ERDC/EL TR-13-9

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Ecosystem Management and Restoration Research Program

Propagation and Establishment of Native Plants for Vegetative Restoration of Aquatic Ecosystems

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June 2013

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Research Program

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Final report

Prepared for US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

Aquatic plants are a vital, but often missing, component of shallow, freshwater systems. Manmade systems, such as multipurpose reservoirs, of course do not come equipped with aquatic plant communities. Even natural systems, such as streams, ponds, and lakes, have often been so disturbed that they, too, lack aquatic plants. An absence of plants often results in relatively poor aquatic habitat; shoreline erosion; water quality problems; development of noxious algal blooms; and, often, susceptibility to invasion by harmful, non-native, aquatic weeds.

If resource managers wish to avoid these problems and to realize sustainable environmental benefits, they must take action to "restore" a diverse plant community dominated by native species. To date, the best method to ensure successful establishment of a diverse, native plant community is to plant robust propagules of desirable species in selected, favorable environments and to provide them with protection from grazing.

This report provides general information on production of aquatic plant propagules and on methods of planting and protection that should facilitate the development of diverse native plant communities in aquatic systems. We document the successful application of these techniques in a number of aquatic ecosystems.

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Preface

The report was published as part of the Ecosystem Management and Restoration Research Program (EMRRP). The EMRRP is sponsored by Headquarters, US Army Corps of Engineers, and is assigned to the US Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, Mississippi. The EMRRP Program Manager is Glenn Rhett.

This report was prepared by Dr. Gary Dick, Dr. Michael Smart, and Lynde Dodd, Aquatic Ecology and Invasive Species Branch (EE-A ERDC-EL), under the general supervision of Dr. Timothy E. Lewis, Chief EE-A; Dr. Edmond J. Russo, Jr., Chief, Ecosystem Evaluation and Engineering Division, EL; and Dr. Beth Fleming, Director, EL.

At the time of publication of this report, COL Kevin J. Wilson was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

Aquatic plants and the ecosystem

Many ecosystems, such as rain forests and grasslands, are defined by the plant communities that they support. Plants in aquatic systems, however, are often overlooked as critical components of a healthy ecosystem, possibly because of the smaller scale of inland water bodies in relation to more familiar ecosystems. Aquatic and riparian plants provide valuable food and cover for invertebrates, fish, and wildlife; improve water clarity and quality; reduce shoreline erosion and sediment resuspension; and help prevent the spread of nuisance exotic plants (Dibble et al. 1996; Engel 1985; French 1988; James and Barko 1995; James and Barko 1990; Petr 2000; Smart et al. 1994). These qualities contribute significantly to ecosystem health and function, which in turn improves the value of the natural resource.

Inland water bodies in the US include ponds, reservoirs, riverine systems, large and small lakes, and permanently inundated wetlands. Water bodies in poor ecosystem health often exist in one of three conditions interrelated with aquatic plants: 1) they completely lack native aquatic plants, 2) they support native plant communities that are insufficient to provide system-wide benefits, or 3) they are infested with nuisance species that cause both environmental and water resource problems. Symptoms of an unhealthy ecosystem in water bodies existing under the first two conditions generally include poor water quality, shoreline erosion, weak fishery development, reduced usage by waterfowl and other aquatic wildlife, and turbid waters from sediment resuspension. These conditions make the water body susceptible to invasions by nuisance plants and harmful algal blooms (Doyle and Smart 1995). Water bodies that support aquatic plants are sometimes infested with nuisance species such as hydrilla (*Hydrilla verticillata*), Eurasian watermilfoil (*Myriophyllum spicatum*), or cattails (*Typha* spp.), which may offset ecosystem benefits provided by desirable native aquatic plants and may interfere with other system functions such as flood control, navigation, water supply, power generation, and recreation. Excessive biomass associated with these plants may also lead to degraded water quality and may harm fisheries (Smart et al. 2009).

While most managers are familiar with ecosystem health problems within the water bodies that they manage, many remain unaware of the extent of benefits that they can gain by promoting growth of desirable native aquatic vegetation. Efforts to establish native aquatic plants can provide benefits far outweighing those gained from put-and-take fisheries, erosion barriers, nuisance plant control, and other lake management endeavors. Best management practices for water bodies suffering from any of the three conditions discussed above should therefore focus on ecosystem health, with provision for active development of sustainable native aquatic vegetation communities.

Managing aquatic plants to manage the ecosystem

When aquatic plant communities are deemed unsatisfactory for any reasons (usually including one the three conditions listed above), one generally can take corrective action through establishing native plants or enhancing existing native plant communities. If aquatic plants are absent or minimal in a water body, adding plants alone may be sufficient to meet this management goal. However, when nuisance species are present, an integrated management approach that simultaneously suppresses the growth of nuisance plants while promoting the growth and spread of native species is also required. Short-term removal of nuisance species may necessitate strong action, such as lake-wide chemical control, drawdown, or high density stocking of biocontrol herbivores such as grass carp (*Ctenopharyngodon idella*). Longer-term management of weedy species recovery following treatment should include less disruptive management strategies that target the recovery of problematic species, including spot and selective chemical control, introduction of host-specific biological control agents, lower density grass carp stocking (possibly achieved by population attrition from initial high density stocking), water level manipulation, or an appropriate combination of these.

Ideally, one should formulate strategies to manage nuisance plants in a manner that allows for recovery or establishment of native plant communities. While we have made attempts to control nuisance plants, with emphasis on retaining or enhancing native plant communities (e.g., Lake Gaston, North Carolina/Virginia; Lake Conroe, Texas), results have been mixed and may not be applicable to other water bodies. To achieve this goal, lake managers need guidance from additional research and field tests.

Establishing native aquatic plants

While this document does not provide specific guidance for integrated nuisance plant management, it does summarize methods developed by the USACE Aquatic Plant Control Research Program (APCRP) for establishing native aquatic plants in reservoirs and other water bodies. These techniques should be useful as mechanisms for establishing or enhancing native aquatic plant communities with or without control of nuisance species, with the caution that some control techniques may negatively affect efforts to establish native vegetation.

Establishing native aquatic vegetation is not an exact science. Each water body exhibits combinations of characteristics that one must overcome to allow plants to establish and grow, and efforts to establish them will require system-specific planning. Additionally, characteristics that inhibit plant establishment and growth are prone to change over time, so projects may require an adaptive management component to achieve success. Understanding limitations to plant establishment is critical for identifying factors that may affect the outcome of native aquatic plant restoration.

Man-made water bodies (reservoirs, ponds, etc.) are ecologically young and are often remote from natural populations of aquatic plants. As a result, many have no aquatic plant seed bank and receive only limited inputs of seed and other plant propagules from their watersheds or from other sources. Rather than supporting beneficial native plants, these water bodies often remain unvegetated or become colonized by nuisance weeds, frequently a result of accidental or intentional introduction. Because many nuisance species are adapted for exploiting disturbed conditions, they can quickly spread to become problematic, especially in the absence of native vegetation (Smart and Doyle 1995). Moreover, nuisance plants can prevent colonization by beneficial native plants, regardless of subsequent propagule availability, by preemptively occupying areas suitable for their growth. In contrast, many natural lakes and rivers have historically supported native aquatic plants but have since lost much or all of their vegetation owing to natural and human disturbances, or to a combination of the two. Increased water level fluctuations (storms, droughts, and water-use); high nutrient and pollutant inputs; indiscriminant herbicide applications; and exotic species introduction, including common carp or aggressive aquatic plants, have all played roles in declines of native plants and their seedbanks. Nearly all inland water bodies in the US are therefore potential candidates for ecosystem management through native aquatic plant establishment.

Establishing or re-establishing native aquatic plants in any water body can be challenging, and one must consider several major factors to promote plant growth and spread. Our approach deals with common abiotic and biotic obstacles that one must overcome to provide conditions suitable for timely plant establishment, growth, and spread. Abiotic conditions unfavorable to plant establishment generally include excessive water level fluctuations, high turbidities, pollutants, and shifting sediments, among others. As an example, newly established plants are especially vulnerable to changing water levels that may place them in water too deep or too murky to allow for adequate light for photosynthesis or so shallow as to expose them to turbulence or desiccation (Doyle and Smart 1995). Biotic disturbances are caused by a number of aquatic and semi-aquatic organisms. Fish and other animals that feed or root in sediments dislodge seedlings and other small plants and increase turbidities, making it difficult for submersed plants to grow. In addition, studies show that intense grazing by turtles, crayfish, insect larvae, mammals, and waterfowl can prevent the establishment of aquatic plants and damage existing stands (Lodge 1991; Dick et al. 1995; Doyle et al. 1997). Understanding and addressing these and other plant establishment obstacles specific to a water body are necessary to ensure vegetation establishment success.

2 Approach

While we have conducted most of our work in larger water bodies, our aquatic vegetation establishment methods are applicable to all scales, from small ponds to large reservoirs. A major difference is that one can plant smaller systems at full or near full-scale while the large size of many reservoirs and natural lakes logistically precludes planting at that level. To compensate for this, we have developed an approach for accelerating the natural process of aquatic plant spread by using **founder colonies**. Founder colonies are typically composed of moderately small (less than 1 ha) plantings made at strategic locations within the water body (Figure 1). The principal function of a founder colony is to overcome one of the major impediments to aquatic vegetation establishment: availability of propagules. Continual provision of propagules (seeds, fragments, etc.) ensures that they are present when conditions are suitable for natural spread, greatly shortening the time required for lake-wide colonization. Once established, founder colonies spread in two ways—vegetative expansion from the founder colony itself (e.g., along stolons or rhizomes) and formation of new colonies from fragments, seeds, etc. (Smart et al. 1996; Smart et al. 1998). In addition to supplying propagules, founder colonies provide immediate small-scale habitat improvement in large and intermediate systems and potentially complete habitat improvement in smaller systems. Because we use protective exclosures to establish founder colonies (discussed further in Section 4), they may also serve as refugia for aquatic plants in water bodies prone to periodic disturbances (drought, floods, etc).

