ERDC/TN APCRP-CC-05
October 2006

Selective Control of Eurasian Watermilfoil and Curlyleaf Pondweed Using Low Doses of Endothall Combined with 2,4-D

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PURPOSE: This study was designed to evaluate early spring applications of low doses of endothall (1 mg/L ai) combined with 2,4-D (0.5 mg/L ai) to selectively control the invasive species curlyleaf pondweed (*Potamogeton crispus* L) and Eurasian watermilfoil (*Myriophyllum spicatum* L) in Minnesota lakes.

BACKGROUND: Invasive submersed plants form dense canopies on the surface of water bodies which can adversely affect navigation, recreation, and water quality. These canopies reduce dissolved oxygen, increase water temperatures, and inhibit light penetration required for native plant growth (Bowes et al. 1979, Honnell et al. 1993). Selective removal of these exotic plants can improve recreational use of the lake, stabilize water quality, and increase native plant diversity (Getsinger et al. 1997). The potential for restoration of native aquatic plant communities has been documented by numerous small-scale research studies (Netherland et al. 1997, Sprecher et al. 1998, Skogerboe and Getsinger 2001, Skogerboe and Getsinger 2002, Poovey et al. 2002) and field demonstrations (Madsen et al. 2002, Poovey et al. 2004). Successful use of aquatic herbicides for selective control of submersed weeds can vary depending on composition of native plant communities, and unintended consequences may result when the wrong herbicide is selected for a particular situation.

The dipotassium salt of endothall (7-oxabicyclo[2.2.1]heptane-2-3dicarboxylic acid) may be applied as either a liquid or granular formulation. The mode of action for endothall is uncertain, and has been described as a broad spectrum contact-type, membrane-active herbicide (Ashton and Crafts 1981). Some have shown that endothall may be slowly taken up by submersed weeds (Haller and Sutton 1973, Reinert and Rogers 1986, Van and Conant 1988), while others have reported that endothall may cause rapid membrane disruption in plant cells, while inhibiting oxygen consumption (MacDonald et al. 1993).

Endothall can effectively control of a wide range of aquatic plants, including monocotyledons (monocots) and dicotyledons (dicots) (Westerdahl and Getsinger 1988, Madsen 1997a). This herbicide is effective at controlling Eurasian watermilfoil at 2 to 3 mg/L ai (maximum label rate = 5 mg/L ai) where exposure times of 18 to 72 hr are maintained (Netherland et al. 1991). Native aquatic plant sensitivity varies greatly among species (Skogerboe and Getsinger 2001, 2002). Eurasian watermilfoil and pondweeds such as curlyleaf pondweed, Illinois pondweed (*Potamogeton illinoensis* Morong.), southern naiad [*Najas guadalupensis* (Sprengel) Magnus] and sago pondweed (*Stukenia pectinata* L.) are very sensitive to endothall, while coontail (*Ceratophyllum demersum* L.) is moderately sensitive. Other plants such as elodea (*Elodea canadensis* Michx), wildcelery (*Vallisneria americana* L.), water stargrass [*Zosterella dubia* (Jacq.) MacM.], and many floating-leaf and emergent species are more tolerant of endothall. Endothall therefore has the potential to selectively control Eurasian watermilfoil and/or curlyleaf pondweed in sites where pondweeds do not dominate the plant community.

The herbicide 2,4-D (2,4-dichlorophenoxyacetic acid) is applied as a butoxethyl ester or a dimethylamine salt formulation. The product is a systemic growth regulator with hormone-like activity. It readily stimulates cell division, resulting in necrosis of apical growth and eventually total cell disruption and plant death. Generally, dicots such as Eurasian watermilfoil are sensitive to 2,4-D and are controlled with applications of 2 to 4 mg/L ai (maximum label rate = 4 mg/L ai), while monocots such as curlyleaf pondweed are not. In the northern United States, the ester is applied as a granule for control of Eurasian watermilfoil and the salt is typically applied as a liquid for control of floating leaf plants.

Variable control of Eurasian watermilfoil using 2,4-D has been reported (Elliston and Steward 1972, Lim and Lozoway 1976, Hoeppel and Westerdahl 1983); however good control of that plant was achieved when 2,4-D exposure times exceeded 24 hr (Green and Westerdahl 1990). Because 2,4-D is specific to dicots, it can frequently be used for selective control of Eurasian watermilfoil, where native plant populations are dominated by monocots such as wildcelery, elodea, and pondweeds including *Potamogeton, Stukenia, and Zannichellia spp*. In situations where dicots are abundant in submersed plant communities, selectivity of 2,4-D may be greatly limited.

Both curlyleaf pondweed and Eurasian watermilfoil may remain viable through the winter and continue to photosynthesize even under ice cover. Following ice-out (late winter - early spring) both species begin accelerated growth under low light, and form dense surface canopies that can limit light penetration needed by the later emerging native species (Wehrmeister and Stuckey 1992). Applying herbicides in early spring can potentially increase their selectivity by targeting curlyleaf pondweed and Eurasian watermilfoil at a time when these species are actively growing and when many native species remain dormant (Netherland et al. 2000). In addition, invasive species have low carbohydrate reserves in early spring (Madsen 1997b, Woolf and Madsen 2003) and may be more sensitive to lower doses of herbicides at this time. Endothall has been shown to effectively control curlyleaf pondweed at water temperatures of 15^{o}C, when exposure times of 24 to 72 hr were maintained (Poovey et al. 2002).

