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Advantages and Disadvantages of Aquatic Plant Management Techniques

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Introduction

As I work on aquatic plant management research projects around the United States, the most frequent statement I hear is: "I hope you can figure out some way of getting rid of these weeds." When I was younger (and more patient), I would explain many of the available options. After a few years, I realized that the major obstacles to effective management of aquatic plants were sociological rather than scientific. In most instances, a motivated resource management group (whether they be a lake association or a local, regional, state or federal agency) could use a half-dozen of the available options to manage aquatic plants in their lake. The limitations to effective management are time, patience, and funds, not the lack of an effective management tool.

All aquatic plant management techniques have positive and negative attributes. None of the techniques is without some adverse environmental impact; all have both strengths and weaknesses. In selecting management techniques, selections need to be based on economic, environmental, and technical constraints.

Management decisions should be made on a site-specific basis (Madsen 1997). Management techniques should be considered on their technical merits. A truly integrated aquatic plant management approach will vary the use of techniques both spatially and temporally. Spatial variation in technique selection should be based on site use intensity, economic, environmental and technical constraints.

Management should be tailored to the priority and goals of each site. All areas within the lake should be categorized as to use, restrictions, and priority. Based on these categories, management techniques can be selected. For instance, swimming beaches and boat launches are high-use areas, and should have a high priority. Wildlife areas (e.g., refuges) have lower intensity use, and some restrictions to management. Based on these categories, management techniques can be selected. The high-priority, high-intensity use sites might justify high-cost management techniques such as benthic barriers or diver-operated suction harvesting. Low-intensity use areas might either remain untreated if resources are low, or would be categorized for less expensive techniques such as herbicides. Likewise, areas with higher concentrations of plants should receive more resources than areas with no plants or with acceptable levels of infestation. Dan Helsel's article in this issue provides more detail about selecting the proper level of management through the preparation of an aquatic plant management and protection plan.

Eurasian watermilfoil

As dense colonies are brought under control, maintenance management approaches can be used (Deschenes and Ludlow 1993). After a target plant species has entered a system, continuous management will be required. However, under no circumstances should management be discontinued once plant densities are low. If management techniques are very successful, management may entail only monitoring the system and hand-removing individuals that are occasionally found. Scale the control technique to the level of infestation, the priority of the site, the use, and the availability of resources.

Several useful computer programs and other useful information systems are currently available on a CD-ROM format as the Aquatic Plant Information System (APIS). Some helpful websites are listed in Table 1. Another excellent source of information on target and nontarget plants and their management is the Aquatic Plant Information Retrieval System, operated by the University of Florida's Center for Aquatic Plants. In addition to free bibliographic searches, the Center has a variety of educational materials available.

Table 1. Useful websites for aquatic plant management information.

Federal Government	
Aquatic Plant Control Research Program	www.wes.army.mil/el/aqua
USACE Operational Support Center	www.saj.usace.army.mil/conops/apc/apc_page.html
USGS Aquatic Non-indigenous Species	nas.er.usgs.gov

State Government

Washington State Department of Ecology	www.ecy.wa.gov/programs/wq/wqhome.html

University

Center for Aquatic and Invasive Plants	aquat1.ifas.ufl.edu

Professional Society

Aquatic Plant Management Society	www.apms.org
North American Lake Management Society	www.nalms.org

Foundations

Aquatic Ecosystem Restoration Foundation	www.aquatics.org

One important rule to remember is that no management technique is intrinsically superior to another, nor will one management technique (e.g., a single chemical, or herbicides as a group) be sufficient for all situations in a management program. Rather, all techniques should be considered tools in the manager's toolbox. Some are more expensive but will better control dense populations in larger areas. For small nuisance plant populations (<0.1 acres, 0.03 hectare) or new colonies, hand picking may actually be the best approach. Each site should be evaluated and management techniques selected based on the desired level of control, and environmental and economic constraints.

Biological Management Techniques. Many exotic and native organisms have been used for biological control programs (Gallagher and Haller 1990); however, current operational or research and development efforts center on a few: grass carp (or white amur, *Ctenopharyngodon idella*) and introduced insects for hydrilla, naturalized pathogens for Eurasian watermilfoil and hydrilla, and naturalized insects for Eurasian watermilfoil (Table 2).

Table 2. Summary of biological management methods for aquatic plants.