The methods used to establish founder colonies that we present here have been well tested in multiple systems. However, they may not be universally applicable because of differences among plant species, among regions of the country, among water bodies, and even within water bodies. These techniques are certainly not the only means of establishing aquatic vegetation; therefore, we, along with other scientists, continue to develop and evaluate new methodologies to improve success. Likewise, we have thus far attempted to establish only a relatively few plant species potentially suitable for ecosystem management projects, with many more potentially useful in these efforts.

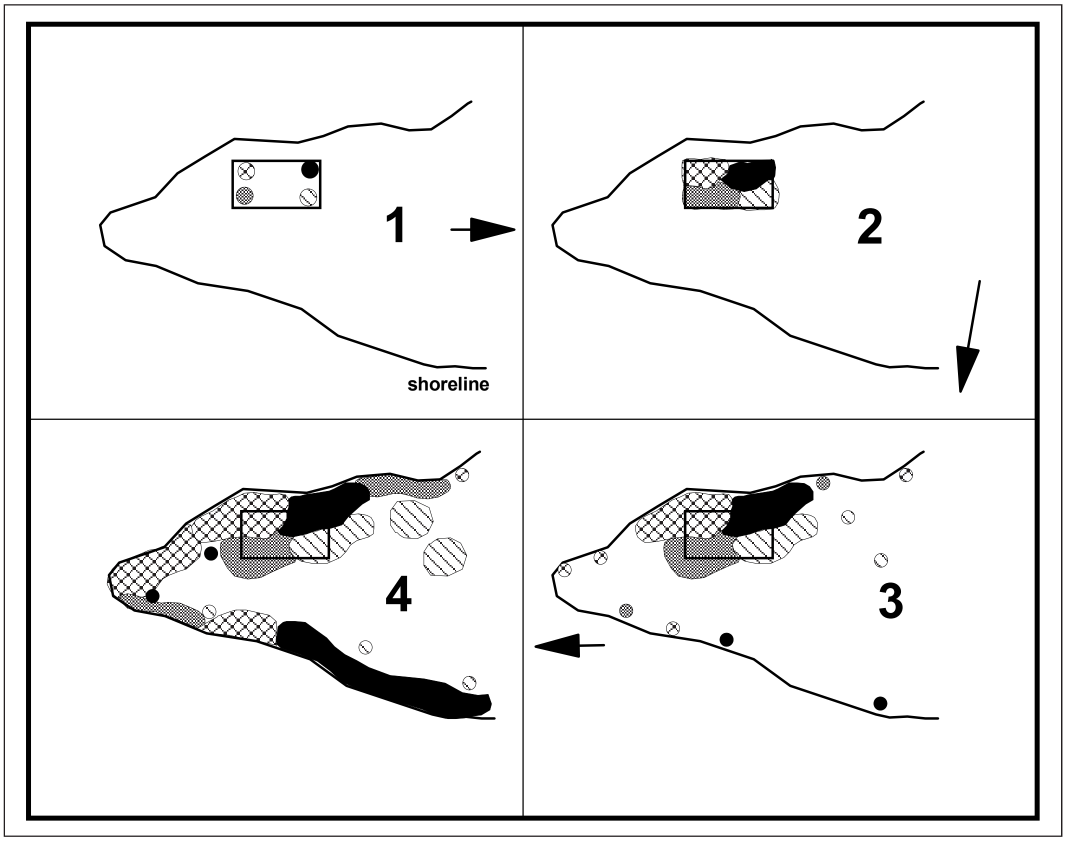

Figure 1. Founder colonies (1) are established by planting in well-protected areas. Plants grow (2) to fill protected areas and begin to spread. Spread continues (3), and new colonies begin to develop from seeds and fragments. New colonies then spread (4) to provide larger-scale benefits.

3 Plant Species Selection and Propagule Production

Species selection

Plant species selected should be historically native to the region (or state) in which one is conducting the project. Include a diversity of growth forms (submersed, floating-leaved, and emergent plants) tolerant of as wide an array of conditions as possible. In general, submersed plants are those that produce mostly underwater leaves and stems and must be in water to actively grow, whereas floating-leaved (most stems underwater and most leaves on the water surface) and emergent (most leaves and stems above the water) plants can actively grow in both water and moist soils. One can then focus on species that show the most promise for a particular water body. Table 1 provides some common species that have demonstrated high potential for establishment in various types of water bodies.

Table 1. Native submersed, floating-leaved, and emergent aquatic plants that we have successfully used in founder colony establishment in US water bodies.

Common Name	Scientific name	Growth form	Flood tolerance (6+ weeks)	Drought tolerant* (6+ weeks)
American pondweed	*Potamogeton nodosus*	submersed	Yes	No
Coontail	*Ceratophyllum demersum*	submersed	Yes	No
Horned pondweed	*Zannichellia palustris*	submersed	Yes	No
Illinois pondweed	*Potamogeton illinoensis*	submersed	Yes	No
Sago pondweed	*Stuckenia pectinata*	submersed	Yes	Yes
Small pondweed	*Potamogeton pusillus*	submersed	Yes	No
Southern naiad	*Najas guadalupensis*	submersed	Yes	No
Water stargrass	*Heteranthera dubia*	submersed	Yes	Yes
Wild celery	*Vallisneria americana*	submersed	Yes	No
American lotus**	*Nelumbo lutea*	floating-leaved	No	Yes
Blue water lily	*Nymphaea elegans*	floating-leaved	No	Yes
Fragrant water lily	*Nymphaea odorata*	floating-leaved	Yes	Yes
Spatterdock	*Nuphar lutea*	floating-leaved	Yes	Yes
Watershield	*Brasenia schreberi*	floating-leaved	Yes	No
Yellow water lily	*Nymphaea mexicana*	floating-leaved	No	Yes

Common Name	Scientific name	Growth form	Flood tolerance (6+ weeks)	Drought tolerant* (6+ weeks)
American bur-reed	*Sparganium americanum*	emergent/submersed	Yes	Unknown
Bulltongue	*Sagittaria graminea*	emergent/submersed	Yes	Yes
Tall burhead	*Echinodorus berteroi*	emergent/submersed	Yes	No
American bulrush	*Schoenoplectus americanus*	emergent	No	Yes
American water plantain	*Alisma subcordatum*	emergent	No	Yes
Arrow arum	*Peltandra virginica*	emergent	No	Yes
Arrowhead	*Sagittaria latifolia*	emergent	No	Yes
Cherokee sedge	*Carex cherokeensis*	emergent	No	Yes
Creeping burhead	*Echinodorus cordifolius*	emergent	No	Yes
Flatstem spikerush	*Eleocharis macrostachya*	emergent	Yes	Yes
Giant bulrush	*Schoenoplectus californicus*	emergent	Yes	Yes
Lizard's tail	*Saururus cernuus*	emergent	No	Yes
Marsh pennywort	*Hydrocotyle umbellata*	emergent	No	Yes
Pickerelweed	*Pontederia cordata*	emergent	No	No
Slender spikerush	*Eleocharis acicularis*	emergent	No	Yes
Softstem bulrush	*Schoenoplectus tabernaemontani*	emergent	Yes	Yes
Squarestem spikerush	*Eleocharis quadrangulata*	emergent	Yes	Yes
Sweetflag	*Acorus calamus*	emergent	Unknown	Yes
Tall burhead	*Echinodorus berteroi*	emergent/submersed	Yes	No
Water hyssop	*Bacopa monnieri*	emergent	Yes	Yes
Water pepper	*Polygonum aquaticum*	emergent	Yes	Yes
Buttonbush	*Cephalanthus occidentalis*	emergent shrub	Yes	Yes
Crimsoneyed mallow	*Hibiscus moscheutos*	emergent shrub	No	Yes
Halberdleaf mallow	*Hibiscus laevis*	emergent shrub	No	Yes
Rosemallow	*Hibiscus lasiocarpos*	emergent shrub	No	Yes

*Other than from seeds.

**Not recommended for small or shallow systems.

Additionally, select species based on specific lake habitats or anticipated environmental conditions. For instance, in a water body known to follow a pattern of significant water elevation loss, concentrating on drought-tolerant species may be best. While the body of knowledge that we present here may provide guidance for most vegetation establishment projects, predicting environmental changes and plant responses in a particular water body is difficult; and we strongly recommend conducting test plantings (see Section 4) of as many species as possible to ascertain which may be best suited for that water body.

Containerized plant production

Figure 2. Potted wild celery plants are much more likely to survive transplanting into the field than are bareroot plants or other less robust propagules.

There are a number of ways to acquire plants for aquatic ecosystem restoration, with most of them involving direct transplanting of propagules collected from the field. However, we issue a strong caution against transplanting propagules from one site to another, and especially from one water body to another, to avoid accidental introduction of nuisance species, a common problem with restoration efforts. Through much trial and error, we have found that using containerized (potted) plants (Figure 2) is the most efficient and successful approach for establishing aquatic plants in the field, as well as the least likely to result in a spread of invasive species. Potted plants appreciably outperform (higher long-term survival) other commonly used propagules such as seeds, fragments, tubers, and bareroot plants. Unlike other propagule types, properly grown potted plants have well-developed and relatively undisturbed root systems, making them easy to anchor in field substrates. Perhaps more importantly, potted plants are capable of withstanding harsh environmental conditions (such as desiccation) immediately on transplanting. Because acquiring large numbers of appropriate potted plant can be difficult in a timely manner, we have developed methods for producing these field-ready, robust propagules suitable for most projects. Although one may use commercial suppliers to provide some plant materials needed for restoration projects, it may be preferred or necessary to produce propagules in-house for several reasons:

- Currently, only a limited selection of aquatic plant species (particularly potted, submersed plant species) is readily available from commercial sources.
- Many propagule types (e.g., stem fragments, seeds, tubers, etc.) offered commercially may not be suitable to overcome the harsh environmental

conditions in which they will be placed, but they may be useful as starter propagules for in-house production if otherwise suitable.

