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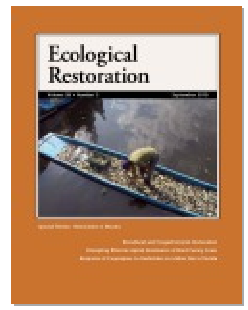

RESEARCH REPORT

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ABSTRACT

As our understanding of the importance of natural lakeshores in providing wildlife habitat and water quality protection has grown, so too has interest in restoring degraded lakeshore. Advances in lakeshore restoration practice have been hindered by a lack of field-based evaluations to guide decisionmaking and by gaps in our knowledge of how to revegetate littoral and shoreline areas. To understand how the choices practitioners are making affect restoration outcomes, we surveyed 22 lakeshore restoration projects in the Minneapolis/St. Paul, Minnesota (USA), metropolitan area that ranged in age from 1 to 6 years. We conducted comprehensive, floristic surveys of the vegetation found on each site and investigated site maintenance practices. We found that 29% of species planted in the upland zone of the lakeshore reliably established; long-term protection of the site from adjacent land uses improved the likelihood that planted vegetation would endure. The greatest revegetation failure occurred along the shoreline; 44% of species planted did not establish at this land-water transitional zone. Approximately 30% of the aquatic zone restorations did not contain any planted vegetation, although ten aquatic plant species were found to establish dependably on at least some of the remaining sites. In aquatic and transition zones, vegetative composition was most clearly related to exposure to wave activity. This survey suggests two restoration practices that should be improved to increase the likelihood of lakeshore restoration success: 1) choosing plants so they match the prevailing light and flooding conditions within sites; and 2) providing both upland and aquatic protection.

Keywords: littoral, restoration, revegetation, shoreland

Lakeshore restoration is increasingly pursued to mitigate the consequences of housing and recreational lakeshore development. Removal of aquatic macrophytes, a common occurrence when lakeshore is developed, results in reduced structural complexity and diminished spawning, nesting, and feeding habitat for fish and waterfowl (Wilcox and Meeker 1992). In addition, soil erosion increases because wave energy is no longer dissipated when macrophyte beds are lost. Lastly, replacing forested upland vegetation with turf can increase runoff and nutrient loading to lakes. Lakeshore development often alters the entire area between the upland and open water. Thus, restoration typically encompasses the riparian upland, shoreline, and the adjacent shallow water. In spite of many attempts over the past two decades, lakeshore restoration is still an uncertain practice with high failure rates.

The success of lakeshore restorations depends, to a large degree, on the reliability of practices across a range of environmental conditions. Restorationists must decide which species to introduce to the various zones at project sites and how to plant them. Decisions regarding the timing of planting, whether to protect aquatic plantings from wave impacts and herbivory, and how to maintain the restoration immediately after installation and for the long term must also be made. Understanding how these myriad decisions combine to influence the restoration outcome is crucial to improving the effectiveness of lakeshore restoration.

There is very little reliable guidance available to aid in restoration decisionmaking, in part because restorations receive minimal evaluation. Projects are typically assessed based on whether the project plan was implemented, rather than if the desired site conditions were achieved. In many programs, staff conducts the final project evaluation before final grant reimbursements are released to ensure that the restoration plan has been implemented but do not monitor progress afterwards. Consequently, restoration proceeds without the benefit of an understanding of the long-term effectiveness of specific practices (Bernhardt et al. 2007).

Thorough, routine project evaluations can yield information crucial for improving lakeshore restoration practices and help practitioners understand

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if program goals are being met. Most published information regarding lakeshore restorations result from specific research rather than from broader site evaluations. From these research studies, we know that removing existing vegetation prior to planting reduces the number and cover of unwanted species (Weiher et al. 2003), likely because the vegetation on-site at the time of restoration is weedy annuals and perennials that colonize after a site is commercially developed. Seeded sites also generally have greater species richness and more desirable volunteer species once established (that is, after two growing seasons) than those planted with seedlings, except when the site receives no preparation prior to planting (Weiher et al. 2003). Recent research on restoration of littoral wetlands indicates that the size and condition of stock, month of planting, and type of rootstock were all important factors for survival of *Scirpus validus* transplants (Vanderbosch and Galatowitsch, forthcoming). While such studies are useful, they are limited in number and do not address the broad array of decisions that need to be made when restoring lakeshore. Routine project monitoring is needed to provide reinforcing feedback on a wide variety of restoration practices that affect the quality of restoration programs.

We conducted a survey of 22 lakeshore restoration projects located within the Minneapolis/St. Paul, Minnesota, metropolitan area to understand how the choices restorationists are making affect restoration outcomes. Extensive lakeshore destruction has occurred in this urban area, and there is growing interest in reversing this damage. Over the past seven years, more than two dozen lakeshore restoration projects have been implemented in this small geographic area, which provides an interesting opportunity to survey a number of projects with similar urban development histories and adjacent land-use characteristics. Our specific goals were to 1) evaluate the most common choices made in lakeshore restoration projects; 2) investigate which choices are the most effective; and 3) assess how adjacent land uses affect the outcome of the restoration effort. By surveying over twenty lakeshore restorations, we sought to identify the most reliable practices. We hope to inform and improve decisionmaking for lakeshore restoration.

