Efficacy of Benthic Barriers as a Control Measure for Eurasian Watermilfoil (*Myriophyllum spicatum*)

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The use of benthic barriers alone or in combination with other control methods could initiate the eradication of pioneer populations of Eurasian watermilfoil and facilitate maintenance of acceptable population levels in water bodies where the weed is widely established. We evaluated the effects of duration of geotextile fabric panel placement on small Eurasian watermilfoil population control and nontarget plant abundance. In 2006, benthic barriers were placed over Eurasian watermilfoil infestations and removed at intervals of 4, 8, 10, and 12 wk. The 4-wk duration reduced Eurasian watermilfoil biomass 75%, and all other duration treatments reduced Eurasian watermilfoil biomass 100%. The 4-wk treatment had no effect on native plant biomass, whereas other treatments reduced native plant biomass by 79 to 93%. At the conclusion of the 12-wk study, Eurasian watermilfoil biomass had increased in the 4-wk treatment but did not reestablish within treatment plots of longer duration. Native plant biomass had increased to 21% of the untreated control in the 8-wk barrier treatment. Results suggest the 8-wk duration is sufficient for removal of Eurasian watermilfoil while allowing regrowth of native aquatic plants. A walk-in growth chamber experiment was established to evaluate the effect of sediment accumulation on the benthic barrier. Eurasian watermilfoil fragments grown on sediment depths of 0 to 3 cm (0 to 1.2 in) did not differ for shoot or root biomass. At sediment depths of 4 and 5 cm, Eurasian watermilfoil root and shoot biomass increased when compared with the control, suggesting benthic barrier maintenance should include sediment removal when sediment reaches a depth of 4 cm.

Nomenclature: Eurasian watermilfoil, *Myriophyllum spicatum* L.

Key words: *Myriophyllum spicatum*, benthic barriers, biomass reduction, native aquatic plants, sediment accumulation.

Aquatic ecosystems can be severely impaired when nonnative, invasive Eurasian watermilfoil (*Myriophyllum spicatum* L.) infestations displace native plant communities critical for fish and wildlife, diminish human recreational opportunities, and reduce property values (Boylen et al. 1999; Bremigan et al. 2005; Engel 1995; Madsen et al. 1991; Newroth 1985). Since the first documented occurrence in an Idaho pond in1992, Eurasian watermilfoil has become pervasive in many Idaho waterways, with an estimated 2,833 ha (7,000 ac) of surface water infested (Milfoil Task Force 2006). Resource managers at the state and local level are interested in exploring the effectiveness and ecological effects of control measures as part of ongoing efforts to develop management plans.

Methods for eradication and control of Eurasian watermilfoil include mechanical harvesting, underwater cultivation, diver-operated suction harvesting, diver hand-pulling, water-level manipulation, biological control, aquatic herbicide application, and bottom modification treatments, all of which have been used with mixed success throughout North America (Bates et al. 1985; Brooker and Edwards 1975; Couch and Nelson 1985; Eichler et al. 1993). A weed management program integrating the various tools available into a long-term, dynamic strategy that incorporates environmental, cultural, economic, and management objectives can be an effective system for achieving the desired level of suppression (Flint and Gouveia 2001; Monaco et al. 2002).

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Interpretive Summary

Exotic weeds have invaded and impaired aquatic ecosystems in western North America. Restoring native aquatic habitats degraded by exotic plants should decrease invader abundance and also result in a return to preinvasion levels of desirable vegetative communities and native diversity. Eurasian watermilfoil is a submersed, aquatic, Eurasian perennial plant that that has invaded waterways throughout the United States and Canada, forming dense mats of vegetation on the water's surface, which interfere with water-based recreational activities, inhibit water flow, and impair critical fish and wildlife habitat. Bottom modification treatments, including the use of portable panels of synthetic weed fabric placed on the bottom of ponds and lakes can be an effective control measure for widely established populations of Eurasian watermilfoil and can be used to remove small populations. Although the effectiveness of bottom barriers for the control of nuisance aquatic plants in confined areas has been shown in previous studies, evaluation of optimum coverage time, maintenance requirements, and nontarget plant community response is lacking. We recorded the weight of Eurasian watermilfoil and native plants in 40 plots on the bottom of Round Lake in 2006 and Chatcolet Lake in 2007 near Plummer, ID. We also recorded shoot weight, root weight and length, and sediment depth during an aquarium-based study conducted at the University of Idaho in Moscow, ID, in 2007. The results of this study suggest that the 8-wk barrier placement is sufficient for removal of Eurasian watermilfoil while allowing regrowth of native aquatic plants. Our results also suggest that barriers should be cleaned of sediment when deposition reaches a depth of 4 cm to prevent weed establishment.