- Seasonal availability of propagules offered commercially may not coincide with project schedules.
- Non-local, commercially available propagules (from other regions of the US) may not be genetically compatible with project needs.
- Commercially available propagules are often misidentified or include viable contaminants of nuisance species.

Because in-house cultivation of local plant stocks of desired species is currently the best means of supplying suitable plants free of nuisance species, this section is intended as a guide for those who choose to produce their own propagules. We cover general requirements and considerations for culturing a variety of aquatic plants, focusing on the three aquatic plant growth forms: submersed, floating-leaved, and emergent. We have successfully cultured a number of plant species for use in restoration projects, including all of those provided in Table 1. Other species, particularly those closely related to any listed here, should respond similarly to our culturing methodologies, as should, in general, submersed, floating-leaved, and emergent species. However, we have not tested many North American species that are potentially suitable for restoration projects in the US.

Production facilities

Production of aquatic plant propagules requires adequate facilities, but these need not be complicated or expensive. One may use small ponds (with caveats) or tanks to grow aquatic plants. To minimize transportation costs and inevitable damage that occurs while transporting plant materials, production facilities ideally should be located as close as possible to the restoration site. In the following section, we provide guidelines on the suitability of various facilities for plant production.

Existing ponds

Ponds may serve as sites for culturing aquatic plants, although we typically use them only for producing planting stock to be used for growing containerized plants in tank facilities. Any pond that has a reliable water source (and water depth) can serve as a plant culture vessel, but those in which drainage and filling are easily accomplished are preferred—gravity-fed water source and drainage are usually the most economical. This allows the grower to manipulate water levels for cultivation needs such as planting, weeding, fertilizing, and harvesting.

However, potential problems with using existing ponds as culture vessels often outweigh their one significant advantage: pre-existence and therefore minimal cost to activate. Problems with using ponds can include the following:

- Infestation with native or non-native vegetation, which can contaminate cultures.
- Poor accessibility for standard culture operations.
- Difficulties in excluding aquatic animals that can damage cultures such as waterfowl, crayfish, and nutria.
- Difficulties in segregating culture species.

Because of these and other problems, we do not recommend using ponds (existing or to-be-constructed) for culturing containerized aquatic plants unless no other means are available. Instead, we suggest using aboveground tanks.

Tanks

Tanks are the preferred vessels for growing potted aquatic plants. Advantages of tank culture include accessibility, water quality management, and easy separation of species. Many sizes and shapes of fiberglass and plastic tanks are available commercially to fit existing space and the needs of a plant-culturing project. While these are generally manufactured for aquaculture of fish and invertebrates, some models are well suited for aquatic plant production.

Tank dimensions are critical for facilitating plant growth and care. Easy access to all points within a tank is necessary for good plant cultivation. A tank width of about 1.3 m is the maximum for access to plants without having to enter the tank. The length of the tanks is less important (our tanks range from 2 to over 10 m long), but make sure there is level space for installation of the full length of tanks selected. Tank depth is also important: for most species of submersed and floating-leaved plants, we recommend tanks in the range of 0.5 to 1.0 m deep. We use shallower tanks (25 cm or less) for growing most emergent species. If one uses deeper tanks for growing emergent species, we recommend installation of standpipes to control maximum water depths to prevent excessive inundation mortality.

Rather than using manufactured tanks, constructing custom tanks may be desirable and cost-effective for most projects. For long-term cultivation, one can build concrete vats to size for specific plant types. Such structures should have permanent plumbing, including filling and drainage piping when possible. One can construct less expensive tanks from available building materials (lumber or concrete blocks) and pond liner material (Figure 3). Installing permanent pumps and drains or via hoses and siphons (or submersible pumps) will allow the movement of water in and out of the tanks. Supporting tank walls should be sufficient to enable complete filling of the tank without collapse of walls.

Figure 3. Commercial and custom built containers are suitable for growing most species of submersed, floating-leaved, and emergent aquatic plants.

Shelters and overwintering

Ideally, plant production begins in the spring, and one brings plants to the field that same growing season. However, delays in field operations, holding over starter stock (e.g., propagules produced by cultures), and other factors may cause a need to overwinter plants. Because of our location (north central Texas), we do not use shelters for most of our plant production, with all species going dormant during winter months and sprouting as temperatures rise during spring. We can keep plants outdoors year-round as long as tanks or pots do not freeze solid; we have had consistent successes growing plants without shelter as far north as northern Oklahoma and North Carolina. Filling the tanks to full capacity during winter reduces the likelihood of solid freezing at those cultures. For projects that require earlier-in-the-year planting, we sometimes use greenhouses, hothouses, and cold frames incorporated into tank designs to force plants to break dormancy.

In most northern states, where one expects tanks or pots to freeze solid during the winter, heated shelters can provide cold protection. Because shelters may be cost-prohibitive, an alternative is to deploy cattle tank heaters or freeze prevention pumps.

Plant growth requirements

General considerations

The key to growing any plant is to provide conditions that fulfill its requirements for nutrients and sustain a rate of photosynthesis sufficient for respiration and growth. Plants have a basic need for water and for an environment that provides appropriate temperatures and adequate light for growth. In general, growing aquatic plants is relatively straightforward, with some distinct differences between the needs of the three growth forms. For instance, while floating-leaved and emergent plants acquire carbon atmospherically, photosynthesis by submersed aquatic plants occurs underwater and depends on a continual supply of inorganic carbon (dissolved carbon dioxide or bicarbonate). Growing submersed species therefore requires provision for replenishment of dissolved carbon in culture water. Additionally, though light penetration in water is not a factor in growing floating-leaved and emergent plants, culture water for submersed species must be sufficiently clear to transmit adequate light to the leaves to enable photosynthesis. Finally, excessive nutrients in the water column, particularly phosphorus, may lead to excessive algal growth, which can compete with submersed plants for inorganic carbon and reduce light penetration by increasing turbidity.

Substrates

Aquatic plants will grow in a variety of substrate types, ranging from pure sand to heavy clays. However, for optimum production, a fine-textured substrate with a low to moderate organic content (10–20%) appears ideal for most species. Overly sandy substrates are unsuitable as a culture medium because they are generally infertile and because added nutrients will diffuse into the water column, causing algal problems. On the other hand, highly organic substrates can be inhibitory to plant growth by fouling the water column (Barko and Smart 1983, 1986). When available, we recommend using fine-textured sediments from ponds or lakes in which aquatic plants are known to grow but from which nuisance species have not been reported. If the growth potential of sediments is in doubt, conduct small-scale trials (with and without fertilizer amendments, see below) to ascertain suitability for supporting aquatic plant growth. Because floating-leaved and emergent plants are more tolerant of poor substrates than are submersed plants, substrate suitability tests should include each growth form. Substrates require heat sterilization if nuisance species occur or have occurred in the past in the water body from which substrates are collected. Subjecting substrates to 90°C under dry (24 hours) or wet (25 minutes) heat is sufficient to kill aquatic plant seeds and other organisms that may be dormant in substrates.

Because suitable natural sediments may not always be available, acquiring commercial potting soils or topsoils may be necessary. For relatively small-scale efforts, bagged soils available from commercial nurseries may be practical. When one selects a soil for aquatic use, the lowest priced product will often be the most suitable as it will generally contain the fewest additives. Avoid using products that contain non-soil additives such as vermiculite or perlite. For large-scale projects, one may purchase local topsoils in bulk after ensuring their suitability (by conducting small-scale plant growth trials). In either case, excessive leaching of nutrients may foul the water, so commercial substrates should be “washed” several times before planting. Substrates are most easily washed by placing substrate-filled containers in growing vessels (tanks) and flushing two or three times over a several days prior to planting propagules.

Containers

Producing propagules suitable for transplanting into lakes entails growing the plants in pots. We recommend using plastic nursery pots with drain holes in the bottoms (Figure 4). Various sizes and shapes of commercial nursery pots are available, but we have had the most success with quart- (4-in. diameter) and gallon- (6-in. diameter) sized (nominal sizes) pots for growing a wide variety of aquatic plant species. For economy, acquiring blow-molded plastic pots permits reuse at least several times.

Size the pots to the plants being cultured. In general, we grow all floating-leaved and some emergent species (bulrushes, Cherokee sedge, pickerel-weed, mallows, and buttonbush) in 6-in. pots and all submersed species and remaining emergent species (from Table 1) in 4-in. pots. A notable exception is American lotus, which we grow in 30 cm diameter plastic oil pans because of its prolific production of stolons, which would soon escape from smaller diameter containers.

Figure 4. Gallon-sized (left) and quart-sized (right) blow-molded commercial nursery pots are suitable for growing aquatic plants.

Because smaller planted pots (4 in.) tend to be unstable when placed in water, we use commercial nursery trays designed to hold groups of 12–15 pots. In addition to helping stabilize the pots, trays of this size allow us to move potted plants in small groups. In our experience, 6-in. pots are stable, and use of trays is not necessary.

Fertilization

Nutrient uptake by all aquatic plants depends on a supply of critical nutrients, generally taken up by roots anchored in nutrient-amended substrates. Although many substrates mentioned above contain most of the essential nutrients required for growing plants to field-ready condition, many lack sufficient nitrogen to produce the most robust propagules possible. We therefore fertilize substrates to ensure that nitrogen availability does not limit growth. To fertilize substrates, we place a layer of unamended substrate into the pot to cover the holes (about $^1/_4$ full), add the appropriate quantity of fertilizer (see below), and then fill the pot with substrate to about $^4/_5$ full. This serves to hold fertilizer near the bottom of the pot and reduces the likelihood that it will leach out of the substrates before the plants can use it. We use different fertilizers and rates of fertilization depending on the growth form of the plants.