Methods

We began the process of site selection by reviewing restoration projects that received funding from the Minnesota Department of Natural Resources (DNR) Shoreland Habitat Restoration Grant Program and were located within the seven-county metropolitan area (Ramsey, Hennepin, Dakota, Washington, Scott, Carver, and Anoka counties). Thirty-six lakeshore restoration projects met these criteria. From this initial pool, ten sites were eliminated because the projects were restorations of areas other than lakeshore or were located on private property, with restricted site access.

We reviewed DNR records for each of the 26 projects remaining in our pool of study candidates. These records consisted of a restoration plan, a prescription for site preparation, and a planting list. In nearly all cases, we found invoices or progress reports that listed the names and quantities of planted species. If the plant list information was incomplete, we interviewed staff from the responsible agency to obtain the missing information. Four sites were eliminated after the review because records were too incomplete. The 22 lakeshore restoration sites ultimately included in our study were restored by various state and local units of governments; all are located on public land (Figure 1; also see Appendix available at uwpress.wisc.edu/journals/journals/er_suppl.html). Sites were restored using a variety of techniques, including seeding, plug-planting, and prevegetated coir mat. Mowed turf typically surrounds the upland zones of sites included in this study, although several are also adjacent to paved walking paths. Information on prerestoration site condition and postplanting management was not routinely included in DNR records. To compile this information, we interviewed agency staff responsible for the restorations.

The lists of native species planted at each restoration site obtained from DNR records guided our search for vegetation during field surveys. We surveyed the species in three distinct zones that ran parallel to shore: upland, transition, and aquatic. The upland zone was defined as the area above the ordinary high-water level (OHWL) for the lake, the transition zone as the seasonally inundated area below the OHWL, and the aquatic zone as the persistently flooded area below the OHWL. For all but 2 of the 22 sites, the restoration encompassed all three zones. The three zones of each site were comprehensively surveyed in late summer 2005 and again in spring 2006 to record spring-blooming species; all species present were identified across the entire planted area (i.e., a modified releve). We estimated the cover of each planted species using six classes (Mueller-Dombois and Ellenberg 1974): 1) less than 1% cover; 2) 1–4%; 3) 5–24%; 4) 25–49%; 5) 50–74%; and 6) 75–100%. Plant nomenclature follows Gleason and Cronquist (1991); voucher collections were made to verify identifications for difficult-to-determine taxa.

We also recorded the overall cover for the site into one of three categories (planted, unplanted, and bare ground) and recorded occurrences and cover estimates for all other (that is, unplanted) species with a cover of greater than 5%. Slope and length of the site and its exposure to wind were also noted.

To determine which native plant species reliably established on lakeshore restoration sites, we created a master list of all species observed during field surveys. These species fit broadly into two categories: those planted on few sites (1–3) and those