Portable panels of porous synthetic weed fabric (benthic barriers) placed on the bottom of ponds and lakes can be an effective control measure for nuisance aquatic plants, such as Eurasian watermilfoil (Engel 1984), and can be used to remove small infestations. Benthic barriers can be confined to specific areas of a water body, are out of sight, and can be used in water too deep for harvesting or where chemical application is not acceptable or desirable. Installation of benthic barriers creates an immediate open area of water and can be useful in places such as around boat docks, in swimming areas, and along shorelines. In larger water bodies where Eurasian watermilfoil is widely established, fabric barriers can also be a valuable tool as part of an integrated weed management strategy. In combination with other control methods, barriers can be used to maintain reduced or acceptable population levels. Shortcomings of this technique may include nonselectivity (i.e., all plants are eliminated beneath the barriers), accumulation of sediment on top of the barriers allowing for the establishment of new plants, and reinfestation of plants after barrier removal. The effectiveness of synthetic fabric barriers for control of aquatic macrophytes in confined areas has been shown in previous studies (Engel 1984; Perkins et al. 1980; Ussery et al. 1997); however, to our knowledge, evaluations on the optimum coverage time, maintenance requirements, and nontarget aquatic plant community response is lacking.

To investigate the efficacy of benthic barriers as a control measure for Eurasian watermilfoil at different barrier coverage times, the effect of coverage time on nontarget plants, and the effect of sediment deposition on benthic barrier maintenance requirements, studies were conducted in Round Lake and Chatcolet Lake near Plummer, ID, and in a walk-in growth chamber at the University of Idaho in Moscow, ID. The field study had two objectives: (1) to determine the optimum coverage time needed for benthic barriers to eliminate Eurasian watermilfoil, and (2) to determine the effect of barrier duration time on nontarget native plants. The growth chamber study objective was to determine the minimum sediment deposition on top of benthic barriers that would support reestablishment and growth of Eurasian watermilfoil.

Materials and Methods

Benthic barrier studies were conducted within the Coeur d'Alene Tribal Waters in Round Lake and Chatcolet Lake, two of four lakes surrounding the mouth of the St. Joe River at the south end of Coeur d'Alene Lake, near Plummer, ID (Figure 1). Coeur d'Alene Lake is approximately 40 km (24.85 mi) long, between 1.6 and 3.2 km wide, and lies in a naturally dammed river valley that discharges into the Spokane River (Figure 2). The 1906 impoundment of the Spokane River and Coeur d'Alene Lake by the Post Falls Dam permitted summer pool levels to be raised approximately 2.4 m (7.87 ft), leading to inundation and the formation of shallow "chain lakes" known as Benewah, Chatcolet, Hidden, and Round lakes. A dense infestation of Eurasian watermilfoil was reported in 2001 in Chatcolet Lake, and an aquatic vegetation survey initiated in 2004 showed scattered populations throughout, but limited to, Benewah, Chatcolet, Hidden,