Submersed aquatic plants

For short-term (single growing season or less) cultivation of submersed aquatic plants, an initial fertilization of the potting medium is usually sufficient. Often, adding only nitrogen (N) is required to achieve optimum growth (Smart et al. 1995). We generally use ammonium sulfate (21% N) at rates of 2.5 g per 4-in. pot or 10.0 g per 6-in. pot (0.5 g N/L of medium), which is sufficient to support growth during this period. While one may use other compounds as a source of N, always add it as an ammonium salt, not as nitrate or urea. We have also had some successes growing submersed plants with slow-release, low-phosphorous 10–15 g fertilizer pellets that approximate 0.5 to 1.0 g N/L. Take care not to over fertilize with N to prevent damage to plants roots and thereby inhibit growth.

Longer-term cultivation of submersed aquatic plants may require periodic addition of N or other nutrients. Adding ammonium sulfate to the water at a rate of 4.0 g per 1000 L can sustain the growth of mature transplants if one notes symptoms of nitrogen deficiency (e.g., yellowing of leaves). Because excess levels of nitrogen can damage or even kill submersed aquatic plants, total N concentrations should never exceed 4.0 mg/L.

Floating-leaved and emergent aquatic plants

Floating-leaved and emergent growth forms generally produce more biomass than submersed growth forms and have proportionately greater demands for nutrients. Therefore, use fertilizers containing N-P-K (nitrogen-phosphorus-potassium) ratios such as 15-5-5 (or similar) with micronutrients instead of N alone. Fertilizer rates should not exceed 1.0 g N/L substrate to prevent damage to roots. Adding the same fertilizers directly to culture water when plants show signs of nutrient limitation (yellow leaves, stunting, etc.) can sustain long-term growth of floating-leaved and emergent growth forms.

Water quality

In general, water suitable for rearing freshwater fish is adequate for growing submersed plants. Ideally, water should be clear and relatively nutrient-free (at least phosphorus-free) to permit adequate light penetration and to reduce the potential for algae growth. Floating-leaved and emergent plants are not as particular as submersed species and generally thrive as long as the water is moderately clean. We do not recommend using municipally treated water for growing plants unless chlorine is first removed.

For our submersed plant cultures, we use lake water (Lewisville Lake, Denton County, Texas) that we have polished or treated to acceptable quality. In one method, we use a vegetated pond to reduce turbidity and remove most dissolved phosphorus (P) from the water column; we pump water from the pond and run it through a sand filter before we add it to our culture tanks. In a second method, we pump lake water into a holding tank where we treat it with aluminum sulfate (approximately 0.1 kg per 1000 L) to flocculate clays and suspended material and to remove P by sorption onto precipitates. We allow the resultant flocculent to settle, and we pump the clear surface waters to our culture tanks. For a large-scale plant production system, we use a 1.5-m-deep, lined water supply pond as a reservoir. We pump lake water into the pond, treat it with aluminum sulfate, and mechanically filter it with sand (Dick et al. 1997). The pond liner (synthetic rubber) prevents nutrients and clay minerals from releasing or suspending from the soil into the water column. This system provides an abundance of high-quality water for growing submersed aquatic plants. Although production of water in these ways is not necessary for growing floating-leaved and emergent plants, the processes we use to prepare the water provide a secondary but critical benefit of screening out nuisance species (plant and animal) from all of our cultures.

Additional requirements for water used to grow submersed aquatic plants include a source of inorganic carbon and a balanced chemical composition including calcium, magnesium, and potassium ions (Smart and Barko 1984, 1985). Periodic replacement of part of the water may maintain favorable levels of alkalinity, dissolved inorganic carbon, and dissolved ions, assuming source water contains adequate quantities of these essentials. Because alum treatment tends to lower alkalinity, we periodically add sodium or potassium bicarbonate and calcium (as either a sulfate or chloride salt) directly to our submersed species culture tanks to help maintain adequate levels of these constituents. One may also need aeration (see below) to maintain a steady supply of inorganic carbon.

Carbon for submersed plants

In unlined, earthen ponds, sediment respiration provides an abundant and continuous supply of carbon dioxide to support the photosynthesis of submersed aquatic plants. However, in lined ponds or tanks, carbon dioxide availability may be a factor limiting plant growth. Consequently, we recommend aeration of tank cultures for some (not all) submersed species, including wild celery, sago pondweed, small pondweed, horned pondweed, Southern naiad, and coontail. A regenerative blower/compressor aeration system supplies the air, and vigorous bubbling of atmospheric air through air stones usually provides adequate carbon dioxide. Some submersed species (including American pondweed, Illinois pondweed, and water stargrass), floating-leaved, and emergent species acquire sufficient carbon dioxide directly from the atmosphere, and therefore do not require aeration.

Propagules for starting containerized cultures

Many commercial suppliers sell aquatic plant propagules. We do not recommend using these propagules for establishing plant colonies in the field, but they are often adequate as starter materials for plant production in tanks or ponds. However, commercial availability is often seasonal, and plants may not be available when needed. Also, one should always attempt to use locally or regionally adapted plants if possible. If one knows of local or regional populations of a particular species, we recommend harvesting from these populations to obtain starter propagules. If undertaking harvests from existing populations, make sure not to remove excessive quantities of a given species. Additionally, do not harvest from communities that include nuisance species. This caution applies to commercially acquired plant materials, as well: nuisance species infest many commercially acquired shipments (Maki and Galatowitsch 2004).

One may use stem fragments, daughter plants, root crowns, tubers, winter buds, even seeds (depending on the species) as starter materials for aquatic plant cultures. We suggest planting more pots than needed for a project, especially if planning other projects in the future. After establishing a culture of a particular species, one can use it as a source for the next generation of cultivation. This reduces the need to harvest from wild donor populations and reduces possible negative impacts of overharvesting.

Stem and rhizome fragments

Many aquatic plant species spread vegetatively from stem and rhizome (underground stem) fragments. To propagate new plants from stem fragments, cut healthy stem tips to lengths of 10 to 15 cm. When selecting material, remember that more stem nodes are better, as most nodes can produce roots as well as leaves and branches. Plant the cuttings at least 5 cm deep, making sure that the growing tip is at least 5 cm above the substrate. For faster potted plant development, plant several cuttings in each pot. Established plants grown from stem fragments readily regenerate new meristematic tissues after cutting, so once the culture is actively growing, one can take cuttings to plant additional pots. Aquatic plants that can grow from stem fragments include pondweeds (*Potamogeton* spp.), water stargrass (*Heteranthera dubia*), coontail (*Ceratophyllum demersum*), water hyssop (*Bacopa monnieri*), water smartweed (*Polygonum aquaticum*), and water willow (*Justicia americana*). Some aquatic plants, such as white water lily (*Nymphaea odorata*), spatterdock (*Nuphar luteum*), spikerushes (*Eleocharis* spp.), and bulrushes (*Schoenoplectus* spp.), can propagate in a similar manner from sprouts along their rhizomes.

Bareroot plants

Some aquatic plant species, such as wild celery (*Vallisneria americana*) and many emergent forms, produce daughter plants along stolons (Figure 5). To propagate these species, divide multi-plant clumps with roots intact or clip small plants from the parent and plant them directly into new pots. A relatively dense, firm substrate is important for these species because most are buoyant and, without sufficient anchoring, dislodge easily from the potting medium. At the same time, bareroot and daughter plants tend to grow basally, and one must take care not to excessively cover this growing area when planting. Replant dislodged plants over a several day period, if necessary. Place a layer of coarse sand or fine gravel over the substrate after planting to help anchor the plants.

Figure 5. Plant immature wild celery daughter plants (bareroot plants) individually or in clumps.

Dormant perennating structures

Figure 6. Use spouted (pictured) or unsprouted arrowhead tubers to produce potted plants for transplanting into the field.

Aquatic plants such as American pondweed (*Potamogeton nodosus*), bulltongue (*Sagittaria graminea*), and arrowhead (*S. latifolia*) survive periods of cold and desiccation by producing tubers and other underground structures (Figure 6). One can collect these propagules, hold them in a dormant state by refrigeration (variably for up to 8 weeks or so), and then plant them when desired. Some tubers are buoyant, and one should plant them at least 5 cm deep and cover them completely with substrates. One can prepare extra pots (or larger containers) and can hold plants over winter to complete their annual life cycle either to produce tubers to harvest and use for restoration projects or to produce subsequent crops.

Seeds

Most aquatic plant species that we use for restoration projects produce viable seed. However, ease of propagation of most of these by other means and our rather limited knowledge of seed storage and germination requirements limit the usefulness of seed as a starting material for producing plant propagules. We have used seed- or spore-laden sediments (obtained from drained ponds free of exotic species) to start plants of several annual species such as Southern naiad, horned pondweed, and the macro-alga muskgrass (*Chara vulgaris*). When available, seeds are also the propagule of choice for culturing large-seeded species such as American lotus and arrow arum.

Planting the cultures

The general procedure for producing potted aquatic plants (mature transplants) is as follows:

- Fill the pot to about $^1/_4$ full with substrate to cover the bottom holes.
- Add fertilizer.
- Add more substrate until the pot is $^4/_5$ full.
- Place the pots in growing vessel (pond, tank, etc.).

- With clean water, slowly fill the growing vessel to 15 cm above the pot to saturate the substrate.
- Flush the growing vessel (drain and fill) at least two times over a 48-hour period.
- Allow the pots to cure for 3 to 4 weeks. If water "greens," flush and fill as necessary.
- Make an indentation in the center of the substrate.
- Plant the propagule, and backfill to ensure that the plant is anchored.
- Fill the growing vessel to the desired cultivation depth with clean water.

Completely submerge submersed and floating-leaved plants following planting. Following planting, we generally maintain water levels 15 cm or so above the tops of the pots and raise levels as plants begin to grow and reach the water surface. Do not completely submerge emergent species, on the other hand, with the exceptions of bulltongue and tall burhead. Following planting, hold water levels so that pots are continually saturated but not overtopped. Once plants begin to sprout and grow, raise water levels to above the tops of pots. However, be sure not to submerge more than 50% of the stems and leaves.

