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Influence of Water Temperature on the Efficacy of Diquat and Endothall versus Curlyleaf Pondweed

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ABSTRACT

Studies were conducted in a greenhouse facility and a pond to determine the impact of water temperature on the efficacy of the contact herbicides diquat (6,7-dihydrodipyrido [1,2-α:2',1'-c] pyrazinediium ion) and endothall (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid) for control of the exotic nuisance species curlyleaf pondweed (*Potamogeton crispus* L.) across a range of water temperatures. Although *P. crispus* is reported to be highly susceptible to contact herbicides, treatments are usually conducted late in the growing season after turion formation has occurred. These turions are the major source of reinfestation the following spring, and treatment strategies to prevent their production would require applications at water temperatures which are generally thought to inhibit herbicide efficacy. Herbicide treatments were applied to 50-L aquaria containing curlyleaf pondweed growing at water temperatures of 10, 12.5, 15, 20, and 25C. Both diquat and endothall efficacy was inhibited as water temperature decreased; however, treatments at all temperatures significantly reduced biomass and turion formation. Although treatments conducted at 25C were the most efficacious, waiting until the water warms to this temperature limits the potential for reducing turion production. Endothall treatment of small plots in a pond infested with curlyleaf pondweed demonstrated that a late March treatment (18C water) reduced turion densities by 86%, whereas a mid-May treatment (25C water) reduced turions by 40% compared to untreated plots. Based on results of this study, it is recommended that early spring and fall treatment strategies are tested to determine if curlyleaf pondweed can be more effectively managed on a long-term basis by reducing turion populations.

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Key words: Potamogeton crispus, herbicide, chemical control, Aquathol K™, Reward™.

INTRODUCTION

Curlyleaf pondweed (*Potamogeton crispus* L.) is an exotic submersed species that has invaded and dominated the submersed plant community of many lakes in the northern United States. Although curlyleaf pondweed is a perennial species, it has characteristics of an annual because the vegetative part of the plant dies back completely in the early summer, and the only component of the plant that "oversummers" are seeds and vegetative turions. The compact turions formed by this plant remain dormant throughout the summer, sprout in the fall, and then rapidly elongate in the spring after ice melt, when water temperatures reach 5C (Sastroutomo 1981). While curlyleaf pondweed seed production can be prolific, Rogers and Breen (1980) found that less than 0.1% could be stimulated to germinate, and concluded that this species depends mainly on turions for year to year survival. Vigorous growth of curlyleaf pondweed occurs between 5 and 20C and turion production is maximal at water temperatures >15C and day lengths >12 hr (Bouldan et al. 1994). Tobiessen and Snow (1984) reported that robust early spring growth allows curlyleaf pondweed to utilize resources with limited competition from other submersed species and suggested that early growth of curlyleaf pondweed negatively impacts both the establishment and distribution of native macrophytes. Moreover, curlyleaf pondweed naturally senesces in late June and early July after turion production, which allows curlyleaf pondweed to avoid direct competition with the majority of submersed macrophyte species that thrive in the warmer summer months. Algal blooms have been associated with senescence in response to the release of nutrients following decline of large stands of curlyleaf pondweed (Hill 1979, Hill and Webster 1982). Due to its nonnative status and its ability to form extensive surface canopies that can negatively impact native plant communities, water quality, and recreational use of a water body, curlyleaf pondweed is often considered a nuisance plant that requires management.

Curlyleaf pondweed is highly susceptible to the herbicides diquat and endothall (Westerdahl and Getsinger 1988); however, current herbicide applications in the upper Midwest often occur in late May or early June during peak biomass, just prior to a temperature-related natural senescence of the plants in late June and early July. While herbicides provide control of the vegetative mat late in the plant's life cycle, these treatments do not prevent turion formation and can create a situation which requires annual herbicide applications to manage nuisance growths. Although treatment of curlyleaf pondweed prior to turion formation would seem a logical strategy for disrupting the plant's life cycle, low water temperatures (5-15C) during this active growth period are currently thought to reduce herbicide efficacy. The endothall label[6] (Aquathol K™) specifically states that water temperatures should be at least 18C prior to treatment, whereas the diquat label[7] (Reward™) states that "aquatic weeds" should be actively growing prior to treatment. It should be noted that the majority of submersed plants (especially nuisance species requiring treatment) are not actively growing and elongating at temperatures below 15C. Although published literature on the impact of using contact herbicides at low water temperatures is very limited, observations from the field often attribute failed treatments for species other than curlyleaf pondweed to cool water temperatures. Westerdahl and Getsinger (1988) suggest that efficacy problems in cooler waters are linked to low metabolic activity which inhibits herbicide uptake by the target plant. Many failed treatments are probably due to treating macrophytes that were metabolically inactive in cooler waters; however, the unique physiology of curlyleaf pondweed that allows it to grow at such low water temperatures suggests it may be susceptible to contact herbicides in cooler waters.

The ability to control curlyleaf pondweed early in the spring prior to initiation of turion production, or in the fall when the turions are newly germinated requires that herbicide treatments be conducted at water temperatures that are cooler than is generally recommended. Aside from anecdotal observations following early spring treatments, limited data exist on the effect of water temperature on diquat and endothall efficacy versus curlyleaf pondweed.