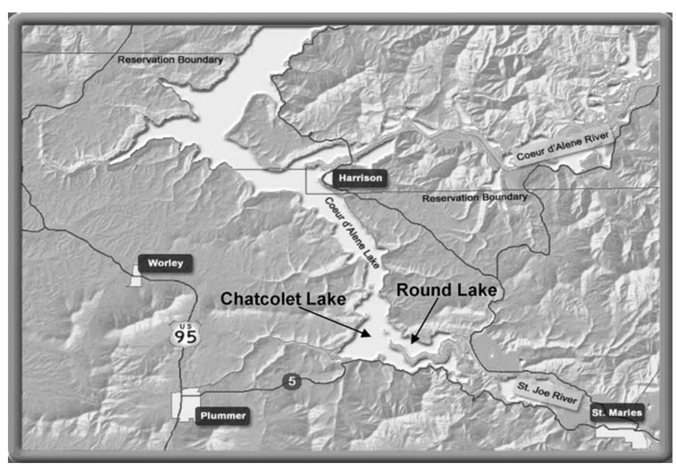

Figure 1. Map of benthic-barrier 2005 preliminary study in Round Lake, east of the St. Joe River, ID, and the 2006 study in Chatcolet Lake, west of the St. Joe River, ID.

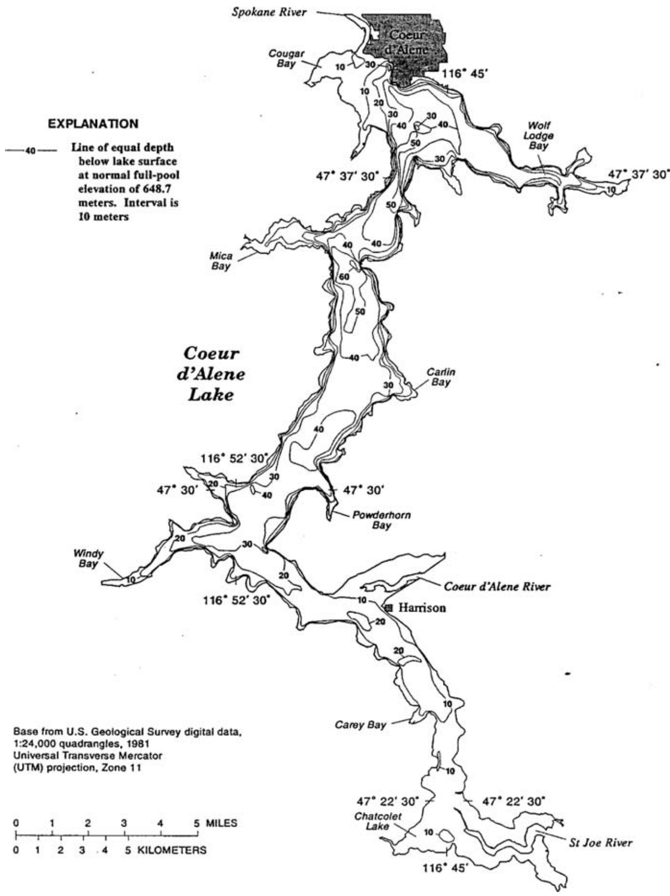

Figure 2. Bathymetric map of Coeur d'Alene Lake, ID.

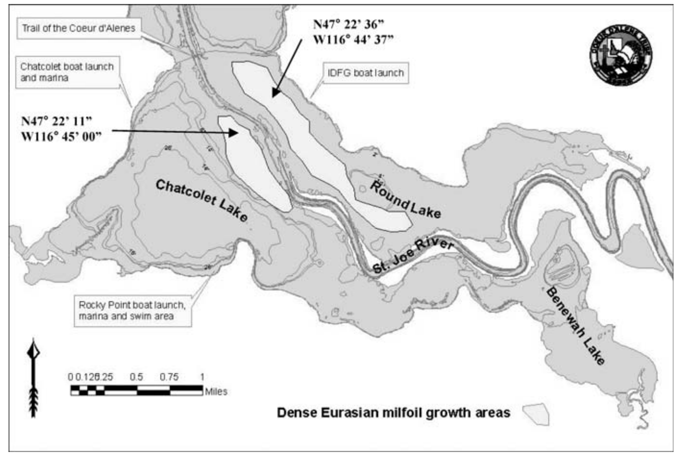

Figure 3. Location of dense Eurasian watermilfoil infestations in Round and Chatcolet lakes, ID, mapped following a vegetation survey by Coeur d'Alene Tribe Lake Management staff, and the 2005 Round Lake and 2006 Chatcolet Lake Eurasian watermilfoil benthic barrier study sites.

and Round lakes. A subsequent survey carried out during 2005 and 2006 revealed fragments and small populations of Eurasian watermilfoil beginning to move northward within the lake system. In 2005, a preliminary barrier study was conducted in Round Lake, east of the St. Joe River (47°22′36″N, 116°45′37″W) (Figure 3).

