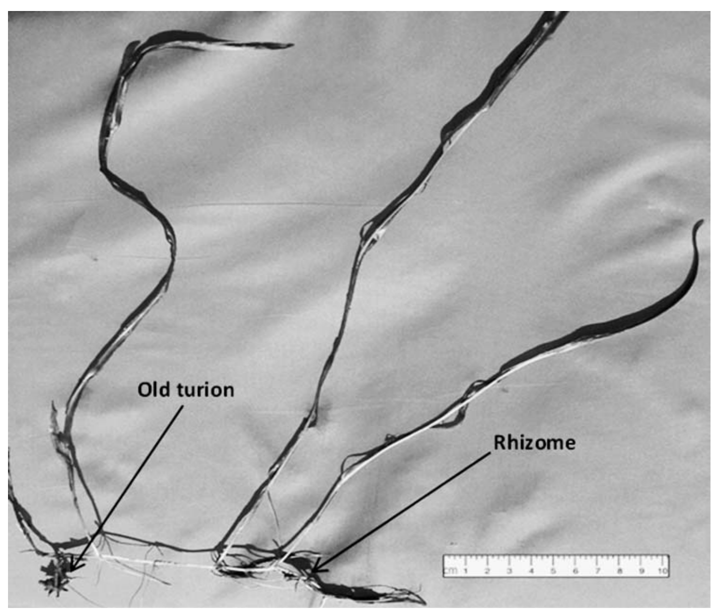

Figure 2. Curlyleaf pondweed harvested with a grapple. No new turions on stems but previous-year turion (bottom left) is attached to rhizome.

Table 2. Stem length (mean ± se) of curlyleaf pondweed and the presence of new (current-year) and old (previous-year) turions prior to treatment of Crystal Lake with diquat ($n = 36$).

Year	Stem length (cm)	Stems with new turions (%)	Stems growing from old turions (%)
2007	46 ± 8.2	0.0	30.6 ± 13.9
2009	121 ± 14.4	0.0	44.4 ± 7.9
2010	82 ± 3.7	0.0	0.0

frequency) and Eurasian watermilfoil (23% frequency) (Figure 3). Brittleleaf naiad also occurred in 2006, but its frequency was only 2%. In the treatment years of 2007, 2009, and 2010, the frequency of curlyleaf pondweed dropped to near zero, indicating the efficacy of the diquat treatment was high. In 2008, after a single-year treatment in 2007, the frequency of curlyleaf pondweed recovered to 68% but was still significantly lower than in 2006 (pretreatment). In 2011, after consecutive yearly treatments in 2009 and 2010, the frequency of curlyleaf pondweed was 59%. This was significantly less than 2006 (pretreatment) but not statistically different than 2008. In the treatment years of 2007 and 2009, 31% and 44% of the plants, respectively, were growing from old (previous-year) turions, but in 2010 (the second year of consecutive treatments) none were growing from old turions (Table 2). Johnson et al. (2012) found a similar drop-off in curlyleaf pondweed turions in the year after early-season herbicide applications. Curlyleaf pondweed turion longevity in hydrosoil needs additional documentation, but in Minnesota lakes, they are known to survive for over 5 yr (Johnson et al. 2012). No plants appeared to have propagated from seeds, but many plants were attached to rhizomes (Figure 2). If these rhizomes are perennial, they may promote regrowth in the year after treatment and account for the plants that were growing without attachment to old turions.

Inspection of curlyleaf pondweed plants prior to each treatment found no new (current-year) turions or seeds. This confirmed that treatments were performed prior to the formation of these propagules (Table 2) and regrowth in the following year could not be attributed to the treatment year's turions or seeds. The yearly mean length of curlyleaf pondweed plants ranged from 46 to 121 cm (Table 2) and in no years did the plants reach the surface prior to treatment; thus, subsurface injection with weighted hoses was not needed. A concern that early-season water temperatures would be cooler than optimal for diquat efficacy (< 10 C, Netherland et al. 2000) proved unfounded with water temperatures on treatment days ranging from 16 to 18 C near the surface and 15 to 16 C near the bottom (data not shown). Robb et al. (2014) provides additional information on the temporal and spatial changes in water chemistry and diquat concentrations that occurred during this study in 2010.

