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THE ROLE OF SUBMERSED AQUATIC VEGETATION AS HABITAT FOR FISH IN MINNESOTA LAKES, INCLUDING THE IMPLICATIONS OF NON-NATIVE PLANT INVASIONS AND THEIR MANAGEMENT

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Executive Summary

This review updates the Division of Fish and Wildlife's understanding of the role of submersed aquatic vegetation (SAV) in providing fish habitat in Minnesota lakes. Below, are several generalizations and recommended approaches for aquatic plant management.

1. Many fish, such as sunfish, largemouth bass, northern pike, and muskellunge, depend on SAV for food and shelter. Nongame fish such as darters, minnows, and killifishes depend primarily on nearshore emergent and submersed vegetation.
2. The presence of SAV tends to promote higher water clarity.
3. Black bullhead and common carp often dominate turbid lakes with little to no SAV. Carp are an invasive non-native species that contributes to the loss of native SAV by dislodging rooted plants and resuspending sediments.
4. Generally, conditions for game fish deteriorate when the percentage of a basin that is covered with SAV falls below 10% or exceeds 60%. This range does not consider basin morphometry (i.e., shallow versus deep) which ultimately controls how much vegetation naturally grows within a lake.
5. Studies show native plants provide higher quality habitat for desirable fish than invasive non-native plants such as curly-leaf pondweed or Eurasian watermilfoil. However, these non-native plants provide better habitat than little or no SAV.
6. Minnesota lakes infested with curly-leaf pondweed or Eurasian watermilfoil have not seen large declines in game fish populations.
7. Lake productivity and initial plant conditions appear to greatly affect selective whole-lake herbicide's (such as fluridone) effect on fish habitat. Whole-lake studies in infested, moderately-productive (mesotrophic) Michigan lakes with abundant native plants, showed neutral to positive effects of fluridone on fish habitat.

13. Fluridone applications in infested productive (eutrophic) Minnesota lakes with low cover of native SAV can have dramatic negative effects on SAV habitats, water clarity, and fish communities.

14. Aquatic plant management policies should reflect a precautionary approach where it is understood that any alteration to SAV will invariably have some effect on a lake's fish community. Therefore, policies should ostensibly be conservative with the intent to minimize habitat degradation.
15. Limiting the cumulative amount of SAV removal may be the most prudent approach towards precautionary management. However, thresholds should be dependent on lake type. The current 15% rule (maximum treatment area within the 15 foot depth zone) for chemicals and 50% rule for mechanical harvesting may be reasonable for some lakes (e.g., small eutrophic lakes); stricter thresholds may be needed for others (e.g., soft water lakes, large or deep lakes).
16. Overall, whole-lake aquatic plant treatment is risky. Significant biological risks associated with large-scale manipulations include excessive removal of fish habitat and thus decline of fish populations, loss of sensitive plant species, declines in water clarity and potential long-term cumulative effects of multiple treatments, since eradication of non-native plant species is highly unlikely.
17. Vegetated, nearshore habitat is critical for fish recruitment. Any removal should be viewed as habitat loss, and efforts should be made to minimize this loss. It follows that 100 feet of removal is worse than 50 feet of removal even if the removal is of a non-native species.
18. Mechanical harvesting may be the best alternative for managing nuisance surface growth of vegetation. Although this requires perpetual maintenance, harvested boat lanes through surface-growing vegetation represents a positive benefit for recreational access and fish habitat (harvested strips of SAV increases edge and may benefit game species).

Introduction

The role of submersed aquatic vegetation (SAV) in structuring lake ecosystems, and in particular fish communities, has been the source of much research during the last 25 years. Several published papers comprehensively review these roles and demonstrate that the relationship between SAV and fish is highly complex and variable (Dibble et al. 1996; Weaver et al. 1996; Diehl and Kornijów 1998; Petr 2000). Nevertheless, several generalizations have emerged from this collective body of research. They are discussed here in the context of Minnesota lakes.

The relationship of SAV and fish varies among lake types, thus we must first establish a framework on which these generalizations may be based. The quality of lakes as habitat for fish, depend on their glacial history, climate, water chemistry, productivity, and morphometry (Tonn and Magnuson 1982; Tonn 1990; Schupp 1992). In Minnesota, we see a great diversity of lake types, each displaying its own physical and biological 'signature' (Figure 1, Table 1). Environmental filters, hierarchical in space and time (i.e, continental → regional or watershed → lake-type → within-lake), determine these signatures and constrain fish communities within a defined range (Tonn 1990). Herein, we focus primarily on the lake type and within lake effects of SAV on fish populations. However, the following generalizations should be interpreted as nested within the context of these larger filters operating on any particular waterbody of interest.

Aquatic plants serve many ecosystem functions including primary production, stabilizing sediments, maintaining water clarity, and providing habitat for zooplankton, macroinvertebrates, and numerous fish species (Carpenter and Lodge 1986; Dibble et al. 1996; Diehl and Kornijów 1998). Many

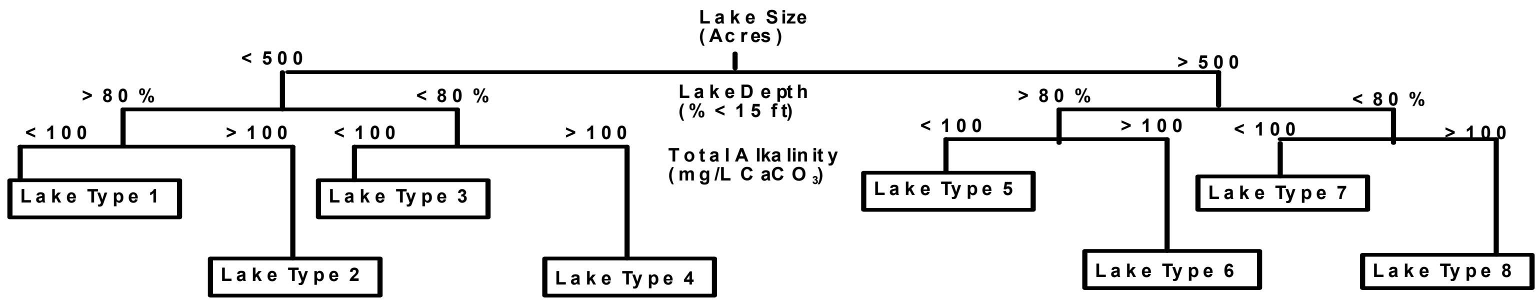

Figure 1. Physical classification of Minnesota Lakes using a reduction or 'lumping' of Schupp's (1992) lake classification groupings. Separation of large and small lakes is arbitrary and relative to the size range of lakes in Minnesota.

Table 1. Characteristics of the eight distinct types of Minnesota Lakes identified in Figure 1.