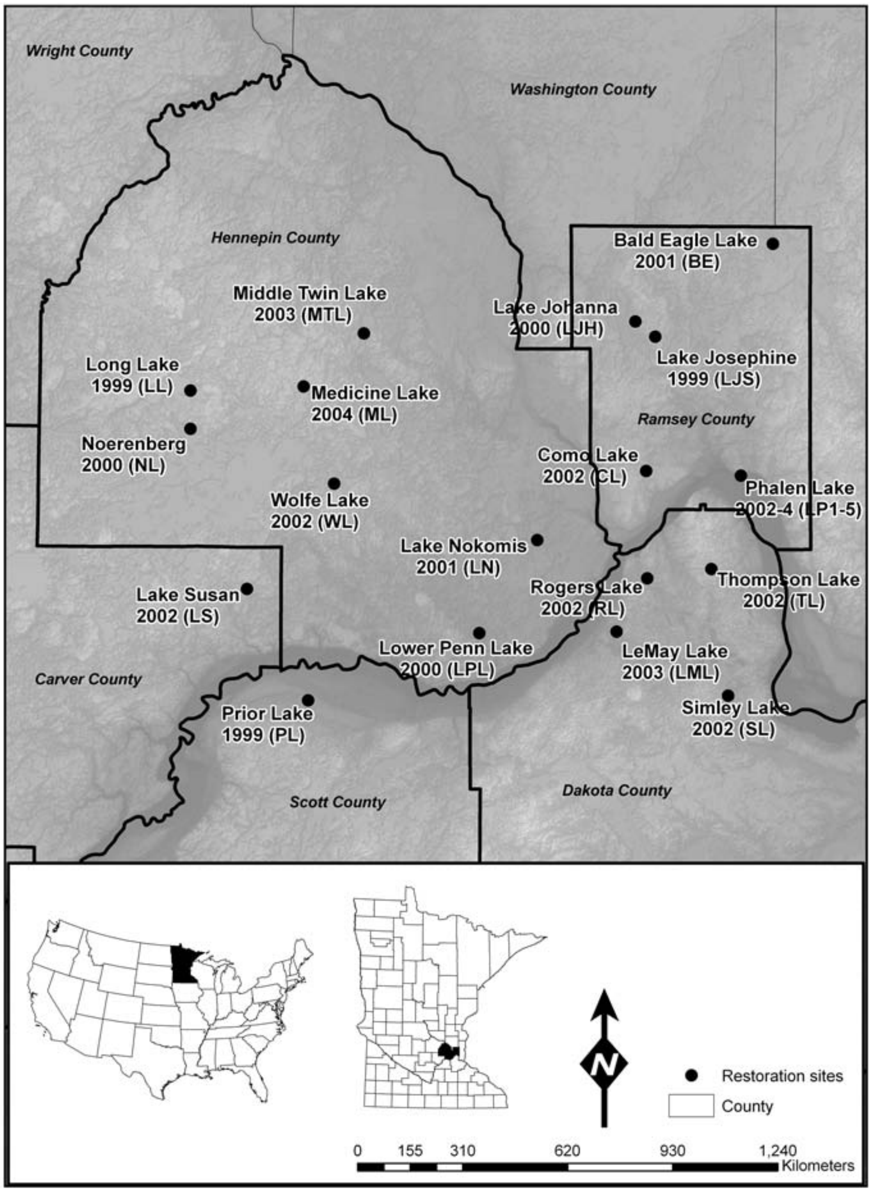

Figure 1. Location of the 22 lakeshore restoration projects (latitude 44°97' N and longitude 93°60' W to 45°07' N, 92°98' W) in central Minnesota (USA) included in this study. The sites were restored by various state and local units of government, and all are located on public parkland. Native vegetation was restored to these sites using a variety of techniques, including seeding, plug-planting, and prevegetated coir mat. Five separate sites, restored at different times, were evaluated at Phalen Lake.

planted on many sites (≥ 4). Species planted on three or fewer sites were categorized as having established always on each site planted, never established, or occasionally established. Species planted on four or more sites were categorized as having established often (> 75% of the time), established occasionally (25%–75% of the time), or established seldom (< 25% of the time). Species that colonized but were not planted were also included. Twenty-two plants did not have diagnostic features and could not be identified to species; these were excluded from the analysis. Species that survived each time when planted on one to three sites, those that survived greater than 75% of the time when planted more frequently than that, and species that achieved *at least* 25% cover on at least one site were considered "reliable" for lakeshore restoration (Table 1). In developing the list of reliable plants, we included only species for which we had dependable planting records. Observations of colonizers and species that we assumed had been planted by the restorationist, but for which we could find no planting record, were omitted. For each restoration site surveyed, we then calculated the percent of reliable species relative to the total number of species planted and the overall survivorship of reliable species on each site. A species' suitability to seasonally inundated soils was classified according to the Wetland Indicator Status (USDA 2008). Unplanted species that achieved ≥ 25% cover without assistance on at least one site and unplanted species found on four or more restored sites were identified as species that readily colonize restored lakeshore (Table 2).

To identify the most important practices affecting species composition, we used Principal Components Analysis (PCA—PCOrd, vers. 4) and evaluated correspondence between plant community composition (presence/absence) and site factors for each zone (upland, transition, aquatic). We calculated PCA scores using a cross-products matrix of correlation coefficients and then graphically inspected all combinations of the first three axes. For analysis of the upland zone, we compared species composition to site age, protection used after planting, and maintenance the year of and following planting. Transition zone species composition was compared to the site age and exposure, whether or not the upland and aquatic areas received protection after planting, and maintenance of the site the year of and following planting. We compared aquatic species composition to site age and exposure and whether or not the aquatic plantings were protected. All aquatic species were included in the analysis; for the upland and transition zones we excluded species found on three or fewer sites. Five sites were removed from the aquatic zone analysis because they contained numerous species found only at one site, limiting a meaningful graphical representation of the data.

Table 1. Floristic list of species (per Gleason and Cronquist 1991) that reliably established in lakeshore restoration projects in the Minneapolis/St. Paul, Minnesota, metropolitan area. Species are indicated as having always survived when attempted on between one and three restorations, having survived > 75% of the time when planted on four or more restorations, or having achieved ≥ 25% cover on at least one site. U = upland; T = transitional shoreline area between upland and open water; A = open water aquatic zone.

100% success Few (1–3) attempts	Zone	> 75% success Many (4+) attempts	Zone	≥ 25% cover At least one site	Zone
Asclepias incarnata	U	*Achillea millefolium*	U	*Anemone canadensis*	U
Aster lateriflorum	U	*Agastache foeniculum*	U	*Eleocharis palustris*	A
Aster umbellatus	U	*Andropogon gerardii*	U	*Monarda fistulosa*	U
Bidens aristosa	T	*Asclepias incarnata*	U	*Rudbeckia hirta*	U
Calamagrostis canadensis	A	*Aster lanceolatus*	U	*Rudbeckia triloba*	U
Carex bebbi	U	*Aster novae-angliae*	U	*Schizachyrium scoparium*	U
Carex hystericina	T	*Calamagrostis canadensis*	T	*Scirpus acutus*	A
Carex lacustris	U	*Campanula rotundifolia*	U	*Scirpus americanus*	T
Carex vulpinoidea	U	*Cornus racemosa*	U	*Scirpus fluviatilis*	A
Cornus amomum	T	*Cornus sericea*	U	*Scirpus validus*	A
Cornus sericea	T	*Eleocharis palustris*	T	*Sparganium eurycarpum*	A
Corylus americana	U	*Elymus canadensis*	T,U	*Spartina pectinata*	T
Diervilla lonicera	U	*Eupatorium maculatum*	T,U		
Echinochloa crus-galli	T	*Eupatorium perfoliatum*	T,U		
Glyceria striata	U	*Euthamia graminifolia*	T,U		
Helianthus grosseserratus	U	*Helenium autumnale*	U		
Helianthus maximiliani	U	*Iris versicolor*	T		
Helianthus occidentalis	U	*Juncus torreyi*	T		
Impatiens capensis	U	*Lobelia siphilitica*	U		
Iris versicolor	A,U	*Monarda fistulosa*	U		
Juncus effusus	U	*Pycnanthemum virginianum*	U		
Mentha arvensis	U	*Ratibida pinnata*	U		
Potentilla arguta	U	*Rudbeckia hirta*	U		
Ratibida columnifera	U	*Rudbeckia triloba*	U		
Rudbeckia triloba	T	*Sagittaria latifolia*	T		
Sambucus canadensis	U	*Schizachyrium scoparium*	U		
Scirpus atrovirens	U	*Scirpus acutus*	A,T		
Scirpus cyperinus	A,U	*Scirpus americanus*	A,T		
Scirpus fluviatilis	U	*Scirpus atrovirens*	T		
Sisyrinchium montanum	U	*Scirpus fluviatilis*	T		
Solidago speciosa	T	*Silphium perfoliatum*	U		
Spartina pectinata	A	*Solidago rigida*	U		
Thalictrum dasycarpum	U	*Spartina pectinata*	T		
Tradescantia occidentalis	U	*Verbena hastata*	T,U		
Tradescantia ohioensis	U	*Verbena stricta*	U		
Tradescantia virginiana	U	*Vernonia fasciculata*	U		
Viburnum lentago	U	*Veronicastrum virginicum*	U		
		Zizia aurea	U		