Management Method	Description	Advantages	Disadvantages	Systems where used effectively	Plant species response
Grass Carp / White Amur	Herbivorous Fish	Long-term (decades), relatively inexpensive	Cannot control feeding sites, difficult to contain in water body, tendency for "all or none" community response, persistent	Isolated water bodies, effective against hydrilla and other preferred species. Operational.	Fish have strong preference for hydrilla and some native plants, avoid Eurasian watermilfoil, generally do not prefer floating plants
Neochetina spp.	Waterhyacinth	Species selective	Not effective in reducing	Released in Florida, Gulf	Leaf scars, some

	weevils		areal coverage in many situations	Coast states. (Developmental)	reduction in growth
Hydrellia spp. *Bagous* spp.	Hydrilla fly, hydrilla stem weevil	Species Selective	Has not yet been established	Released in Florida, Alabama, Texas. (Research)	Limited
Euhrychiopsis lecontei and other native insects	Weevil - native or naturalized	Already established in U.S.	Less selective, currently under R&D	Currently under study in Vermont, Minnesota (Research)	Plants loose buoyancy, weevil interferes with transfer of carbohydrates
Mycoleptodiscus terrestris (Mt)	Fungal pathogen; acts as a contact bioherbicide	Low dispersion, fairly broad spectrum	Expense, cross-contamination, inconsistent viability and virulence of formulation	Under R&D for both Eurasian watermilfoil and hydrilla	"Contact Bioherbicide", plants rapidly fall apart, but regrow from roots
Native Plant Community Restoration	Planting of desirable native plant species or community	Provides habitat, may slow reinvasion or initial invasion	Expensive, techniques still under development	Under R&D around the country	Native plants provide ecosystem benefits, slow invasion

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Grass carp, a popular control agent for aquatic plants especially in small ponds or isolated bodies of water, are particularly effective in controlling hydrilla. These fish have strong feeding preferences (Pine and Anderson 1991) and will selectively feed on plants in a mixed community from the most to the least preferred. If hydrilla is the target plant, this may be beneficial--at least until the hydrilla is eaten (Van Dyke et al. 1984). If Eurasian watermilfoil is the target, all other plants may be eaten first, and grass carp may in fact never completely remove Eurasian watermilfoil (Fowler and Robson 1978). In addition, there are many concerns about using grass carp, including the length of time they remain in the system, the difficulty of controlling where and what they eat, the highly variable results for large systems (>500 acres), the escape of carp from the managed system, the impact of their feeding on nontarget plant and animal species, and the difficulty of removing them when control is no longer needed (Bonar et al. 1993).

Grass carp

An initial concern regarding reproduction of grass carp (Stanley et al. 1978, Webb et al. 1994) has been addressed largely through the use of sterile triploids (Durocher 1994). The effectiveness of grass carp is strongly influenced by water temperature and seasonality, with northern ecosystems typically requiring substantially higher stocking rates than southern ones (Stewart and Boyd 1994). In addition, stocking rates can vary by an order of magnitude, depending on whether adequate results are required in 3 years as opposed to the need for more immediate results (Stewart and Boyd 1994). The problem of lag time can be moderated by combining stocking of grass carp with herbicide treatments in the first year (Eggeman 1994). However, a strong tendency for obtaining either no perceived control with understocking or complete plant elimination with overstocking remains--it has been termed the "all-or-none" dilemma (Haller 1994). If achieving an intermediate density of plants is even possible using grass carp, it is certainly very difficult and must be based on a more sophisticated understanding of interacting factors than have been considered in the past.

Insect biocontrol agents currently under research and development for hydrilla were discovered from overseas investigations of native habitats and brought in through the biocontrol "pipeline" (Cofrancesco 1994). Hydrilla biocontrol agents include the flies *Hydrellia pakistanae* and *H. balciunasi* (Buckingham and Okrah 1993) and the weevils *Bagous hydrillae* and *B. affinis* (Grodowitz et al. 1995). Although several introduced biocontrol agents feed in a complementary fashion to stress hydrilla populations, it is too early in the research and development process to predict operational-scale success. For instance, mathematical models of *H. pakistanae* growth rates suggest that even if the fly were successful in central Florida, its development rate may be too slow in the colder climate of northern Alabama to be effective (Boyd and Stewart 1994).

Although foreign surveys for biocontrol agents for Eurasian watermilfoil have been recently initiated (Buckingham 1995), most effort has been spent looking at naturalized or native insects that feed on this species (Kangasniemi 1983). In particular, laboratory, mesocosm, and field research have been vigorously pursued on the pyralid moth *Acentria nivea* (Creed and Sheldon 1994) and on the weevil, *Euhrychiopsis lecontei* (Creed and Sheldon 1993, 1994, Newman and Maher 1995). *Euhrychiopsis lecontei* looks promising in that it is capable of cutting off the flow of carbohydrates to root crowns, reducing the plant's ability to store carbohydrates for over wintering (Newman et al. 1996) and reducing the buoyancy of the canopy (Creed et al. 1992). However, an effective strategy for large-scale applications using these naturalized insects at an operational level has yet to be verified.