In order to determine the effect of water temperature on the efficacy of diquat and endothall for curlyleaf pondweed control, greenhouse studies were conducted over a range of temperatures, with a pond demonstration study to provide field verification of greenhouse studies. Results of this study will provide initial guidance on the feasibility of early spring or fall treatments to disrupt vegetative reproduction of curlyleaf pondweed in northern tier states.

MATERIALS AND METHODS

Studies were conducted from April to June 1997 and January to April 1998, at the Lewisville Aquatic Ecosystem Research Facility (LAERF), Lewisville, TX, in a greenhouse containing twelve, 1200 L fiberglass tanks which were modified to act as temperature regulated water baths. Each fiberglass tank contained eight vertical glass aquaria (50 L capacity). Water in each aquarium was isolated from the surrounding water in the fiberglass tanks to prevent dilution and cross-contamination among treatments. Water temperature in the fiberglass tank-water (and thus the experimental aquaria) was regulated by continuously re-circulating the water through a Remcor™ chiller (Remcor Products Company, Glendale Heights, IL) set to a specific temperature, and wrapping the outside of each fiberglass tank with 5 cm foil-faced Owens Corning fiberglass insulation.

[6]Aquathol K™: Aquatic Herbicide. 1995. EPA Reg. No. 4581-204. Label by Elf Atochem North America, Inc. Agchem Division, 2000 Market Street, Philadelphia, PA 19103.

[7]Reward™: Landscape and Aquatic Herbicide. 1997. EPA Reg. No. 10182-404. Label by Zeneca Professional Products, 1800 Concord Pike, Wilmington, Delaware 19850.

Greenhouse Study 1

In April 1997, curlyleaf pondweed was collected from ponds at the LAERF and three stem apices were planted in each of 800 beakers (300 ml capacity) containing pond sediment that was amended with granular Osmocote fertilizer (19:6:12 at a rate of 1.6 g per Kg of sediment). Ten planted beakers were placed into individual aquaria containing filtered pond water at a temperature of 15C. After an equilibration period of three days, water temperatures in selected tanks were slowly adjusted to the target temperatures of 10, 15, and 20C. Four tanks were used per temperature, with one aquarium per herbicide treatment per tank. Air was circulated through each aquarium to provide complete mixing of the water.

One beaker was removed from each aquarium at 12 and 1 day pretreatment to provide an estimate of pretreatment biomass and to demonstrate that actively growing plants were being treated. Plants were dried to a constant weight at 55C and mean shoot biomass per aquarium at each temperature was based on values of 28 samples for the pretreatment biomass value.

Herbicide rates were based on current field use rates for curlyleaf pondweed control in the midwestern United States. Since the objective of this study was to compare herbicide efficacy at three different water temperatures, the exposure times tested were somewhat conservative in comparison to those that would be expected to provide almost 100% plant control (i.e. if all experimental treatments provided 100% control, there is no basis to compare temperature effects). Treatment rates and exposures for the aquaria in each fiberglass tank are shown in Table 1. Stock solutions of endothall (20 ml/L as Aquathol K™) and diquat (8.2 ml/L as Reward™) were applied to the aquaria to achieve target treatment concentrations. Based on current use patterns, the copper-based compound Cutrine Plus (stock solution of 5 ml/L) was added to the 0.32 mg/L diquat treatment to test for enhanced efficacy of combination treatments.

Table 1. Herbicide treatment rates and exposure times used for the curlyleaf pondweed study. Field rates represent gallons of herbicide that would have to be applied to a 1 acre plot that is 4.5 feet in depth in order to achieve equivalent aqueous concentrations to those used in the laboratory.

Herbicide	Rate (mg/L)	Exposure (hr)	Field Rate[a] (gallons[b]/acre)
Untreated	0	0	0
Diquat			
Greenhouse Study 1	0.16	12	0.5
	0.32 (+ 0.18 copper)	9	1 (2.4)
	0.50	9	1.4
Greenhouse Study 2	0.16	12	0.5
	0.32	9	1.0
Endothall			
Greenhouse Study 1	0.45	12	1.3
	0.90	8	2.4
	1.4	5	3.7
Greenhouse Study 2	0.90	16	2.4
	1.40	10	3.7

[a]Based on an acre of water that is 4.5 feet in depth.
[b]Gallons of Reward™ (Diquat) and Aquathol K™ (endothall) applied.

Prior to treatment, 35 L of unfiltered pond water was added to each aquarium to better simulate turbidity conditions that exist prior to a herbicide application. Treatment of water without natural turbidity enhances the effectiveness of diquat relative to that observed in the field. Following the designated static exposure period, treated water in each aquarium was exchanged with untreated water (of the same temperature) at a rate of 4 L/ 5 min for 2 hours in order to simulate a gradual dissipation of residues. Aquaria receiving herbicide treatments were arranged in a completely randomized manner in each fiberglass tank. The fiberglass tanks were arranged in a randomized block design to account for potential differences in light intensity within the greenhouse. Each temperature was replicated four times, with one herbicide treatment per fiberglass tank.

Minimum and maximum water temperatures were monitored on a daily basis in each fiberglass tank. During herbicide exposures, temperatures were monitored every half-hour and any change of greater than ± 1C resulted in adjustment of the chiller back to the target temperature.