Results and Discussion

Patterns of Species Establishment

Twenty-five native species were planted in the aquatic zones of restored sites. We observed 45 species in the aquatic zones, of which 20 (44%) were planted on at least some of the sites. Eight planted aquatic species (32%) did not establish or had low rates of establishment. One hundred twenty-eight native plant species were restored to the transition zones of study sites. Of the 128 species observed in the transition zone, 71 (56%) were planted on at least some of the sites. Sixty-five species planted in the transition zones (51%) did not establish or experienced low rates of establishment. One hundred ninety-six native species were planted in the upland zones of restored sites. We observed a total of 214 species in the upland zone. Of those, 130 (61%) were planted on at least some of the sites. Sixty-eight species planted on the upland of restored sites (35%) did not establish or experienced low rates of establishment.

Table 2. Unplanted species (per Gleason and Cronquist 1991) that readily colonized lakeshore restoration sites in the Minneapolis/St. Paul, Minnesota, metropolitan area. Species are indicated as having colonized ≥ 25% of at least one restoration or having been present on four or more restorations. U = upland; T = transitional shoreline area between upland and open water; A = open water aquatic zone. *Unplanted species known to be introduced and invasive (USDA 2008).

≥ 25% cover at 1+ site(s)	Zone	Many (4+) sites	Zone
*Ambrosia artemisiifolia**	U	*Ambrosia artemisiifolia**	T,U
Bidens cernua	T	*Ambrosia trifida*	U
Conyza canadensis	U	*Asclepias syriaca**	U
Eleocharis acicularis	A	*Conyza canadensis*	U
Elodea canadensis	A	*Cyperus esculentus*	T
Fraxinus pennsylvanica	U	*Fraxinus pennsylvanica*	U
Lemna minor	A	*Glechoma hederacea**	U
*Myriophyllum spicatum**	A	*Lotus corniculatus**	U
Najas flexilis	A	*Lycopus americanus*	T
Potamogeton foliosus	A	*Medicago lupulina**	U
Ulmus americana	T	*Melilotus alba**	U
		*Myriophyllum spicatum**	A
		Nymphaea odorata	A
		*Phalaris arundinacea**	A,T,U
		*Plantago major**	U
		Polygonum lapathifolium	T
		Populus deltoides	T
		*Setaria glauca**	U
		Solidago canadensis	U
		*Taraxacum officinale**	U
		*Trifolium repens**	U

Figure 2. An effective wave break design provides protection from wave impacts to newly planted aquatic and transition zone vegetation during establishment. Transition and aquatic zone vegetation is planted in the sheltered area within each "V." Wave breaks are used until plants are well established, sometimes up to three or four years. They must be removed in autumn before lakes freeze and reinstalled the following spring after ice thaw.

At least some of the planted species established in the transition and upland zones of all restored sites; however, no planted aquatic species established in 27% of the restorations. One factor contributing to low success in establishment of aquatic zone species may be that emergent littoral plant communities are typically composed of one to a few species. If planting focuses on one dominant species that does not establish, then the planting fails. Softstem bulrush (*Scirpus validus*) is one of the most widespread emergent aquatics found on undisturbed lakeshores of north-central North America and also one of the most common species used in aquatic revegetation projects. In a related study, we examined factors affecting bulrush reestablishment on lakes. In these controlled experiments, 85% of the bulrush died, with mortality highest for late summer and fall plantings and for bulrush plants with underdeveloped roots and rhizomes (Vanderbosch and Galatowitsch, forthcoming). Minimizing muskrat (*Ondatra zibethicus*) herbivory was also important in this study. Optimal conditions of early season plantings, minimal disturbance, and strong pre-planting root development led to a 39% survival rate for softstem bulrush.

The number of planted native species that failed to establish was much higher in the transition zone (44%) than the aquatic (24%) and upland (33%) zones. The majority of species that failed to establish were planted on only one site. Twenty-two of the 56 species (39%) that did not establish in the transition zone are usually found in uplands and are not suited for soils that are seasonally inundated, indicating that plant selection was a factor in these failures. The planting method also likely affected species establishment in the transition zone. Approximately one-half of the transition zone species were planted as seed, which are especially vulnerable to being washed away by wave action (Doyle 2001). Failure to establish may also stem from waves that uproot newly planted vegetation in the shoreline area (Vanderbosch and Galatowitsch, forthcoming). Transplants of aquatic vegetation exposed to even modest wave energy develop more slowly, suggesting that plants that remain rooted may continue to be vulnerable to wave damage and less likely to survive (Doyle 2001).