Pathogens, like insects, are usually discovered by searching overseas for pathogens in the native range of the target plant. Despite overseas searches (Harvey et al. 1995), no foreign pathogen agents are currently under development. Actually, the best potential pathogen control agent for submersed aquatic plants appears to be an endemic species, *Mycoleptodiscus terrestris* (Mt) (Shearer 1995). Small-scale field tests indicated that Mt was an effective mycoherbicide, and acted like a contact herbicide with little spread or drift (Shearer 1995). In addition, Mt has shown promise in the laboratory as part of an integrated management strategy in which applications of Mt combined with low dosage rates of the herbicide fluridone act synergistically (Nelson et al. 1998). However, more research and development effort must be accomplished before an effective marketable mycoherbicide is available for use.

The last type of biological management technique, native plant restoration, is an ecological approach to managing for a desired plant community. The basic idea is that restoring a native plant community should be the end goal of most aquatic plant management programs (Nichols 1991, Smart and Doyle 1995). Lakes currently lacking a native plant community can have these communities established (Smart et al. 1996a,b). Extant native plant communities should be protected from invasion by nonnative species through mechanisms detailed later. In communities that have only recently been invaded by nonnative species, a propagule bank probably exists that will restore the native community after management of the nonnative plant (Getsinger et al. 1997). However, in communities that have had monospecific nonnative plant dominance for a long period of time (e.g., greater than 10 years), native plants may have to be reintroduced after a successful maintenance management program has been instituted. A healthy native plant community might slow invasion or reinvasion by nonnative species and will provide the environmental and habitat needs of an aquatic littoral zone. However, even healthy, well-developed native plant communities may eventually be invaded and dominated by nonnative species (Madsen et al. 1991).

Chemical Management Techniques. In many ways, chemical management techniques have changed dramatically in the past 20 years. Increased concern about the safety of pesticide use in the 1960s and 1970s changed the review process for all pesticides, particularly for products used in water. Currently, no product can be labeled for aquatic use if it poses more than a one in a million chance of causing significant damage to human health, the environment, or wildlife resources. In addition, it may not show evidence of biomagnification, bioavailability, or persistence in the environment (Joyce 1991).

The greatest change for herbicides came with the passage of the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) first passed in 1972 and amended in 1988 (Getsinger 1991, Nesheim 1993). Due to more stringent and costly standards for testing, fewer compounds are now available for aquatic use. In 1976, 20 active ingredients were available; as of 1995, only six are available (Table 3), with one additional compound (triclopyr) undergoing the registration process.

Table 3. Characteristics of U.S. Environmental Protection Agency-approved aquatic herbicides.

Compound	Trade Name	Company	Formulation; Contact vs. Systemic	Mode of Action	Bluegill 96 hr. LC$_{50}$ (mg/L)
Complexed Copper	Cutrine-Plus Komeen Koplex K-Tea	Applied Biochemists (Cutrine) Griffin Corporation	Various complexing agents with copper, superior to CuSO$_4$ Systemic	Plant cell toxicant	1250
2,4-D[1]	Aqua-Kleen Weedar-64 Wee-Rhap A-6D Several Others	Applied Biochemists Rhone-Poulenc Inter-Ag	BEE salt DMA liquid IEE liquid Systemic	Selective plant-growth regulator	1.1-1.3 123-230
Diquat[1]	Reward	Zeneca	Liquid Contact	Disrupts plant cell membrane integrity	10-140
Endothall[1]	Aquathol K Hydrothal 191 Aquathol granular	Elf Atochem (All Formulations)	Liquid or granular Contact	Inactivates plant protein synthesis	125 0.06-0.2
Fluridone[1]	Sonar AS Sonar SRP	SePRO	Liquid or granular Systemic	Disrupts carotenoid synthesis, causing bleaching of chlorophyll	9-12.5
Glyphosate[1]	Rodeo	Monsanto	Liquid Systemic	Disrupts synthesis of phenylalanine	4.2-14
Triclopyr (EUP Only)	Garlon 3A (EUP) Renovate (EUP)	SePRO	Liquid Systemic	Selective plant growth regulator	148

However, the compounds no longer registered for aquatic use are not necessarily too dangerous; rather, in most cases, the companies marketing them opted not to pursue registration due to economic reasons. Their reluctance to invest in registration is understandable--it can take $20-40 million and 8-12 years to navigate successfully the registration process and its accompanying series of laboratory and field testing, with no guarantee for return on investment (Getsinger 1991). What remains are six active ingredients that not only are ensured safe for aquatic use (when used according to the label) but also have manufacturers committed to the aquatic market.

The important caveat to remember is that these products are safe when used according to the label. The U.S. Environmental Protection Agency (EPA) approved label provides guidelines protecting the health of the environment, the humans using that environment, and the applicators of the herbicide. In most states, there are additional permitting or regulatory restrictions on the use of these herbicides. A typical state restriction requires that these herbicides may be applied only by licensed applicators. Annual updates from state regulatory and environmental agencies are necessary to check for changes in label restrictions and application policies or permit requirements, before developing or implementing any plans for applying herbicides.

