A Monitoring Protocol to Assess Tidal Restoration of Salt Marshes on Local and Regional Scales

Hilary A. Neckles[1,8]
Michele Dionne[2]
David M. Burdick[3]
Charles T. Roman[4,5]
Robert Buchsbaum[6]
Eric Hutchins[7]

Abstract

Assessing the response of salt marshes to tidal restoration relies on comparisons of ecosystem attributes between restored and reference marshes. Although this approach provides an objective basis for judging project success, inferences can be constrained if the high variability of natural marshes masks differences in sampled attributes between restored and reference sites. Furthermore, such assessments are usually focused on a small number of restoration projects in a local area, limiting the ability to address questions regarding the effectiveness of restoration within a broad region. We developed a hierarchical approach to evaluate the performance of tidal restorations at local and regional scales throughout the Gulf of Maine. The cornerstone of the approach is a standard protocol for monitoring restored and reference salt marshes throughout the region. The monitoring protocol was developed by consensus among nearly 50 restoration scientists and practitioners. The protocol is based on a suite of core structural measures that can be applied to any tidal restoration project. The protocol also includes additional functional measures for application to specific projects. Consistent use of the standard protocol to monitor local projects will enable pooling information for regional assessments. Ultimately, it will be possible to establish a range of reference conditions characterizing natural tidal wetlands in the region and to compare performance curves between populations of restored and reference marshes for assessing regional restoration effectiveness.

Key words: assessment, monitoring protocols, salt marsh, tidal restoration, tidal restrictions.

[1]USGS Patuxent Wildlife Research Center, Augusta, ME, U.S.A.
[2]Wells National Estuarine Research Reserve, Wells, ME, U.S.A.
[3]Jackson Estuarine Laboratory, Department of Natural Resources, University of New Hampshire, Durham, NH, U.S.A.
[4]USGS Patuxent Wildlife Research Center, University of Rhode Island, Narragansett, RI, U.S.A.
[5]Current address: National Park Service, University of Rhode Island, Narragansett, RI, U.S.A.
[6]Massachusetts Audubon Society, Wenham, MA, U.S.A.
[7]National Marine Fisheries Service, Gloucester, MA, U.S.A.
[8]Address correspondence to Hilary A. Neckles, USGS Patuxent Wildlife Research Center, 26 Ganneston Drive, Augusta, ME 04330. E-mail: hilary_neckles@usgs.gov.

Introduction

Tidal flooding is the dominant force that structures coastal wetlands, influencing all aspects of coastal ecosystems (Pennings & Bertness 2001). Obstructions to tidal flooding caused by dikes, roadways, and bridges thus have far-reaching impacts, including altered vegetation (Roman et al. 1984; Sinicrope et al. 1990), sediment biogeochemistry (Portnoy & Giblin 1997), water quality (Portnoy 1991; Roman et al. 1995), sediment inputs (Boumans & Day 1994), and fish and wildlife populations (Burdick et al. 1997). Most salt marsh restoration efforts have focused on removing tidal restrictions to reestablish tidal exchange, with the assumption that the associated structure, function, and sustainability of these natural grasslands will return.

Methods for evaluating the performance of tidal restorations vary with project goals, compliance requirements, organizational priorities, and financial limitations. The strongest inferences are drawn from comparisons of wetland attributes over time between restored marshes and carefully selected reference systems (e.g., Burdick et al. 1997; Dionne et al. 1999; Morgan & Short 2002, this issue; Roman et al. 2002, this issue). This approach provides an objective basis for judging the success of individual restoration projects while identifying meaningful and robust performance standards for future application (Kentula et al. 1992; Short et al. 2000). The consistent monitoring of wetland attributes inherent in this approach is also fundamental to an adaptive management framework, in which regular assessments of restoration progress are used to inform management decisions (Thom 1997). Thus, deficiencies in design of existing projects can be identified and remedied as restored wetlands develop, and knowledge is gained to guide future restoration efforts.