Chatcolet Lake, west of the St. Joe River, is relatively shallow, with a maximum depth of 10.6 m, an estimated mean depth of 2.4 to 3 m, and considerable potential to support submersed plant communities. In 2006, plots were established in a region of this water body where the target weed Eurasian watermilfoil was dominant (47°22′11″N, 116°45′00″W) (Figure 3). Lake bed sediment was collected using a standard Ponar dredge and analysis was conducted on three random, composite sediment samples (Table 1). Measures of water quality were collected using a Hydrolab MiniSonde multiparameter analyzer and are summarized in Table 2.

The concentration of photosynthetic pigments was used to estimate phytoplankton biomass. Syringe water samples were collected subsurface (to a depth of 1 m) in close proximity to the study site using a 2.5 cm, 0.7-µm particle retention Whatman GF/C glass fiber filter (Whatman plc, Springfield Mill, James Whatman Way, Maidstone, Kent ME14 2LE, U.K.) and a 2.5-mm filter holder with a Luer-type fitting. Samples were transported to the laboratory and were kept frozen and excluded from light until analysis of chlorophyll concentrations using standard spectrophotometric techniques. Chlorophyll *a* analysis was performed using a Thermo Spectronic UV/VIS Spectrometer (model BioMate 3, Rochester, NY) according to U.S. Environmental Protection Agency (EPA) method 446.0 (Arar, 1997). Chlorophyll pigments were extracted from plankton concentrates according to American Public Health Association (APHA) method number 10200 H (Eaton et al. 2005). Following extraction, absorbances were measured at 664, 647, 630, and 750 nm. Concentrations of chlorophyll *a* was then determined using the trichromatic equations in EPA method 446.0, section 12.1. Measures of chlorophyll *a* concentration are summarized in Table 3.

Benthic Barrier Placement. The 2005 preliminary study at Round Lake was a completely randomized block design with four blocks and six benthic barrier treatments installed August 3, removed 2, 3, 5, 8, and 10 wk after placement and included an uncovered control. Four blocks measuring 3 by 18 m were established with a 3-m border between them. The benthic barrier panels consisted of 3 by 3-m, weighted, self-anchoring frames made of 2.5-cm-diam polyvinyl chloride (PVC) pipe filled with sand and fitted with Typar (Old Hickory, TN) spun geotextile fabric. The percentage of cover by Eurasian watermilfoil was visually rated under the panels and recorded at the time the panels were placed, and visual assessments of plant vigor and cover were made at each removal time.

The 2006 experimental field plot was a completely randomized block design with four blocks and five 3-by-3–m benthic barrier treatments that were removed 4, 8, 10,

Table 1. Soil fertility analysis of Chatcolet Lake, ID, bed sediment.

Soil characteristics	Sample 1	Sample 2	Sample 3	Mean
Available potassium (µg/g)	120	120	120	120
Available phosphorous (µg/g)	2.8	2.7	2.9	2.8
Available boron (µg/g)	0.16	0.19	0.26	0.20
Nitrogen-nitrite + nitrite (µg/g)	$<$ 0.8	$<$ 0.8	$<$ 0.8	$<$ 0.8
Organic matter (%)	2.7	2.7	2.6	2.66
pH	5.5	5.5	5.4	5.46
Sulfate sulfur (µg/g)	9.8	8.7	8.9	9.13

Table 2. Water-quality measurements collected from Chatcolet Lake, ID, study site during the 8-, 10-, and 12-wk sampling events in 2007.