Lake Type	Description	Number of Lakes	Location	Productivity[a]	Relative Plant Species Richness[b]	Relative SAV Abundance[c]	Alternate Stable States[d]	Non-native Plant Infestations[c]	Fish Species Richness
1	Small, shallow, soft water	991	N. Central – NE	Moderate to high	High	Low		rare	Low
2	Small, shallow, hard water	408	Central – SW	high to very high	Low	Low to High	√	common	Low
3	Small, deep, soft water	685	N. Central – NE	Moderate	High	Low		rare	High
4	Small, deep, hard water	1,173	Central	Moderate to high	Moderate	Low to High	√	common	Low to High[e]
5	Large, shallow, soft water	34	NE	High	High	Low		rare	Low
6	Large, shallow, hard water	190	Central – S. Central	High	Low	Low to High	√	common	Low
7	Large, deep, soft water	102	NE	Low to moderate	No Data	Low		rare	moderate
8	Large, deep, hard water	340	N. Central	Moderate to high	High	High		More than rare, less than common	high

[a] Productivity is based on Trophic State Index (Carlson 1977) and is a combination of water clarity (secchi), phosphorus concentration (total phosphorus), and algal concentration (Chlorophyll a).
[b] Relative plant species richness was determined by DNR vegetation survey species lists.
[c] Statistical analyses (cluster analysis) to determine relative abundance of aquatic vegetation was performed on recent vegetation survey data from 1,410 lakes collected by Minnesota DNR Fisheries field personnel (P. Radomski, unpublished data).
[d] Alternate stable states refers to the dynamic characteristic of shallow lakes whereby abundant vegetation and relatively clear water occupy one state and turbid water with no submersed vegetation occupies another mutually-exclusive state.
[e] Fish species richness in this lake class depends on the productivity and the SAV richness in the lake; highly productive lakes with species poor SAV communities have low fish species richness.

species of fish depend on SAV for their survival. In fact, Dibble et al. (1996) noted that 112 fish species representing 19 families were found in SAV habitats in the Upper Mississippi River Basin. Studies consistently demonstrate that fish abundance is greater in vegetated habitats than in unvegetated habitats (Dibble et al. 1996; Cross and McInerny 2001; Pratt and Smokorowski 2003). Submersed vegetation attracts an abundance of invertebrates that provides prey for many juvenile game fish and nongame fish species (Keast 1984). This attracts larger, predatory game fish that patrol the edge of plant beds or wait in open pockets to ambush fish prey (Killgore et al. 1989). Many fish species depend on SAV for nest building and spawning. Nearshore vegetation is particularly important nursery habitat for young age classes of fish and small nongame fish (Poe et al. 1986; Bryan and Scarnecchia 1992). Nearshore vegetation also is critical for many wildlife species including ducks and wading birds. Aquatic vegetation is consumed by some animals while other animals consume the macroinvertebrates living on SAV.

In Minnesota lakes, SAV is important to game fish such as sunfish *Lepomis* spp., largemouth bass *Micropterus salmoides*, northern pike *Esox lucius*, and muskellunge *Esox maquinongy.* These species depend on SAV for spawning, refuge and foraging. Other species such as smallmouth bass *Micropterus dolomieu,* yellow perch *Perca flavescens*, walleye *Sander vitreus*, crappie *Pomoxis* spp., white bass *Morone chrysops,* and catfish *Ictalurus* spp. are adapted to open water environments, and SAV is of less importance for their populations (Dibble et al. 1996; Cross and McInerny 2001).

Vegetated Minnesota lakes support a diversity of nongame species including numerous minnow and shiner species (Family: Cyprinidae), yellow bullhead *Ameiurus natalis*, banded killifish *Fundulus diaphanus*, brook silverside *Labidesthes sicculus,* and some darter species *Etheostoma* spp. In contrast, black bullhead *Ameirus melas* and non-native carp *Cyprinus carpio* are often associated with turbid lakes with little to no SAV because they are tolerant of the low oxygen environments typically associated with these lakes (Drake and Pereira 2002). Carp directly affect the abundance of SAV by dislodging rooted plants while feeding, and reducing opportunities for reestablishment by increasing the sediment and nutrients in the water column. In doing so, they increase their competitive advantage over most game fish (Breukelaar et al. 1994; Lammens 1999; Parkos et al. 2003).

Given the importance of SAV for fish populations and productive fisheries, fisheries managers have sought to identify the level of aquatic plant abundance that supports high game fish production, particularly for largemouth bass and bluegill *L. macrochirus*. Crowder and Cooper (1979) developed a model that suggested that predator feeding rate, and thus growth and production, should be highest at intermediate levels of plant abundance. At low plant abundances, prey are scarce because of a lack of predator refuges. At high plant abundances, visual and swimming barriers created by dense vegetation reduce the ability of predators to capture fish prey. Indeed, several experimental studies have documented a reduction in predator feeding rates as vegetation becomes more dense (Crowder and Cooper 1982; Savino and Stein 1982; Anderson 1984; Gotceitas and Colgan 1987; Diehl 1988; Valley and Bremigan 2002a).

Numerous studies from southern U.S. lakes and reservoirs have, at least in part, supported this theory. In general, when vegetation covers less than 10% of a waterbody (e.g., turbid reservoirs), vegetation-dependent species are scarce and production of largemouth bass and bluegill is low (Durocher et al. 1984; Bettoli et al. 1992; Maceina 1996; Wrenn et al. 1996, Miranda and Pugh 1997). When vegetation coverage exceeds 40-60% of the entire waterbody (i.e., shallow vegetated lakes or bays), low feeding rates or poor growth by predators commonly result (Colle and Shireman 1980; Bettoli et al. 1992; Maceina 1996; Wrenn et al. 1996; Miranda and Pugh 1997). This suggests that the probability of finding a quality largemouth bass or bluegill population is highest between 10% and 60% total cover of SAV. Less work has been done in north temperate lakes, nevertheless, Wiley et al. (1984), Trebiz et al.

(1997), Schneider (2000), and current studies in Michigan (K. Cheruvelil and N. Nate, Michigan State University, Department of Fisheries and Wildlife, unpublished data) together suggest a preferred range of 18% – 40% total cover of SAV.

Pursuit of this elusive 'optimal' percent coverage of SAV for littoral fish species has revealed numerous complexities of lakes that taken together, question the appropriateness of using a defined percentage in structuring management decisions (Hoyer and Canfield 2001). Below, we list important characteristics and features of lakes that are overlooked when relating coarse estimates of SAV cover to fish.

- Availability of other critical microhabitats such as spawning substrates (Annet et al. 1996; Weaver et al. 1996).
- Ecological constraints operating at scales greater than the scale of analysis (Tonn 1990; Hinch 1991; Dibble et al. 1996; Weaver et al. 1996; Miranda and Dibble 2002).
- Lake depth controls the maximum cover of SAV. Naturally, lakes with > 60% cover are shallow lakes. No published studies to our knowledge show reducing vegetation cover in shallow lakes improves fish growth. In deep lakes, percent whole-lake cover of SAV will never be excessive (Hoyer and Canfield 2001). Most published studies have not explored the effect of a range of SAV cover solely within the littoral zone.
- Lake size, depth, shape, water chemistry, trophic status, substrates (Downing et al. 1990; Downing and Plante 1993; Chick and McIvor 1994; Hoyer and Canfield 1996; Maceina 1996; Weaver et al. 1996; Vestergaard and Sand-Jensen 2000)
- Aquatic plant architecture and patchiness (Chick and McIvor 1994, 1997; Weaver et al. 1997; Valley and Bremigan 2002a). For example, 100% cover of a low-growing macrophyte species such as chara *Chara* spp. provides vastly different habitat than 100% cover of a canopy species such as Eurasian watermilfoil *Myriophyllum spicatum*.
- Composition of the food web and interactions between littoral and pelagic habitats (Diehl and Kornijów 1998; Lodge et al. 1988).