Herbicides labeled for aquatic use can be classified as either contact or systemic. Contact herbicides act immediately on the tissues contacted, typically causing extensive cellular damage at the point of uptake but not affecting areas untouched by the herbicide. Typically, these herbicides are faster acting, but they do not have a sustained effect, in many cases not killing root crowns, roots, or rhizomes. In contrast, systemic herbicides are translocated throughout the plant. They are slower acting but often result in mortality of the entire plant.

Complexed copper compounds include a variety of formulations from different companies, under different names and labels, in which copper is chelated in an organic complexing agent that keeps it in solution. Formerly, copper sulfate was used in applications, predominantly for the control of phytoplankton. However, the copper rapidly precipitated, especially in harder water, and was no longer available, leading to the production of complexed copper agents. Complexed copper is very effective for algal control, somewhat effective for several vascular plants (particularly hydrilla), and is also used in tank mixes with diquat to increase its effectiveness.

A widely used aquatic herbicide for many broadleaf species, such as Eurasian watermilfoil, is 2,4-D. A selective systemic herbicide, it effectively controls broadleaf plants with a relatively short contact time, but does not generally harm the pondweeds or water celery. However, it is also not effective against elodea or hydrilla.

Diquat is a contact herbicide that will act on a very short contact time. It causes a rapid die-off of the shoot portions of the plant it contacts, but is not effective on roots, rhizomes or tubers, requiring subsequent applications. Diquat will bind to particulate and dissolved organic matter, which restricts its use in some water bodies. It is also effective in a tank mix with copper compounds.

Endothall is another contact herbicide. Unlike Diquat, it is not affected by particulates or dissolved organic material. It should not be used in tank mixtures with copper, as it can have an antagonistic reaction with chelated copper compounds.

Fluridone is a nonselective systemic aquatic herbicide. It requires very long exposure times but may be effective at very low concentrations. Fluridone is widely used for both hydrilla and Eurasian watermilfoil management. It appears to work best where the entire lake or flowage system can be managed, but not in spot treatments or high water exchange areas.

Glyphosate is not effective on submersed plants, and triclopyr is not yet labeled for general aquatic use, so neither compound will receive additional attention.

In treating submersed species, the applicator is actually treating the water with a herbicide, and allowing the plant to take up herbicide from the water. This creates a situation in which the applicator needs to know the exchange rate of the water to have a successful application (Getsinger et al. 1991). The exposure time of the plant to the herbicide is determined predominantly by the water exchange rate. The response of different plant species to different herbicides is a function of the properties of both the plant and the herbicide. The applicator also needs to match a herbicide with an appropriate concentration and exposure-time relationship for the target species (Netherland 1991). The concentration and exposure-time relationship for a given compound have been determined from laboratory experiments. For instance, if it is known from water exchange studies that the exposure time will ensure only 24 hours of contact with 1 mg/liter of 2,4-D if applied at full label rate, than a 75% control rate for Eurasian watermilfoil can be expected. If longer exposure times are expected, than lower concentrations can be applied. One goal of this area of research is to allow for lower application rates, both to save money on herbicides and to introduce a lower total amount of herbicide into the aquatic environment. For higher exchange rates, the applicator will have to use higher concentrations of the contact herbicides such as diquat or endothall; slower exchange rates may allow the use of systemic herbicides (Tables 3,4). However, some systems are limited in selecting herbicides for use, because it is never admissible to use concentrations of herbicides higher than the allowed EPA maximum label rate.

Preparing to apply aquatic herbicide

Some herbicides (e.g., 2,4-D and triclopyr) are intrinsically selective, being very effective for controlling broadleaf plants such as Eurasian watermilfoil but not narrow-leaved plants or grasses such as hydrilla (Table 5). Other herbicides may be used selectively but only through application based on the target and non-target plant's biology. Recent research has shown fluridone may be used to selectively manage Eurasian watermilfoil and hydrilla at extremely low (e.g., 5 to 8 ppb) concentrations; however, concentrations must be carefully monitored to avoid failure to control the target species (Getsinger 1998, Netherland et al. 1997).

Table 4. Application restrictions of US Environmental Protection Agency-approved aquatic herbicides.