Herbicides applied in combination are frequently used in agriculture to improve efficacy on target plants to provide more cost-effective control. Previous research indicated that diquat applied in combination with copper significantly increased plant uptake of both herbicides compared to either herbicide applied alone (Mackenzie and Hall 1967, Sutton et al. 1970, Sutton et al. 1972). Others showed that endothall combined with copper or diquat applied at low concentrations could significantly increase control of hydrilla and reduce regrowth (Pennington et al. 2001, Skogerboe et al. 2004). Endothall combined with 2,4-D at low concentrations (1 mg/L ai endothall + 0.5 mg/L 2,4-D) improved control of Eurasian watermilfoil under aquarium scale evaluations (author's unpublished data 2002). This combination may therefore provide improved selective control of two exotic species, including a monocot (curlyleaf pondweed) and a dicot (Eurasian watermilfoil), in a single treatment event. Such single applications could result in reduced environmental loading of herbicides to aquatic sites, and savings in manpower and costs. Improved selectivity, particularly with respect to native dicots, could allow the herbicide combination to be used in plant communities where species of environmental concern, such as water lilies (*Nuphar* spp. of *Nymphaea* spp.) or native milfoils (*Myriophyllum* spp.), occur.

MATERIALS AND METHODS: In spring 2003, four lakes (Auburn, Pierson, Bush, and Zumbra) were selected in cooperation with the Minnesota Department of Natural Resources (MNDNR) for use in this evaluation. Selection criteria included: 1) lakes approximately 50 to 100 hectares (125 to 250 acres) in size, and similar in shape, depth, overall submersed plant coverage, and fish populations (evaluated in a companion study, but not reported here), and 2) lakes with a large percentage of the littoral zones occupied by the invasive plants Eurasian watermilfoil and curlyleaf pondweed. Using these criteria, Auburn and Pierson were used for untreated reference lakes and Bush and Zumbra were designated as herbicide treated lakes. All of these lakes are within the Minneapolis/St. Paul, MN, metropolitan area and serve as recreational resources for local residents.

Assessment of Plant Communities. Plant species diversity was evaluated using a quantitative point intercept method (Madsen 1999). A 50-m by 50-m grid was developed for each lake using Garmin MapSource United States Topographic software and downloaded to a Garmin global positioning system (GPS) accurate to 4 m. At each sample point, a double rake head attached to a rope was thrown twice, approximately 3-6 m away from the boat, and dragged along the bottom back to the boat. Plants contained on the rake head from each throw were identified to species, and plants that could be visually identified below the water from the boat were also identified to species.

Percent occurrence of plant species was calculated by dividing the number of points where a particular species was present by the total number of sample points in the littoral zone. The littoral zone was defined as a depth $\leq$ 4.5 m, the depth used by MNDNR for operational plant control practices. Post-treatment data were compared to pretreatment data using Chi Square ($p \leq 0.05$). Total number of species per sample point in the littoral zone, and total number of native plant species per sample point in the littoral zone were calculated, and post-treatment data were compared to pretreatment data using analysis of variance (ANOVA).

Relative plant abundance was evaluated by randomly selecting 30 to 35 sample points from species diversity evaluations and quantifying the amount of plant material retrieved from each point. Samples were collected using a 36-cm-wide rake attached to a 3-m pole. At each sample point, the rake was lowered from the boat perpendicular to the bottom and then raised up to the water surface while slowly being twisted in a clockwise direction. Plant species from each sample were separated and oven-dried to a constant weight. Data were log transformed to preserve the assumptions of normality and equal variance, and post-treatment data were compared to pretreatment data using ANOVA.

Pretreatment plant evaluations (species diversity and plant abundance) were conducted from 10 to 30 June and from 15 to 31 August 2003 on all lakes, and in mid-April 2004 on herbicide-treated lakes (Bush and Zumbra) prior to chemical applications. Post-treatment plant evaluations were conducted during the same periods in June and August of 2004 on all lakes.

Herbicide Applications. Based on pretreatment plant evaluations, Bush and Zumbra lakes were divided into herbicide treatment zones consisting of separate blocks and narrow strips (Figures 1 and 2). Blocks containing Eurasian watermilfoil and curlyleaf pondweed ranged from 5 to 11.3 ha in size and were treated with liquid herbicide formulations, since effective exposure times could be maintained in these areas. However, the narrow strips were ~ 15 m wide and up to 100 m long (1 to 6.4 ha in size), and were located in areas parallel to the shoreline where water depth increased quickly and vegetation extended only 15 m out from the bank. These narrow plant stands, containing Eurasian watermilfoil and curlyleaf pondweed, required the use of a granular herbicide formulation in order to maintain adequate exposure times in the treatment zones.