Habitats created by plants are affected by, and nested within, other physical forces affecting the total habitat heterogeneity of a particular lake. We use the term 'heterogeneity' to reflect what is commonly referred to as 'quality.' 'Quality' is subjective and difficult to measure. 'Heterogeneity' simply refers to a collection of diverse micro-habitats suitable for a variety of fish species. Factors such as lake size, shape, depth, substrate composition, water chemistry, and productivity influence the distribution of non-macrophyte habitats (e.g., gravel substrates), as well as control the composition, abundance, and distribution of plant species assemblages (Figure 2; Duarte and Kalff 1990; Nichols 1992; Weaver et al. 1996; Vestergaard and Sand-Jensen 2000). Ultimately, heterogeneity will be highest in large lakes with convoluted shorelines and complex basin morphometry (i.e., variable slopes, and numerous points, and islands), high water clarity with moderate nutrient levels, and high substrate diversity (i.e., patches of clay, muck, sand, and gravel). These conditions provide habitats for a diversity of aquatic plant species, thereby providing habitat for a diversity of fish species.

It is widely recognized that holding all the above habitat factors constant, quality fish habitat is associated with diverse plant communities. Diversity in the architectural growth form (arrangement of stems and leaves) of individual plant species and the spatial distribution and species composition of plant beds creates a patchy littoral landscape. Studies demonstrate that a diversity of plant types and patchiness is positively related to fish diversity (Weaver et al. 1996, 1997; Pratt and Smokorowski 2003), abundance

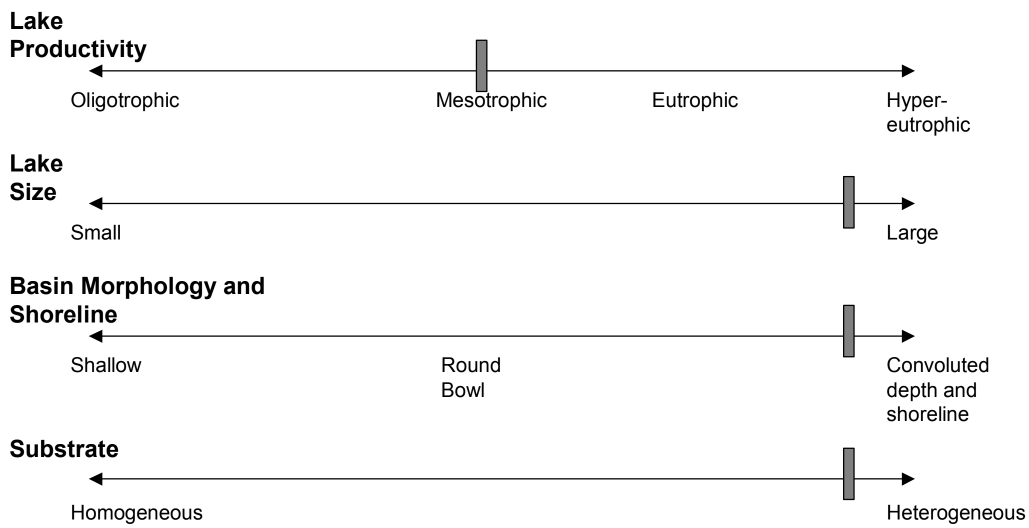

Figure 2. Conceptual heterogeneity "Equalizer" with gray bars demonstrating levels of highest habitat heterogeneity. Collectively, these characteristics generally lead to diverse macrophyte assemblages, thereby providing a feedback to habitat heterogeneity.

(Killgore et al. 1989; Chick and McIvor 1994, Pratt and Smokorowski 2003) and predator foraging abilities (Valley and Bremigan 2002a). Multiple age-classes and species of fish depend on a diversity of habitats for their spawning, foraging, and refuge needs (Chick and McIvor 1994; Werner et al. 1977; Annet et al. 1996; Weaver et al. 1996, 1997).

Patchiness is highly scale-dependent and is perceived differently by species of fish depending on their size and home range (Kotliar and Weins 1990; King 1993; Essington and Kitchell 1999; Pratt and Smokorowski 2003). Therefore, for small vegetation dwelling species, plant composition at small scales (1 x 1 x 1 m volume of water close to shore) is perhaps more important than the spatial arrangement and size of large offshore beds of vegetation. In contrast, larger, more mobile species such as adult largemouth bass, northern pike, and muskellunge respond to patchiness at larger scales, and a lake's patch mosaic becomes increasingly important to their success (Cross and McInerny 2001). Diverse native plant communities produce heterogeneity at multiple spatial scales.

SHALLOW LAKES – UNIQUE IN THEIR STRUCTURE AND FUNCTION

In our consideration of the diversity of Minnesota lakes, shallow lakes (lake types 1, 2, 5, and 6) deserve special attention. Figure 2 suggests, shallow lakes inherently have low habitat heterogeneity. Environmental factors such as oxygen depletion in winter further contributes to poor habitat conditions for fish. In general, fish communities are depauperate in shallow, eutrophic Minnesota lakes (Drake and Valley in review). Rather, SAV in shallow Minnesota lakes serves a greater role in providing habitat for waterfowl and other wetland-associated species.

Hosts of unique biological and physical processes within shallow lakes affect the composition and abundance of macrophytes. Shallow, eutrophic lakes typically occupy one of two alternative states: one characterized by clear water and abundant aquatic vegetation, or one characterized by turbid water and little to no vegetation (Blindow et al. 1993; Scheffer et al. 1993). High external nutrient loads, internal mixing (i.e., "bottom-up" forces) or a high abundance of zooplanktivorous or benthivorous fishes ("top-down" forces), increase the probability that phytoplankton and algae will dominate the water column (Carpenter et al. 1985; Bronmark and Weisner 1992; Jeppesen et al. 1997). Given low external and internal loading, or low abundance of planktivorous fish, aquatic plants can colonize littoral areas and maintain a clear-water state. Return from a turbid to a clear, macrophyte dominated state can be difficult to achieve without substantial intervention. Management techniques include water level drawdowns, substantial reductions to nutrient inputs and control of planktivores through predator stocking or direct removal (e.g., biomanipulation; Hanson and Butler 1990, Moss et al. 1996; Carpenter and Cottingham 1997; Herwig et al. 2004). Deeper lakes are generally more resistant to a conversion to a turbid state because the hypolimnion in stratified pelagic zones act as a sink for nutrients (Carpenter and Cottingham 1997). Nevertheless, deep lakes in heavily developed or agricultural watersheds often occupy a turbid-water state due to perpetually high nutrient loading from the watershed (Cross and McInerny 2001). Some of the same techniques used to rehabilitate shallow lakes may lead to improvements in these deeper lakes.

EFFECTS OF INVASIONS OF NON-NATIVE PLANTS ON FISH HABITAT

Invasion by non-native species of submersed aquatic plants may displace native plant species and reduce the suitability of habitat for certain species of fish, as well as interfere with recreation. In Minnesota lakes, the establishment of non-native invasive species of submersed aquatic plants such as Eurasian watermilfoil and curly-leaf pondweed *Potamogeton crispus* are a concern to lake users, local units of government, and the Minnesota Department of Natural Resources (DNR).

Eurasian watermilfoil–Eurasian watermilfoil (EWM) was introduced into the U.S. in the 1940s and has since spread throughout the nation (Couch and Nelson 1985). It was first found in Minnesota in 1987 in Lake Minnetonka. Despite numerous measures to prevent its proliferation and spread, EWM has spread to 159 lakes as of summer 2004, most being within the Twin Cities metro area. For a detailed life history of Eurasian watermilfoil, consult Smith and Barko (1990).