Our surveys revealed striking differences in aquatic and transition zone vegetation, depending on site exposure to waves and the level of protection provided during establishment. Wave breaks are seldom used in lakeshore restorations in the Minneapolis/St. Paul metropolitan area. Only five (23%) of the restoration sites we surveyed employed wave breaks, and they remained in place for two years or less. Generally, the wave break consisted of sheets of plywood placed parallel to the shoreline or in a V-shape configuration with the point facing the lake. Most wave breaks did not seem to be effective, with no aquatic vegetation observed at two sites, and planted aquatic vegetation reaching 24% cover or less at the remaining three sites.

Effective wave breaks have been designed that can protect new plantings during vegetative establishment (Clark et al. 1999). They consist of a V-shaped structure placed with the point facing the lake and the two ends butted against the shoreline. A second V straddles the first, but is placed 1.5–3 m further out into the water (Figure 2). Transition and aquatic zone vegetation is planted in the sheltered area within each V. Such devices need to be removed in autumn before lakes freeze and reinstalled the following spring after ice thaw. Wave breaks must be used until plants are well established, sometimes up to three or four years. Although these wave-break structures have been successfully used elsewhere in the region (Clark et al. 1999), the nested V-configuration has not been used in our study area.

Seventy-one planted species reliably established in lakeshore restorations (Table 1), which represents only 20% of the total species planted on the sites surveyed. Of these species, 57 were found in the upland, 22 in the transition, and 10 in the aquatic zone. The upland and transition zone species are easy to cultivate and readily available. Fewer options exist for the aquatic zone, and these species are more difficult to obtain commercially. While our evaluation identified many species that can be depended upon to establish successfully, it also underscored the lack of performance of the majority of species used for lakeshore restoration. The use of species that do not reliably establish wastes program resources and reduces the likelihood of restoration success. Better plant selection requires that project designers more carefully match native plant species to the habitat of each lakeshore zone and that native plant producers offer seed mixes comprised of species that are dependable for lakeshore restoration. For the transition zones, in particular, more suitable species need to be commercially available so mixes have adequate diversity. Restoration programs may need to adopt specific plant selection standards to encourage these changes.

We evaluated the restorations in our study to identify site-based factors that limit the successful use of species determined to be dependable for lakeshore revegetation projects. Surveyed sites consisted of 32% to 94% of these reliable species. Survivorship ranged between 78% and 100%, and was lower than this range for only two sites: Prior Lake (73%) and Lake Johanna (37%), both of which are wooded. Urban lakeshore is often cleared of trees to maximize recreational opportunities. Most of the lakeshore restoration sites we surveyed had little or no existing tree canopy cover. Thus, the resulting reliable plant list assembled from our surveys largely comprised species that thrive in full sun, a fact highlighted by the relatively poor survival rates of these species at the Lake Johanna and Prior Lake sites. Seed and plant mixes for shaded sites must be developed and made commercially available if restoration of sites containing existing tree canopy is to succeed.

Floristic surveys identified 29 species that readily colonized restored sites without assistance (Table 2), of which 16 were found in the upland, 8 in the transition zone, and 8 in the aquatic zone. Most of the aquatic zone colonizers were likely present prior to restoration, such as Eurasian watermilfoil (*Myriophyllum spicatum*) and curlyleaf pondweed (*Potamogeton foliosus*). Twelve unplanted species are known to be invasive (USDA 2008); one invasive species, reed canary grass (*Phalaris arundinacea*), colonized all three lakeshore zones. Mowed turf grass and paved areas surround every site; however, the upland and transition zone colonizers could have dispersed from nearby areas or may have been present in the seed bank of soils underlying the restoration site.

Factors Affecting Vegetative Composition

Upland vegetation composition corresponded to the openness of sites and the extent to which they were protected after planting (Figure 3), as evidenced by the principal components analysis. Native perennials species of open meadows, boneset (*Eupatorium perfoliatum*), cup plant (*Silphium perfoliatum*), fox sedge (*Carex vulpinoidea*), western ironweed (*Vernonia fasciculata*), and prairie cordgrass (*Spartina pectinata*), all had high values on Axis 1, whereas native perennial species of partial shade, columbine (*Aquilegia canadensis*) and harebells (*Campanula rotundifolia*), had low values. Upland areas that were not protected by fencing and sites that were not maintained through a routine watering or weeding program (high Axis 2 scores) had strikingly lower species richness than maintained sites with permanent fencing. Species that tolerate disturbance, such as white sweetclover (*Melilotus alba*) and Canada goldenrod (*Solidago canadensis*), had high values on Axis 2, whereas those typical of less disturbed habitats, such as smooth aster (*Aster laevis*), columbine (*Aquilegia canadensis*), showy goldenrod (*Solidago speciosa*), and harebells (*Campanula rotundifolia*), had low values on Axis 2. Fencing the boundary of restorations discourages mower encroachment and human foot traffic. Protective measures such as fencing are potentially useful for the lakeshore restorations included in this study because most are located within heavily used urban parks. Galbraith-Kent and Handel (2007) also found that failing to provide permanent protection and aftercare to urban restorations contributed to diminished establishment of target vegetation; colonizing invasive species prevailed over time.