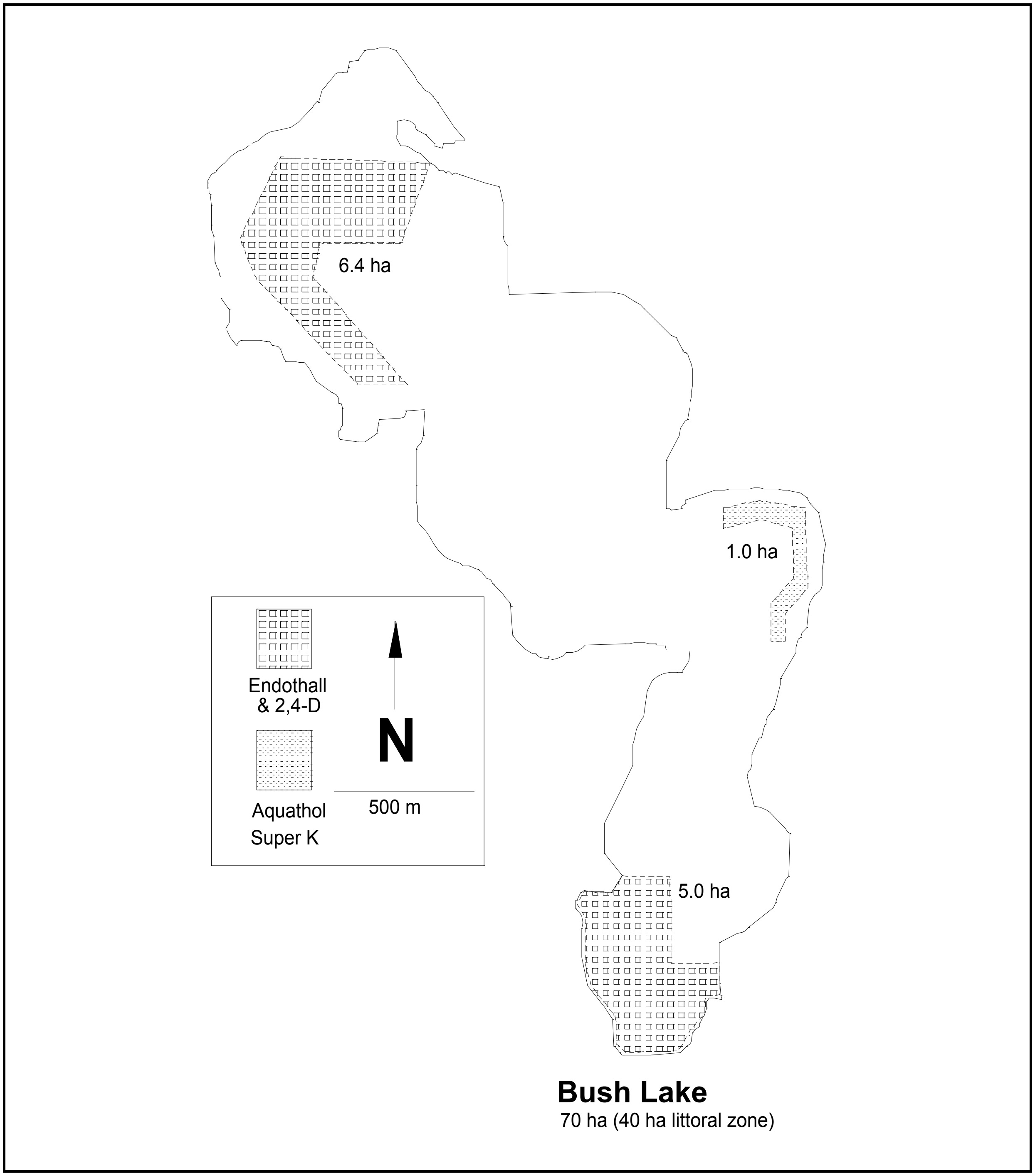

Figure 1. Bush Lake herbicide treatments.

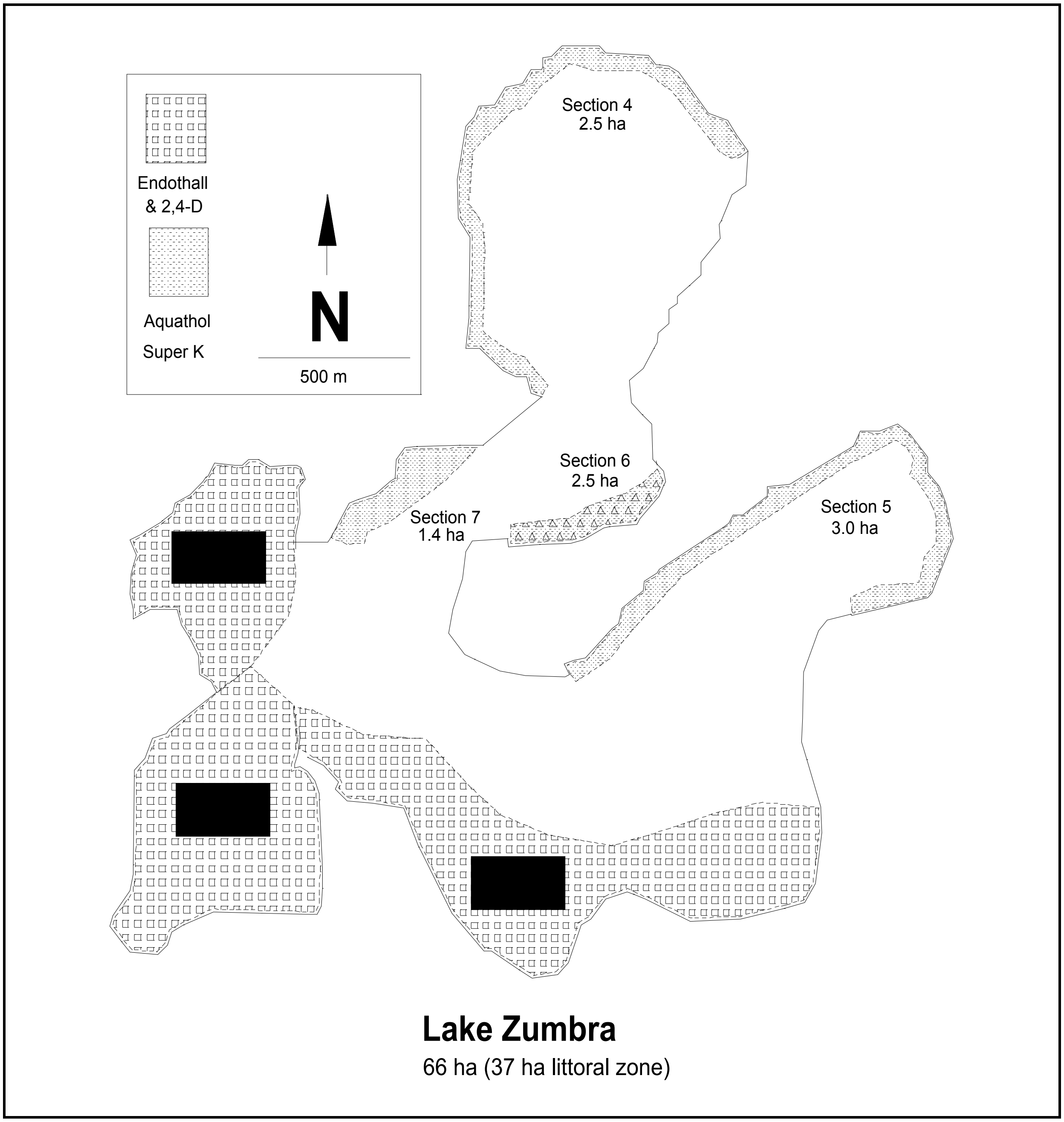

Figure 2. Lake Zumbra herbicide treatments.