Prior to treatment in 2006, Eurasian watermilfoil had a frequency of 22% (Figure 2). In the summer after the first treatment in 2007, none was found. In the nontreatment year of 2008, Eurasian watermilfoil recovered slightly to a frequency of 2%; however, after the treatment in 2009 and

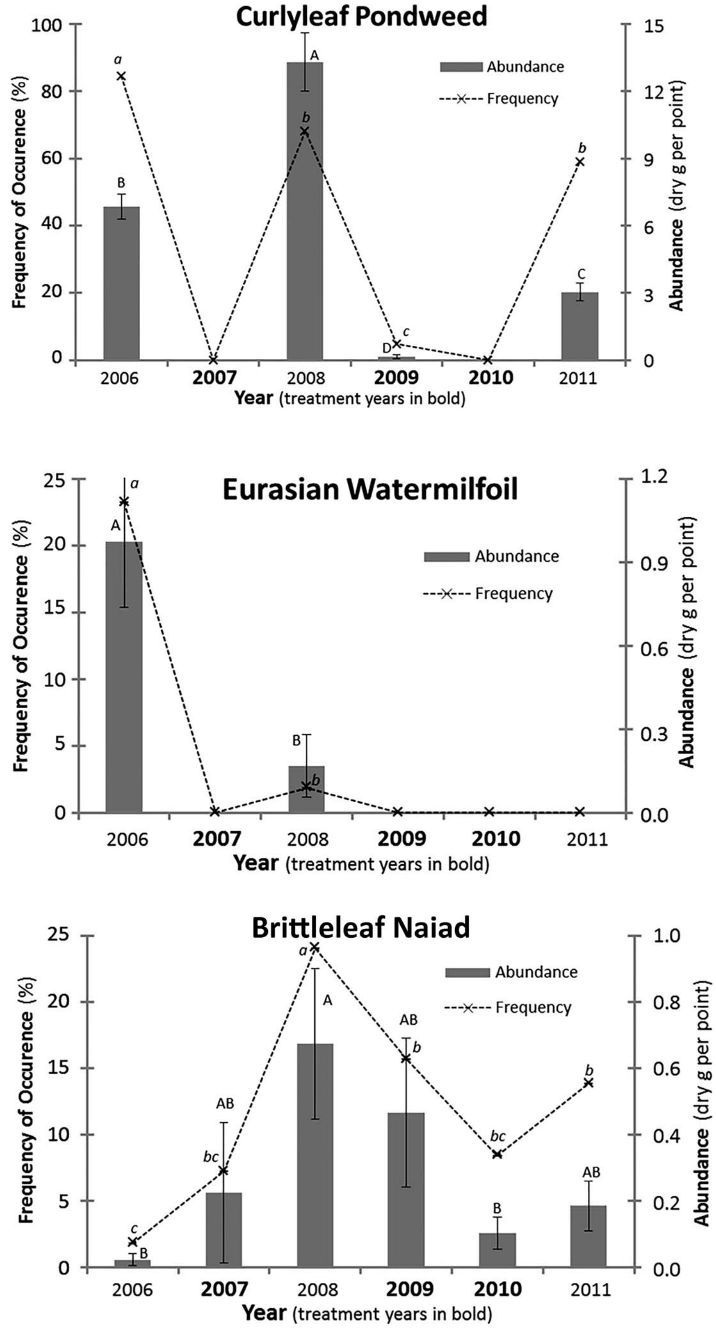

Figure 3. Frequency of occurrence (%) and abundance (dry g point^{-1}) of invasive species in Crystal Lake before and after single and consecutive diquat treatments. Years labeled in bold are treatment years. Error bars equal ± SE. Upper- and lowercase letters represent statistical differences ($P \leq 0.05$) among years detected by *post hoc* analyses for frequency and abundance, respectively.

in all following years it was not found. The complete disappearance of Eurasian watermilfoil in lakes is rare. The Connecticut Agricultural Experiment Station Invasive Aquatic Plant Program (CAES IAPP 2014) has conducted multiple-year surveys of 11 other Connecticut lakes containing Eurasian watermilfoil during the last decade and in no case has the species disappeared. Diquat should not directly harm the Eurasian watermilfoil root system and regrowth

