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Lake Restoration Using Mechanical, Chemical and Biological Control Strategies for Eurasian Water Milfoil (*Myriophyllum spicatum*)

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Introduction

In recent years, communities throughout the United States and Canada have spent millions of dollars in an attempt to restore lakes invaded by the submersed aquatic exotic Eurasian watermilfoil (*Myriophyllum spicatum* L.). Eurasian watermilfoil is native to Europe, Asia and northern Africa, and was introduced into eastern North America sometime between 1880 and 1940, although the exact date is unknown (Couch and Nelson 1985). Since the 1950's, Eurasian watermilfoil has spread westward through the major lake systems of the Great Lakes basin and further to British Columbia, becoming the primary nuisance aquatic plant in many waters as far north as Alaska and as far south as Florida (Smith et al. 1991, Aiken et al. 1979). In Minnesota, Eurasian watermilfoil is found mainly in lakes and rivers in the Minneapolis-St.Paul metropolitan area. Of the 74 bodies of water known to have milfoil infestations, only six are outside the borders of the seven counties making up the metropolitan area, reflecting the high use and boat traffic of these waters. Eurasian watermilfoil (milfoil) adversely affects recreational use by accumulating in large piles on beaches, interfering with boating, swimming and sportfishing. Milfoil also obstructs industrial and residential water intake sites and can alter water temperature profiles by as much as 10° C/m in shallow water (Aiken et al. 1979). Dense canopies of *Myriophyllum spicatum* have been shown to suppress the growth of native submersed macrophytes (Madsen et al. 1991), sometimes completely replacing native species. In some lakes, studies suggest that excessive macrophyte structural complexity, as seen in *Myriophyllum spicatum*, can negatively impact largemouth bass (*Micropterus salmoides*) populations (Crowder and Cooper 1979, Wiley et al. 1984).

M. spicatum is a perennial dicot of the family Haloragaceae, and is typically found in greatest abundance in mesotrophic or slightly eutrophic lakes at depths of 1-10 meters (Smith and Barko 1990). Eurasian watermilfoil is evergreen, resembling the native Northern watermilfoil *Myriophyllum sibiricum*, with shoots originating from an adventitious root system that grows best in non-organic sediments (Hotchkiss 1972). Shoots begin to grow as early as January in lakes of the midwestern United States, sending single stalks to the surface where the plant begins to branch out considerably, forming a dense mat of feather-like leaves (Aiken 1979). Low light conditions due to turbidity favor the surface canopy formation of *M. spicatum*, as plants in clear water do not generally extend to the surface (Barko and Smart 1981, Nichols and Shaw 1986). Eradication of milfoil and restoration of the natural ecology of infested North American lakes has been largely unsuccessful due to the high degree of vegetative dispersal demonstrated by *M. spicatum* (Smith and Barko 1991).

Mechanical Control

Given the reproductive nature of *M. spicatum*, lake restoration defined by the eradication of Eurasian watermilfoil cannot be accomplished by mechanical methods, and so will not be covered here in great detail. However, reclamation of recreational waterways and access areas can be accomplished either through direct harvesting or interruption of photosynthesis using bottom coating fabrics (Grinwald 1968, Engel 1984). The Lake Minnetonka, Minnesota Water Control District harvests milfoil regularly throughout the growing season. Custom designed milfoil harvesters push a 4.9 meter wide underwater boom scythe while raising the vegetation on board using a conveyer belt. This method can only remove milfoil to a depth of 6 feet, and repeated harvesting is needed. Research has demonstrated that mechanical harvesting of Eurasian watermilfoil increases the growth rate of the plant, and can seriously deplete the numbers of herbivorous invertebrates, allowing harvested areas to regain their original biomass in less than one month (Crowell et al.1994). To be cost effective on large lakes, this method of reclamation requires a transfer of harvested vegetation to a fast moving barge in order to expedite transfer of materials to shore for proper disposal. In addition, most state agencies do not have the funding to manage all shorefront property, and thus the financial responsibility of milfoil management defaults to property owners and city governments.

Water drawdown has been used in some Tennessee Valley Authority reservoirs, where water control structures are in place. This method has proven effective but is prohibitively expensive and culturally unacceptable in many situations involving recreation.

Covering lake bottoms with opaque polyvinyl chloride or fiberglass fabric effectively eliminates all vegetation initially, but removal of these barriers is often followed by one or two years of poor native plant growth, followed by regrowth of milfoil (Perkins 1980, Engel 1984, Helsel 1996). Because of the tremendous cost of installation and maintenance, only Florida, Washington and Vermont currently use this strategy for boating lanes (Welling 1997).