Blocks were treated with a liquid formulation of endothall (Aquathol® K, Cerexagri, King of Prussia, PA) at 1 mg/L endothall, and with a liquid formulation of 2,4-D (DMA 4 IVM®, Dow AgroSciences, Indianapolis, IN) at 0.5 mg/L 2,4-D using a dual tank injection system with 3-m drop hoses mounted on the stern of a boat. To avoid compatibility issues, herbicide concentrates were not directly mixed, and were kept in separate tanks. The narrow strips were treated with a granular formulation of endothall (Aquathol Super® K, Cerexagri, King of Prussia, PA) at 1.5 mg/L endothall. This granular formulation was applied using an electric cyclone fertilizer spreader mounted on the bow of a boat.

Herbicides were applied to the treatment zones in Bush Lake on 23 April 2004. Winds were light (8-9.5 kph) from the south and water temperature was 14.8 °C. Treatment zones consisted of two separate blocks (6.4 and 4.8 ha) and one narrow strip (1 ha). The total treated area comprised 27 percent of the littoral zone and 18 percent of the entire lake.

Herbicides were applied to the treatment zones on Zumbra Lake on 1 May 2004. Winds were light (6.5-8 kph) from the south and water temperature was 15.5 °C. Treatment zones consisted of three separate blocks (11.3, 8.9, and 7.7 ha) and four narrow strips (2.8, 2.4, 1.4, and 1.2 ha). The total treated area comprised 91 percent of the littoral zone and 52 percent of the entire lake.

Water Clarity. Secchi disk data were collected by the Citizens Lake Monitoring Program for Pierson and Bush lakes, and by the Three Rivers Park District for Auburn and Zumbra lakes. Secchi disk data included pretreatment data from 1999 to 2003 and one year of post-treatment data (2004).

RESULTS AND DISCUSSION: Table 1 is an overview of the size, littoral zone, and plant community for the four study lakes. Lakes ranged in size from 37 to 106 ha, and littoral zones ranged from 50 to 66 percent of the respective lake areas. Eurasian watermilfoil had formed nuisance-level surface canopies over large areas in all lakes, with portions of the littoral zones infested with that plant ranging from 36 to 80 percent. Portions of the littoral zones occupied by curlyleaf pondweed ranged from 8 to 37 percent, but this amount of coverage was not considered a nuisance level.

Table 1
Characteristics of study lakes in June 2003

Lake	Lake Area (ha)	Littoral Zone (ha)	% Littoral Zone	% Native Plants[1]	% Eurasian Watermilfoil[1]	% Curlyleaf Pondweed[1]
Auburn	106	64	61	89	77	8
Bush	70	46	66	91	36	24
Pierson	95	48	50	73	62	25
Zumbra	66	37	57	90	80	37

[1] Number represents the percentage of the littoral zone where the plant occurred.

While variations in plant species occurrence and abundance were expected in lakes subjected to herbicide treatments, variations in plant community structure also occurred in the untreated reference lakes. Variations in species occurrence and abundance in lakes that are not under active aquatic plant management are most likely due to differences in annual weather conditions and phenological cycles of individual plant species. For instance, the growing season of 2004 was considerably cooler than in 2003, and native species including some of the pondweeds, wildcelery, and water stargrass were slow to break dormancy in 2004. Some of these species were abundant in the lakes by early to mid-July, based on visual observations, but were not present in June when the quantitative evaluations were conducted. Seasonal variation also occurs because some species, such as pondweeds, begin to senesce in mid to late summer. Other species such as Eurasian watermilfoil may grow all summer and spread to new areas in a lake. Summaries of plant community changes measured in each lake are provided below.

Auburn Lake – Untreated Reference. Plant diversity and abundance data for the littoral zone of untreated Auburn Lake are presented in Tables 2 and 3. Some significant differences in percent occurrence and abundance (biomass) of the target weeds and native species were measured between seasons (June to August) and between years (2003 to 2004). Secchi disk readings averaged 2.0 m from 1999 to 2003 and 2.8 m in 2004.

Table 2
Littoral Zone Plant Diversity (percent occurrence) in Untreated Reference Lakes[1]

Auburn Lake	Jun 03	Aug 03	Jun 04	Aug 04
Total number of native species	9	8	10	9
Eurasian watermilfoil	77 ab	69 b	79 ab	80 a
Curlyleaf pondweed	8 b	0 c	15 a	0 c
Native species	89 a	82 a	89 a	87 a
All species	89 a	85 a	94 a	91 a
Pierson Lake	**Jun 03**	**Aug 03**	**Jun 04**	**Aug 04**
Total number of native species	17	19	18	19
Eurasian watermilfoil	62 b	75 a	69 ab	73 a
Curlyleaf pondweed	25 a	2 c	10 b	1 c
Native species	73 a	63 b	64 b	70 ab
All species	77 b	86 a	82 ab	86 a

[1] Means followed by the same letter are not significantly different for a given plant species and lake.

Table 3
Plant Abundance in Untreated Reference Lakes (mean biomass, g dry weight)[1,2]

Auburn Lake	Jun 03	Aug 03	Jun 04	Aug 04
Eurasian watermilfoil	20.4 ± 4.4 b	2.9 ± 1.2 c	42.0 ± 7.9 a	29.9 ± 6.6 ab
Curlyleaf pondweed	0.0 ± 0.0 a	0.0 ± 0.0 a	1.5 ± 1.1 a	0.0 ± 0.0 a
Total native species	29.7 ± 6.0 a	54.1 ± 8.6 a	27.4 ± 4.7 a	31.7 ± 6.1 a
Total all species	50.0 ± 6.2 b	57 ± 8.8 ab	70.9 ± 7.0 a	61.6 ± 8.2 ab
Pierson Lake	**Jun 03**	**Aug 03**	**Jun 04**	**Aug 04**
Eurasian watermilfoil	25.2 ± 7.2 b	34.7 ± 7.2 b	25.5 ± 6.1 b	49.7 ± 9.9 a
Curlyleaf pondweed	0.1 ± 0.1 a	0.1 ± 0.1 a	0.1 ± 0.1 a	0.2 ± 0.2 a
Total native species	30.1 ± 9.1 ab	52.4 ± 17.6 a	14.4 ± 4.1 c	18.3 ± 5.3 bc
Total all species	55.4 ± 9.9 ab	87.2 ± 18.5 a	40.0 ± 6.2 b	66.0 ± 10.3 a

[1] Denotes the standard error.
[2] Means followed by the same letter are not significantly different for a given plant species and lake.