Eurasian watermilfoil grows rapidly, typically forming extensive homogeneous surface canopies that displace native macrophytes (Madsen et al. 1991; Madsen 1997; Figure 3). These dense canopies reduce sub-canopy light, oxygen, and pH (Carpenter and Lodge 1986; Madsen 1997). This results in an inhospitable foraging environment in the sub-canopy that may confine predators to small open pockets or bed edges (Killgore et al. 1989). Young age-classes of largemouth bass are more efficient feeders in native plant assemblages compared with dense EWM canopies (Valley and Bremigan 2002a).

Field studies suggest EWM depresses fisheries only when it forms extensive, homogeneous beds throughout the littoral zone (Keast 1984; Lillie and Budd 1992; Engel 1995). Areas infested by large monospecific beds of EWM tend to have less abundant fish

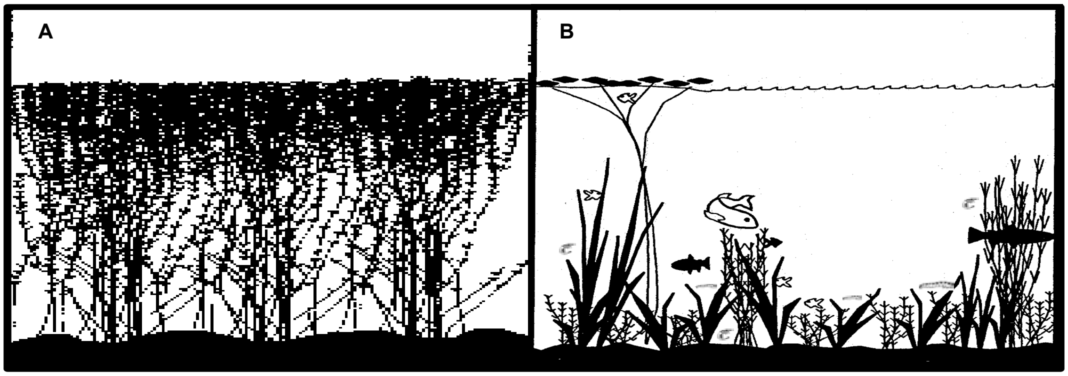

Figure 3. Schematic representation of a canopied macrophyte monoculture (A) and a diverse macrophyte community (B). Figure from Madsen (1997).

and invertebrates than do areas with diverse plants (Keast 1984; Cheruvelil et al. 2001). Nevertheless, if EWM is part of a diverse plant community or if it grows in patches where open pockets permit fish movement, fish populations generally are not negativelyaffected (Weaver et al. 1997; Olson et al. 1998; Valley and Bremigan 2002b). In fact, EWM can be beneficial to fisheries if it occurs in lakes that typically do not support much growth of native submersed species (Engel 1995) because more fish and invertebrates are found in areas with EWM than areas devoid of SAV (Pratt and Smokorowski 2003).

Madsen (1998) investigated the correlation between physical and chemical characteristics of lakes and EWM dominance (percent cover within the littoral zone) in 300 lakes across the US. He found lake trophic status was the best predictor of EWM dominance, with dominance highest in mesotrophic (>10 $\mu g\ L^{-1}$ Total Phosphorus) to eutrophic lakes (< 30 $\mu g\ L^{-1}$TP; Figure 4). Dominance, then, decreased rapidly as lakes approached a hypereutrophic condition (> 30 $\mu g\ L^{-1}$ TP). Madsen (1998) also documented that EWM dominance was inversely proportional to cumulative native plant cover, suggesting the presence of native plants reduces the probability that EWM will dominate the littoral zone. Nevertheless, EWM in-lake spreading can be expected despite current control methods, with some displacement of native plants (Madsen et al. 1991); however, displacement of native plants may not be permanent and EWM dominance may decline over time (approximately 15 years; Nichols and Lathrop 1994).

In non-infested eutrophic lakes, native macrophyte species such as coontail *Ceratophyllum demersum*, naiads *Najas* spp., Canada waterweed *Elodea canadensis*, and northern watermilfoil *Myriophyllum sibiricum* can form monospecific canopies similar to those described for EWM, and thus may affect fisheries in similar ways (Frodge et al. 1990).

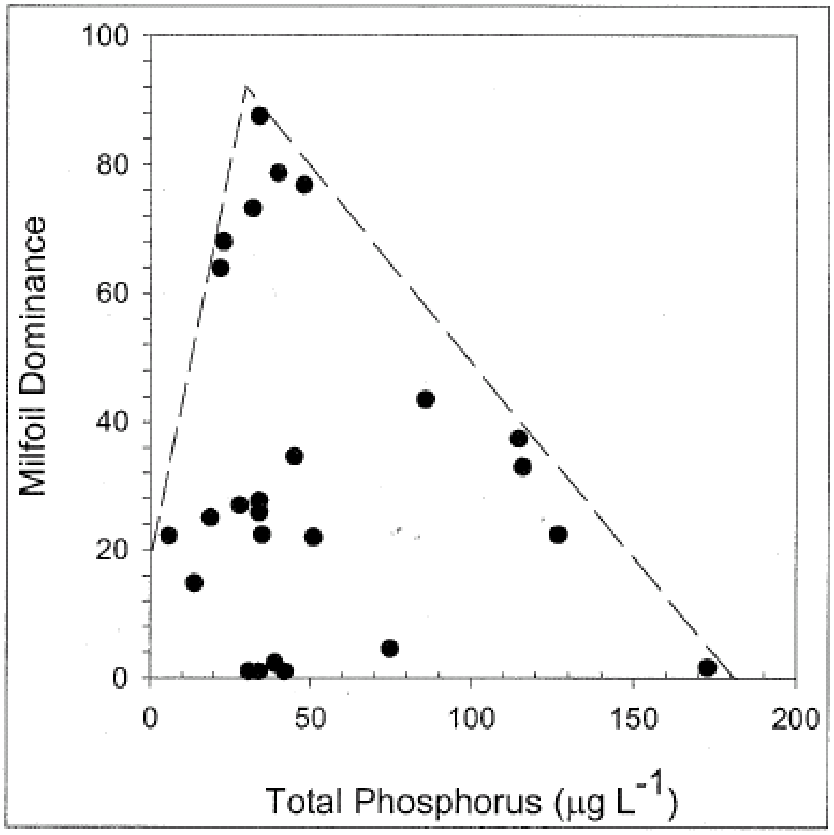

Figure 4. Relationship between Eurasian watermilfoil dominance (percent littoral cover) and total phosphorus for 25 U.S. lakes. From Madsen (1998).

Curly-leaf pondweed –Curly-leaf pondweed (CLP) is a perennial, rooted, submersed vascular plant that was first noted in Minnesota circa 1910 (Moyle and Hotchkiss 1945). Curly-leaf pondweed is currently known to occur in 65 of the 87 Minnesota counties (Exotic Species Program 1997). Curly-leaf pondweed can grow in a variety of habitats, but its most prolific growth occurs in shallow, soft-bottom areas (Nichols 1992). Unlike most native plants, CLP remains green and viable under thick ice and snow cover (Wehrmeister and Stuckey 1978); therefore, it is often the first plant to appear after ice-out. By late spring, it can form dense mats that may interfere with recreation and limit the growth of native aquatic plants (Catling and Dobson 1985). As a response to warm water temperatures in mid-summer, CLP usually senesces, leading to increases in concentrations of phosphorus (Bouldan et al. 1994) and algal blooms. Prior to senescence, CLP plants form vegetative propagules called turions (hardened stem tips) from which new plants sprout in the fall (Catling and Dobson 1985).