Compound	Persistence (half-life, in days)	Maximum Application Rate	Maximum water concentration	Safety Factor	Application Notes	WES Recommended for
Complexed Copper	3	1.5 gal/ft/acre	1.0 mg/L	>50	Algicide / Herbicide	Hydrilla, other submersed spp.
2,4-D	7.5	0.5 gal/acre	2.0 mg/L	>25	Some formulations for special permits only	Eurasian watermilfoil, water-hyacinth, and others
Diquat	1-7	2 gal/acre	2 mg/L	5	Binds with particles	All

					(suspended solids) in water	
Endothall	4-7	13 gal/acre	5.0 mg/L	>10 (Aquathol) <1.0 (Hydrothal)	Fish are sensitive to Hydrothal 191 - over 1 mg/L may cause fish kill	All submersed spp.
Fluridone	21	1.1 qt/acre	0.15 mg/L (150 ppb)	>20	Applications have been successful below 10 ppb	Most submersed spp.
Glyphosate	14	2 gal/acre	0.2 mg/L	>20	Aerial portions only - not for submersed plants	Most emergent and floating spp.
Triclopyr (EUP Only)	na	na	2.5 mg/L	>50	EUP/Special Needs only - US EPA label expected in 1997	Eurasian watermilfoil, water-hyacinth, others

Table 5. Use suggestions for US Environmental Protection Agency-approved aquatic herbicides.

Compound	Exposure Time (Water)	Advantages	Disadvantages	Systems where used effectively	Plant species response
Complexed Copper	Intermediate (18-72 hours)	Inexpensive, rapid action, approved for drinking water	Does not biodegrade, but biologically inactive in sediments	Lakes as algicide, herbicide in higher exchange areas	Broad-spectrum, acts in 7-10 days or up to 4-6 weeks
2,4-D	Intermediate (18-72 hours)	Inexpensive, systemic	Public perception	Waterhyacinth and Eurasian watermilfoil control, Lakes and slow-flow areas, purple loosestrife	Selective to broad-leaves, acts in 5-7 days up to 2 weeks
Diquat	Short (12-36 hours)	Rapid action, limited drift	Does not affect underground portions	Shoreline, localized treatments, higher exchange rate areas	Broad-spectrum, acts in 7 days
Endothall	Short (12-36 hours)	Rapid action, limited drift	Does not affect underground portions	Shoreline, localized treatments, higher exchange rate areas	Broad spectrum, acts in 7-14 days
Fluridone	Very long (30-60 days)	Very low dosage required, few label restrictions, systemic	Very long contact period	Small lakes, slow flowing systems	Broad spectrum, acts in 30-90 days
Glyphosate	Not Applicable	Widely used, few label restrictions, systemic	Very slow action, no submersed control	Nature preserves and refuges; Emergent and floating-leaved plants only	Broad spectrum, acts in 7-10 days, up to 4 weeks
Triclopyr (EUP Only)	Intermediate (12-60 hours)	Selective, systemic	Not currently labeled for general aquatic use	Lakes and slow-flow areas, purple loosestrife	Selective to broad-leaves, acts in 5-7 days, up to 2 weeks

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The future of herbicide use may include applying plant growth regulators (PGR’s), such as flurprimidol and paclobutrazol, which reduce plant elongation rather than cause plant death (Van 1988). The future of this approach dimmed considerably in the U.S. when Du Pont Corporation did not pursue the registration of bensulfuron methyl, which showed great promise in restricting tuber formation in hydrilla (Haller et al. 1992) and PGR activity in Eurasian watermilfoil (Getsinger et al. 1994).

A second area in the future of herbicide use is integrated control, where herbicides are used in conjunction with other management techniques to improve their effectiveness. Herbicides have been used with grass carp (Eggeman 1994), insect biocontrol agents (Haag and Habeck 1991, Van 1988), and pathogens (Nelson et al. 1998, Sorsa et al. 1988) to increase their effectiveness. Combining herbicides with mechanical and physical control techniques is also possible.

Mechanical and Physical Management Techniques. Mechanical management methods have been widespread in attempts to control aquatic plants (Table 6). Yet all too often the approach to a solution is strictly "engineering," rather than applying engineering to a knowledge of biology and ecology of the target organism. Likewise, the erstwhile inventor often neglects a concern for the environmental implications of use of the mechanical control, confirmed in the belief that it must be better than "using poisons."

Table 6. Characteristics of mechanical management techniques.