Four stem tips (3 cm long) of curlyleaf pondweed were removed from each aquarium and analyzed for total chlorophyll content at 2 and 6 weeks after treatment (WAT). A fresh weight of each shoot was obtained and the tip placed in a 10 mL of dimethyl sulfoxide (DMSO) for chlorophyll extraction (Hiscox and Israelstam 1979).

At 6 WAT, beakers were removed from each aquarium and shoot biomass was collected and dried (55C) to a constant weight. In addition, turion production was determined for each treatment by counting the number of turions per beaker.

Greenhouse Study 2

In January 1998, two sprigs of curlyleaf pondweed were planted in each of 600 beakers (300 ml capacity) containing pond sediment that was fertilized as described in Study 1. Ten beakers containing actively growing plants were transferred to individual aquaria containing filtered pond water at a temperature of 15C. Ten days prior to treatment, water temperatures in fiberglass tanks were slowly adjusted to the target temperatures of 10, 12.5, 15, and 25C. Allowing all plants to grow at 15C prior to treatment, insured that initial biomass was similar in all aquaria. Three tanks were used per temperature, with one aquarium per herbicide treatment per tank. In contrast to the first study, artificial lighting (URI Aquasun™ bulbs; Ultraviolet Resources, International) was provided over each fiberglass tank to enhance the low light intensities experienced in the greenhouse during the winter and early spring. The duration of artificial lighting was adjusted every two weeks to simulate the local photoperiod. Air was circulated through each aquarium to provide mixing of the water. Pretreatment biomass was measured as described in study 1.

Treatment rates and exposures for the aquaria in each fiberglass tank are shown in Table 1. Based on results obtained in the first study, endothall exposure periods were extended to determine if increasing contact time could enhance endothall efficacy at different water temperatures. Control provided by diquat in the first study was considered good and therefore treatments were not changed.

Stock solutions of endothall (20 ml/L) and diquat (8.2 ml/L) were applied to the aquaria to achieve target concentrations. Following the designated static exposure period, treated water in each aquarium was exchanged with untreated water (of the same temperature) at a rate of 4 L/ 5 min for 2 hours. In contrast to the first study, following the herbicide exposures, water temperatures in all fiberglass tanks were slowly adjusted over a period of 6 days to 18C for the remainder of the study. This was done to provide similar recovery conditions for all of the plants following the actual herbicide application. Aquaria receiving herbicide treatments were arranged in a completely randomized manner in each fiberglass tank. The fiberglass tanks were arranged in a randomized block design, with three fiberglass tanks per temperature and one herbicide treatment (aquarium) per fiberglass tank.

Water temperatures, chlorophyll content, shoot biomass, and turion production were all monitored and collected as described in Study 1.

Statistics

Data were subjected to analysis of variance (ANOVA) to determine if statistical differences existed between treatments at the same temperature. In addition, ANOVA was used to determine if differences existed between the three water temperatures tested. If differences existed, means were separated using either the LSD test (= 0.05) to compare treatment effects at the three water temperatures or Dunnett's test (= 0.05) to compare herbicide-treated plants to untreated controls. Due to differences in the activity of endothall and diquat that has been previously noted in our laboratory systems, no attempt was made to directly compare the efficacy between the two compounds.

Pond Verification Study

Based on results obtained in the greenhouse, a small-scale study was conducted in late March and mid-May in a pond at the LAERF to compare the impact of two endothall treatments on curlyleaf pondweed. Twelve plexiglass cylinders (44-cm in diameter) were placed in a pond containing a dense infestation of curlyleaf pondweed. On 31 March 1998, endothall was applied at a rate of 0.9 mg/L for a 16-hr exposure period to 4 of the cylinders. Water temperature averaged 18.2 ± 1.6C during the exposure period. At 16 hours, each cylinder was raised and lowered three times to flush out all herbicide. A second set of cylinders were treated as described above on 15 May 1998. Water temperature averaged 25.2 ± 1.8C during the second exposure period. Injury symptoms were visually rated weekly through 18 June 1998. A set of four untreated cylinders were used as an experimental control. Turion and seedhead production were quantified within the area of each cylinder. Data were compared by ANOVA and means separated by an LSD test at the 0.05 level of significance.

RESULTS

Water temperatures were stable and were maintained within ± 1.5C of the target temperature throughout both greenhouse studies. During the herbicide applications and throughout the exposure periods, water temperatures were maintained within ± 0.5C of the target temperature.

Biomass collected at 12 and 1 d pretreatment and 3 and 6 WAT indicated that untreated control plants maintained active growth throughout both studies at all temperatures (Figure 1). Although temperature-related biomass differences were recorded in the first study, biomass increased over time. It should be noted that during the first study, untreated control plants in the 20C treatments required applications of the insecticide Malathion (1.0 mg/L) to the plant canopy at 2 and 3 WAT to control white flies (*Trialeurodes* sp.) feeding on the leaves at the surface. The herbivory observed at the higher treatment temperature may have resulted in reduced biomass later in the study compared to the 10 and 15C treatments.