Transition zone vegetation along the shoreline corresponded to protection from wave impacts (Figure 4). Sites with high diversity of native species and some form of protection from wave impacts had low Axis 1 and high Axis 2 scores. Wet meadow perennials, such as Canada bluejoint grass (*Calamagrostis canadensis*), Canada wild rye (*Elymus canadensis*), swamp milkweed (*Asclepias incarnata*), and broad-leaved arrowhead (*Sagittaria latifolia*), had low values on Axis 1. Native species hardstem bulrush (*Scirpus acutus*) and New England aster (*Aster novae-angliae*) had high

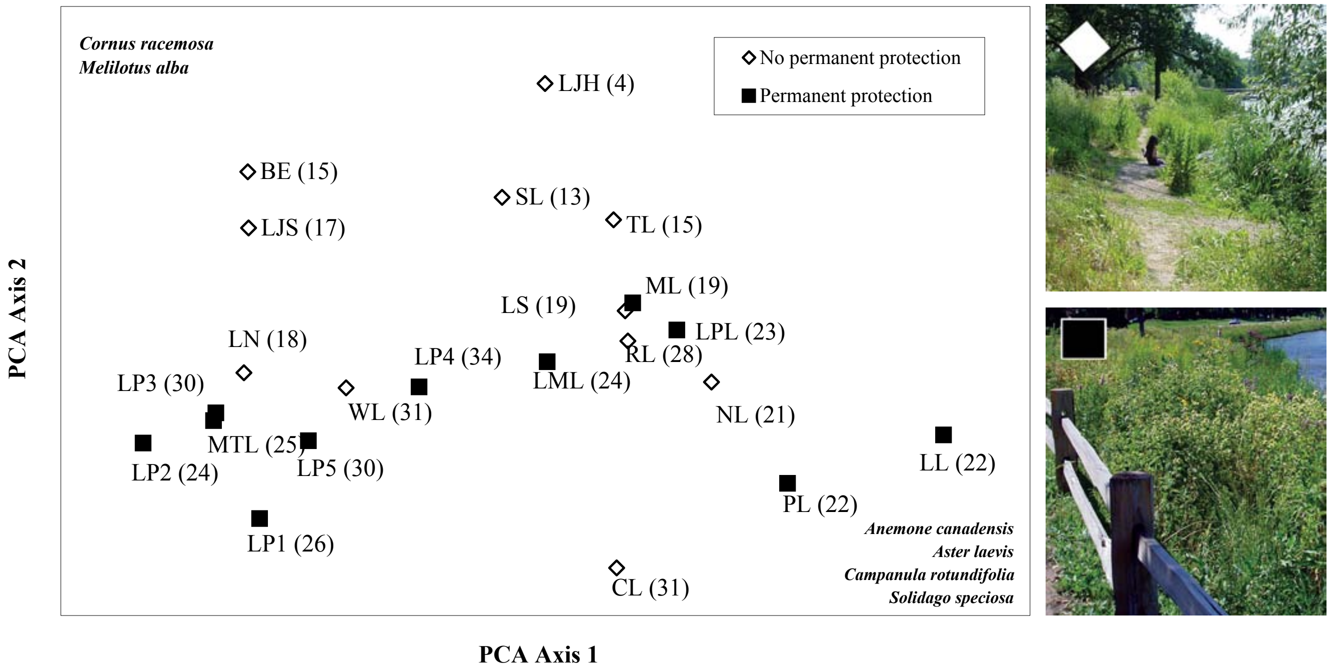

Figure 3. Similarities among lakeshore restorations based on their upland vegetation (Principal Components Analysis). Species richness indicated after the site name (Figure 1) suggests that well-protected sites support a greater number of species, whereas sites not permanently protected have lower species richness. Species shown have PCA Axis 2 eigenvalues > –0.2 or > 0.2. Axes 1 and 2 explained a total of 24% of the variation in the data set.