	Secchi depth transparency	Dissolved oxygen	Dissolved oxygen	Specific conductivity	Temperature	
Sample date	m	mg L^{-1}	%	µs cm^{-1}	C	pH
July 7	1.5	9.08	115	45.7	23.09	8.09
July 24	2.0	10.29	135	51.4	26.16	8.92
August 7	1.7	8.80	106.8	37.5	21.43	8.68
Mean	1.87	9.39	119.1	44.86	23.56	8.56
SD	0.15	0.79	14.84	6.98	2.40	0.42

Table 3. Mean chlorophyll-*a* concentrations in samples taken from the euphotic zone in the Chatcolet Lake, ID, field site.

	Chlorophyll-*a*			
Sample date	Mean[a]	Range	SD	Samples No.
	µg L^{-1}			
May 15, 2006	0.98	0.59–1.76	0.68	3
August 9, 2006	1.96	1.76–2.35	0.34	3
September 20, 2006	0.1	$<$ 0.1–0.0	0	2

[a] Mean computed by assigning detection limit to less than values.

and 12 wk after the May 15 placement on the lake bed and included an uncovered control. The four blocks measured 3 by 15 m with a 3-m border between them. Before benthic barrier installation and at each removal time, the above-sediment portion of plants within a 0.21-m^2 quadrat frame randomly placed within each 3-by-3–m subplot was harvested and transported to a boat where plants were separated by species, bagged, and labeled. Subsequently, samples were taken to a laboratory, dried at 70 C (158 F) for 72 h, and weighed.

SAS/STAT, Version 9.1, software (SAS Institute Inc., Cary, NC) was used for all statistical analyses. Field data were analyzed using general linear model (GLM) ANOVAs. The independent variable was duration of benthic barrier placement, and the dependent variables were biomass of Eurasian watermilfoil and composite biomass of the native aquatic macrophytes. Dependent variables were analyzed using a logarithmic transformation. Pairwise comparisons used Fisher's Protected LSD test means in the GLM procedure.

The 4-wk barrier-treatment plots were resampled 4, 6, and 8 wk after treatment barriers were removed. The 8-wk barrier-treatment plots were resampled 2 and 4 wk after treatment, and the 10-wk barrier-treatment plots were resampled 2 wk after treatment. Sampling ended after 12 wk because of an herbicide application for the study site. Resampling data were analyzed using the GLM ANOVA, split-plot, with repeated measures over time. A logarithmic transformation of Eurasian watermilfoil and composite native plant dry-weight biomass was performed.

Growth and Sediment Depth Experiment. A study was conducted in a walk-in growth chamber in 2006 to evaluate the effect of sediment accumulation over benthic barriers on Eurasian watermilfoil establishment and growth. The experimental design was a randomized complete block with five sediment depth treatments (0, 2, 3, 4, and 5 cm) and four blocks. The experiment was repeated. Typar spun geotextile fabric was fitted to one end of 4.8-cm-diam PVC pipe cut into sections 0.5 to 5 cm in length. Sediment collected from Chatcolet Lake was placed within the horizontally orientated PVC pipe sections over the geotextile fabric at depths of 0, 2, 3, 4, and 5 cm. Five pipe sections were placed in an upright position in each of four 18.4-L (4.86 gal) aquaria filled with deionized water treated with a culture solution simulating natural lake water (Smart and Barko 1984). Photosynthetically active radiation levels were between 382 and 423 µE m^{-2} s^{-1}, and room temperature was between 21 and 23 C (Smart and Barko 1984). Aeration and mixing was provided for each aquarium by four separate aquarium air pumps, and aquaria were covered with transparent Lucite to prevent evaporation and the entry of dust and other airborne contaminants.

A 10-cm apical shoot section of Eurasian watermilfoil was placed on the surface of the sediment or fabric (0 cm sediment) to simulate naturally occurring vegetative reproduction of the species. Shoot length and number of side branches produced were measured 1, 2, 3, and 4 wk after treatment. Apical shoot length and branching data were pooled across two experiments and analyzed using repeated-measures, nested ANOVA. An ANOVA of the rate of change for shoot length and branch number was also conducted. Four weeks after planting, shoot and root biomass were harvested, dried at 70 C for 72 h, and weighed. Data were analyzed using SAS Version 9.1 GLM ANOVA split-plot, repeated measures over time. The independent variable was sediment depth. The dependent variables, Eurasian watermilfoil shoot and root biomass, were transformed by natural logarithm. Pairwise comparisons used least-square means in the GLM procedure.