Management Method	Description	Advantages	Disadvantages	Systems where used effectively	Plant species response
Hand- Cutting/ Pulling	Direct hand pulling or use of hand tools	Low-technology, affordable, can be selective	Labor-intensive, cost is labor-based	Most of the undeveloped world, volunteer labor pools	Very effective in very localized areas
Cutting	Cut weeds with mechanical device (typically boat-mounted sickle bar) without collection	More rapid than harvesting	Large mats of cut weeds may become a health and environmental problem, may spread infestation	Heavily-infested systems	Nonselective, short-term
Harvesting (Cut and Remove)	Mechanical cutting with plant removal	Removes plant biomass	Slower and more expensive than cutting; resuspension of sediments	Widespread use with chronic plant problems	Like cutting, it is cosmetic, non-selective short-term
Grinder or "Juicer" (Cut and Grind)	Mechanical cutting with grinding of plant material and in-lake disposal	Immediate relief of plant nuisance, no disposal	Resuspension of sediments, decomposition of plants in lake, floating plant material	Useful for chronic plant problems where disposal of plants is problematic	Like cutting and harvesting, it is cosmetic, non-selective short-term
Diver-Operated Suction Harvester	Vacuum lift used to remove plant stems, roots, leaves, sediment left in place	Moderately selective (based on visibility and operator), longer-term	Slow and cost-intensive	Useful for smaller nuisance plant populations in which plant density is moderate	Typically have minimal regrowth for Eurasian watermilfoil; not effective for tuber-setting hydrilla
Rotovating	Cultivator on long arm for tilling aquatic sediments	Disrupts Eurasian watermilfoil stem bases, intermediate-term results	May spread large numbers of fragments; resuspension of sediments	Used extensively in the Pacific Northwest and British Columbia, with mixed results	Effective in disrupting Eurasian watermilfoil dense stands; not selective and only intermediate-term

The most common form of mechanical control is actually the use of hand cutters, rakes, or bare hands (no tools) to remove vegetation. Not only is this the most common method worldwide, but also it is the most widely used method by most lakeshore owners in the U.S. In a do-it-yourself guide, McComas (1993) listed a large number of hand implements and other small-scale devices for mechanical control. These techniques are most appropriate for localized nuisance problems of both nonindigenous and native plants.

Larger-scale control efforts require more mechanization (Table 6). The first uses a mechanical cutter, which is typically a boat with a sickle-bar cutting blade. Although cutting alone is relatively rapid, it leaves large mats of plants that can not only spread the plant but also create a floating obstacle, wash up on shorelines, and cause water-quality problems through decomposition. Because of these problems, cutting operations are typically combined with plant removal. However, in some applications, removal is not necessary, in which case cutting alone is sufficient.

A full aquatic harvester travels to unload its cargo

Aquatic harvester

In mechanical harvesting, cutting operations are combined with plant removal. Occasionally, there are separate cutting and harvesting boats. More often, the harvesters have both a sickle-bar cutting blade with a conveyor belt that loads the cut material on a boat. Disposal vehicles carry the plant material away.

One neglected aspect of harvesting operations is disposal of plant material. The plant material is generally more than 90% water and not suitable as a feed and cannot be sold or made into anything truly useful. The common response is to use it as mulch. Due to the disposal problem, some recent machine designs have included a shredder, chopper, or grinder to dispose of the plant material back into the lake. Although some concern has been expressed to the release of nutrients, the actual amount of nutrients released is small relative to other sources. A more realistic concern, at least in southern water bodies, is the attraction of large carnivores (e.g., alligators) to the "chum" resulting from chopped fish and other organisms that are a "by-catch."

Several studies have indicated that one harvest per year provides only brief control, whereas two to three harvests of the same plot in a given year are required to provide adequate annual control. However, cutting three times in a year may also reduce growth the following year (Madsen et al. 1988, Nichols and Cottam 1972). Most researchers directly ascribed successful control to reductions in total stored carbohydrates (Kimbel and Carpenter 1981). Although many claim that harvesting is environmentally superior to herbicide use, most neglect to consider that harvesting removes large numbers of macroinvertebrates, semi-aquatic vertebrates, forage fishes, young-of-the-year fishes, and even adult gamefishes (Engel 1990). The harvester acts as a large, nonselective predator "grazing" in the littoral zone. In addition, harvesting can resuspend bottom sediments into the water column, releasing nutrients and other accumulated compounds.

However, not all secondary effects of harvesting are negative. Removal of large amounts of plants can improve the diel oxygen balance of littoral zones and rivers, particularly in shallower water (Carpenter and Gasith 1978, Madsen et al. 1988). At this point, no studies have indicated whether native communities respond preferentially to harvesting.

In the past, harvesting was widely touted as a mechanism to remove nutrients from lake systems. However, ecosystem studies indicated that harvesting was not likely to significantly improve the trophic status of a lake. For instance, harvesting all available plants in Lake Wingra, Wisconsin removed only 16% of the nitrogen and 37% of the phosphorus net influxes into the lake; these removals were insignificant compared to the lake's internal pools of those nutrients (Carpenter and Adams 1976, 1978). Plant harvesting in Southern Chemung Lake, Ontario removed 20% of the annual net phosphorus input (Wile 1975). In a more eutrophic system (Sallie Lake, Minnesota), continuous harvesting of aquatic plants in the littoral zone during summer removed only 1.4% of the total phosphorus input (Peterson et al. 1974). In a less eutrophic system (East Twin Lake, Ohio), harvesting the entire littoral zone would have removed from 26% to 44% of the phosphorus and from 92% to 100% of the nitrogen net loadings to the lake over a 5-year study period (Conyers and Cooke 1983).