Published data on the relationship between fish and CLP is sparse and thus present understanding is mostly anecdotal. During spring, fish sampling in stands of CLP captures small fish, including juvenile game fish, which suggests that this plant provides habitat for these fish during winter and spring (J. Laurer, MN DNR Fisheries Biologist, personal communication; Miranda and Pugh 1997).

Also low abundance, higher growth, and size-structure of sunfish populations are common in some lakes dominated by CLP (B. Nerbonne, R. Ramsell, MN DNR Fisheries Biologists, personal communications). The mechanisms underlying these observations have not been studied, but limited spawning habitat in spring, high predation upon juveniles after CLP senescence, or high lake productivity of infested lakes are potential factors.

At the end of spring when CLP senesces or dies back, the decrease in submersed vegetation often is followed by increased algal blooms due to the release of phosphorus into the water column. This dramatic shift in habitat conditions may favor disturbance-tolerant fish species such as black bullhead, carp, fathead minnows *Pimephales promelas,* and white sucker *Catostomus commersoni.* Nuisance growth of CLP often occurs in shallow, eutrophic basins (lake types 2 and 6) where native SAV has been lost due to the loss of water clarity and carp.

DIRECT AND INDIRECT EFFECTS OF AQUATIC PLANT MANAGEMENT

Given the ability of non-native plants to alter fish habitat, not to mention impair recreation and aesthetics, effort has been devoted to their management (Madsen 1997). Field evaluations of the effects of aquatic plant management (APM) on fish populations demonstrate that the magnitude of effect is dependent on the degree to which APM alters total plant abundance and patchiness.

Little is known regarding the effects of alternative control methods of CLP on fish habitat and populations. Control methods can target CLP because it grows under ice in winter and is abundant early in the spring before many native macrophytes. However, removing CLP from shallow eutrophic lakes and promoting native species represents a significant challenge to managers. Removal of CLP (or any other plant for that matter) without replacement by native plants compromises fish and wildlife habitat. More studies have been conducted with Eurasian watermilfoil and hydrilla *Hydrilla verticillata.* Below, we discuss some relevant findings.

Biological control with grass carp–Grass carp *Ctenopharyngodon idella* eliminated all vegetation in Lake Conroe (8,100 ha Texas reservoir), which was 44% hydrilla prior to grass carp stocking (Bettoli et al. 1992). Elimination of all vegetation had profound effects on the fish community shifting it from a community dominated by littoral species such as largemouth bass and bluegill to one dominated by pelagic and river species such as shad *Dorosoma* spp., catfish, and white bass (Bettoli et al. 1993). Grass carp are indiscriminate herbivores and feed on native plant species as well. Naturally, complete elimination of aquatic plants would not be desirable for native Minnesota fish.

Whole-lake chemical control–In Little Horseshoe Lake (Crow Wing Co. MN; lake type 4), the aquatic herbicide endothall and 2,4-D, removed all SAV (approximately 50% whole-lake cover prior to treatment) and 60% of the floating-leaf vegetation in 1992 (Radomski et al. 1995). Despite a large reduction in SAV cover, changes in largemouth bass, bluegill, and northern pike abundance and growth could not be attributed to reductions in SAV abundance. Despite continued absence of SAV in 1993 and 1994, fish growth and abundance did not significantly change. Growth indices of bluegill, largemouth bass, and black crappie were significantly positively correlated with summer air temperature. Although slower growth generally occurred after chemical treatment of SAV, observed growth was neither consistently higher nor lower than the predicted growth, based on summer air temperature, after the elimination of SAV. Water temperature (which varied greatly among years) apparently had a more profound influence on fish dynamics in Little Horseshoe Lake than the abundance of SAV. This represents an example where a larger physical force (i.e., climate) exerts a greater effect on the fish populations and overrides within-lake changes in habitat. In addition, bluegill in Little Horseshoe Lake may have altered their distribution in the littoral area, perhaps by using floating-leaf and emergent vegetation cover more than the denuded regions of the littoral area. If bluegill were using shallow emergent cover, foraging success of largemouth bass and northern pike may not have changed appreciably with the elimination of SAV.

In two eutrophic Minnesota lakes (Parkers and Zumbra, Carver Co.; lake type 4), chemical control of EWM by fluridone (> 10 ppb) greatly reduced the cover of vegetation with little recovery of native SAV (whole-lake extent was not documented; Pothoven et al. 1999). Largemouth bass and bluegill temporarily experienced greater growth rates after these lakes were treated, presumably because of greater prey availability. However, most effects did not last into the post-treatment year, despite continuing declining vegetation in Zumbra Lake. Several nongame species present prior to the fluridone treatments in Zumbra Lake were not sampled during the post-treatment year (Pothoven 1996).

Schneider (2000) evaluated the indirect effects of whole lake treatments of the herbicide fluridone on game fish populations in 11 mesotrophic Michigan lakes infested by EWM. Concentration and contact time was not evaluated, but less than 20 ppb was speculated. Schneider (2000) observed large changes in the plant community. In most cases, fluridone initially removed nearly all submersed vegetation. However, chara and wild celery *Vallisneria americana* (common 'pioneer' species in mesotrophic lakes and resilient to fluridone) rapidly recolonized denuded littoral areas and presumably increased the habitat heterogeneity in these lakes. As a result, bluegill and crappie size structure improved significantly in many lakes after treatment with fluridone. Sample sizes for yellow perch, northern pike, and largemouth bass were too small to determine whether fluridone had a significant effect on these populations.

In another Michigan study, eight mesotrophic Michigan lakes were also treated with low doses (5 – 7 ppb) of fluridone to selectively remove EWM. These treatments did not impact the fluridone-hardy, diverse plant community that was present prior to the treatment (Getsinger et al. 2001). However, it is speculated that some fluridone-sensitive native plant species (e.g., *Elodea canadensis* and *Ceratophyllum demersum*) that were absent before and after these treatments were lost as a result of past treatments in these lakes (J. Madsen, Mississippi State University, personal communication). Nevertheless, there was no effect of the treatments on whole-lake cover of SAV and no negative effects of the treatment on fish and invertebrate populations were detected (Cheruvelil et al. 2001; Valley and Bremigan 2002b; Hanson 2001).

In a recent study in Minnesota, low-dose fluridone applications (5 ppb target concentration) were applied to three eutrophic lakes infested with EWM (Crooked Lake, Hennepin Co., Schutz Lake Carver Co. [lake type 4] and Eagle Lake, Carver Co.[lake type 2]) in 2001. Preliminary analyses in these lakes demonstrate large reductions in total plant biomass and water clarity (W. Crowell Minnesota Department of Natural Resources, personal communication). Detailed hydroacoustic assessments were conducted in Schutz Lake during 2002 and 2003 using methods described by Valley et al. (in press). This analysis demonstrated a drastic decline in the total abundance of submersed vegetation within the littoral zone (Figure 5). Average littoral biovolume (percent of the water column occupied by vegetation; excluding water lilies) was 37% just prior to fluridone application (early June 2002; Figure 5A). In August 2002, average littoral biovolume declined to 6.5% (Figure 5B). In June 2003, biovolume was 3% (Figure 5C).