Some challenges associated with this approach are related to the scale of implementation. First, the spatial and temporal variability of natural marshes may mask differences in sampled attributes between restored and reference sites (Simenstad & Thom 1996; Short et al. 2000; Simenstad & Cordell 2000). Although increasing the number of reference sites can improve the power of statistical comparisons, most individual monitoring programs face financial and practical constraints to the number of marshes that can be sampled. Second, independent assessments of one to several restoration projects in a local area cannot address questions regarding the effectiveness of restoration within a regional context. The need to consider cumulative effects of wetland alterations in regional restoration planning is increasingly recognized (Zedler 1996; Bedford 1999). Such regional approaches to restoration demand similarly broad-scale assessments of restoration success. However, other than major government investments in regional restoration-monitoring programs (e.g., monitoring of restored wetlands in coastal Louisiana through the Coastal Wetlands Planning, Protection, and Restoration Act; Steyer et al. 1995), comprehensive regional assessments are beyond the scope of funding available to most organizations involved in tidal restoration.

We developed a hierarchical approach to evaluating the performance of tidal restorations that meets the needs for both local adaptive management of individual projects and regional assessments of restoration success. Importantly, the approach is economically feasible within the general funding levels of ongoing assessment programs. We used the Gulf of Maine region as a model. Extending from Cape Cod Bay, Massachusetts to Cape Sable, Nova Scotia, the Gulf of Maine coast includes about 160 km^2 of salt marsh (Jacobson et al. 1987). Diking has dramatically altered a large proportion of the region's tidal wetlands, and tidal restriction remains the primary cause of ongoing marsh degradation. Many federal, state, provincial, and nongovernmental programs are focused on restoring Gulf of Maine salt marsh through the reintroduction of tidal flushing (Roman et al. 1984, 1995; Dionne et al. 1998).

The cornerstone of our approach is a standard protocol for uniform monitoring of tidal restorations and natural reference marshes throughout the region (Neckles & Dionne 2000). The regional protocol was developed through collaboration and consensus among nearly 50 tidal marsh scientists and resource managers from the northeastern United States and maritime Canada. Investment and ownership by a majority of practitioners in the region helps ensure that the protocol will be used during routine evaluations of local project performance, and implementation of a consistent protocol across the region enables the pooling of comparable data from multiple sites into a regional data set. As the number of projects adopting the standard protocol increases throughout the region, monitoring data from a large number of restored and reference marshes will be compiled. Ultimately, the performance of individual projects can be compared with populations of other restored and reference marshes to support site-specific adaptive management goals. In addition, performance curves of marsh attributes over time can be compared between populations of restored and reference marshes (Kentula et al. 1992) to assess the effectiveness of restoration on a regional scale. Here we outline the regional monitoring protocol, describe the rationale for selecting the attributes included, and discuss implementation within a regional framework.

Methods for Protocol Development and Implementation

The regional protocol was developed at a 1999 workshop (Neckles & Dionne 2000). Potential monitoring variables were evaluated in terms of information content, cost, skill level required for measurement, and spatial and temporal sampling frequency needed. A suite of core variables was selected for application to all tidal restoration monitoring in the region. Core variables are cost-efficient measures of wetland structure that collectively provide basic information on ecosystem responses to tidal restoration. The protocol also identifies additional variables for application to individual restoration projects as the availability of monitoring resources allows or as is warranted by specific project goals and circumstances. Most additional variables are indicators of marsh functions that may help elucidate the processes underlying system responses.

Restoration sites are matched with one or more reference marshes for monitoring (e.g., Havens et al. 1995; Burdick et al. 1997; Dionne et al. 1999). Reference marshes should be similar to restoration sites in terms of size, geomorphology, potential tidal range, landscape position, adjacent land use, water quality, and other characteristics. The protocol stresses the use of a statistically valid sampling design with random sample allocation (Neckles & Dionne 2000). Monitoring data should be collected for a minimum of 1 year before restoration, annually for 2 or 3 years after restoration actions, and then every several years thereafter until long-term success criteria for the project are achieved. Recent data suggest that some functions of restored salt marshes in the Gulf of Maine are equivalent to reference marshes in 4 to 6 years (Short et al. 2000), although others may take much longer (Morgan & Short 2002, this issue).

Monitoring Variables

Baseline Habitat Map

Base maps should be prepared to document initial conditions of restoration sites before and immediately after restoration actions and of reference marshes at the start of long-term monitoring. The map provides a foundation for monitoring activities and a baseline for spatial change analysis. It includes fundamental features of the site, vegetation patterns, and potential stresses on the marsh ecosystem (Table 1, core variables). If more extensive geographic data are available, additional detail can make the map more useful (Table 1, additional variables).