Harvesting aquatic plants is not an effective tool for reducing nutrient loads in a lake; in none of the above scenarios was the internal nutrient pool reduced. In the best-case scenario, removing all the plants in the lake only kept pace with the amount of external nitrogen loading and with not quite half of the external phosphorus loading. Because no operational control program is going to remove all plants in the littoral zone, it is unlikely that any operational harvesting program will significantly impact the internal nutrient balance of the system.

The use of diver-operated suction harvesting (or dredging, as it is often called) is a fairly recent technique. Called "harvesting" rather than "dredging" because, although a specialized small-scale dredge is used, sediments are not removed from the system. Sediments are resuspended during the operation, but using a sediment curtain mitigates these effects. Divers use this device to remove plants from the sediment (NYSDEC and FOLA 1990). The technique can be very selective; divers can literally choose the plants to be removed. Removal is efficient and regrowth is limited. The system is very slow (100 m^2 per person-day; Eichler et al. 1993), and disposal of plant material must also be resolved. However, it is an excellent method for small beds of plants or areas of scattered clumps of plants too large for hand harvesting.

The last major mechanical management technique is rotovating, which is widely used in the Pacific Northwest and, formerly, in British Columbia for management of Eurasian watermilfoil. This method uses rotovator heads on submersible arms to till up the bottom sediments and to destroy the root crowns. Rotovating is relatively rapid and can effectively control dense beds of Eurasian watermilfoil for up to 2 years (Gibbons and Gibbons 1988). However, it spreads Eurasian watermilfoil fragments, resuspends large amounts of sediments and nutrients, causes high levels of turbidity, disrupts benthic communities, and is nonselective.

Physical management methods may or may not utilize large equipment but are distinguished from mechanical techniques in the following manner: in mechanical techniques the machines act directly upon the plants, in physical techniques the environment of the plants is manipulated, which in turn acts upon the plants. Several physical techniques are commonly used: dredging, drawdown, benthic barriers, shading or light attenuation, and nutrient inactivation (Table 7).

Table 7. Characteristics of physical management techniques.

Management Method	Description	Advantages	Disadvantages	Systems where used effectively	Plant Species Response
Dredging/ Sediment Removal	Use mechanical sediment dredge to remove sediments, deepen water	Creates deeper water, very long-term results	Very expensive, must deal with dredge sediment	Shallow ponds and lakes, particularly those filled in by sedimentation	Often creates large usable areas of lake, not selective
Drawdown	"De-water" a lake or river for an extended period of time	Inexpensive, very effective, moderate-term	Can have severe environmental impacts, severe recreational/ riparian user effects	Only useful for manmade lakes or regulated rivers with a dam or water control structure	Selective based on perennation strategy; effective on evergreen perennials, less effective on herbaceous perennials
Benthic Barrier	Use natural or synthetic materials to cover plants	Direct and effective, may last several seasons	Expensive and small-scale, nonselective	Around docks, boat launches, swimming areas, and other small, intensive use areas	Nonselective, plant mortality within one month underneath barrier
Shading / Light Attenuation	Reduce light levels by one of several means: dyes, shade cloth, plant trees (rivers)	Generally inexpensive, effective	Nonselective, controls all plants, may not be aesthetically pleasing	Smaller ponds, man-made waterbodies, small streams	Nonselective, but may be long-term
Nutrient Inactivation	Inactivate phosphorus (in particular) using alum	Theoretically possible	Impractical for rooted plants limited by nitrogen	Most useful for controlling phytoplankton by inactivating water column P	Variable

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Dredging is usually not performed solely for aquatic plant management but to restore lakes that have been filled in with sediments, have excess nutrients, have inadequate pelagic and hypolimnetic zones, need deepening, or require removal of toxic substances (Peterson 1982). However, lakes that are very shallow due to sedimentation typically have excess plant growth. This method is effective in that dredging typically forms an area of the lake too deep for plants to grow, thus opening an area for riparian use (Nichols 1984). By opening more diverse habitats and creating depth gradients, dredging may also create more diversity in the plant community (Nichols 1984). Results of dredging can be very long term. Biomass of *Potamogeton crispus* in Collins Lake, New York remained significantly lower than pre-dredging levels 10 years after dredging (Tobiessen et al. 1992). Due to the cost, environmental impacts, and the problem of disposal, dredging should not be performed for aquatic plant management alone. It is best used as a multi-purpose lake remediation technique.