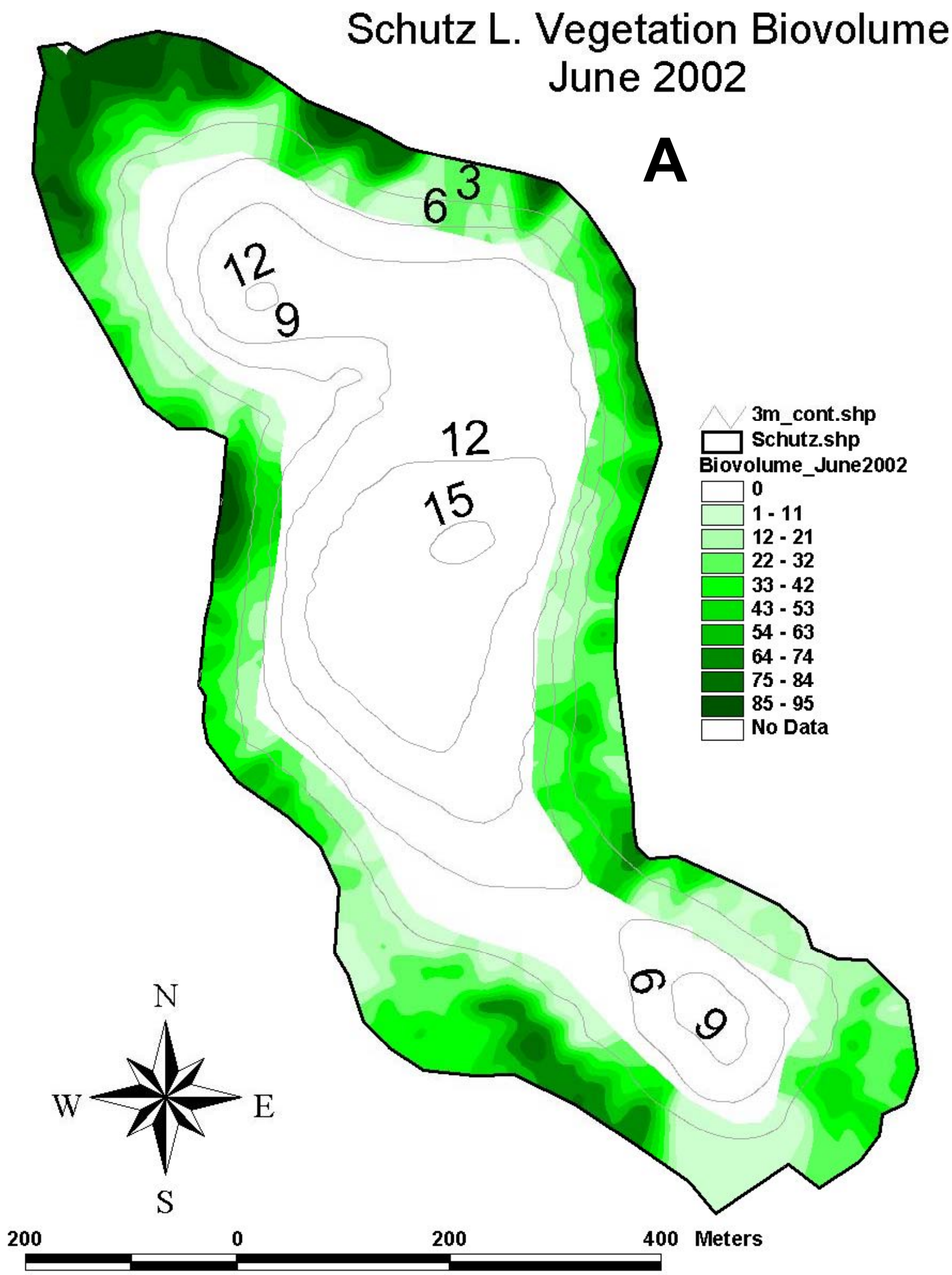

Figure 5. Distribution of vegetation biovolume (percent of water column occupied by vegetation) in Schutz Lake just prior to 5 ppb fluridone applications during June 2002 (A), August 2002 (B), June 2003 (C), and August 2003 (D). Extensive floating-leaf vegetation was present during both August sampling periods.