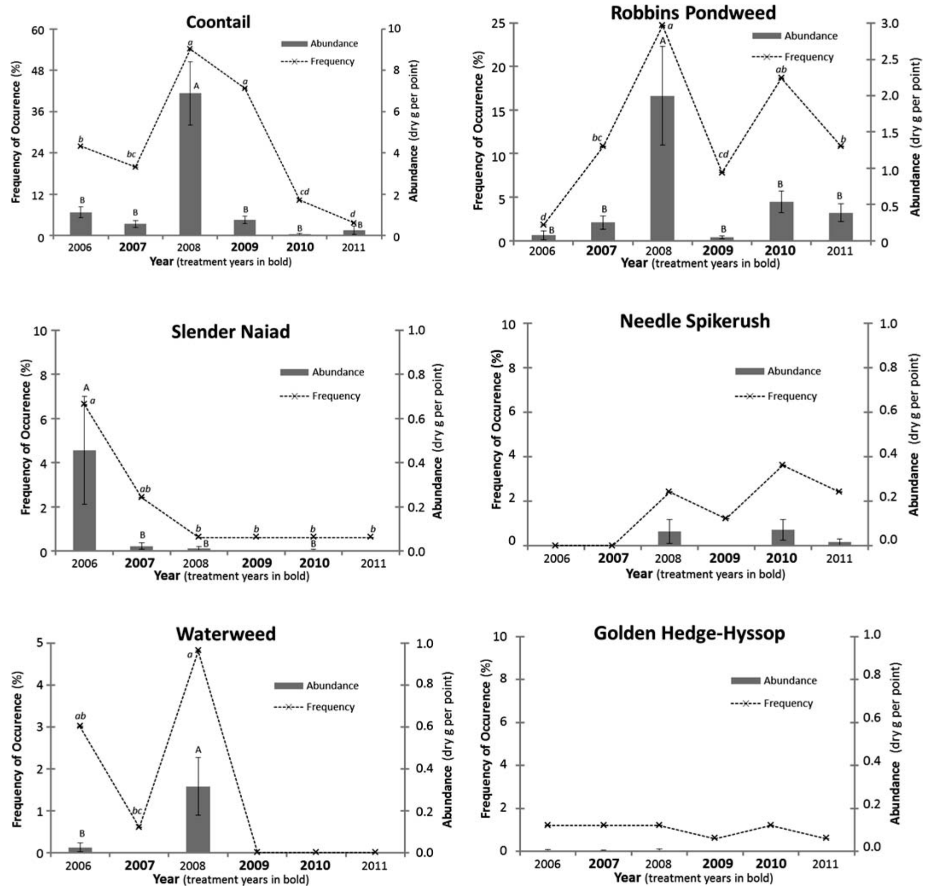

Figure 4. Frequency of occurrence (%) and abundance (dry g point^{-1}) of native species in Crystal Lake before and after single (1-yr) and consecutive (2-yr) diquat treatments. Years labeled in bold are treatment years. Error bars equal ± 1 SE. Upper- and lowercase letters represent statistical differences ($P \leq 0.05$) among years detected by *post hoc* analyses for frequency and abundance, respectively.

would be expected. Furthermore, less competition from curlyleaf pondweed could favor its regrowth. Diquat treatments to manage Eurasian watermilfoil usually occur later in the season than performed here and it is possible that the early-season growth of this species has a greater sensitivity to diquat. Another possible explanation is that Crystal Lake has known populations of milfoil weevils (*Euhrychiopsis lecontei* Dietz) (CAES IAPP, unpub. data). Reducing the Eurasian watermilfoil population with diquat could have exposed the remaining milfoil to increased predation by these or other biological control agents, causing a collapse similar to that in the Kawartha Lakes (Painter and McCabe 1988).

Brittleleaf naiad's frequency was 2% in 2006 (pretreatment) but increased significantly in all years except the treatment years of 2007 and 2010 (Figure 2). The frequency of brittleleaf naiad peaked at 24% in 2008 (untreated), following the single year of treatment in 2007. This represented a nearly 10-fold increase compared to pretreatment (2006). In 2010, after two consecutive yearly diquat treatments, the frequency of brittleleaf naiad was not statistically different than pretreatment (2006). In the untreated year of 2011, the frequency of brittleleaf naiad remained significantly greater than pretreatment but not different than 2010. This suggests that even consecutive early-season diquat treatments provide little control of brittleleaf naiad. Brittleleaf naiad is a prolific seed-producing annual (Haynes 1988) that may benefit from decreased competition resulting from the diquat treatments occurring prior to the germination of its seeds.

The abundance of curlyleaf pondweed was near zero in all treatment years, confirming the short-term efficacy of early-season diquat applications (Figure 2). In 2008, after the single-year treatment in 2007, the spring abundance of curlyleaf pondweed (13.3 dry g point^{-1}) was nearly double pretreatment 2006 levels (6.8 dry g point^{-1}). This may have been caused by a stimulation of the turion bank by the previous year's decrease in vegetative canopy and associated increase in light reaching old turions in the hydrosoil (Bolduan et al. 1994). In 2011, after two consecutive yearly treatments, the abundance of curlyleaf pondweed dropped to 3.0 dry g point^{-1}. This was its lowest abundance in any nontreatment year and coincided with reduced impairment of recreational activities.