While Eurasian watermilfoil occurrence declined slightly in Auburn Lake between June and August 2003 (79 to 69 percent), the measured biomass declined almost tenfold (20.4 to 2.9 g DW/m^2). This decline in abundance was driven by the blackening and disappearance of older leaf whorls (apical leaves were healthy) due to unexplained natural causes. Moreover, inspection of injury symptoms exhibited on the plants suggested that the leaf necrosis was not indicative of damage by milfoil weevils (R. Newman, Univ. of Minnesota, Minneapolis, MN, personal communication), known as milfoil pathogens, such as *Mycolyptidiscus terrestris* (J. Shearer, USAE Research and Development Center, Vicksburg, MS, personal communication), or aquatic herbicides. In 2004, Eurasian watermilfoil occurrence was similar between June and August, and similar to 2003, but biomass had recovered to levels greater than those measured in 2003, comprising over 50 percent of total plant abundance.

Percent occurrence of curlyleaf pondweed declined in Auburn Lake between June and August of both 2003 and 2004, and was highest in June 2004. This spring-to-summer decline is typical with curlyleaf pondweed, which begins its annual senescence in mid to late June. Though present in the lake at measurable levels (8 percent occurrence, June 2003 and 15 percent occurrence, June 2004), curlyleaf pondweed biomass represented < 2 percent of total plant abundance.

Total number of native plants recorded varied little during the evaluation period, ranging from 8 to 10 species (Table 2), and the list of species observed for both years is presented in Table 4. Occurrence of native species ranged from 82 to 89 percent and no significant differences were measured between seasons or years. Native plant biomass increased by a factor of 1.8 between June and August of 2003, and increased by a factor of 1.2 between June and August of 2004, but these increases were not statistically significant. Biomass was less in June 2004 compared to June 2003 (-8 percent) and in August 2004 compared to August 2003 (-41 percent), but differences were not statistically significant. Native plant abundance represented 51 to 95 percent of total plant biomass, with the exception of June 2004 at 39 percent. Plant biomass in June 2004 was dominated by a high abundance of Eurasian watermilfoil.

Pierson Lake – Untreated Reference. Plant diversity and abundance data for the littoral zone of untreated Pierson Lake are presented in Tables 2 and 3. Some significant differences in percent occurrence and abundance (biomass) of the target weeds and native species were measured between seasons (June to August) and between years (2003 to 2004). Secchi disk readings averaged 2.2 m from 1999 to 2003 and 2.0 m in 2004.

Occurrence of Eurasian watermilfoil increased slightly in Pierson Lake between June and August in 2003 (62 to 75 percent), as did biomass (25.2 to 34.7 g DW/m2). A similar increase in percent occurrence was measured between June and August of 2003, but Eurasian watermilfoil biomass nearly doubled in that year, representing 75 percent of total plant mass in the lake.

As in the other untreated reference lake, percent occurrence of curlyleaf pondweed declined between June and August of both 2003 and 2004, but was highest in June 2003. Though present at measurable levels at all sampling events (up to 25 percent occurrence), curlyleaf pondweed biomass represented < 1 percent of total plant abundance in the lake.

Total number of native plants recorded varied little during the evaluation period, ranging from 17 to 19 species (Table 2); the list of species observed for both years is presented in Table 4. Occurrence of native species was essentially stable, ranging from 63 to 73 percent across seasons or years. Native plant biomass increased between June and August in both years, but these declines were not statistically significant. However, biomass was significantly less between seasons in both years (-48 percent and - 65 percent, respectively). Native plant abundance represented 54 to 60 percent of total plant biomass in 2003, but only 28 to 36 percent in 2004.

Table 4
Native Plant Species Composition for Each Lake (submersed and floating leaf species)[1,2,3]

Species	Auburn	Pierson	Bush	Zumbra
Brasenia schreberi	X		X	
Ceratophyllum demersum	X	X a	X a	X
Elodea canadensis	X	X b	X a	X
Myriophyllum verticillatum		X		
Myriophyllum sibiricum	X	X	X	X
Najas flexilis		X	X a	X
Nelumbo lutea			X	
Nymphaea oderata	X	X	X a	X a
Nuphar advena	X	X		
Polygonum amphibium			X	X a
Potamogeton amplifolius		X	X	X b
Potamogeton gramineus		X		
Potamogeton illinoensis		X	X a	X
Stukenia pectinata	X a	X	X	X
Potamogeton foliosus			X	X
Potamogeton natans	X	X		X
Potamogeton praelongus				X
Potamogeton pusillus				X
Potamogeton richarsonii		X	X	
Potamogeton robbinsii		X	X	
Potamogeton friessii			X b	
Potamogeton zosteriformis	X	X	X b	X
Ranunculus longirostris	X	X	X b	X
Sagittaria graminea			X a	
Utricularia vulgaris		X		X
Vallisneria americana		X	X a	
Zannichellia palustris		X	X	
Zosterella dubia	X	X	X a	X
Chara sp.		X	X	X

[1] X – denotes species that were present in each lake
[2] a - species occurrence increased by ≥ 10 percent between August 2003 and August 2004
[3] b - species occurrence decreased by ≥ 10 percent between August 2003 and August 2004

Bush Lake - Herbicide Treated. Plant diversity and abundance data for the littoral zone of herbicide-treated Bush Lake are presented in Tables 5 and 6. Some significant differences in percent occurrence and abundance (biomass) of the target weeds and native species were measured between seasons (June to August) and between years (2003 to 2004). Secchi disk readings averaged 2.3 m from 1999 to 2003 and 2.5 m in 2004.