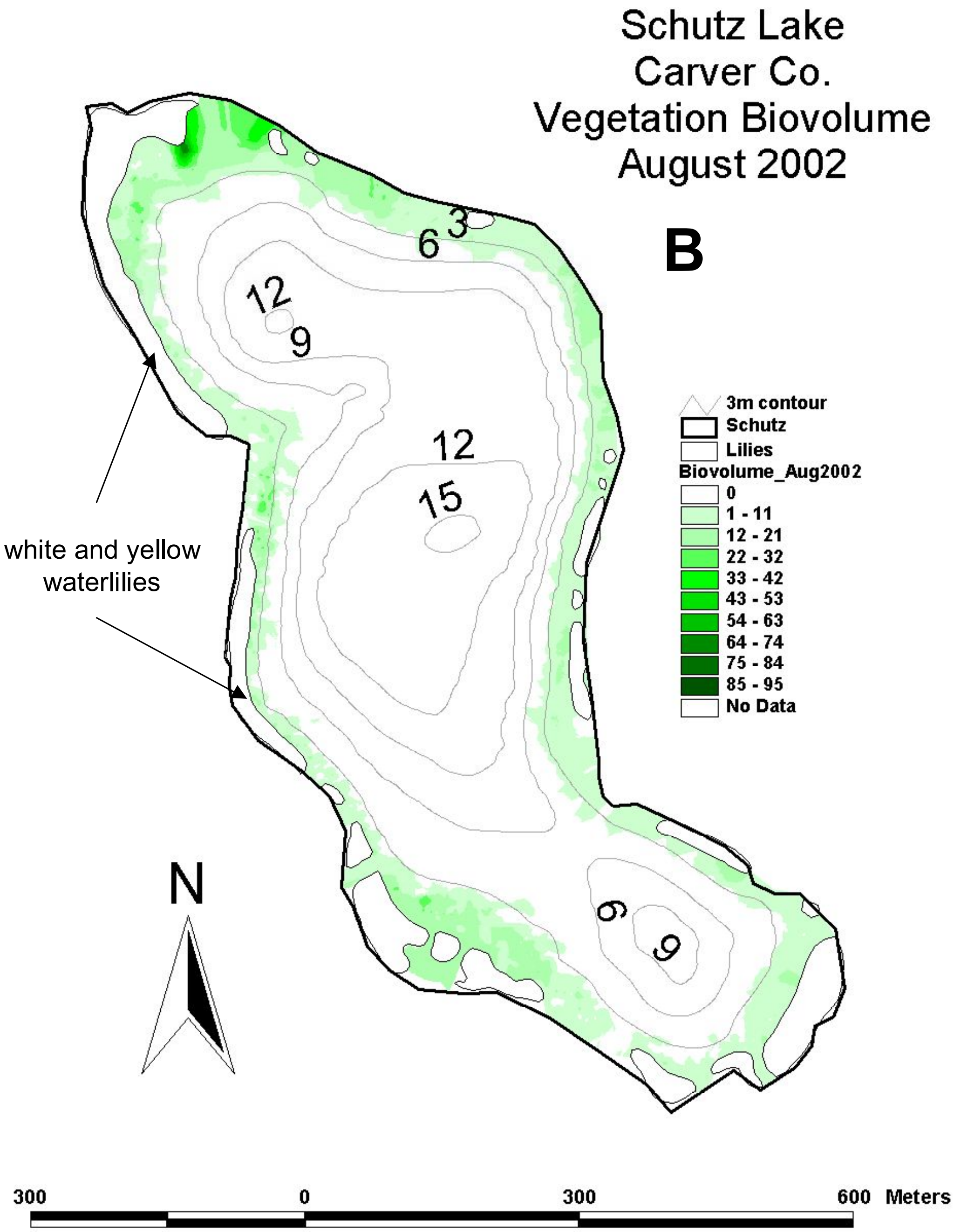

Figure 5. Continued

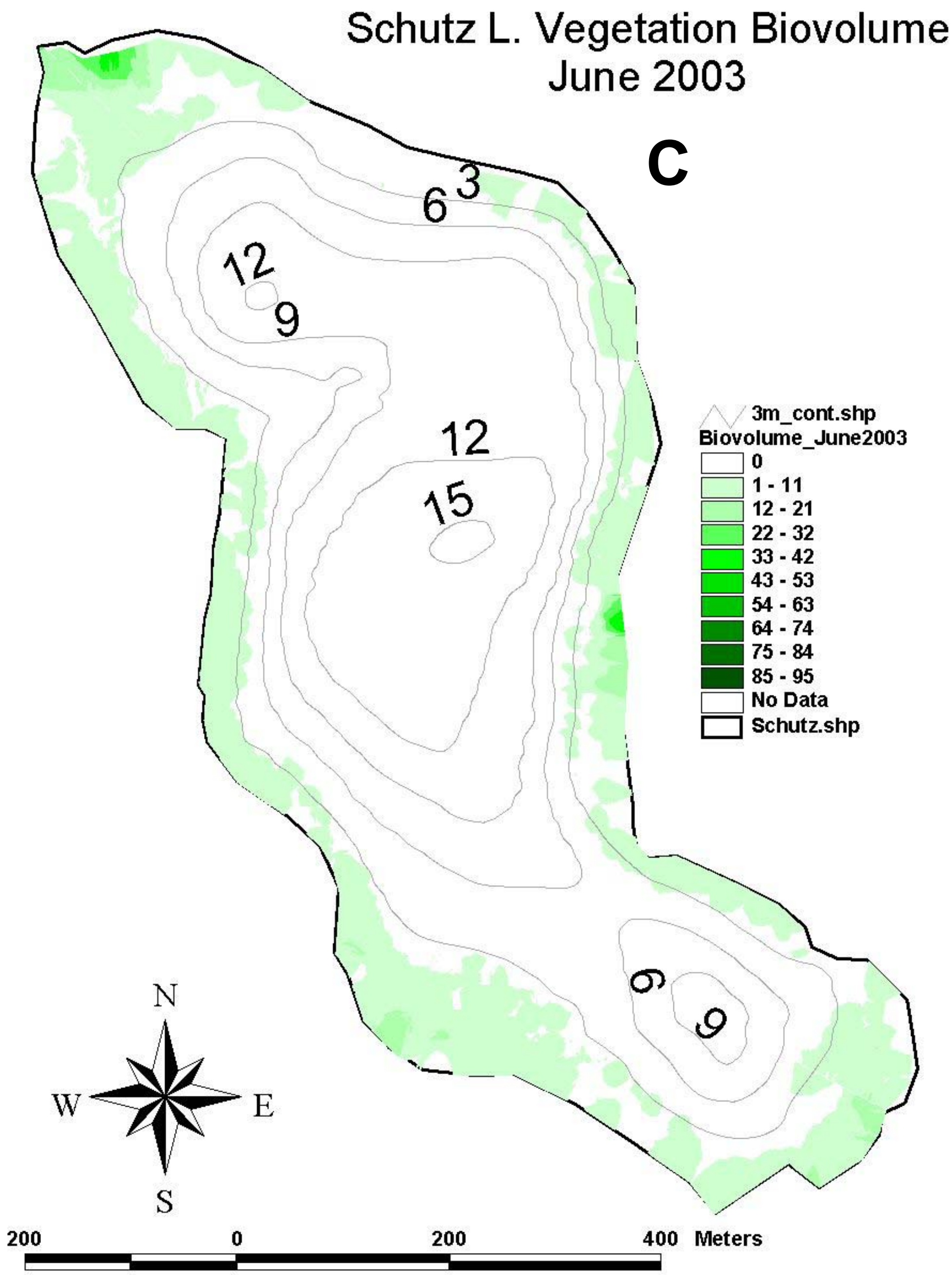

Figure 5. Continued

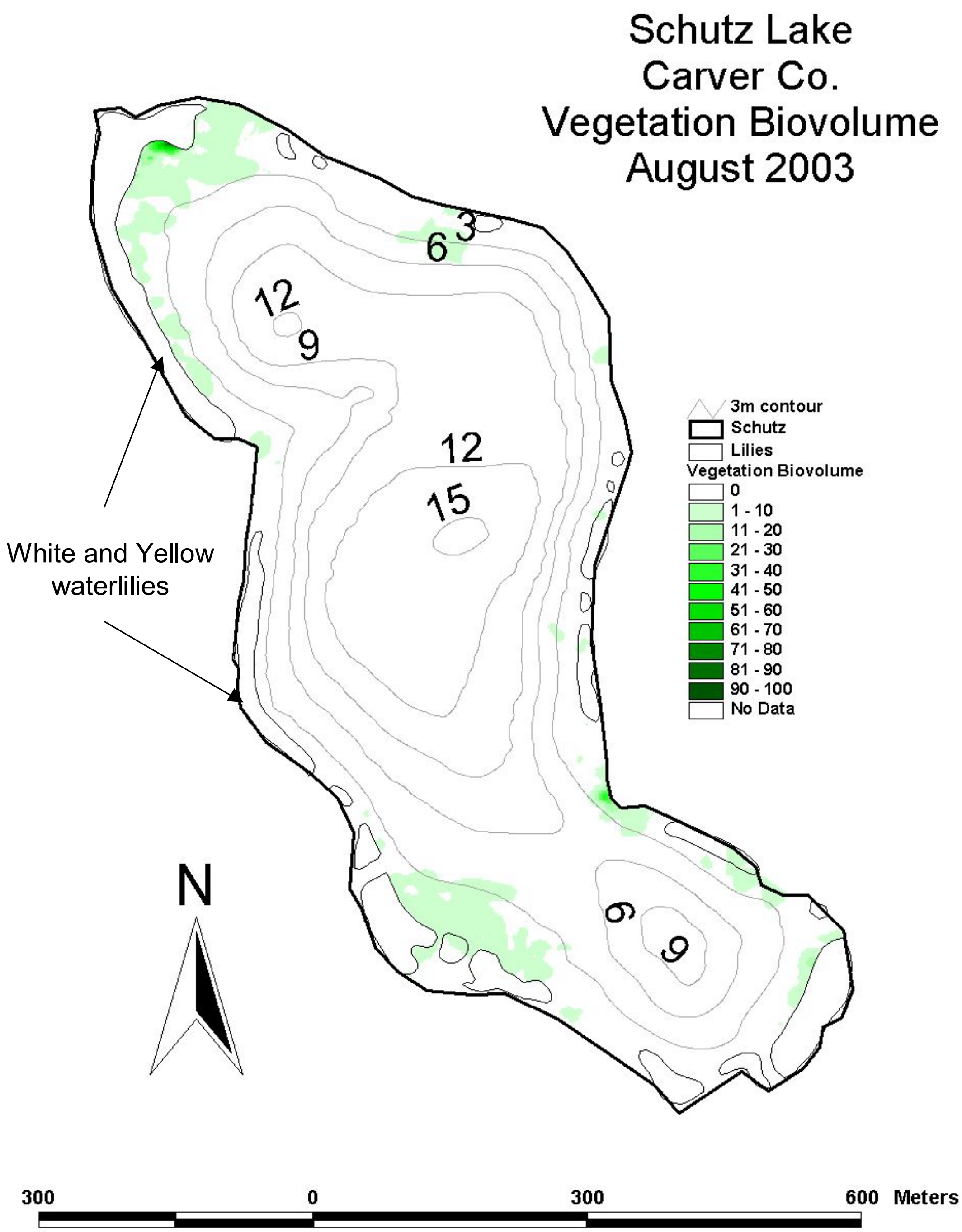

Figure 5. Continued

In August 2003, littoral biovolume declined to 0.6% (Figure 5D). Despite low target concentrations designed to selectively remove EWM, fluridone had negative indirect effects on total plant cover because the removal of large amounts of EWM from the water column favored algal growth rather than recolonization of barren areas by the few remaining native species. Carp inhabited all three treatment lakes and may have resuspended bare sediments, further exacerbating turbidity.