Results and Discussion

The initial percentage of macrophyte cover ratings before bottom barrier placement in August 2005 in Round Lake ranged from 60 to 90% Eurasian watermilfoil, 0 to 40% waterweed (*Elodea* sp.), and 0 to 20% exposed substrate. The average overall plant height was 1.5 m. Visual ratings of percent of cover during barrier removal of the preliminary study proved difficult because of substrate disturbance and consequent loss of clarity when barriers were removed. Following removal of bottom barriers after 2 wk of coverage time, Eurasian watermilfoil plants beneath barriers resumed vertical positioning in the water column. These plants exhibited stem elongation and apical growth, likely a response to light deprivation. Native *Elodea* sp. was not affected at that time. After 5 wk under barrier panels, Eurasian watermilfoil plants lost foliage along the stem and branches. Percentage of cover by all plants was reduced to 50%, with *Elodea* sp. as the dominant species. At 8 and 10 wk, the remaining Eurasian watermilfoil plants were easily pulled from the substrate once barriers were removed, and the root mass of these plants was greatly reduced and degraded. Results of the preliminary study indicated that an earlier initial barrier coverage date and a minimum coverage time of 4 wk or greater would increase the effectiveness of benthic barriers in eliminating Eurasian watermilfoil infestations. Modifications to the subsequent (2006) study included the installation of barriers 3 mo earlier, and increased barrier duration times between initial and successive sampling dates.

In 2006, the barrier study was installed over known dense infestations of Eurasian watermilfoil in mid May before submersed macrophytic species emergence. In addition to Eurasian watermilfoil, species presence over the course of the study included natives common elodea (*Elodea canadensis* Michx.), coontail (*Ceratophyllum demersum* L.), and pondweed (*Potamogeton* spp.). Benthic barriers removed at 4 wk reduced biomass of Eurasian watermilfoil by 76% of the control (Figure 4a). However, by the end of the 12-wk trial, Eurasian watermilfoil biomass increased 88%, and the time effect of regrowth 4, 6, and 8 wk after removal of the 4-wk barrier placement was significant (Figure 4a). Native plant growth was not reduced by the 4-wk barrier placement, compared with the untreated control, and biomass at 4, 6, and 8 wk after barrier removal was not significantly different than immediately after barrier removal (Figure 4b).

Benthic barriers removed at 8 wk effectively controlled Eurasian watermilfoil (Figure 4c). Eurasian watermilfoil continued to grow over time in the untreated control; however, no regrowth occurred 2 and 4 wk after barrier removal (Figure 4c). Native plant growth was reduced by 79%, but not eliminated by the 8-wk barrier placement. Over time, native plant biomass increased to 21% of the no-barrier control, and the time effect of regrowth both 2 and 4 wk following barrier removal was significant (Figure 4d).

Benthic barriers removed at 10 wk also effectively controlled Eurasian watermilfoil (Figure 4e). Although Eurasian watermilfoil continued to grow over time in the untreated control, no regrowth had occurred 2 wk after barrier removal (Figure 4e). The 10-wk barrier placement reduced native plant growth 93% compared with the no-barrier control, and regrowth 2 wk after removal of the barriers was not significant (Figure 4f). The results of the duration of barrier-placement study indicated that the 8 wk benthic barrier coverage time resulted in the greatest