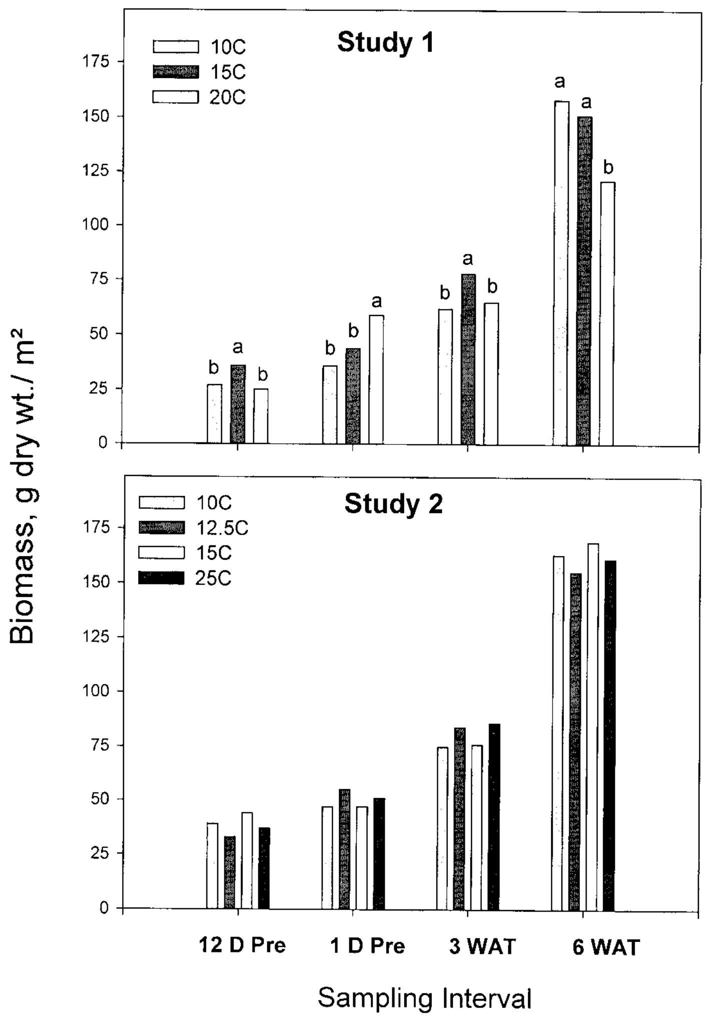

Figure 1. Shoot biomass of untreated curlyleaf pondweed under various water temperature regimes at 12 and 1 day pretreatment, and at 3 and 6 weeks after treatment. Letters above the bars represent significant differences among temperatures within each sampling period according to an LSD test at the 0.05 level of significance. For Study 1, temperatures remained constant throughout the duration of the study. For Study 2, aquarium water temperatures were slowly adjusted to 18C following the date of the herbicide applications to allow recovery at similar temperatures. Error bars indicate + 1 standard error of the mean (n = 4).

Greenhouse Study 1

Diquat Evaluation. Within days following diquat application, visual symptoms were noted at the 15 and 20C water temperatures, but injury symptoms were not evident in the 10C treatments. At 2 WAT, all diquat treatments reduced chlorophyll content compared to untreated controls; however, curlyleaf pondweed chlorophyll levels at 10C were greater than the 15 and 20C treatments, suggesting a delayed response to treatment at this temperature (Table 2).

Shoot biomass results showed a trend toward reduced diquat efficacy at 10C compared to the 15 and 20C treatments at 6 WAT (Figure 2). Although efficacy was inhibited at 10C, biomass remained suppressed compared to untreated controls at 6 WAT. Biomass recovery was limited by 6 WAT; however, chlorophyll levels had greatly increased and were beginning to approach levels of the untreated controls (Table 2). This lag between biomass and chlorophyll recovery has been noted in other laboratory studies (Spencer et al. 1989, Netherland et al. 1991).

Turion production was reduced by all diquat treatments compared to untreated controls (Figure 2). As shown in other studies, a temperature of 10C inhibited turion production when compared to production at 15 and 20C (Sastroutomo 1980, Chambers et al. 1985, Bouldan et al. 1994).

The addition of 0.18 ml of chelated copper did not enhance or reduce the efficacy of diquat when compared to diquat treatments alone. Nonetheless, many combinations of diquat and copper are used by commercial applicators, and results of this study do not preclude a synergistic effect between these compounds for curlyleaf pondweed control. It should be noted that plants used for this laboratory study were generally free of epiphytes, and it has been suggested that addition of copper improves efficacy in the field by killing epiphytes which allows increased herbicide uptake by macrophytes.

Endothall Evaluation. Visual injury symptoms (leaf discoloration and waterlogging of stems) were manifested within 1 WAT; however, further evidence of endothall injury was difficult to discern throughout the remainder of the study. Chlorophyll analyses suggested some plant injury was still notable at 2 WAT (Table 3). Shoot biomass was reduced compared to untreated controls at the higher treatment rates. Reducing endothall rates to 0.45 mg/L resulted in little treatment effect on shoot biomass (Figure 3). Although chlorophyll values were not greatly impacted at 2 and 6 weeks, shoot biomass was significantly reduced by 6 WAT.

Despite the lack of visible injury symptoms and limited biomass reduction, turion production was significantly reduced by all endothall applications when compared to untreated controls (Figure 3).

Table 2 Chlorophyll content of curlyleaf pondweed apices at 2, and 6 weeks following treatment with diquat. For Study 1, target temperatures of 10, 15, and 20C were maintained throughout the entire study. For Study 2, following herbicide treatment at temperatures of 10, 12.5, 15, and 25 C, aquarium temperatures were slowly adjusted to 18C to allow for similar recovery conditions between treatments.