Hydrology

The fundamental control on the structure and function of salt marsh habitat is flooding with salt water (Mitsch & Gosselink 2000). The hydroperiod of the marsh, or the frequency and duration of flooding, is determined by tidal regime and elevation (Table 2). Although tidal predictions may be available for astronomical tides affecting coastal areas close to the restoration site, local variation demands that actual measurements be made at specific sites. The elevation of the marsh surface relative to the tidal height must also be measured (resulting in either a contour map or a hypsometric curve; e.g., Boumans et al. 2002, this issue). Regional comparisons require linking elevation data to an established vertical datum. Application of the elevation data to marsh surface area provides an estimate of the area of marsh flooded for any particular tidal height and, coupled with tidal regime, yields the hydroperiod. Additional hydrologic variables (Table 3, hydrology) provide information useful for assessing the effectiveness of structures built to increase tidal exchange.

Soils and Sediments

Soil salinity largely determines the distribution and abundance of plant species in salt marshes (Niering & Warren 1980). Many restoration projects are initiated with the goal of reestablishing plant communities characteristic of salt marshes. This may also involve reducing the abundance of freshwater plants, including invasive species like *Lythrum salicaria* (purple loosestrife), *Phragmites australis* (common reed), or *Phalaris arundinacea* (reed canarygrass). In these instances plant distributions after restoration are expected to change as increasing soil salinity exceeds thresholds of species tolerance (Kuhn & Zedler 1997; Roman et al. 2002, this issue; Thom et al. 2002, this issue). Measurements of soil salinity should be focused on plant growing seasons, especially before flowering, at critical rooting depths (Table 2).

Tidal restrictions have resulted in subsidence of the marsh surface and the inability of marshes to build in elevation with sea level rise (Burdick et al. 1997; Mitsch & Gosselink 2000). Both flooding and salinity control the decomposition rate of organic-rich sediments (Neckles & Neill 1994; Mendelssohn et al. 1999), and sediment rebuilding after restoration depends on the influx and deposition of inorganic sediments and the growth of belowground portions of plants (Good et al. 1982; Stevenson et al. 1986). Determination of soil organic content, sediment accretion rate, and sediment elevation provides direct insights into processes controlling vertical marsh growth after restoration (Table 3, soils and sediments). The availability of oxygen in marsh soils exerts strong influences on the pathways and rates of organic matter decomposition (Hackney & de la Cruz 1980;

Table 1. Variables to be included on base map of all monitoring sites.

Variable	*Description*
Core variables	
Locator map	State, province, city, or town of salt marsh monitoring site
Key features	Locator and cultural features associated with monitoring site, such as rivers, roads, and culverts
Wetland area/cover types/ sediment condition	Delineated salt marsh, fresh/brackish marsh, forested wetland, shrub-dominated wetland, open water (creeks, pannes, pools, ditches), invasive species or species of interest, from National Wetland Inventory (U.S.) or Canadian Wetlands Atlas (Canada) if available; soil organic matter content at sampling stations
Manipulations	Location of pre- and post-restoration actions, such as culverts, dredging, removal or addition of fill, excavations, etc.
Sampling locations	Locations of pre- and post-restoration monitoring stations (transects, plots, wells, bird observation stations, etc.)
Base map documentation	Sources of base map (e.g., U.S. or Canadian topographic maps; aerial photographs including scale, type, and date; tax maps; National Wetland Inventory or Canadian Wetlands Atlas database), scale of map and north arrow, latitude and longitude
Additional variables	
Detailed, geo-referenced site information	Detailed cover-type mapping, ownership boundaries, elevation contours, 100-yr floodplain boundary

Table 2. Core variables to be monitored on all restored and natural marshes in the regional program.