Culture maintenance

Water levels

Do not let cultures dry out. We recommend checking water levels at least several times weekly, especially during hot (more prone to rapid desiccation) and very cold (more prone to freezing solid) conditions. Generally, hold water levels so that submersed and floating-leaved species tanks are at near capacity at all times. Short-term lowering of water levels to flush excess nutrients, pests, etc., without exposing too much biomass should not harm most submersed and floating-leaved plants.

Long-term cultures of emergent species can benefit from periodic short-term exposure of substrates (2 or 3 days). However, make sure substrates remain moist. Longer-term exposures risk root damage and may enable establishment of unwanted terrestrial plants from seed in emergent culture substrates.

Weeds

As with any culture or crop, nuisance weeds may cause problems. Sediments and topsoils may contain seeds and spores of aquatic and riparian species that might interfere with production of desired species, and certain terrestrial weeds establish readily in shallow cultures used for emergent species production. Although expensive and labor-intensive, one can heat sterilize sediments to avoid or reduce this problem. If weeds do begin to establish, removing unwanted plants requires hand weeding; and while this is time consuming and labor intensive, it is necessary to produce robust propagules for planting in the field. Weed management in cultures also provides a form of quarantine to reduce the risk of introducing unwanted species to field sites. In cases where very aggressive and resilient nuisance species become established in cultures (e.g., hydrilla), we recommend destroying the contaminated culture and starting over.

Potted plants grown in mixed pond or tank cultures are susceptible to cross-contamination. When grown for the same project, cross-contamination of a culture by another cultured species may not be of concern, with each pot supporting multiple species destined for the same field site. However, some species may be difficult to culture under this condition; so we recommend segregating species by tank to reduce the likelihood of cross-contamination. If contamination does occur, rigorous hand weeding may correct the problem; but restarting the culture may be necessary if the target species begins to decline significantly.

Algae

Although usually not a significant problem for emergent and floating-leaves cultures, excessive algal growth is always a concern in cultures of submersed aquatic plants. High concentrations of nutrients (especially phosphorus and nitrogen) in the water column will generally support algal growth. Algae, whether growing in the water, on the water surface, or on the plants themselves, may cause problems by competing with and reducing the growth of cultivated plants. Using low-nutrient water and avoiding over fertilization will usually prevent algal problems. Reducing existing algal blooms may require exchanging the water with low-nutrient water. It may also require hand removal of filamentous growths or filtering the water to remove phytoplankton.

Grazing pests

Herbivore damage may become a problem in aquatic plant cultures. One must protect pond cultures from turtles, carp, waterfowl, muskrats, and some invertebrates. We discuss protective devices in the following chapter. Aphids and caterpillars can reach nuisance proportions in tank cultures and may require control. Because the use of commercially available pesticides is not permitted in water, we recommend using fish, such as *Gambusia*, and mosquito dunks; removing pests by hand; spraying pests with water; inundating; and flushing to control problematic species such as aphids.

Transporting to the field

While one must consider several factors when moving potted aquatic plants to the field, the major concern is water. Varying periods of exposure to dry conditions damage and kill aquatic plants, necessitating transporting the plants under moist conditions.

While submersed and floating-leaved plants are most susceptible to desiccation, one need not transport them in water, which can be logistically difficult, at best. We use small, lidded plastic tubs (dimensions approximately 30 × 60 × 30 cm tall) that hold 12 to 15 small pots (4 in.) and 6 to 8 larger pots (6 in.), making them moderately easy to carry by most field workers. We remove the potted plants from cultures one at a time, inspect them for rigor and for the presence of unwanted species, and then place them in the lidded tubs. Under these conditions, substrates remain saturated, and humidity is high enough to prevent desiccation of aboveground biomass for up to 3 or 4 days. Stacking lidded tubs enables transporting large numbers of plants in truck beds or on trailers. Because direct sunlight can raise temperatures inside of the lidded tubs and damage plants, we use either covered truck beds or trailers, or we cover tubs with tarps for shade.

We generally use similar tubs for emergent species, which are more tolerant of desiccation, but do not lid many species because of their height. When transporting in uncovered truck beds or trailers, we use tarps to reduce potential wind damage during transport. We do not recommend clipping aboveground biomass of emergent species to facilitate transport.

4 Establishing Founder Colonies in the Field

Site selection

Select founder colony sites based on several criteria. We choose well protected (from winds, waves, and currents), shallow areas with depths less than 1 m deep—preferably with gradual slopes—for establishing aquatic plants. We prefer fine-textured substrates, which generally indicate favorable, low energy environments. One can usually avoid areas of high sediment resuspension, and thus high turbidity, by selecting wind- and wave-protected coves. These are generally the clearest shallow waters available.

Other than as an indicator of physical conditions, sediment texture does not seem to be critical for plant establishment; and we have had similar results on sandy, clay, and even gravelly substrates. The major considerations are whether we can dig a hole into the substrate by hand and that the substrate is firm enough to anchor the plant. Therefore, when possible, avoid substrates that are difficult to excavate, such as hardpan and rocky substrates. At the same time, sediments should not be so unconsolidated as to prevent anchoring of plants.

Although we have had very few problems with vandalism of sites, we recommend avoiding high-use areas such as developed (e.g., bulkheaded) shorelines and areas favored by bank anglers, swimmers, and users of recreational watercraft. In addition, heavily wooded shorelines can be a problem because of excessive shading, which greatly reduces the light available to submersed aquatic plants, and because of damage by falling limbs and trees. Avoid areas with signs of heavy animal activity—particularly hogs, cattle, or beaver. Also avoid areas with excess structure (e.g., stumps, large rocks, etc.) unless otherwise exceptionally suitable.

Species selection for specific sites and test planting

Common sense dictates that one should select plants based on anticipated environmental conditions of a water body. For instance, in a lake known to follow a pattern of significant water elevation change, concentrating on desiccation-tolerant species might be best, avoiding those that may not tolerate anticipated periods of low water. However, because of the difficulty in accurately predicting environmental conditions and plant tolerances to them, we recommend conducting test plantings of as many species as possible to guide the selection of species for a full-scale restoration. In addition to usually ensuring long-term establishment of at least some species, this approach is more likely to develop diverse plant communities, therefore providing the greatest water quality and habitat benefits over the long-term.

Small-scale test plantings using the methods described below can help to evaluate species suitability and herbivore protection needs in a particular water body. Several test plantings of each species, with and without protection from herbivores, are usually sufficient to ascertain species and site suitability, at least in the short-term. To deem a plant suitable, plants should increase in size during the growing season in which they were planted and exhibit recovery from dormancy the following spring. Test planting sites can later serve as full-scale restoration sites for those species that survive and grow.

Planting

Initial planting depths

Two of the greatest abiotic influences on aquatic establishment are water level fluctuations and high turbidity. Because submersed aquatic plants require light to survive, planting at proper depths is critical, particularly if the water is turbid. Water levels of most water bodies are influenced by both natural (seasonal or climatic) events and operations (storage or release of floodwaters or water supplies, power generation, etc.), both of which are generally beyond our control. For planning, we review historical water level fluctuations to estimate expected levels during early establishment of plants. Based on expected water levels and knowledge of the biology of the plant species, we assign an appropriate depth or depth range for each species. In general, submersed plants will establish best at depths of 50 to 100 cm, floating-leaved plants from 25 to 75 cm, and emergent plants from 0 to 25 cm. Once established at these depths, most can tolerate a wide range of shallower or deeper water for variable lengths of time.

Timing of planting

Timing can be as critical as species selection for successful establishment to occur. However, unlike seeds or less robust propagules, one can plant mature potted plants over a wide seasonal range. If produced locally, potted plants' growth stages are often synchronized with seasons (e.g., tubers set for winter) and plants may be emplaced at virtually any time that conditions allow workers to access planting sites. Depending on location, this usually ranges from late winter to late fall.

Putting plants in place

Planting potted aquatic plants is much like planting potted landscaping plants but is usually done at depths of 25 to 100 cm. When installing plants, take care taken to ensure that root balls are not buried too shallow or that apical tips (especially in rosette-forming species) are not buried too deeply. Figure 7 provides general instructions for planting potted plants.

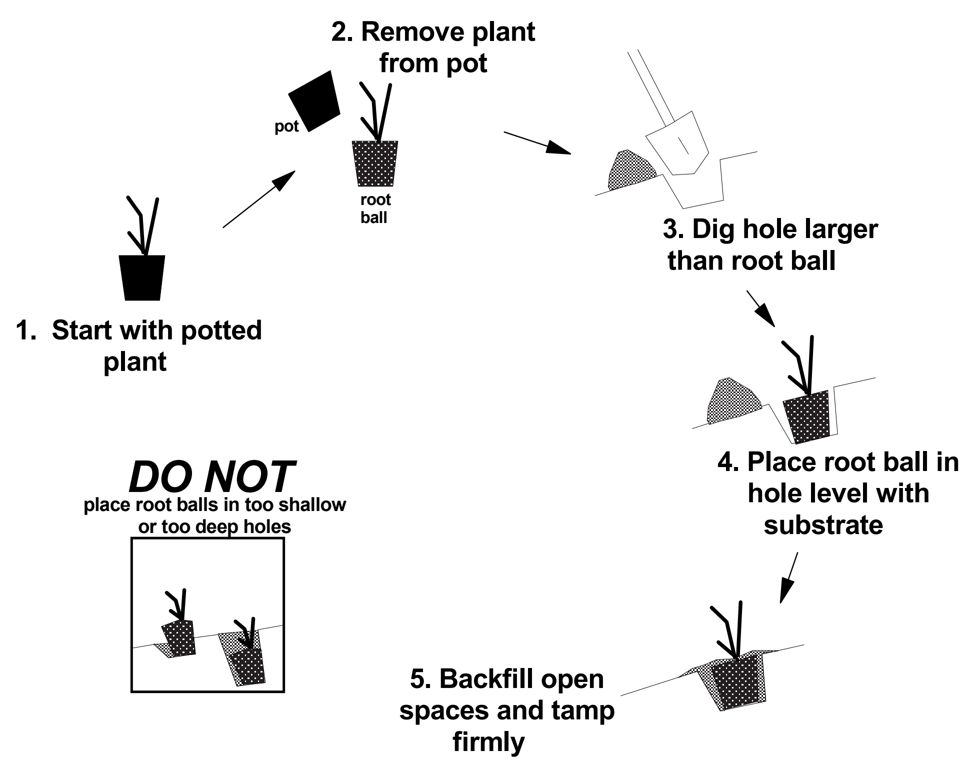

Figure 7. Install plants carefully to improve transplant survival.