Table 5
Littoral Zone Plant Diversity (percent occurrence) in Herbicide-Treated Lakes[1]

Bush Lake	Pre Treatment Jun 03	Pre Treatment Aug 03	Pre Treatment Apr 04	Post Treatment Jun 04	Post Treatment Aug 04
Total number of native species	22	19	10	19	20
Eurasian watermilfoil	36 a	37 a	21 b	4 d	18bc
Curlyleaf pondweed	24 a	0 c	15 b	3 d	8 c
Native species	91 a	90 a	73 b	88 a	93 a
All species	93 a	91 a	80 b	88 a	93 a
Zumbra Lake	**Jun 03**	**Aug 03**	**Apr 04**	**Jun 04**	**Aug 04**
Total number of native species	17	10	7	10	15
Eurasian watermilfoil	80 a	64 b	62 b	6 c	8 c
Curlyleaf pondweed	37 a	0 b	2 b	0 b	1 b
Native species	90 ab	92 a	65 c	85 b	92 a
All species	91 ab	94 a	79 b	86 b	91 ab

[1] Means followed by the same letter are not significantly different for a given plant species and lake.

Table 6
Plant Abundance in Lakes Treated with Herbicide in April/May 2004 (mean biomass, g dry weight)[1,2]

Bush Lake	Jun 03	Aug 03	Apr 04	Jun 04	Aug 04
Eurasian watermilfoil	10.4 ± 2.8 a	3.3 ± 1.6 b	1.2 ± 0.4 b	0.0 ± 0.0 b	0.2 ± 0.2 b
Curlyleaf pondweed	1.0 ± 0.3 a	0.0 ± 0.0 b	0.7 ± 0.3 a	0.0 ± 0.0 b	0.4 ± 0.3 ab
Total native species	21.5 ± 4.7 bc	53.9 ± 15.8 a	15.9 ± 4.9 c	10.9 ± 2.7 c	38.2 ± 7.9 ab
Total all species	32.9 ± 5.1 bc	57.1 ± 16.7 a	17.7 ± 4.9 bc	10.9 ± 2.7 c	38.8 ± 7.8 ab
Zumbra Lake	**Jun 03**	**Aug 03**	**Apr 04**	**Jun 04**	**Aug 04**
Eurasian watermilfoil	26.8 ± 8.3 a	16.1 ± 4.4 a	2.4 ± 0.7 b	0.0 ± 0.0 c	0.1 ± 0.0 c
Curlyleaf pondweed	0.6 ± 0.3 a	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b	0.0 ± 0.0 b
Total native species	47.3 ± 14.2 b	107.7 ± 29.7 a	37.7 ± 11.9 b	37.1 ± 8.1 b	64.6 ± 12.7 b
Total all species	74.7 ± 14.7 ab	123.8 ± 29.4 a	39.6 ± 11.8 c	37.1 ± 8.1 c	64.6 ± 12.7 b

[1] ± denotes the standard error.
[2] Means followed by the same letter are not significantly different for a given plant species and lake.

The herbicide treatments in April 2004 significantly reduced the percent occurrence of Eurasian watermilfoil in June 2004, representing nearly 90 percent control of that target plant. Though percent occurrence of Eurasian watermilfoil had increased slightly by August 2004, its presence was still significantly less than pretreatment levels. Much of the Eurasian watermilfoil observed in August 2004 was from re-growth occurring in a 6-ha zone of the lake that was treated with 2,4-D (112 kg/ha on 28 June 2003), outside the scope of this study. Because of this unscheduled application, that area of the littoral zone was not re-treated as part of the April 2004 study. While scattered Eurasian watermilfoil shoots were present during the 2004 post-treatment period, that plant accounted for 1 percent or less of total vegetative biomass in the lake at that time.

Visual observations indicated that most of the curlyleaf pondweed was dead by mid-May, approximately three weeks after herbicide application, and therefore production of vegetative reproductive propagules (turions) was essentially eliminated. percent occurrence of curlyleaf pondweed was significantly reduced in June 2004, following the herbicide treatment in April, and remained low in August 2004. Some plants from newly sprouted turions were observed in June and August 2004. These propagules represented turions deposited on the sediment from previous years of curlyleaf growth and sprouted well after the 2004 herbicide applications. Though still present at post-treatment sampling events, curlyleaf pondweed only accounted for 1 percent or less of the total biomass in the lake.

Total number of native plants recorded varied little during the evaluation periods in June and August, ranging from 19 to 20 species (Table 5); the list of species observed for both years is presented in Table 4. Occurrence of native species was essentially stable, ranging from 88 to 93 percent between June and August measurements, both within a given year and between years. Native species occurrence was lower in the April 2004 pretreatment sample period because these plants typically begin growth later in the spring. Native plant biomass increased between June and August of 2003 by a factor of 2.5, and increased by a factor of 3.5 between June and August of 2004. While the increase in native plant abundance in 2004 is probably linked to the removal of Eurasian watermilfoil and curlyleaf pondweed biomass following the herbicide application, it was still 29 percent (June) to 49 percent (August) less than that measured in 2003. As noted earlier, some of this reduction could have been due to cool temperatures and the late growing season in 2004.

Zumbra Lake - Herbicide Treated. Plant diversity and abundance data for the littoral zone of herbicide-treated Zumbra Lake are presented in Tables 5 and 6. Some significant differences in percent occurrence and abundance (biomass) of the target weeds and native species were measured between seasons (June to August) and between years (2003 to 2004). Secchi disk readings averaged 2.3 m from 1999 to 2003 and 3.2 m in 2004.