Treatment Rate (mg/L)/hr	Study 1 Chloropyll Content, mg/g fresh wt.[a] 2 WAT	6 WAT
10C		
Untreated	1.41	1.24
0.16/12	0.69*	0.94*
0.32/9	0.84*	1.29
0.32 + 0.18 Cu/9	0.87*	1.11
15C		
Untreated	1.41	1.44
0.16/12	0.46*	1.07*
0.32/9	0.29*	1.31
0.32 + 0.18 Cu/9	0.33*	1.11*
20C		
Untreated	1.59	1.34
0.16/12	0.52*	0.92*
0.32/9	0.37*	1.38
0.32 + 0.18 Cu/9	0.60*	1.25
	Study 2 Chlorophyll Content mg/g fresh wt.[a] 2 WAT	**6 WAT**
10C		
Untreated	1.21	1.31
0.16/12	0.79*	1.05*
0.32/9	0.71*	1.25
12.5C		
Untreated	1.41	1.20
0.16/12	0.77*	1.18
0.32/9	0.82*	1.31
15C		
Untreated	1.29	1.41
0.16/12	0.67*	1.31
0.32/9	0.49*	1.19*
25C		
Untreated	1.28	1.33
0.16/12	0.32*	0.42*
0.32/9	0.31*	0.38*

[a]Values denoted by asterisks are significantly different from corresponding untreated reference values according to Dunnett's test at the p = 0.05 level of significance (N = 4).

Greenhouse Study 2

Diquat Evaluation. Chlorophyll was reduced by all diquat treatments at 2 WAT; however, the increases in chlorophyll concentrations noted between 2 and 6 WAT suggested that curlyleaf pondweed was recovering from treatment (Table 2). Biomass results indicated that diquat was much more effective at 25 C than at 10, 12.5, or 15C (Figure 4). Chlorophyll recovery between 2 and 6 WAT was noted for all treatments with the exception of plants treated at 25C. While a trend of increasing efficacy with increasing water temperatures was noted in the 0.16 mg/L / 12 hr treatment, this was not strongly evident following the 0.32 mg/ L /5 hr treatment, until the temperature was increased to 25C.

Endothall Evaluation. Increasing the exposure period up to 16 hr had a dramatic impact on the efficacy of endothall in greenhouse study 2 (Figure 5). Visual injury symptoms were

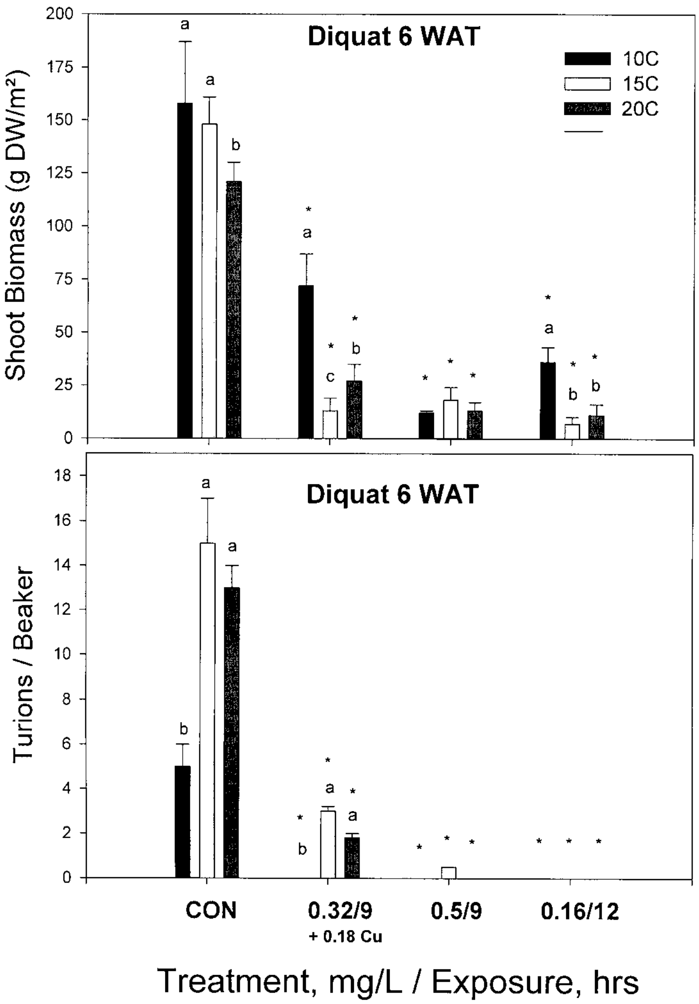

Figure 2. Shoot biomass and turion production of curlyleaf pondweed following diquat treatment at 10, 15, and 20C. Water temperatures remained constant throughout the study. Letters above the bars represent significant biomass and turion differences among water temperatures at each treatment rate according to an LSD test ($\alpha = 0.05$, n = 4). Asterisks above bars represent significant differences between treated plants and untreated controls at the same temperature according to Dunnett's test ($\alpha = 0.05$, n = 4). Error bars indicate + 1 standard error of the mean.

noted within 1 WAT, with the most severe injury noted in the 25C treatments. Chlorophyll analyses supported visual injury ratings as chlorophyll content at 2 WAT generally decreased with increasing temperatures (Table 3). By 6 WAT greater than 80% curlyleaf pondweed control was noted in all treatment aquaria, with only slight differences noted between temperatures. Chlorophyll analyses indicated that despite the greatly reduced biomass, some shoot recovery might be likely for plants treated at 10, 12.5, and 15C. Due to the low turion production noted throughout the study (a total of 15 turions were collected in all untreated tanks), no attempts were made to statistically compare the treatments.