Herbivore protection

New colonies of aquatic plants in many water bodies will require protection from large herbivores (Smart et al. 1996; Doyle et al. 1997). Site visits, discussions with lake and fisheries managers, and trapping can provide preliminary estimates of the kinds and densities of grazers that may hamper efforts to establish vegetation. In general, problematic herbivores in aquatic ecosystems include common carp (*Cyprinus carpio*), grass carp, turtles, waterfowl, aquatic mammals, crayfish, and numerous terrestrial grazers that may inflict damage on aquatic plants when water levels are low. To prevent or reduce grazing on newly installed plants, we have used several types of herbivore exclosures.

While exclosure designs suitable for protecting aquatic plantings vary, a common component is their material. PVC-coated, galvanized welded-wire is more expensive but much more durable than non-coated wire, and we highly recommend its use in aquatic restoration projects. We do not recommend using plastic mesh because it is highly susceptible to damage and degradation.

Mesh size can be important. In some cases, 2- × 4-in. mesh (nominal size) is adequate to exclude common grazers such as carp and large turtles; and it is more economical than smaller mesh wire. However, the presence of smaller herbivores may require costlier smaller mesh. To ascertain the level of protection that one might need in a particular water body, we suggest including a test of several mesh sizes for submersed species (the most herbivore-susceptible growth form) when conducting plant species suitability tests.

Depending on the project, we use one or two scales of protection: small and large. When conditions merit, we combine the two to increase effectiveness of establishment efforts.

Small-scale protection

Small exclosures can provide complete protection from large herbivores if constructed of appropriate materials and properly deployed. Small exclosures are most suitable for single-species planting: different species planted within a single small exclosure may compete with one another for resources, and one will likely be dominant, potentially negating the effort of establishing diverse plant communities. However, because small exclosures are easy to construct and install, one can use groups of them to produce diverse founder colonies.

Although nearly any construction design will suffice, we most frequently use a simple design we call a ring cage. Ring cages are wire cylinders that protect single or small groups of aquatic plants (Figure 8). We cut welded-wire of suitable mesh into 3- to 6-m lengths, roll them into cylinders, and fasten the ends with c-rings (or hog rings). We anchor the resultant cages (1 to 2 m in diameter) firmly into substrates using earth staples, tent stakes, or rebar. The entire bottom edge of the cage must be in contact with or buried in substrates to prevent herbivores from swimming or crawling under. We recommend 14-gauge, PVC-coated welded-wire for smaller diameter cages (less than 1.5 m) and recommend 12-gauge wire for larger diameter cages (greater than 1.5 m). Heights of ring cages should not exceed 1.25 m unless otherwise supported (e.g., T-posts) to ensure cage strength. In cases where we expect the water depth periodically to exceed the tops of installed ring cages, or where the cage is planned for complete submersion, we attach covers using the same mesh to the tops to prevent entry by swimming herbivores.

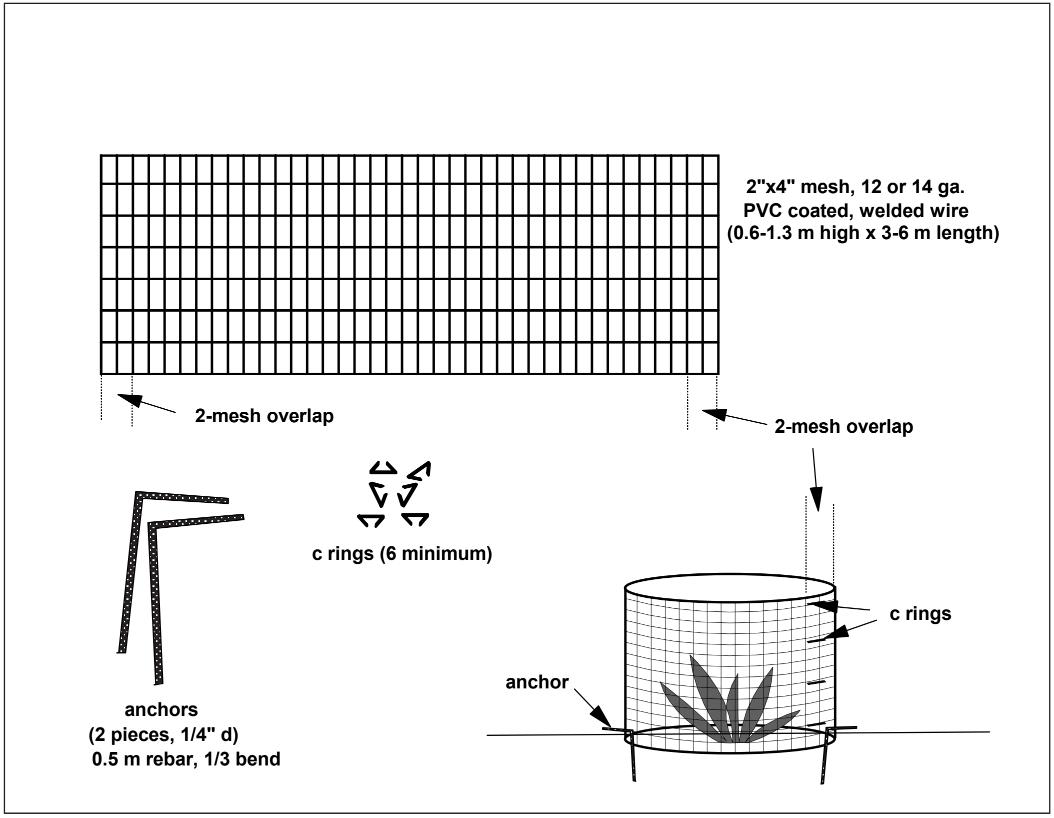

Figure 8. Ring cages provide protection from grazing for small plant colonies.

Large-scale protection

Larger herbivore exclosures are more economical to construct than ring cages (e.g., four 1-m diameter ring cages = 12-m mesh = 2.6-m^2 protected area compared with one 3- × 3-m pen = 12-m mesh = 9.0-m^2 protected area). In addition to potentially protecting a much larger area using the same resources, one can plant multiple species in large exclosures without initial concerns of planted species competing with one another. However, large exclosures usually offer protection primarily from waterborne grazers such as carp and turtles: waterfowl can fly into them, aquatic mammals may be able to climb over them, etc. Another major drawback to large exclosures is that a single breach (via damage to the mesh or overtopping during high water conditions) may put the entire founder colony at risk.

We have used several large exclosure designs to establish founder colonies in both large and small water bodies (Figure 9). We have constructed all of them from T-posts (approximate 2.5-m spacing) and PVC-coated welded-wire (12 or 14 gauge) fencing. After setting T-posts (and installing safety caps), we attach fencing using aluminum wire ties or UV-resistant plastic cable ties. Fencing should extend 25 cm or more above normal high water levels during the growing season. The bottom of the fencing should be firm against the substrate at all points to prevent burrowing under by grazers. The interface between the fence and the bottom sediment is critical, and a 30-cm or so wide fencing flange attached to the bottom of the fence with cable ties (extending away from the protected area) will discourage burrowing.

Because large-scale exclosures are difficult to cover, carp, turtles, and other herbivores may invade them during periods of high water. When water levels recede, the grazers may be trapped inside and must be removed, either manually or by using traps (hoop nets, fall-in turtle traps, etc.). We have also had some success installing simple mesh funnels into exclosure sides that enable fish and turtles to escape without permitting entry.

We have commonly used combinations of small- and large-scale exclosures for establishing founder colonies. We conduct site and species suitability tests during the first growing season of planting using ring cages for protection. Expanding the test site to a larger founder colony site the following growing season can then include the addition of planted ring cages for species that require protection and planting without protection for those that do not. Installing large exclosures around ring cages supporting plants hampered by herbivores can then increase coverage of those species, enabling production of greater numbers of propagules.

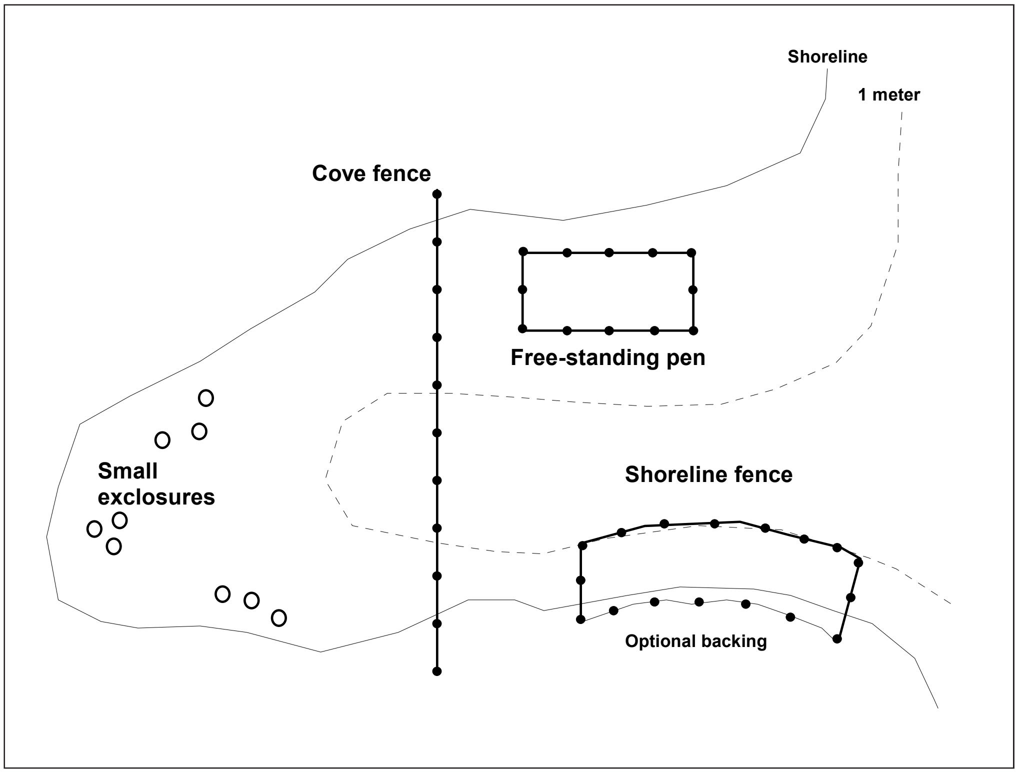

Figure 9. Large exclosures are designed to protect relatively large plant colonies from grazers.