The herbicide treatments in April 2004 significantly reduced the percent occurrence of Eurasian watermilfoil throughout 2004, representing between 87 and 92 percent control of that target plant. While scattered Eurasian watermilfoil shoots were present during the 2004 post-treatment period, that plant accounted for less than 1 percent of the total vegetative biomass in the lake at that time.

As in the other herbicide-treated lake, visual observations indicated that most of the curlyleaf pondweed was dead by mid-May, approximately three weeks after herbicide application, and therefore production of vegetative reproductive propagules (turions) was essentially eliminated. Percent occurrence of curlyleaf pondweed was significantly reduced in June 2004, following the herbicide treatment in April, and remained such in August 2004. The plant was extremely scarce during the post-treatment sampling period, and essentially contributed nothing to the total biomass in the lake at that time.

Total number of native plants recorded varied somewhat during the evaluation periods in June and August, ranging from 10 to 17 species (Table 5); the list of species observed for both years is presented in Table 4. Occurrence of native species was fairly stable ranging from 85 to 92 percent between June and August measurements, both within a given year and between years. Native species occurrence was lower in the April 2004 pretreatment sample period because these plants typically begin growth later in the spring. Native plant biomass increased between June and August of 2003 by a factor of 2.3, and increased by a factor of 1.7 between June and August of 2004. Native plant abundance declined between June 2003 and 2004 by 22 percent and between August 2003 and 2004 by 40 percent. As noted earlier, some of this reduction could have been due to cool temperatures and the late growing season in 2004.

SUMMARY: Early spring application of 1 mg/L ai endothall (Aquathol® K) combined with 0.5 mg/L ai 2,4-D (DMA 4 IVM®) or granular endothall (Aquathol Super® K) applied alone at 1.5 mg/L effectively controlled both Eurasian watermilfoil and curlyleaf pondweed in the littoral zones of Bush and Zumbra Lakes for at least one growing season.

Control of both species was nearly 100 percent with respect to plant abundance data, and approximately 90 percent with respect to percent occurrence. In contrast, littoral zones of untreated reference lakes, Auburn and Pierce, continued to be dominated by nuisance levels of Eurasian watermilfoil and potentially problematic levels of curlyleaf pondweed. Water clarity in the treated lakes was not adversely affected by the herbicide treatments, and was 10 to 40 percent higher by post-treatment year 2004, compared to values from 1999 through 2003.

These early season applications were designed to control Eurasian watermilfoil and curlyleaf pondweed before susceptible native plants, such as pondweeds, were actively growing. Native plant data showed that these communities were not adversely affected by the herbicide treatments. Treatment of Eurasian watermilfoil and curlyleaf pondweed early in the growing season can provide a temporal selectivity by preventing the exposure of sensitive native plants to the herbicides during periods of active growth. Furthermore, the exposure of the actively growing target species allows native species a window to grow with greatly reduced competition. Also, the early removal of curlyleaf pondweed prevents the formation of new turions critical for the continued survival of that plant in future years.

The use of endothall alone would have required higher concentrations (2 to 3 mg/L) to control Eurasian watermilfoil in the large treated blocks and would have risked damage to some of the native plants, particularly coontail. Furthermore, many native species that are sensitive to endothall (e.g., pondweeds and naiads) remained dormant until that herbicide had sufficiently degraded or dissipated and thus were not affected. 2,4-D applied alone at 2 to 4 mg/L ai to control Eurasian watermilfoil would not have controlled curlyleaf pondweed and would have risked damage to water lilies, which are protected by MNDNR from general herbicide treatments.

FUTURE WORK: The prescriptive and selective use of herbicides, such as early season – low dose strategies, may allow herbicides to be used as a maintenance tool to prevent exotics from reaching nuisance levels and to protect important native plant communities. However, little is known of the long-term effects of manipulating plant communities on water quality and fisheries. This study will continue for the next three to five years, and herbicides will be used to maintain Eurasian watermilfoil and curlyleaf pondweed below nuisance levels, while protecting native plant communities. Plant, fish, and invertebrate communities and water quality are being monitored to determine the long-term effects of lake management using aquatic herbicides on these factors.

ACKNOWLEDGMENTS: Partial support for this work was provided by the Aquatic Ecosystem Restoration Foundation and Cerexagri Inc. The authors thank Chip Welling and Wendy Crowell of the Minnesota Department of Natural Resources for their help in planning and conducting this study. The authors also thank the Three Rivers Park District, City of Bloomington, and Zumbra Lake Association for allowing us to include their lakes in this study. Lake Restoration Inc. and Midwest AquaCare provided valuable assistance in applying the herbicide. The contents of this technical note are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such products.

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> Skogerboe, J. G., and K. D. Getsinger. 2006. *Selective control of eurasian watermilfoil and curlyleaf pondweed using low doses of endothall combined with 2,4-D*. APCRP Technical Notes Collection (ERDC/TN APCRP-CC-05). Vicksburg, MS: U.S. Army Engineer Research and Development Center, Vicksburg, MS.
> http://el.erdc.usace.army.mil/aqua/

REFERENCES

Ashton, F. M. and A. S. Crafts. 1981. *Mode of action of herbicides*. Wiley Interscience Publications. 414-416.

Bowes, G. A., A. S. Holaday, and W. T. Haller. 1979. Seasonal variation in the biomass, tuber density and photosynthetic metabolism of hydrilla in three Florida lakes. *J. Aquat. Plant Manage.* 17: 61-65.

Elliston, R. A., and K. K Steward. 1972. The response of Eurasian watermilfoil to various concentrations and exposure periods of 2,4-D. *Hyacinth Contr. J.* 10: 38-40.

Getsinger, K. D., J. D. Madsen, E. G. Turner, and M. D. Netherland. 1997. Restoring native vegetation in a Eurasian watermilfoil-dominated plant community using the herbicide triclopyr. *Regul. Rivers Res. and Manage.* 13: 357-375.

Green, W. R. and H. E. Westerdahl. 1990. Response of Eurasian watermilfoil to 2,4-D concentrations and exposure times. *J. Aquat. Plant Manage*. 28: 27-32.