Pond Verification Study

Endothall applications conducted in both March and May resulted in near complete reduction of standing curlyleaf pondweed biomass in the treatment cylinders (data not shown). In contrast, untreated cylinders maintained a thick canopy of curlyleaf pondweed up to the June harvest. Treatments conducted in March resulted in significant reductions in both production of turions and seedheads when compared to the May treatment and the untreated experimental controls (Figure 6). Pretreatment turion densities were not

Table 3. Chlorophyll content of curlyleaf pondweed apices at 1, 2, and 6 weeks following treatment with endothall. For Study 1, target temperatures of 10, 15, and 20C were maintained throughout the entire study. For Study 2, following herbicide treatment at temperatures of 10, 12.5, 15, and 25C, aquarium temperatures were slowly adjusted to 18C to allow for similar recovery conditions between treatments.

Treatment Rate (mg/L) hr	Study 1 Chloropyll Content, mg/g fresh wt.[a] 2 WAT	6 WAT
10C		
Untreated	1.41	1.24
0.45/12	1.29	1.42*
0.90/8	0.98*	1.29
1.4/5	1.22	1.21
15C		
Untreated	1.59	1.44
0.45/12	1.21*	1.29
0.90/8	1.14*	1.11*
1.4/5	1.07*	0.97*
20C		
Untreated	1.41	1.34
0.45/12	1.29	1.39
0.90/8	0.96*	1.22
1.4/5	0.86*	1.45
	Study 2 Chloropyll Content, mg/g fresh wt.[a]	
	2 WAT	6 WAT
10C		
Untreated	1.21	1.31
0.9/16	0.38*	0.74*
1.4/10	0.51*	0.81*
12.5C		
Untreated	1.41	1.20
0.9/16	0.41*	0.55*
1.4/10	0.39*	0.92*
15C		
Untreated	1.29	1.40
0.9/16	0.32*	0.39*
1.4/10	0.20*	0.48*
25C		
Untreated	1.38	1.33
0.9/16	0.10*	0.01*
1.4/10	0.13*	0.02*

[a]Values denoted by asterisks are significantly different from untreated reference values according to Dunnett's test at the p = 0.05 level of significance (N = 4).

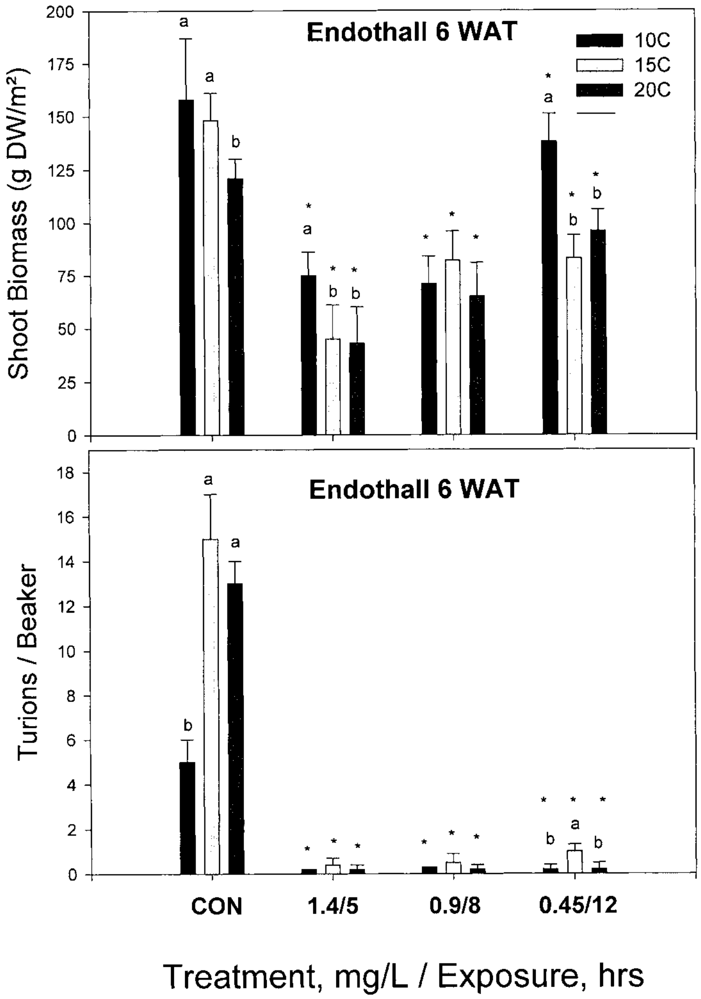

Figure 3. Shoot biomass and turion production of curlyleaf pondweed following endothall treatment at 10, 15, and 20C. Water temperatures remained constant throughout the study. Letters above the bars represent significant biomass and turion differences among water temperatures at each treatment rate according to an LSD test (α = 0.05, n = 4). Asterisks above bars represent significant differences between treated plants and untreated controls at the same temperature according to Dunnett's test (α = 0.05, n = 4). Error bars indicate + 1 standard error of the mean.