Chemical control

Herbicides have been used to control Eurasian watermilfoil since the 1960's. Having been shown to be particularly susceptible to 2,4-D (2,4-dichlorophenoxyacetic acid) treatment in lentic environments, *M. spicatum* can be eliminated in the laboratory with a 48 hour exposure to 2,4-D concentrations as low as 1.0 ppm water. In many Canadian and U.S. lakes, a popular chemical treatment used is a granular pellet formulation of 20% attaclay and 2,4-D butoxyethanol ester (Aqua-KleenÒ), which operates by slow release of 2,4-D into the treated water column. In aquatic macrophytes, 2,4-D is taken up both by the roots and leaves, and causes increased cell division and metabolism resulting in injury susceptibility and eventual cell death. A twisting and downward curvature of stems and leaves is an obvious system of plant injury and herbicide effectiveness (Welling 1997a).

Field success is predictable in low movement lentic systems, with milfoil elimination possible at 0.5 mg acid equivalent 2,4-D/L for a 72 hour minimum exposure (0.19 mg ae per mg of herbicide). Exposure times can be shortened to 36-48 hours for 1.0 mg ae/L and to 24-36 hours for 2.0 mg ae/L 2,4-D. Field conditions vary tremendously, and herbicidal concentrations can increase with current, depth and temperature, requiring careful calculation by the manager (Getsinger and Netherland 1997). An additional problem for managers is that the Environmental Protection Agency limits the use of 2,4-D for milfoil control to 111 kg/ha, ignoring concentration values and thus limiting the efficacy in some lakes. Minnesota has encountered some difficulty in controlling *M. spicatum* populations due to the restrictions on treatment amounts (Welling 1997a). Current procedures for some agencies also do not require depth measurements for 2,4-D application, and base amounts on a per acre or per hectare measurement. Consequently, the final concentration of herbicide in some areas could be far from the target concentration. The Army Corps of engineers recommends continuing studies of chemical exposure time to minimize the concentration of herbicides needed for successful control.

Since the early 1980s, experiments have examined the efficacy of fluridone herbicide (1-methyl-3-phenyl-5-[3-(triflouromethyl)phenyl]-4(1H)-pyridinone) on *M. spicatum* in the laboratory and in the field. Fluridone (SonarÒ) is usually applied to whole lakes or bays to control a variety of submersed macrophytes and has a mean aquatic half life of approximately 20 days (Range 5-60 days)(West et al. 1983). Although initial plant injury correlates positively with increasing concentration of fluridone, long term control of several species is similar after exposure to concentrations ranging from 10 to 10,000 m g/L (Netherland et al. 1993). Laboratory trials have also shown that longer exposure to lower fluridone concentrations can be successful in controlling *Hydrilla verticillata* and *M. spicatum*. Concentrations of less than 1 m g/L were shown to suppress milfoil recovery after the plants had been treated with high concentrations (^{3} 25 m g/L). Various half life evaluations have concluded that exposure of *M. spicatum* to high (>10 ug/L) initial fluridone concentrations would damage the plant sufficiently to cause lethal injury. The high initial concentrations also ensured the slow release of fluridone over time, allowing for levels of 1-3 ug/L for up to 170 days after treatment (Netherland and Getsinger 1995).

In separate restoration attempts, the Minnesota DNR applied fluridone to two mesotrophic lakes (Zumbra and Parkers) infested with Eurasian watermilfoil. Aqueous suspensions of fluridone were applied to yield concentrations recommended by the manufacturer (10-20 ppb). Zumbra Lake was treated at 10 ppb and the concentration of fluridone remained at this level for 30 days; eventually dropping to approximately one ppb 24 weeks post treatment. Treatment resulted in a 30% drop in the percentage of sampling stations showing any vegetation. Plant species diversity dropped to 25% of the original value and remained at this level 2 years after application. After two years*, M. spicatum* did not reappear, but the three common native plants had not returned to pre-treatment levels (Welling et al. 1997).