Drawdown is another effective aquatic plant management technique that alters the plant’s environment. Essentially, the water body has all of the water removed to a given depth. It is best if this depth includes the entire depth range of the target species. Drawdown, to be effective, needs to be at least 1 month long to ensure thorough drying (Cooke 1980b). In northern areas, a drawdown in the winter that will ensure freezing of sediments is also effective. Although drawdown may be effective for control of hydrilla for 1 to 2 years (Ludlow 1995), it is most commonly applied to Eurasian watermilfoil (Siver et al. 1986) and other milfoils or submersed evergreen perennials (Tarver 1980). Drawdown requires that there be a mechanism to lower water levels. Although it is inexpensive and has long-term effects (2 or more years), it also has significant environmental effects and may interfere with use and intended function (e.g., power generation or drinking water supply) of the water body during the drawdown period. Lastly, species respond in very different manners to drawdown and often not in a consistent fashion (Cooke 1980b). Drawdown may provide an opportunity for the spread of highly weedy or adventive species, particularly annuals.

Benthic barriers or other bottom-covering approaches are another physical management technique that has been in use for a substantial period of time. The basic idea is that the plants are covered over with a layer of a growth-inhibiting substance. Many materials have been used, including sheets or screens of organic, inorganic and synthetic materials, sediments such as dredge sediment, sand, silt or clay, fly ash, and combinations of the above (Cooke 1980a). The problem with using sediments is that new plants establish on top of the added layer (Engel and Nichols 1984). The problem with synthetic sheeting is that the gasses evolved from decomposition of plants and normal decomposition activities of the sediments underneath the barrier collect under the barrier, lifting it (Gunnison and Barko 1992). Benthic barriers will typically kill plants under them within 1 to 2 months, after which they may be removed (Engel 1984). Sheet color is relatively unimportant; opaque (particularly black) barriers work best, but even clear plastic barriers will work effectively (Carter et al. 1994). Sites from which barriers are removed will be rapidly recolonized (Eichler et al. 1995). In addition, synthetic barriers may be left in place for multi-year control but will eventually become sediment-covered and will allow colonization by plants. Benthic barriers, effective and fairly low-cost control techniques for limited areas (e.g., <1 acre), may be best suited to high-intensity use areas such as docks, boat launch areas, and swimming areas. However, they are too expensive to use over widespread areas, and heavily effect benthic communities.

A basic environmental manipulation for plant control is light reduction or attenuation. This, in fact, may have been the first physical control technique. Shading has been achieved by fertilization to produce algal growth, application of natural or synthetic dyes, shading fabric, or covers, and establishing shade trees (Dawson 1986, Dawson and Hallows 1983, Dawson and Kern-Hansen 1978, Madsen et al. 1999). During natural or cultural eutrophication, phytoplankton growth alone can shade macrophytes (Jones et al. 1983). Although light manipulation techniques may be useful for narrow streams or small ponds, in general these techniques are of only limited applicability.

The final physical management method often discussed is nutrient inactivation. Nutrient inactivation is commonly done for algal or phytoplankton control by adding alum to the water column, which binds phosphorus and thus limits the growth of algae (McComas 1993). However, larger vascular aquatic plants are typically limited by nitrogen rather than phosphorus and derive most of their nutrients from the sediment rather than from the water column. No chemical is available that binds nitrogen as readily as alum binds phosphorus. Additionally, the difficulties of adding a binding agent to the sediment rather than to the water column are obvious. Despite these limitations, nutrient inactivation has been attempted, but with limited success (Mesner and Narf 1987). At this point, nutrient inactivation for control of aquatic vascular plants is still in the research and development phase.

The author measuring Eurasian watermilfoil densities

No Action. While doing nothing is not, on the face of it, a management technique; the "no-action" alternative is one often used as the "baseline condition" for permits or environmental impact comparisons. "No action" is also the default choice of regulators and managers everywhere. Who can blame them? The direst of bureaucratic punishments is reserved for those who try and fail, while those who do nothing are rarely even reprimanded, much less punished.

When evaluating the various management techniques, the assumption is erroneously made that doing nothing is environmentally neutral. In dealing with nonnative species like hydrilla, giant salvinia and Eurasian watermilfoil, the environmental consequences of doing nothing may be high, possibly even higher than any of the effects of management techniques. Unmanaged, these species can have severe negative effects on water quality, native plant distribution, abundance and diversity, and the abundance and diversity of aquatic insects and fish (Madsen 1997). Nonindigenous aquatic plants are the problem, and the management techniques are the collective solution. Nonnative plants are a biological pollutant that increases geometrically, a pollutant with a very long residence time and the potential to "biomagnify" in lakes, rivers, and wetlands.

Conclusion. Despite the views of some, there is no single cure-all solution to aquatic plant problems, no single "best choice." For that matter, several of these techniques can be made to work to work for most aquatic plant problems, given enough time and money. None of these techniques are evil or inherently unacceptable; likewise, none of these techniques are without flaws or potential environmental impacts. Rather, it is up to each management group to select the most appropriate techniques for their situation given a set of social, political, economic and environmental conditions.

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