Mechanical control–In theory, mechanical control of vegetation with harvesting can be used to increase edge and vegetation patchiness, thus potentially benefiting game fish such as largemouth bass and bluegill (Smith 1993; Trebitz et al. 1997). Cross et al. (1992) examined the effect of harvesting multiple plots (6% - 11% vegetation removal) in two Minnesota lakes (Mary and Ida lakes, Wright Co.; lake type 4) on largemouth bass, bluegill, and northern pike populations. The authors did not detect any significant effects of the harvesting on the population metrics examined; however, they reported increased first year growth of largemouth bass in the treatment lakes. Cross et al. (1992) speculated the manipulation was not large enough to effect detectable changes in population metrics. Indeed, Trebiz et al. (1997) determined approximately 20% - 40% of a fully vegetated littoral zone would need to be removed in patchy fashion to affect population growth rates and size structure of bluegill and largemouth bass populations.

In Wisconsin, Olson et al. (1998) harvested many deep-cut channels perpendicular to shore throughout littoral zones dominated primarily by EWM in several lakes, with approximately 20% total vegetation removal for each lake. Extensive pilot work was done prior to this study to ensure the ability to detect significant effects if they did occur (Carpenter et al. 1995; Trebitz et al. 1997). Olson et al. (1998) documented increases in growth for some age-classes of largemouth bass and bluegill; however, plants returned to pretreatment densities after one growing season; consequently, this management strategy requires harvesting each year.

Mechanical harvesting can unintentionally kill juvenile fish, amphibians, and turtles (Haller et al. 1980; Booms 1999). Haller et al. (1980) reported losses of 460 juvenile fish per hectare of harvested hydrilla, and Booms (1999) reported losses of 406 per hectare of harvested EWM. Apparently, fewer fish are killed by deep-cutting compared with mowing the surface (Unmuth et al. 1998).

Removing vegetation will have varying effects on fish populations depending on the extent and distribution of manipulated areas. Harvesting and maintaining deep-cut channels through offshore Eurasian watermilfoil or curly-leaf pondweed beds could benefit game fish populations because this type of manipulation increases edge (Trebitz et al. 1997; Olson et al. 1998). However removing nearshore SAV and emergent vegetation (typically used as nursery areas) can have adverse effects on fish diversity and game fish production (Brian and Sarnecchia 1992; Jennings et al. 1999; Radomski and Goeman 2001). Radomski and Goeman (2001) documented reduced biomass and mean size of northern pike and sunfish populations in MN lakes with little emergent or floating-leaf vegetation.

CONCLUSIONS

Given the diversity of Minnesota lakes and the unique fish and habitat relationships that are often found in these lakes, we cannot responsibly prescribe a uniform level of SAV abundance that is optimal for Minnesota fish populations. Nevertheless, high coverage of SAV within the littoral zone is highly important to many fish species, especially in large or deep lakes where SAV cover is limited.

With respect to non-native aquatic plant species, our primary goal should be to prevent (or more realistically, slow) their spread among lakes. Within infested lakes, probability of spread is high regardless of any current control technique. For now, we must accept that eradication of heavily infested lakes is not a realistic management goal. Accordingly, actions should include those that manage the nuisance to allow recreational access without significant losses of fish habitat. This recognizes that non-native plants do serve as habitat. In fact, there is little evidence to suggest introductions of Eurasian watermilfoil or curly-leaf pondweed into lakes will lead to dramatic declines in fisheries.

When managing nuisance aquatic plant species, managers should carefully consider the lake type (i.e., Figure 1, Table 1) and associated risks prior to making aquatic plant management decisions. Large manipulations such as whole-lake herbicide treatments in eutrophic lakes (e.g., lake types 2, 4, 6, and 8) dominated, by mass, by the target species can lead to large declines in total plant abundance and water clarity. From a fisheries and wildlife perspective, overly abundant SAV is more desirable than no SAV. For mesotrophic lakes with diverse plant communities, whole-lake treatments with selective herbicides may be less risky. However, the cumulative long-term risks of repeated treatments are unknown and must be considered.

Vegetated or woody nearshore habitats are especially important for fish populations and any removal is a loss of fish habitat. Accordingly, within any particular lake, recreational access must be balanced with the long-term sustainability and integrity of the lake ecosystem. Past and ongoing land use and SAV removal practices have permanently altered many lakes within agricultural areas of Minnesota and the Twin Cities metropolitan area. In others parts of the state, lakes are threatened by rapid development.

The Minnesota DNR is charged with protecting and managing Minnesota's aquatic resources and associated fish communities for their intrinsic values and long-term ecological, commercial, and recreational benefits to the people of Minnesota. *Long-term sustainability* is the key objective and recreation and commercial benefits must be regulated to protect long-term sustainability.

To achieve this end, a precautionary management approach has been encouraged not only in Minnesota (Welling 2001), but globally as well (FAO 1996; Richards and Maguire 1998; Restrepo et al. 1999; Auster 2001). The precautionary approach advocates action in advance of formal proof and shifts the burden of proof to those challenging precautionary policy. A fundamental principle of the precautionary approach requires proof that proposed resource exploitation or manipulation will not have significant adverse affects on the resource (FAO 1996). For example, in the context of APM, alterations to lakes invariably has some effect on the lake's fish community and the onus should be on individuals or groups proposing manipulation to habitats to prove that their activities will not significantly harm fish populations (FAO 1996). It follows, that it is easier to prevent harm than to later repair it.

Important elements of the precautionary approach are the rules controlling SAV removal, program and lake management plans, monitoring, enforcement, and evaluation. A program management plan should include mechanisms to monitor and control shoreline alterations, and their aggregate impact on fish habitat. Current limits for SAV control that state no more than 15% of the area less than 15 feet may be treated with chemicals or no more than 50% of this area for mechanical harvesting should not be viewed as some desirable level of plant removal, but rather define limits that when exceeded, compromise fish habitat.

It is precautionary to have different thresholds for different methods (e.g., more regulation for APM where risks are larger). Current APM thresholds may be safe for some lakes, however, stricter thresholds may be needed for soft water lakes and large, deep, hard water lakes where SAV is more limited. Also, a precautionary approach requires that management be evaluated. Evaluations should attempt to determine if management is robust to uncertainty, prevents undesirable outcomes, and monitors and addresses non-compliance.

Finally, socio-economic and political considerations must be built into a precautionary framework. Without significant attention paid to these forces, precautionary management will not succeed (Rosenberg 2002). Simplicity, transparency, and flexibility of regulatory frameworks are key components of successful precautionary management (Rosenberg 2002). Building decision frameworks where key biological, socio-economic, and political questions are raised and influence the direction of policy decisions are currently being used in Atlantic salmon management (NASCO 2000). This decision analysis demonstrates a method of making precautionary decisions and has implications for structuring APM policy.

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