In the rehabilitation attempt at Parkers Lake, species richness and diversity also dropped, but returned to pre-treatment levels within two years of exposure to fluridone. Eurasian watermilfoil was found prior to the end of the first year of treatment, and by the end of the second year, had returned to pre-treatment levels. The abundance of curly-leaf pondweed (*Potamogeton crispus*), another Minnesota exotic was not affected by the herbicide. Fluridone treatment resulted in the long term reduction of certain plant species, including northern watermilfoil, waterweed (*Elodea* sp.), large-leaf pondweed (*Potamogeton amplifolius*), and coontail (*Ceratophyllum demersum*). In Zumbra Lake, fluridone had a significant effect on fish populations, causing a 30% decline in the number of fish species, most of which are dependent on submersed macrophytes for cover. A similar effect was shown on Parkers Lake, where removal of cover resulted in a decreased mean length of bluegills *(Lepomis macrochirus*). The reason for the decline in these fish populations is probably due to increased predation due to lack of cover rather than a toxic effect of the herbicide. Based on this data and inconsistent data from two other lakes, the Minnesota DNR has determined that treatment of lakes with fluridone does not meet the criteria for selective control of Eurasian watermilfoil and therefore cannot be widely used as a viable method of eradication at this time (Welling et al. 1997). If public pressure was great enough, and natural fish and vegetation communities could be readily restored, then high concentrations of fluridone may become acceptable.

Other herbicide treatments include Triclopyr, (3,5,6-trichloro-2-pyridinyloxyacetic acid), Bensulfuron methyl, and the contact herbicides, Endothall, Diquat and copper. These herbicides have undergone some laboratory trials, but field data is limited.

Iron complexing of nutrients has been proposed as a method of destroying milfoil populations while leaving native plants unharmed. In experiments testing the effect of iron treatments on water quality, Clear Water Technologies Inc. (CWTI - Fridley, MN) serendipitously discovered a potential method of nuisant aquatic weed control. CWTI uses a patented method whereby elemental iron is used as an electron acceptor in anaerobic sediments, with Fe^{2+} forming ionic bonds with sulfur and phosphorous. The density of the iron powder facilitates rapid incorporation into the anoxic sediments, and can be effectively removed with magnets. Sediment iron removes nutrients through the production of ferrous sulfate and ferrous phosphate, resulting in a decline in the production of hydrogen sulfide, increase in Secchi depth, and dramatic reduction in blue-green algae populations (Hogen and Rupert 1997). Laboratory studies demonstrate that iron treatment at 3.9g Fe^{2+}/ft^2 slowed the growth of *M. spicatum*, while doses above 6.52g Fe^{2+}/ft^2 were lethal to all Eurasian watermilfoil plants tested.

Lake rehabilitation trials on two small Minnesota lakes resulted in decreases in total phosphate, sulfide and sulfate concentrations, and complete eradication of Eurasian watermilfoil in treated areas. If iron complexing proves to be successful in the long term, the advantage is that application is independent of concentration, and can be based on square footage, thus eliminating the depth parameter that can make herbicide application problematic. The field studies in which sediment was treated at 19g Fe^{2+}/ft^2 resulted in no milfoil growth for at least five years, while the 10g Fe^{2+}/ft^2 dose resulted in the initial eradication of milfoil with an eventual regrowth (Hogen and Rupert 1997). This technology needs more detailed experimentation, but has shown selective eradication of *M. spicatum* and *P. crispus*, while leaving native species unaffected. MN DNR fisheries data has shown no negative effects of treatment on fish populations.

The exact process by which the iron treatment effects the death of milfoil plants is unknown at this time. CWTI hypothesizes that the removal of sulfur from the system may be responsible for the selectivity of the process. The Minnesota Pollution Control Agency has delayed efforts to field test this process due to concerns about exceeding iron levels and other possible effects. Removal of the complexed iron from treated lakes would raise the expense of the treatment, but total treatment costs would still be less than one half of the cost of herbicide treatment. CWTI is pursuing application of the iron complexing technology in other states with lake restoration plans (Hogen 1997).

Biological Control

In recent years, the control of exotics by biological means has come into the forefront of ecosystem restoration technology. Early in the 1990s, Robert Creed and Sallie Sheldon hypothesized that the decline of milfoil biomass in Brownington Pond, a 64 ha Vermont lake, could have been caused by a native herbivorous weevil, *Euhrychiopsis lecontei* (Creed and Sheldon 1993, Creed and Sheldon 1994). *E. lecontei* was initially found to reduce the buoyancy of Eurasian watermilfoil, with the weevils causing an 80% decrease in the percentage of floating plants over the control (Creed and Sheldon 1993). Adult weevils feed on meristem, leaves and stems of *M. spicatum* and *M. sibiricum*, while larvae start feeding in the meristem and then move down the stems, burrowing into the tissue. The consequences of *E. lecontei* herbivory include loss of buoyancy, weakening of stems, disruption of nutrient passage and direct removal of leaves (Creed and Sheldon 1995, Newman et al. 1996). Samples of milfoil beds in Brownington Pond from 1990-1992 demonstrated that the biomass of milfoil decreased substantially as the number of weevils per milfoil stem increased. There were approximately three weevils per stem during the summer of 1992, when milfoil biomass reached its lowest level (Creed and Sheldon 1995).