Haller, W. T. and D. L. Sutton. 1973. Factors affecting the uptake of endothall ^{14}C by hydrilla. *Weed Sci.* 21: 446-448.

Hoeppel, R. E. and H. E. Westerdahl. 1983. Dissipation of 2,4-D DMA and BEE from water, mud, and fish in Lake Seminole, Georgia. *Water Res. Bull.* 19: 197-204.

Honnell, D. R., J. D. Madsen, and R. M. Smart. 1993. *Effects of selected exotic and native aquatic plant communities on water temperature and dissolved oxygen.* Information Exchange Bulletin A-93-2. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Lim, P. G. and Lozoway, K. R. 1976. *Studies of aquatic macrophytes Part X. A field experiment with granular 2,4-D for control of Eurasian watermilfoil.* Water Investigation Branch Report No. 2613. Victoria, British Columbia.

MacDonald, G. E., D. G. Shilling, and T. A. Bewick. 1993. Effects of endothall and other aquatic herbicides on chlorophyll fluorescence, respiration and cellular integrity. *J. Aquat. Plant Manage.* 31: 50-55.

Mackenzie, J. W. and L. Hall. 1967. Elodea control in southeast Florida with diquat. *Hyacinth Control J.* 6:37-44.

Madsen, J. D. 1997a. Methods for management of nonindigenous aquatic plants. In *Assessment and management of plant invasions,* J. O.Luken and J. W. Tieret, ed. 145-171. New York: Springer-Verlag.

Madsen, J. D. 1997b. Seasonal biomass and carbohydrate allocation in a southern population of Eurasian watermilfoil. *J. Aquat. Plant Manage.* 35: 15-21.

Madsen, J. D. 1999. *Point intercept and line intercept methods for aquatic plant management*. Aquatic Plant Control Research Program Technical Notes Collection (TN APCRP-M1-02). Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://el.erdc.usace.army.mil/aqua/.

Madsen, J. D., K. D. Getsinger, R. M. Stewart, and C. S. Owens. 2002. Whole lake fluridone treatments for selective control of Eurasian watermilfoil: II. Impacts on submersed plant communities. *Lake and Reserv. Manage.* 18(3): 191-200.

Netherland, M. D., W. R. Green, and K. D. Getsinger. 1991. Endothall concentration and exposure time relationships for the control of Eurasian watermilfoil and hydrilla. *J. Aquat. Plant Manage.* 29: 61-67.

Netherland, M. D., K. D. Getsinger, and J. G. Skogerboe. 1997. Mesocosm evaluation of the species-selective potential of fluridone. *J. Aquat. Plant Manage.* 35: 41-50.

Netherland, M. D., J. G. Skogerboe, C. S. Owens and J. D. Madsen. 2000. Influence of water temperature on the efficacy of diquat and endothall versus curlyleaf pondweed. *J. Aquat. Plant Manage.* 38: 25-32.

Pennington, T. G., J. G. Skogerboe, and K. D. Getsinger. 2001. Herbicide/copper combinations for improved control of *Hydrilla verticillata*. *J. Aquat. Plant Manage.* 39: 56-58.

Poovey, A. G., J. G. Skogerboe, and C. S. Owens. 2002. Spring treatments of diquat and endothall for curlyleaf pondweed control. *J. Aquat. Plant Manage.* 40: 63-67.

Poovey, A. G., J. G. Skogerboe, and K. D. Getsinger. 2004. *Efficacy of AVAST fluridone formulation against Eurasian watermilfoil and nontarget submersed plants*. ERDC/EL TR-04-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Reinert, K. H. and J. H. Rogers. 1986. Validation trial of predictive fate models using an aquatic herbicide (endothall). *Environ. Toxicol. Chem*. 5: 449-461.

Skogerboe, J. G. and K. D. Getsinger. 2001. Endothall species selectivity evaluation: southern latitude aquatic plant community. *J. Aquat. Plant Manage.* 39: 129-135.

Skogerboe, J. G., and K. D. Getsinger. 2002. Endothall species selectivity evaluation: Northern latitude aquatic plant community. *J. Aquat. Plant Manage.* 40: 1-5.

Skogerboe, J. G., T. G. Pennington, J. M. Hyde, and C. Aguillard. 2004. *Use of endothall in combination with other herbicides for improved control of hydrilla-a field demonstration.* APCRP Technical Notes Collection (TN APCRP-CC-04). Vicksburg, MS: U.S. Army Engineer Research and Development Center, Vicksburg, MS. http://el.erdc.usace.army.mil/aqua/.

Sprecher, S. L., K. D. Getsinger, and A. B. Stewart. 1998. Selective effects of aquatic herbicides on sago pondweed. *J. Aquat. Plant Manage.* 36: 64-68.

Sutton, D. L., W. T. Haller, K. K. Steward, and R. D. Blackburn. 1972. Effect of copper on uptake of diquat—14C by hydrilla. *Weed Sci.* 18(6): 703-707.

Sutton, D. L., L. W. Weldon and R. D. Blackburn. 1970. Effect of diquat on uptake ofn copper in aquatic plants. *Weed Sci.* 18(6): 703-707.

Van, T. K., and R. D. Conant. 1988. *Chemical control of hydrilla in flowing water:Herbicide uptake characteristics and concentration versus exposure.* Technical Report A-88-2. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Wehrmeister, J. R., and R. L. Stuckey. 1992. Life history of *Potamogeton crispus*. *The Mich. Bot.* 31: 3-16.

Westerdahl, H. E., and K. D. Getsinger (eds.). 1988. *Aquatic plant identification and herbicide use guide; Vol. II: Aquatic plants and susceptibility to herbicides.* TR A-88-9. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station.

Woolf, T. E., and J. D. Madsen. 2003. Seasonal biomass and carbohydrate allocation patterns in southern Minnesota curlyleaf pondweed populations. *J. Aquat. Plant Manage.* 41:113-118.