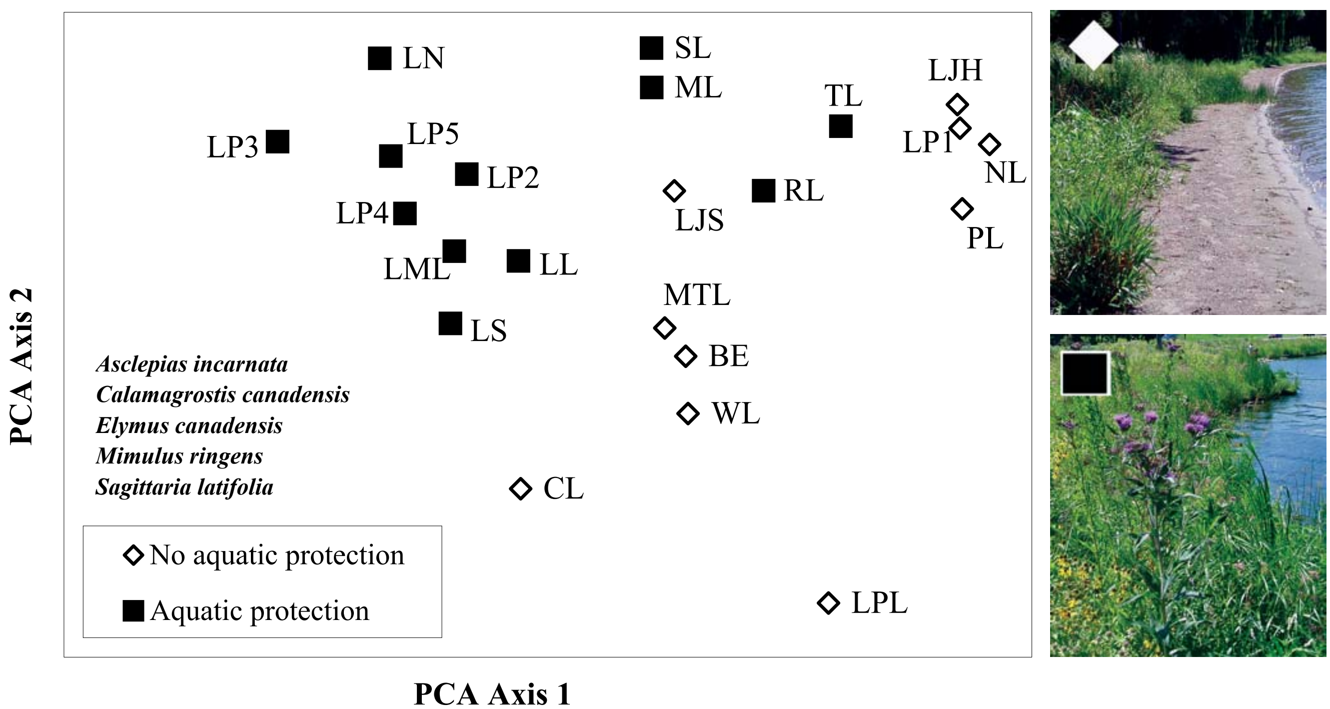

Figure 4. Similarities among lakeshore restorations based on their transition zone vegetation (Principal Components Analysis). Sites with protected shorelines (i.e., wave breaks) are more likely to support native meadow and emergent perennials along their banks; exposed sites are often sparsely vegetated. Species shown have PCA Axis 1 eigenvalues < –0.25 (none have values > +0.25). Axes 1 and 2 explained a total of 27% of the overall data variation.

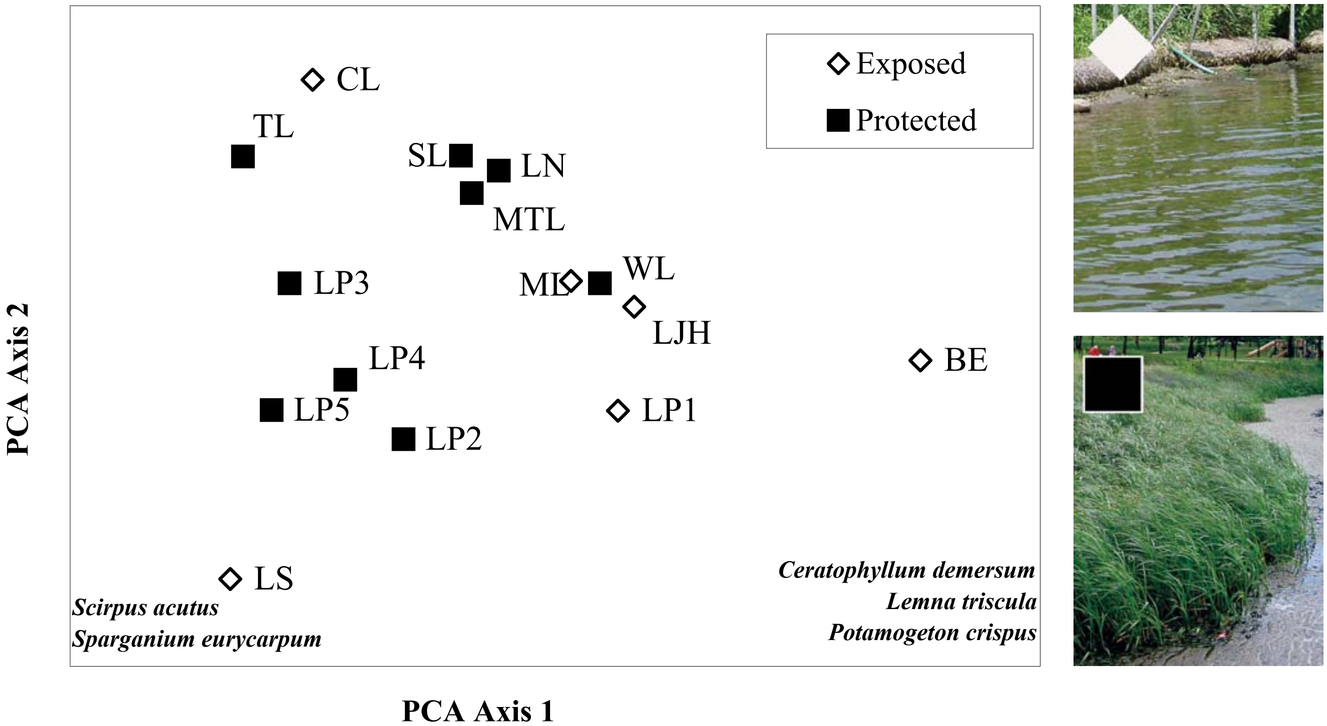

Figure 5. Similarities among lakeshore restorations based on their aquatic vegetation (Principal Components Analysis). Exposed sites lacked planted emergent vegetation and were dominated by submersed and floating vegetation, whereas more sheltered sites generally contained planted emergent vegetation. Species shown have PCA Axis 1 eigenvalues > 0.3 or < –0.3. Axes 1 and 2 explained a total of 35% of the variation in the data set.

values on Axis 2. Unprotected transition areas had higher abundances of a variety of annuals such as common ragweed (*Ambrosia artemisiifolia*) and weedy perennials capable of colonizing disturbed sites, for example reed canarygrass. Wet meadows are slow to establish and must be carefully maintained and protected during the initial years following restoration to prevent annuals or invasive perennials like reed canarygrass that thrive in disturbed soils from overtaking the site (Galatowitsch et al. 2000, Bohnen and Galatowitsch 2005). Prioritizing naturally sheltered shoreline for restoration or providing wave-break protection should increase the success of transition zone plantings.