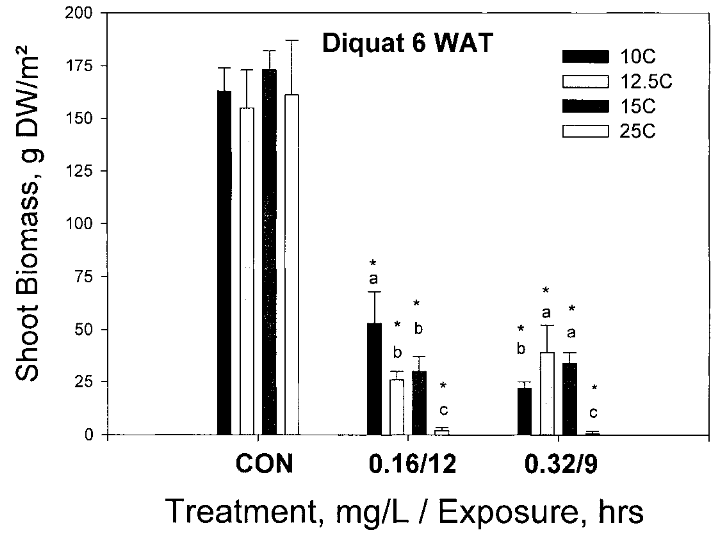

Figure 4. Shoot biomass of curlyleaf pondweed following diquat treatment at 10, 12.5, 15, and 25C. Water temperatures were adjusted to 18C following herbicide treatment to allow for similar recovery conditions between treatments. Letters above the bars represent significant biomass differences among water temperatures at each treatment rate according to an LSD test (α = 0.05, n = 3). Asterisks above bars represent significant differences between treated plants and untreated controls at the same temperature according to Dunnett's test (α = 0.05, n = 3). Error bars indicate + 1 standard error of the mean.

measured, and it was not determined if the turions collected in the cylinders following the March treatments represented dormant populations from the previous year or if these turions had been formed prior to the herbicide application.

DISCUSSION

Greenhouse results indicated that efficacy of both diquat and endothall on curlyleaf pondweed was reduced at lower water temperatures; however, most treatments provided excellent biomass reduction and completely inhibited the formation of turions regardless of water temperature. Based on results obtained with endothall, the exposure period was critical in determining the outcome of these treatments. The limited biomass reduction achieved with endothall in the first study was greatly enhanced by extending the exposure period in the second study. Previous laboratory studies have demonstrated that exposure period is especially critical when using endothall (Netherland et al. 1991). Results strongly suggest that both diquat and endothall were most effective for curlyleaf pondweed control at 25C, thus supporting observations that curlyleaf pondweed is highly susceptible late in its life cycle when water temperatures are warmer. Nevertheless, it is clear that waiting for water to warm to near 25C negates the possibility for treating curlyleaf pondweed prior to turion production.

The pond verification study demonstrated that endothall was effective in controlling curlyleaf pondweed in water that was near the label-recommended 18C minimum for endothall. Moreover, based on the greenhouse studies, it is likely that endothall would have provided good control of curlyleaf pondweed in even cooler water. Results suggest that given an adequate exposure period, endothall may be effective in controlling curlyleaf pondweed early in the spring prior to turion formation.

While the focus of the vast majority of herbicide applications is on biomass reduction, the ability to disrupt the formation of reproductive propagules should not be overlooked. Greenhouse studies suggest that early season treatments inhibit turion formation. While commercial applicators may be resistant to changing practices that have resulted in excellent control of curlyleaf pondweed biomass over the years, inhibiting turion production is likely important to the long-term management of curlyleaf pondweed. Treatments that provide only partial biomass control, but greatly reduce turion formation, may improve long-term management strategies by reducing the available propagule bank. While this treatment strategy would require treating water at temperatures between 10 and 18C, prior to formation of mature turions, it

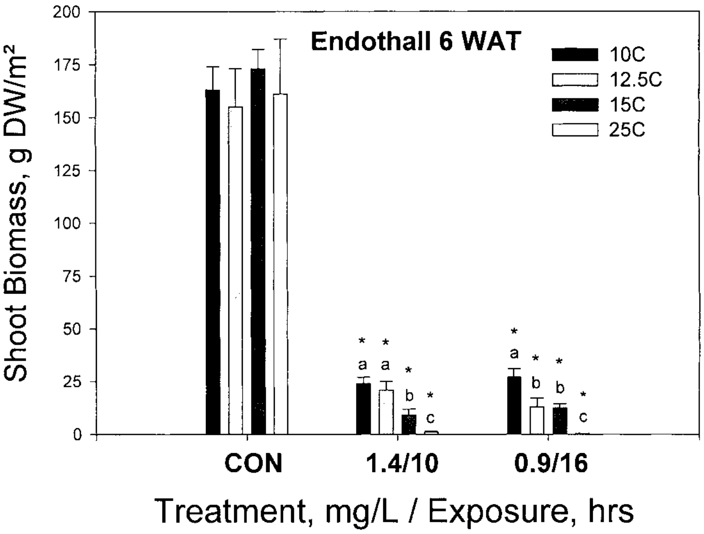

Figure 5. Shoot biomass of curlyleaf pondweed following endothall treatment at 10, 12.5, 15, and 25C. Water temperatures were adjusted to 18C following herbicide treatment to allow for similar recovery conditions between treatments. Letters above the bars represent significant biomass differences among water temperatures at each treatment rate according to an LSD test (α = 0.05, n = 3). Asterisks above bars represent significant differences between treated plants and untreated controls at the same temperature according to Dunnett's test (α = 0.05, n = 3). Error bars indicate + 1 standard error of the mean.

could potentially reduce injury of native vegetation that is metabolically inactive or with propagules that are quiescent at these temperatures.