Variable Name	*Description*	*Sampling Method*	*Annual Sampling Frequency*
		Hydrology	
Tidal signal	Pattern of water level change with respect to a reference point	Continuous water level recorders *or*	2 to 4 week period of operation
		Tide staff observations at 10-min intervals	13-hr observation periods during three spring and three neap tides
Elevation	Marsh surface elevation at contour intervals of 15 cm or less	Contour map *or*	
		Hypsometric curve (cumulative frequency distribution of elevation of set of points on marsh surface)	Once
		Soils and sediments	
Pore–water salinity	Parts dissolved salts per thousand (also referenced to Practical Salinity Scale) of soil water collected from 5–20 cm depths	Groundwater wells, soil cores, or sippers	At low tide, six times between early (April/May) and mid (July/August) growing season, including spring and neap tides
		Vegetation	
Composition	Identity of all plant species occurring per m^2	Permanent plots positioned along transects at intervals necessary to maintain independence (>10–20 m)	(Frequency applies to all variables) Once at time of maximum standing biomass (mid-July through August)
Abundance	Percent cover per m^2 by species	Permanent plots on transects	
Height	Mean height of three tallest individuals of each species of concern per m^2	Permanent plots on transects	
Density	Number of shoots per m^2 in plots restricted to species of concern	Permanent plots established within distinct stands of species of concern	
Photo stations	Photographs from permanent stations	Panoramic views of entire marsh from several compass bearings; close-ups of permanent plots	
		Nekton	
Composition	Identity of each animal sampled	(Methods apply to all variables)	
Species richness	Total number of species represented	Throw traps in creeks and channels (small fish) *and*	At mid-tide during two spring tides in August
Density	Number of animals per area (throw traps and marsh surface fyke nets)	Fyke nets in creeks > 15 m wide (large fish) *and*	Installed at slack high tide: two spring tides during early season migration of diadromous fish; two spring tides in August
Length	Length (fish, shrimp) or width (crabs) of individual animals to the nearest 0.5 mm, by species	Fyke nets on marsh surface (fish catch data must be standardized by marsh area)	Installed at low tide to sample ebb tide, one spring tide in August
Biomass	Wet weight of animals in sample, by species		
		Birds	
Density	Number of birds per ha, by species	(Methods apply to all variables) 20-minute observation periods in the morning from site-specific vantage points that provide an uninterrupted view of at least a portion of the salt marsh	(Frequency applies to all variables) At high and low tides: two times during breeding season (May/June); once per week during waterfowl migration (March/April and October/November); once per week during shorebird migration (July–September)
Species richness	Total number of species represented		
Feeding/breeding behavior	Type of behavior (e.g., feeding, roosting, breeding, preening) per observation interval, by species		

Table 3. Additional variables to be monitored as warranted by the goals and resources of specific projects.

Variable Name	Description
Hydrology	
Tidal creek cross-section	Cross-section profiles of major tidal creeks measured at permanent locations.
Water table depth	Level of groundwater at permanent wells or piezometers installed within the marsh and along the upland marsh edge. Sampled at low tide, six times between early and mid-growing season, including neap and spring tides.
Surface water chemical and physical characteristics	Water quality parameters sampled in main tidal channel: dissolved oxygen, salinity, temperature, and pH.
Current profiles	Tidal current in main channel assessed over several tidal cycles.
Soils and Sediments	
Organic matter	Organic content of 20-cm soil cores sectioned into 5-cm segments.
Sediment accretion rate	Accumulation of inorganic and organic material above a marker horizon over a known time interval.
Sediment elevation	Short-term changes in sediment elevation measured with sediment elevation tables.
Redox potential	Redox potential at 1- and 15-cm depths.
Sulfide	Concentration of sulfide in pore water.
Vegetation	
Aboveground biomass	Biomass of living aboveground plant material collected from additional randomly positioned quadrat in vicinity of permanent quadrat.
Stem density	Number of shoots per m^2, by species, within permanent quadrats.
Proportion flowering	Proportion of shoots of each species that are flowering within permanent quadrats.
Nekton	
Biomass	Wet weight of individuals in sample, by species, recorded from throw trap and fyke net samples.
Fish growth	Fish condition (length/biomass) within size classes for selected species collected in throw trap and fyke net samples.
Fish diet	Gut contents of subsample of fish collected in throw trap and fyke net samples.
Larval mosquitoes	Dip samples collected weekly from April through August along transects that intersect standing water on the marsh.
Birds	
Small passerines and other cryptic species	20-minute observation periods from center of 50-m radius counting circles established in the salt marsh.
Birds in the buffer	20-minute observation periods from center of 50-m radius counting circles established in the habitat adjacent to the salt marsh.
Waterfowl in winter	20-minute observation periods from site-specific vantage points continued throughout the winter (as long as marsh is ice free).

Neckles & Neill 1994) and the species composition and growth of marsh vegetation (Crooks et al. 2002, this issue). Measurement of the chemical reduction/oxidation (redox) potential and pore-water sulfide concentrations (Table 3, soils and sediments) are two indicators of the oxygen status and decomposition pathways in the soil, thus providing insights into marsh maintenance processes.