Alternative measures for protecting plants

Options other than constructing exclosures may provide moderate protection for newly establishing aquatic plants. However, rather than attempting to use any of these methods exclusively, we suggest incorporating their use into projects that include exclosure protection for at least portions of plants installed. We have taken advantage of three methods for reducing herbivore impacts, including 1) “masking” by existing vegetation, 2) focusing on herbivore-resistant plant species, and 3) managing herbivore populations.

Masking has sometimes proven effective for initial establishment when we have installed plants in stands of existing vegetation. Evidently, existing biomass may be sufficient to limit access by herbivores or reduce the attraction (visual, olfactory, etc.) of new plantings. Most of our long-term masking successes have come from planting in patches of water primrose (*Ludwigia peploides*) and water willow to protect emergent plant species.

We have observed herbivore-specific resistance or tolerance for some species of aquatic plants. In our projects, for instance, we have observed only very few instances of growth inhibiting herbivory on water willow; and these were made by deer browsing on this species during periods of low water. While published information suggests that some aquatic herbivores exhibit feeding preferences and selectively feed on certain plant species over others, in the absence of preferred species, many herbivores will feed on less palatable species, making most plants used in restoration efforts subject to potential herbivory. Additionally, many water bodies are host to a number of grazing species, especially basking turtles and common carp. While some aquatic plants appear to be shunned by one type of herbivore, none that we have worked with have shown herbivore-resistance to communities of herbivores. Wild celery, for instance, appears to be able to withstand grazing by common carp, grass carp, and crayfish; but at the same time, it ranks high on the preferred diet list of semi-aquatic turtles (Dick et al. 1995; Ott 2005). While smaller aquatic systems with limited herbivore populations may permit selection of plants based on their unlikelihood to be eaten, this method is usually not possible in larger systems.

Managing herbivore populations to improve vegetation establishment has been successful in small systems. To promote the establishment of aquatic vegetation in small wetland ponds, Williams and Hudak (2005) used largemouth bass (*Micropterus salmoides*) to control crayfish populations. With good success, we have used floating fall-in and funnel traps to live-trap turtles from small ponds and from inside large exclosures in larger water bodies . Although not removing all turtles, reducing their numbers appears to reduce pressure on plants, permitting better growth and more rapid expansion in unprotected areas. Unfortunately, the lack of any large-scale methods for the removal of common carp and turtles limits the use of herbivore population control to smaller systems.

Planting densities

Planting densities will vary depending on plant species and exclosure type. Table 2 provides a general planting density guideline that we recommend for most aquatic plants when using exclosures. Higher densities will result in faster establishment of founder colonies and will reduce the likelihood of complete establishment failure: one plant may die, but another may survive.

Table 2. Planting densities depend on plant growth form and exclosure type.

Growth form	Small exclosures (less than 2-m diameter)	Large exclosures
Submersed	2 to 8 plants	1- to 2-m centers
Floating-leaved	1 to 2 plants	2- to 3-m centers
Emergent	2 to 4 plants	1- to 2-m centers

Founder colony layout

The size of a founder colony site is less important than substrates, protection from wind and waves, and other considerations. However, larger sites that contain more exclosures tend to be the most successful in terms of spread after establishment of plants within exclosures. We try to select sites that permit construction of both large-scale and small-scale exclosures, usually ranging from 0.5 to 1.0 ha in area. Because well-protected areas with large expanses of shallow (less than 2 m deep), soft-bottomed, relatively flat areas are not common in many water bodies, one may also have to consider smaller sites and deploying only small-scale exclosures.

A single founder colony may be sufficient to serve as a propagule source for an entire water body. However, we recommend multiple sites distributed throughout the system to improve success. Despite our best evaluations, some sites will be better suited for plants than will others; and risking success at a single site may not be prudent. Our experience suggests that installing three to four large founder colonies (100+ ring cages and several large-scale exclosures) is most successful. Establishing 10 or so small sites (< 30 rings cages each) has also proven successful in some systems. However, greater numbers of sites often dilute efforts to an extent that monitoring and maintenance can become difficult (see below), resulting in poor overall success of the project.

A number of factors dictate the spacing of exclosures within a founder colony, including size, number of exclosures, and areas within the site that are suitable for cage placement and anchoring. Generally, we set ring cages along appropriate depth contours for the growth form we are planting on 3- to 8-m centers. We occasionally cluster ring cages (particularly for submersed plants) on 1- to 2-m centers if we anticipate constructing larger exclosures to surround them.

Sustaining the founder colonies

Our experience has shown that emplacing potted plants in water bodies can result in rapid colonization of planted species within protective exclosures. Once plants reach the borders of exclosure protection, however, their rate of spread reduces greatly or even halts, typically owing to intense levels of grazing occurring outside exclosures. Periodically during the growing season, plants seem to get ahead of herbivores, resulting in spread to unprotected areas. This usually happens in conjunction with falling water levels, and we believe aquatic grazers are less likely to eat plants found in very shallow depths (15 cm and less), thus permitting at least temporary establishment of plants from fragments and other propagules in otherwise unprotected areas. In some cases, when water levels return to normal, herbivores move in and eliminate the unprotected colonies. However, in other cases, enough spread has taken place (presumably relative to herbivore populations) that the unprotected colonies persist. We hope to achieve these latter cases in all reservoir restoration efforts.

For plants to spread, well-established founder colonies must be in place at all times during the growing season so that propagules for natural spread are present in sufficient numbers when the right conditions exist. To ensure founder colonies are present at all times, we must deal with, in the longer term, the same two obstacles that we overcame to establish the colonies (water level fluctuations and herbivory).

Long-term maintenance of founder colonies

Continued protection of founder colonies from herbivores is critical to their successful establishment and subsequent spread. Materials used in exclosure construction vary in their ability to withstand the ravages of underwater installation. For instance, galvanized welded-wire may remain functional only one or two growing seasons before the galvanization dissolves and the wire rusts. Plastic mesh is susceptible to UV degradation and damage by beaver, nutria, and muskrats. PVC-coated welded-wire is stronger and longer-lived than other types but, along with the others, floating logs, boats, or large animals (such as cattle) can damage it. In addition to damage to materials, we frequently find that larger herbivores, such as beaver, dig under exclosures either to gain access to plants or to reach areas fenced off from the reservoir. These openings provide access to smaller herbivores such as turtles and carp.

Because exclosures are subject to breaches of many types, we recommend including a scheduled maintenance program. Inspect exclosures as frequently as possible; and repair when damaged, remove herbivores when they are trapped inside exclosures, and replant with species found suitable for that water body or site when exclosures do not appear to support the existing plants. Exclosures that do not support plants do not function as founder colonies.

Planting at multiple depths when required

Because many water bodies serve as flood control and municipal water supplies, one expects water levels to fluctuate, in some cases significantly. Founder colonies planted at a single depth relative to conservation pool may well spend much of the year out of water or under depths too great for plant growth; and those times during the year with ideal water depths may not coincide with the growing seasons of a particular species. Establishing founder colonies at multiple depths increases the possibility that plants will be actively growing and producing propagules for natural spread throughout the growing season.

We have recently devised a planting schedule that addresses fluctuating water levels and the necessity for active growth of founder colonies. Typically, we plant submersed plants at 60–100 cm depths, floating-leaved plants at 25–60 cm depths, and emergent species at 0–25 cm depths. If water levels drop (or rise) by 75 cm, we construct new exclosures and plant using the same depth schematic. In a typical Texas reservoir, water levels may fall throughout the growing season, and establishing three or more depth tiers of plants is common. Plants exposed to desiccation (or too great depths) generally decline but often recover when water levels return to suitable depths. Once colonies are in place at multiple depths, water level fluctuations are less likely to affect the growth of founder colonies, and the colonies may achieve a continuous production of propagules.

5 Successes and Failures

We measure project success by looking at one of two (or both) main parameters: founder colony establishment and spread to unprotected areas of the reservoir. We deem founder colony establishment successful when the following criteria are met: plants exhibit growth within protected areas, they recover following ecological disturbances (e.g., low water levels), and they persist over multiple growing seasons. In addition to measuring growth and establishment of plants within protected areas, we measure the function of founder colonies by the occurrence of spread to unprotected areas. We consider the founder colony approach successful when at least one of two types of spread occurs: expansion and colonization. Expansion represents contiguous growth of a protected colony to outside the protected area, and is generally caused by the vegetative growth of the protected plants exceeding consumption rates by grazers. Colonization takes place through noncontiguous development of new colonies away from protected colonies, usually owing to fragment or seed dispersal to unprotected areas that grow to form new colonies.

Our efforts using the founder colony approach over the past 10 or so years have resulted in a mix of successes and failures. Most of our attempts to establish founder colonies have been successful, and these sites have provided small-scale habitat for fish and other aquatic wildlife. We attribute successes primarily to materials selection and consideration of water level fluctuations (multiple plantings). We attribute failures to low effort, improper materials selection, and failure to address changes in water levels. Success of the founder colony approach has followed a similar trend: long-term commitment to maintaining founder colonies established with suitable materials and consideration for water level fluctuation have provided the best results when considering spread from founder colonies. Our experience suggests that founder colonies are not difficult to establish when one properly selects propagules and takes into consideration herbivory and water level fluctuations, but spread from founder colonies strongly depends on their maintenance over a period of several to many years. Table 3 provides a condensed history of our aquatic vegetation establishment efforts in large (500 ha and greater) southern reservoirs.