Much remains to be learned of turion ecology of curlyleaf pondweed in response to management practices. While dormancy of curlyleaf pondweed turions has been documented (Sastroutomo 1981), the percentage of turions that sprout

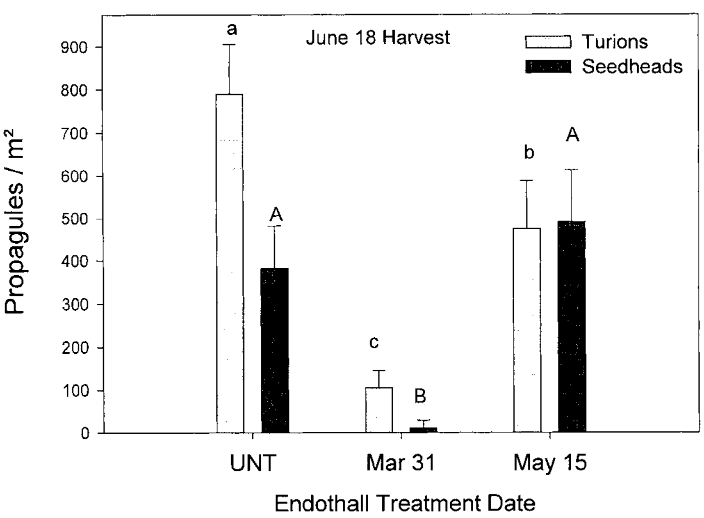

Figure 6. Curlyleaf pondweed turion and seedhead production measured on June 18, 1998 following endothall applications on March 31 (18C water temperature) and May 15 (25C water temperature). Letters above the bars represent significant differences between treatments according to an LSD test (α = 0.05, n = 5). Error bars indicate + 1 standard error of the mean.

each fall and eventually establish as mature plants the following spring is generally not well documented. It is unknown if reducing turion populations by 50 to 90% would impact the level of curlyleaf pondweed infestation observed the following spring. Intraspecific competition between sprouted turions may greatly reduce the number of turions that actually establish as mature plants, and management techniques that reduce turion numbers may simply decrease intraspecific competition. Nonetheless, complete inhibition of turion production would result in the carryover of only the dormant turions, and these propagules have been shown to be less viable than newly formed turions (Sastroutomo 1981). Based on the findings of these studies, future work to determine the response of curlyleaf pondweed to both early spring and fall management is recommended to determine if turion reduction is a viable management option.

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LITERATURE CITED

Bouldan, B. R., G. C. VanEeckhout, H. W. Quade, and J. E. Gannon. 1994. *Potamogeton crispus*—The other invader. Lake Reserv. Manage. 10: 113-125.

Chambers, P. A., D. H. N Spence, and D. C. Weeks. 1985. Photocontrol of turion formation by *Potamogeton crispus* L. in the laboratory and natural water. New Phytol. 99: 183-194.

Hill, B. H. 1979. Uptake and release of nutrients by aquatic macrophytes. Aquat. Bot. 7: 87-93.

Hill, B. H. and J. R. Webster. 1982. Aquatic macrophyte breakdown in an Appalachian river. Hydrobiologia. 89: 53-59.

Hiscox, J. D. and G. Israelstam. 1979. A method for the extraction of chlorophyll from leaf tissue without leaf maceration. Can. J. Bot. 57: 1332-1334.

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

Rogers, K. H. and C. M. Breen. 1980. Growth and reproduction of *Potamogeton crispus* in a South African lake. J. Ecol. 68: 561-571.

Sastroutomo, S. S. 1980. Environmental control of turion formation in curlyleaf pondweed (*Potamogeton crispus*). Physiol. Plantarum 49: 261-264.

Sastroutomo, S. S. 1981. Turion formation, dormancy, and germination of curlyleaf pondweed, *Potamogeton crispus* L. Aquat. Bot. 10: 161-173.

Spencer, D. F., G. G. Ksander, and L. C. Whitehand. 1989. Sago pondweed (*Potamogeton pectinatus*) tuber size influences its response to fluridone treatment. Weed Sci. 37: 250-253.

Tobiessen, P. and P. D. Snow. 1984. Temperature and light effects on the growth of *Potamogeton crispus* in Collins Lake, New York State. Can J. Bot. 62: 2822-2826.

Westerdahl, H. E. and K. D. Getsinger. 1988. Aquatic plant identification and herbicide use guide. Vol. 1: Aquatic herbicides and application equipment. Technical Report A-88-9, U.S. Army C. Engineer, Waterways Experiment Station, Vicksburg, MS. 146 pp.