As with transition zone plant assemblages, patterns in aquatic vegetation reflected the extent to which sites were protected from exposure to wave impacts (Figure 5). Emergent macrophytes giant bur-reed (*Sparganium eurycarpum*) and hardstem bulrush had low values on Axis 1, whereas submersed/floating aquatics such as star duckweed (*Lemna trisulca*), curlyleaf pondweed, and coontail (*Ceratophyllum demersum*) had high values on Axis 1. Most aquatic zones with high wave exposure had high Axis 1 scores; these lacked planted emergent vegetation. Aquatic zones sheltered from wind had low scores on Axis 1 and contained planted emergent vegetation. The observed presence or absence of emergent vegetation suggests that selecting sites protected from wind and wave energy increases the likelihood of emergent macrophyte planting success. These results agree with Wilson and Keddy (1988), who found that biomass accumulation was significantly related to site exposure to wave action and tended to be greatest on sheltered shores. The use of wave-breaking technologies, such as those described earlier, would provide protection to the aquatic zones of more exposed sites during the establishment phase of restoration.

Conclusion

This study identified key improvements needed at the regional scale (program coordination and native plant production, for example) and at the site scale (project planning and implementation, for example) to improve lakeshore restoration success. We recommend the following guidelines for these aspects of lakeshore restoration.

For Restoration Program Managers or Native Plant Producers

Develop seed mixes for use on shady sites. Currently, seed mixes used for lakeshore restoration contain perennials requiring full-sun conditions and, consequently, have limited success where tree canopies are present. Designing seed mixes that contain shade-tolerant species will broaden the range of lakeshore sites that can be revegetated.

Increase the availability of aquatic plants. Our evaluation indicated that six aquatic species used in restoration reliably establish. Although commonly found in natural lake littoral zones, these species are not widely available commercially as transplants. Increasing the production of these aquatic plants will ensure ready access for lakeshore restoration practitioners.

Select sites that are sheltered from strong wave action. Site exposure to waves compromises efforts to restore the transition and aquatic zones. Where possible, prioritizing restoration efforts to favor sheltered, more easily revegetated sites will maximize the cost-effectiveness of restoration programs.

Provide support for aquatic/transition zone protection. Our research emphasizes the importance of wave-break protection for revegetation in the shallow water and shoreline areas. Restoration program managers need to commit funding for these structures along with guidance on how to construct and maintain them properly.

For Restoration Planners and Installers

Protect the upland portion of the restoration with permanent fencing. Unprotected sites tend to be dominated by weedy plant species that favor disturbed soils. Fencing will discourage damage to the site from adjacent land uses (such as mower encroachment and human traffic).

Provide protection to the aquatic and transition zones during the initial establishment phase. This study indicates that sites exposed to wave energy failed to support aquatic zone revegetation and had greater abundances of annuals and weedy perennials in the transition zone. Providing temporary protection from wave impacts will reduce the likelihood that newly planted vegetation will be uprooted and will minimize the potential for shoreline erosion.

Plant species known to establish reliably. Although practitioners plant a great variety of species, only 20% of species planted in lakeshore restorations that we surveyed were dependable (Table 1). These 71 species can serve as the core planting list for future restorations in urban areas of the temperate United States.

Use plants and seed mixes appropriate for the hydrological zones. Establishment failure is more likely in the transition zone than in either the aquatic or upland zones, and our evaluation of species restored to the transitional area of the lakeshore suggests that many are unsuitable for moist soils. Although providing protection from waves is important, using species with habitat preferences for periodically inundated soils will also promote successful establishment in the transition zone.

Research Needs

There is a dearth of information to serve as a basis for confidently designing and implementing restoration in some kinds of lakeshore situations. The following highlights information needs that became apparent as a result of this study.

Develop techniques to restore understory in shoreland areas. We lack an understanding of appropriate plant selection and maintenance practices for restoration of shoreland areas with mature tree canopy, yet much of our natural lakeshore is located in forested ecosystems. By developing techniques for restoring shady sites, we will expand our ability to replace lakeshore habitat in a variety of ecoregions.

Investigate the role of soils and substrate in lakeshore restoration. There has been no research exploring how soils and substrate influence lakeshore restoration outcomes. This is a large and potentially critical gap in our knowledge.

Develop strategies to avoid high mortality from waves and herbivory. Aquatic and transition zones require protection after restoration, but most practitioners do not employ wave breaks. More troubling is the fact that muskrat damage to restored aquatic zones is prevalent, yet we have no understanding of how to manage this plant-animal interaction effectively during vegetative establishment. An inability to clarify this relationship and develop methods to circumvent herbivory likely limits the extent to which we can restore littoral wetlands.

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