The response of native aquatic macrophytes to the diquat treatments was species-specific (Figure 4). Five native species were found prior to treatment in 2006 (Table 1), with coontail (*Ceratophyllum demersum* L.) and slender naiad [*Najas flexilis* (Wild.) Rostk. & Schmidt.] having the highest frequencies (26% and 7%, respectively) (Figure 4). Robbins pondweed (*Potamogeton robbinsii* Oakes), western elodea

[*Elodea nuttallii* (Planch.) St. John], and golden hedge-hyssop (*Gratiola aurea* Pursh) were also present in the pretreatment year of 2006 but at frequencies of less than 3% (Figure 4). Coontail increased in frequency from 26% in 2006 (pretreatment) to 54% and 43% in 2008 and 2009, respectively. In 2010 and 2011 coontail frequencies declined to below the pretreatment (2006) levels. The frequency of slender naiad declined significantly in 2008 and never recovered. Robbins pondweed showed a large increase in frequency from 2% in the pretreatment year (2006) to 25% in the year after the single treatment (2008). In the year after the two consecutive yearly treatments (2011), the frequency of Robbins pondweed declined to 12%, which was significantly less than the high of 2008 but still greater than pretreatment (2006). From 2009 to 2011 western elodea was no longer found, suggesting that this species may be sensitive to consecutive yearly diquat treatments; however, the low pretreatment frequencies could also be susceptible to changes caused by natural population dynamics. Needle spikerush [*Eleocharis acicularis* (L.) Roem. & Schult.] and golden hedge-hyssop were rarely found and showed no change in frequency from year to year.

Native macrophyte abundance followed a pattern similar to frequency (Figure 4). The abundance of western elodea, coontail, and Robbins pondweed increased in 2008 after 1 yr of treatment but declined in 2011 after the consecutive treatments in 2009 and 2010. Spikes in the abundance of these plants in 2008 may have been due to decreased competition from curlyleaf pondweed and Eurasian watermilfoil or as a response to community disturbance. The reductions in 2011 may have been due to the cumulative effects on the consecutive treatments in previous years. Slender naiad was most abundant pretreatment and then declined to near zero. The abundances of needle spikerush and golden hedge-hyssop were limited and no yearly differences were found. Variability in weather between years could have influenced the structuring of the aquatic plant assemblages.

Invasive species richness (Table 1) decreased from three in 2006 to two in 2011 because of the elimination of Eurasian watermilfoil. Native species richness increased from a pretreatment level of five in 2006 to a posttreatment level of nine in 2011 (Table 1). The increase was due to the appearance of waterpurslane [*Ludwigia palustris* (L.) Elliot], needle spikerush, small pondweed (*Potamogeton pusillus* L.), snailseed pondweed (*Potamogeton bicupulatus* Fernald), and fragrant waterlily (*Nymphaea odorata* Aiton). Some of these plants may have been responding to open niches resulting from decreased competition from curlyleaf pondweed, aquatic plant community disturbance, or natural variations.

This study confirms that early-season diquat treatment provides excellent control of curlyleaf pondweed in the treatment year and prevents the formation of turions that can provide propagules in future years. If no treatments are made in the year following one yearly treatment, curlyleaf pondweed frequency may decrease but abundance can increase. This is probably due to decreased competition from cohabitating native vegetation that was adversely affected by the treatment. This study also finds that considerable regrowth of curlyleaf pondweed can occur the year following two consecutive treatments but the frequency and abundance can be significantly reduced from pretreatment conditions. Thus, more than two consecutive yearly early-season diquat treatments are needed to deplete the hydrosoil of the propagules capable of regenerating considerable populations of curlyleaf pondweed. Because work with endothall has found similar results (Johnson et al. 2012), diquat could be used as an alternative or in a rotation with this or other herbicides. Additional research is needed on turion and rhizome longevity. Early-season diquat treatments may significantly reduce cohabitating Eurasian watermilfoil while populations of seed-producing annuals, such as brittleleaf naiad, could expand. These results also suggest that populations of many native aquatic macrophytes will increase following a single yearly early-season diquat treatments but may decrease if used in consecutive years.

SOURCES OF MATERIALS

[1]Reward®, Syngenta Corp., 341 Silverside Road, Wilmington, DE 19810.

[2]ProXT®, Trimble Inc., 935 Stewart Dr., Sunnyvale, CA 94085.

[3]GPS76®, Garmin International Inc., 1200 E 151st St., Olathe, KS 66062.