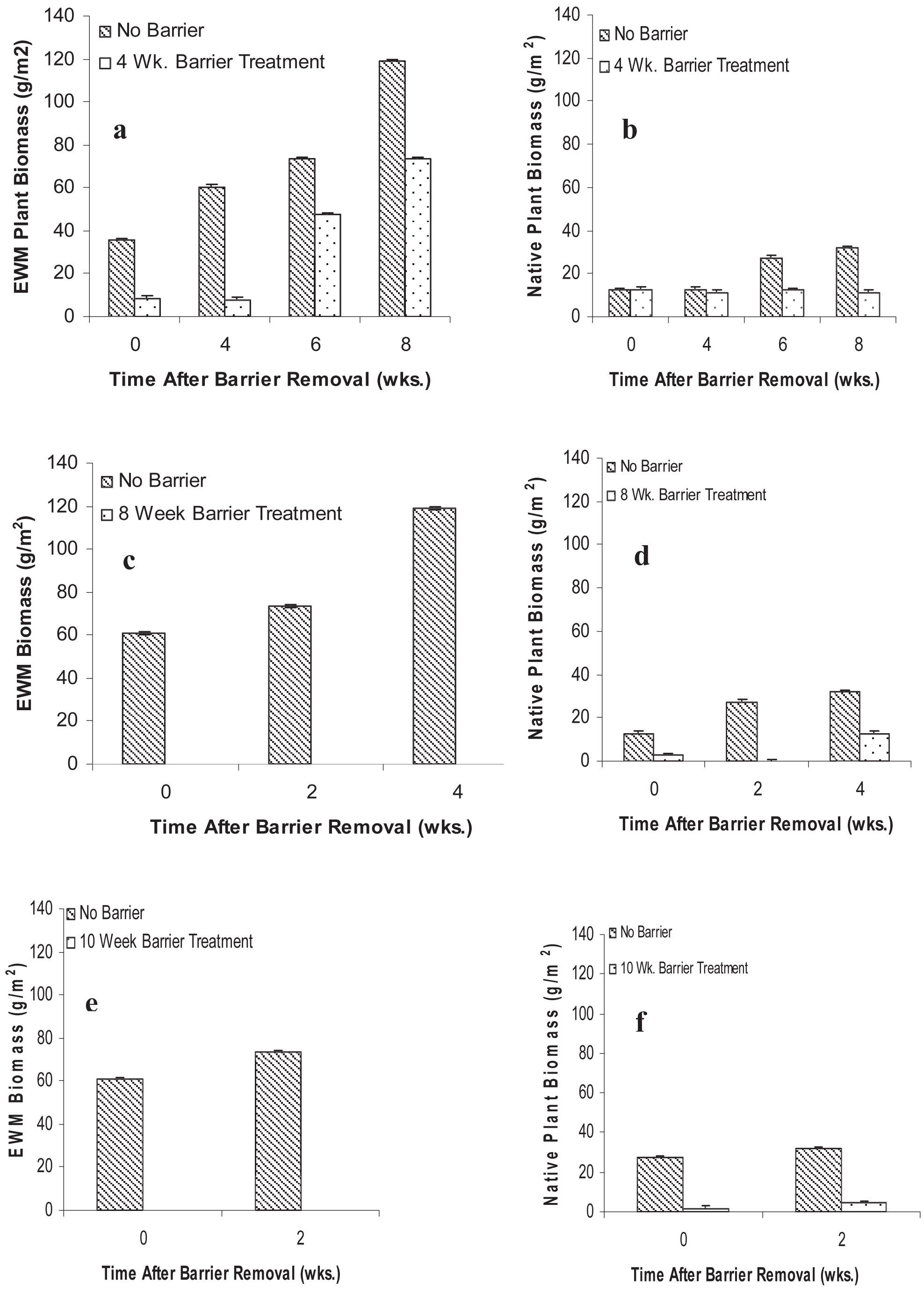

Figure 4. Eurasian watermilfoil and pooled native plant biomass from samples collected following removal of benthic barriers after (a and b) 4-, (c and d) 8-, and (e and f) 10-wk barrier duration treatments and the no-barrier controls. All statistical inferences were based on log transformations. Error bars represent the standard error. Pairwise comparisons using least-square means were used to separate means and differences within a treatment over time at P = 0.05.

reduction of Eurasian watermilfoil biomass with the least reduction in native plant biomass (Figures 4a–f).