Table 3. Success and failures of aquatic plant founder colony establishment and evaluation of founder colony approach in large southern reservoirs. Water level fluctuations were low (< 1 m annually), medium (1–2 m annually), or high (> 2 m annually). Scale of effort was small (1–3 founder colony sites), moderate (4–8 founder colony sites), or large (9+ founder colony sites).

Reservoir (fluctuation; area)	Scale of effort	Founder colony establishment	Spread (× protected area)	Comments
Arcadia Lake, OK (medium; 750 ha)	Large	Successful after 2 years	3X spread after 2 years	Negatives: Common carp, turtles, beavers, and resident geese; high turbidity; exclosure degradation; 2-year effort; fluctuation not addressed Positives: Some plants persisting after 10 years
Lake Austin, TX (low; 650 ha)	Large	Successful after 1 year	7X spread after 4 years	Negatives: Resident waterfowl, crayfish, turtles, common carp, and grass carp; vandalism; hydrilla and other exotics; flow events (riverine reservoir); 3 m annual winter drawdown Positives: Ongoing 4-year effort; water level control; continued spread of plants
Bull Shoals Reservoir, AR (high; 18,000 ha)	Moderate	Successful after 2 years	No spread after 3 years	Negatives: Very high fluctuation (10 m +); turtles, common carp, deer, and cattle; 2-year effort Positives: Plants persisting after 5 years; fluctuation addressed
Choke Canyon Lake, TX (high; 10,500 ha)	Moderate	Successful after 1 year	12X spread after 4 years	Negatives: High fluctuations (8 m +); hydrilla infestation; turtles Positives: Rapid expansion following periods of low water; 3-year effort; fluctuation addressed; plants persisting after 8 years
Coleman Lake, TX (high; 800 ha)	Moderate	Successful after 4 years	240X spread after 7 years	Negatives: High, long-term fluctuation (5 m + over 3 years); turtles, common carp, and cattle Positives: Rapid expansion following periods of low water; recovery after 3 years of exposure; 5-year effort; fluctuation addressed; plants persisting after 8 years
Lake Conroe, TX (low; 8,500 ha)	Large	Successful after 1 year	280X spread after 6 years	Negatives: Grass carp and turtles; hydrilla infestation Positives: Rapid expansion in unprotected areas; 7-year effort; plants persisting after 10 years
Cooper Lake, TX (high; 9,250 ha)	Small	Successful after 2 years	230X spread after 4 years	Negatives: Common carp and turtles; long periods of low water Positives: Rapid expansion following periods of low water; 4-year effort; fluctuation addressed; plants persisting after 8 years

Reservoir (fluctuation; area)	Scale of effort	Founder colony establishment	Spread (× protected area)	Comments
Lake Cypress Springs, TX (medium)	Large	Successful after 1 year	Some spread	Negatives: Turtles, common carp, grass carp, and nutria; hydrilla and *Lyngbya* infestations; extended period of low water. Positives: Rapid expansion; 5-year effort; fluctuation addressed; plants persisting after 5 years
El Dorado Lake, KS (medium; 4,400 ha)	Large	Successful after 2 years	10X spread after 4 years	Negatives: Common carp, turtles, and beavers; high turbidity and wave action; exclosure degradation; fluctuation not addressed. Positives: 3-year + effort; some plants, especially water willow, persisting after 10 years
False River, LA (low; 1,300 ha)	Small (test only)	Not successful	No spread	Negatives: High turbidity resulting from watershed disturbances; 1-year effort Positives: Rapid initial growth
Lake Gaston, NC (low; 8,200 ha)	Small (test only)	Successful after 1 year	2X spread after two years	Negatives: Grass carp, common carp, and turtles; hydrilla infestation; herbicide applications; 1-year effort Positives: Rapid establishment and growth inside exclosures; continued effort likely
Grand Lake, OK (medium; 23,950 ha)	Large	Successful after 2 years	< 1X spread after 3 years	Negatives: Turtles, common carp, and resident waterfowl; variances from scheduled water levels; degradation of exclosure materials Positives: Good establishment within exclosures; fluctuation addressed; ongoing effort (3-years +)
Grapevine Lake, TX (high; 2,900 ha)	Moderate	Successful after 2 years	4X spread after 4 years	Negatives: High fluctuations (4 m +); turtles and common carp; exclosure degradation; vandalism during low water periods Positives: Rapid expansion following periods of low water; fluctuation addressed; 5-year effort
Lake Jacksonville, TX (medium; 550 ha)	Moderate	Successful after 2 years	80X spread after 6 years	Negatives: Turtles, common carp, and beavers; hydrilla infestation; herbicide applications; vandalism during low water periods Positives: Rapid expansion following periods of low water; fluctuation addressed; 6-year effort

Reservoir (fluctuation; area)	Scale of effort	Founder colony establishment	Spread (× protected area)	Comments
Lyndon B. Johnson Lake, TX (low; 2,600 ha)	Moderate	Successful after 2 years	No spread	Negatives: Turtles, common carp, and resident waterfowl; exclosure damage and degradation; 2-year effort Positives: Good establishment; undamaged exclosures
Lake Livingston, TX (medium; 36,400 ha)	Moderate	Not successful	No spread	Negatives: Nutria, common carp, and turtles; inadequate exclosure materials; 1-year effort; high turbidity; fluctuation not addressed. Positives: Good growth of plants prior to exclosure damage by nutria
Lewisville Lake, TX (high; 11,950 ha)	Large	Successful after 2 years	< 1X spread occurs periodically	Negatives: Common carp and turtles; water levels; exclosure degradation; 2-year effort (with the exception of one site) Positives: Good initial establishment of plants; long-term persistence and periodic spread from site maintained for greater than 2 years; fluctuation addressed
Lake Waco, TX (medium-high; 2,800 ha)	Moderate	Successful after 1 year	750X spread after 5 years	Negatives: Turtles and common carp; conservation pool change (+2.3 m) Positives: Rapid spread following periods of moderately low water; 4-year effort; fluctuation addressed; plants persisting after 9 years

The projects reported in this table were funded by various sponsors and were conducted cooperatively with state and local resource management agencies, including Arkansas Game and Fish Commission; the cities of Austin and Jacksonville, Texas; Franklin County Water District; Kansas Department of Wildlife and Parks; Louisiana Department of Natural Resources; Lower Colorado River authority; Oklahoma Department of Wildlife Conservation; Oklahoma Water Development Board; Point Coupee Parish Police Jury; Texas Parks and Wildlife Department; and the following Corps of Engineer Districts: Fort Worth, Little Rock, Nashville, and Tulsa. The Corps of Engineers' Aquatic Plant Control Research Program funded the development of the technology employed and also provided funds for data collection and analysis.

6 Conclusions

In addition to protecting watersheds (e.g., reducing nutrient and pollutant inputs) and countering invasions by nuisance species, establishing and reestablishing sustainable communities of native vegetation is a critical requirement for restoring health to aquatic ecosystems in the US. We believe that our work and the work of others has shown that establishment of substantial native aquatic plant communities can be achieved in inland waters; but the formula to attain consistent, large-scale success remains inexact. Each water body has a unique set of characteristics that requires taking an adaptive management stance to enable the successful establishment of beneficial native plants. In this report, we have provided an approach that overcomes the obstacles that we have identified as limiting to natural establishment of aquatic plants in many water bodies: a lack of suitable propagules, adverse environmental conditions (including invasive species), and herbivory. The founder colony approach transcends scales of aquatic ecosystem restoration and is applicable to a range of water bodies, from small ponds to large reservoirs. Our hope is that this report will inspire others to attempt ecosystem restoration using native aquatic plants, as well as encourage additional, much needed research into developing better methodologies for achieving the goal of aquatic ecosystem restoration.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* June 2013	**2. REPORT TYPE** Technical Report/Final	**3. DATES COVERED *(From - To)***
4. TITLE AND SUBTITLE Propagation and Establishment of Native Plants for Vegetative Restoration of Aquatic Ecosystems		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Gary Owen Dick, R. Michael Smart, and Lynde Lynne Dodd		**5d. PROJECT NUMBER**
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lewisville Aquatic Ecosystem Research Facility US Army Engineer Research and Development Center 201 E. Jones St. Lewisville, TX 75057		**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/EL TR-13-9
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, U.S. Army Corps of Engineers Washington, DC 20314-1000		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

Ecosystem Management and Restoration Research Program (EMRRP)

14. ABSTRACT

Aquatic plants are a vital, but often missing, component of shallow, freshwater systems. Manmade systems, such as multipurpose reservoirs, of course do not come equipped with aquatic plant communities. Even natural systems, such as streams, ponds, and lakes, have often been so disturbed that they, too, lack aquatic plants. An absence of plants often results in relatively poor aquatic habitat; shoreline erosion; water quality problems; development of noxious algal blooms; and, often, susceptibility to invasion by harmful, non-native, aquatic weeds.

If resource managers wish to avoid these problems and to realize sustainable environmental benefits, they must take action to "restore" a diverse plant community dominated by native species. To date, the best method to ensure successful establishment of a diverse, native plant community is to plant robust propagules of desirable species in selected, favorable environments and to provide them with protection from grazing.

This report provides general information on production of aquatic plant propagules and on methods of planting and protection that should facilitate the development of diverse native plant communities in aquatic systems. We document the successful application of these techniques in a number of aquatic ecosystems.

15. SUBJECT TERMS

Aquatic plant establishment
Aquatic plant propagation
Aquatic plant restoration
Founder colony
Native aquatic plant
SAV
Submersed aquatic plant
Submersed aquatic vegetation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	None	48	**19b. TELEPHONE NUMBER *(include area code)***