[4]ArcGIS 3D Analyst®, ESRI Corp., 380 New York St., Redlands, CA 92373.

[5]SYSTAT 13®, Systat Software, Inc., 225 W. Washington St., Suite 425, Chicago, IL 60606.

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LITERATURE CITED

Bolduan BR, Van Eeckhout CG, Quade HW, Gannon JE. 1994. *Potamogeton crispus*—The other invader. Lake Reserv. Manag. 10:113–125.

Bugbee GJ, Barton ME, Gibbons JA. 2012. Connecticut's Invasive Aquatic and Wetland Plants Identification Guide. 2nd ed. The Connecticut Agricultural Experiment Station. Bull. 1035. 42 pp.

[CAES IAPP] Connecticut Agricultural Experiment Station Invasive Aquatic Plant Program. 2014. The Connecticut Agricultural Experiment Station Invasive Aquatic Plant Program (CAES IAPP). http://www.ct.gov/caes/iapp. Accessed June 3, 2014.

Capers RS, Selsky R, Bugbee GJ, White J. 2007. Aquatic plant community invasibility and scale-dependent patterns in native and invasive species richness. Ecology 88:3135–3143.

Funderburk HH, Jr, Lawrence JM. 1964. Mode of action and metabolism of diquat and Paraquat. Weeds, 12:259–264.

Haynes RH. 1988. Reproductive biology of selected aquatic plants. Ann. Missouri Bot. Gard. 75:805–810

Jacobs RP, O'Donnell EB. 2002. A Fisheries Guide to Lakes and Ponds of Connecticut. Connecticut Department of Environmental Protection. Bulletin 35. Hartford, CT. 354 pp.

Johnson JA, Jones AR, Newman RM. 2012. Evaluation of lakewide early season herbicide treatments for controlling invasive curlyleaf pondweed (*Potamogeton crispus*) in Minnesota lakes. Lake Reserv. Manag. 28:346–363.

Jones AR, Johnson JA, Newman RM. 2012. Effects of repeated, early season, herbicide treatments of curlyleaf pondweed on native macrophyte assemblages in Minnesota lakes. Lake Reserv. Manag. 28:364–374.

Madsen, JD. 1999. Point Intercept and Line Intercept Methods for Aquatic Plant Management. U.S. Army Corps of Engineers Aquatic Plant Management Note MI-02. 11 pp.

Netherland MD, Skogerboe JD, Owens CS, Madsen JD. 2000. Influence of water temperature on the efficacy of diquat and endothall versus curlyleaf pondweed. J. Aquat. Plant Manag. 38:25–32.

Nichols SA, Shaw BH. 1986. Ecological life histories of the three aquatic nuisance plants. *Myriophyllum spicatum*, *Potamogeton crispus* and *Elodea canadensis*. Hydrobiologia. 131:3–21.

Painter DS, Mccabe KJ. 1988. Investigation into the disappearance of Eurasian watermilfoil from the Kawartha Lakes. J. Aquat. Plant Manag. 26:3–12.

Poovey AG, Skogerboe JG, Owens CS. 2002. Spring treatments of diquat and endothall for curlyleaf pondweed control. J. Aquat. Plant Manag. 40:63–67.

Robb CS, Eitzer BD, Gibbons JA, June-Wells M, Bugbee GJ. 2014. Persistence and movement of diquat and the effectiveness of limnobarriers after curlyleaf pondweed treatment in Crystal Lake, CT. J. Aquat. Plant Manag. 52:39–46.

Rogers KH, Breen CM. 1980. Growth and reproduction of *Potamogeton crispus* in a South African lake. Ecology 68:561–571.

Sastroutomo SS, Ikusima I, Numata M, Iizumi S. 1979. The importance of turions in the propagation of pondweed (*Potamogeton crispus* L.). Ecol. Rev. 19:75–88.

Smith CS, Pullman GD. 1997. Experiences using Sonar A.S. aquatic herbicide in Michigan. Lake Reserv. Manag.13:338–346.

Stuckey RL. 1979. Distributional history of *Potamogeton crispus* (curly pondweed) in North America. Bartonia 46:22–42.

Woolf T. 2009. Curlyleaf pondweed, pp. 125–128. In: Gettys LA, Haler TH, Bellaud M (*eds*.). Biology and control of aquatic plants- A best management practices handbook. Aquatic Ecosystem Restoration Foundation, Marietta, GA.

Woolf TE, Madsen JD. 2003. Seasonal biomass and carbohydrate allocation patterns in southern Minnesota curlyleaf pondweed populations. J. Aquat. Plant Manag. 41:113–118.