The possible application to large scale restoration of lakes is aided in that weevil damage has a negative effect on the viability of *M. spicatum* fragments, and could inhibit the spread of the plants. Being a native species, *E. lecontei* satisfies two of the three requirements for successful biocontrol agents (Harley and Forno 1992), including permanence of the agent in the biota, and self reproducing and perpetuating agent populations. The third and most important criteria, providing acceptable control of the target plant, is currently under investigation. Using native biocontrol agents can present fewer problems than introduction of exotic control agents, but the consequence of using native agents is that those agents are probably already adapted to some relationship with native plants. However, once exposed *to M. spicatum*, *E. lecontei* has been shown to prefer *M. spicatum* over *M. sibiricum* and non-milfoil hosts (Newman et al. 1996, Solarz and Newman 1996). Another problem with *E. lecontei* strategies is that mechanical harvesting usually removes the top 1-6 feet of milfoil beds, which includes the majority of the *E. lecontei* preferred habitat. Mechanical removal can have a serious negative impact on weevil populations (Sheldon and O'Bryan 1996). No large scale field studies have attempted to use *E. lecontei* to reduce milfoil populations.

Although other aspects of biological control have been investigated, none show as much promise as *E. lecontei*, which is partly due to the fact that research into plant pathogens specific to *M. spicatum* is limited (Shearer 1997). Field studies in the use of the herbivorous grass carp (*Ctenopharyngodon idella*) have had very limited success, as *M. spicatum* is one of the grass carp's least preferred species.

Conclusions

Habitat restoration in lakes infested with milfoil can be achieved by removing the stressor (exotic species) and allowing native plants to regain dominance (Hogen and Rupert 1997). In examples where herbicides have been used, however, dominant native species are sometimes lost or depleted (Welling et al.1997). Lake restoration defined by the complete eradication of Eurasian watermilfoil and re-establishment of native species is a daunting task, and to date, no attempts have been successful in completely removing milfoil from large bodies of water. Some lakes in

California have been cleared of *Hydrilla verticillata*, but these involved draining the lakes, and treating all sediments and tributary water sources with herbicides (Smith et al. 1991). Herbicidal restoration will not be socially or politically acceptable until there is a specific method for killing only exotics, as broad spectrum herbicides destroy too much of the native flora. In Minnesota and other states, unnecessary destruction of vegetation in state waters is not permitted.

Little research has been conducted into combining different mechanical, chemical and biological treatments of Eurasian watermilfoil, however; Army Corps of Engineer researchers have demonstrated successful integration of chemical and biological agents in the control of *Hydrilla*. Treatment of *Hydrilla* with the microbial pathogen *Mycoleptodiscus terrestris* greatly enhanced the effectiveness of fluridone treatment (Netherland and Shearer 1996). Successful eradication is also highly dependent on the prevention of re-invasion through human activity (Smith et al. 1991).

Lake reclamation defined by successful control and management of Eurasian watermilfoil populations at acceptable levels may be the most viable strategy, pending successful selective removal strategies. Successful high intensity management in British Columbia involves rototilling, dredging and herbicide treatment in combination with boater education and inspection programs. Still, despite intense control efforts, Shuswap Lake milfoil populations increased in density and spread to other lakes (Smith et al. 1991). Many of the lakes of concern have *M. spicatum* problems because they are heavily populated and intensely used by traveling recreationalists and sportfishers. Due in part to the high use, these lakes are often warm (25-30° C), have low organic sediments, high nutrient levels, and some algal growth, making them prime candidates for milfoil proliferation.

Laboratory and small scale field studies have demonstrated some successes in controlling Eurasian watermilfoil growth and spread, but the future of lake restoration and reclamation will require large scale field tests to determine if methods are scale dependent. Adaptive management scenarios involving large experiments on candidate lakes should be considered. Public education is needed to make large scale experiments acceptable and to ensure their successful completion without unnecessary human disturbance.

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