Shoot biomass was significantly different in both repetitions of the sediment depth growth chamber study (Figure 5a and 5b). Root biomass was not different in the first repetition of the experiment, and those data are not shown. Placement of sediment within PVC rings fitted with the geotextile fabric and anchoring of Eurasian watermilfoil fragments within the rings were more precise in the second repetition of the study, which may have

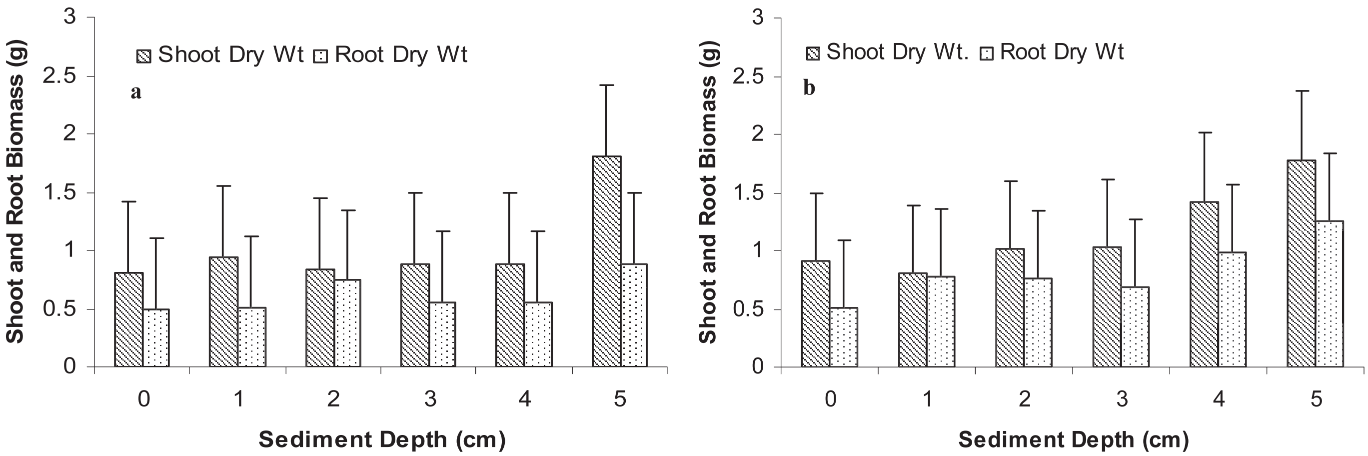

Figure 5. Eurasian watermilfoil shoot and root biomass harvested after 4 wk from aquaria located in a walk-in growth chamber. Apical growing shoot sections 10 cm in length were placed on geotextile fabric covered with lake sediment at depths of 0 to 5 cm. Letters on charts denote the following: a, repetition 1; b, repetition 2. All statistical inferences were based on log transformations. Error bars represent the standard error. Pairwise comparisons using least-square means were used to separate means and differences at P = 0.05.

resulted in differences in root biomass being detected (Figure 5b). Results of the sediment-depth study showed that, at 1 to 3 cm sediment depths, Eurasian watermilfoil shoot and root biomass were not different from the 0 sediment control, indicating the plants were able to draw nutrients from the water without establishing on the fabric barrier material. The increase in shoot and root biomass at sediment depths of 4 and 5 cm in the second repetition of the study (Figure 5b) indicated the plant's ability to establish and draw nutrients from the sediment. Sediment depth did not affect shoot length and branch number, and those data are not shown. Based on the growth chamber study, sediment deposition of 4 cm or greater over benthic barrier treatments would enable reestablishment of Eurasian watermilfoil; therefore, sediment should be removed from the barriers before a sediment accumulation of 4 cm.

Overall conclusions from this study are that benthic barriers can be a valuable tool for incorporation into integrated control strategies, can be useful in situations in which herbicides will not be applied, and may have the potential to eradicate small infestations of Eurasian watermilfoil.

Results of the growth chamber study suggest that regular monitoring and maintenance of sediment deposition over benthic barriers is critical to barrier effectiveness, and barriers should be cleaned of sediment when sediment reaches a 4 cm depth. Sediment deposition varies among different water bodies because of differences such as site exposure, basin morphology, and sediment particle size; therefore, predicting the timing of maintenance is not feasible.

Acknowledgments

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