Vegetation

A protocol for monitoring restoration projects must be capable of detecting changes in marsh vegetation in the years after restoration actions and differences from vegetation of natural systems over that time period. In addition, restoration projects frequently focus on the control of a specific plant species such as *P. australis.* In these cases more detailed information on individual species of concern may be warranted. Accordingly, the protocol in Table 2 should be applied routinely to the marsh plant community in general, with additional data collected on species of concern as appropriate. The protocol adopts use of permanent plots positioned systematically along randomly established transects (Elzinga et al. 1998) for sampling the marsh community (Neckles & Dionne 2000). Previous investigations suggest that New England salt marsh plant communities can be adequately described using 20 quadrat samples (Roman et al. 2001). The height of species of concern provides information on plant vigor (e.g., Howard & Mendelssohn 1999), and photographs provide valuable qualitative information on the changes in the plant community over time (Table 2). More intensive sampling of plant characteristics can provide information on the mechanisms causing observed patterns of vegetation response (Table 3, vegetation).

Nekton

Fish and macrocrustaceans are useful indicators of tidal marsh ecosystem functions. Their position in the upper levels of marsh food webs and their dependence on a wide range of food and habitat resources serve to integrate salt marsh ecosystem elements and processes (Kwak & Zedler 1997). Salt marsh nekton are also important ecological links to fisheries in near-shore and potentially offshore waters (Deegan 1993; Kneib 1997).

Fish are highly mobile and have well-developed senses, making them a challenging group to quantify. This is especially true in vegetated systems. Attributes of the fish community must be determined within the tidal creeks and channels and in flooded vegetation (Table 2). Fish growth trajectories and fish gut contents, combined with the source of food items, can indicate whether diets of fish captured in restored marshes differ from those of fish in reference systems (Table 3, nekton). Finally, although not traditionally considered a nektonic species, larval mosquitoes can be used as indicators of some aspects of tidal marsh hydrology. Information on mosquito densities is particularly warranted for restoration projects that include mosquito control as a primary goal.

Birds

Birds are another group of higher trophic-level organisms with species that are strongly dependent on salt marsh habitats, providing integrative indicators of restored marsh structure and function. In addition, a major goal of some restoration projects is to increase the bird use of salt marsh habitat, so that monitoring birds may be an important criterion for measuring success. However, most bird species that are often the target of restoration efforts (e.g., herons, shorebirds, waterfowl, raptors) have home ranges much larger than the size of typical salt marsh restoration projects in the Gulf of Maine region. Therefore, intensive sampling over a wide area may be required to draw conclusions about use of a restored marsh by all possible bird species. Wetland birds in particular have specific habitat preferences, such as a large percentage of open water or pannes, that may not be present in a given restoration site (Reinert & Mello 1995). Sampling difficulties notwithstanding, quantitative observations of bird marsh-use provide an indicator of the habitat value of restored salt marshes. Observations should be made from a high point above the marsh during avian breeding and migratory seasons (Table 2) (Hutto et al. 1986). Some birds, such as small passerines, rails, and bitterns, will likely be under-represented in observations taken from a high vantage point. To account for these species additional observations can be made at ground level (Table 3, birds). Similar observations in habitat adjacent to the salt marsh can provide information on the importance of a buffer zone to salt marsh birds. Further information about the use of the restored marsh by wintering waterfowl can be gained by extending waterfowl counts throughout the winter (Table 3, Birds).

Discussion

Assessing the performance of tidal restoration is based on the comparison of ecosystem attributes among restored and reference sites before and after restoration. The core monitoring variables we recommend are simple cost-effective measures of structure that can be applied to any tidal restoration project. Collectively, information on core variables is useful to evaluate site-specific responses and to guide restoration approach. For example, the hydrology, elevation, and vegetation responses at Drakes Island Marsh in southern Maine clearly showed that the inadvertent hydrologic restoration was inadequate to restore vegetation structure (Boumans et al. 2002, this issue). In contrast, a rapid increase in bird use of the restored Gog-Le-Hi-Te wetland, within the Puyallup River estuary of Puget Sound, Washington, showed the return of at least some habitat functions (Simenstad & Thom 1996). At two salt marshes in Massachusetts, hydrology, vegetation, and fish monitoring are being used to evaluate responses to reintroduction of tidal flow through an adjustable culvert (Argilla Marsh in Ipswich, R. Buchsbaum, unpublished data; Hatches Harbor on Cape Cod, C. Roman, unpublished data).

Process-level measurements are important to assess functional responses to restoration. Rapid increase in sediment elevation at one marsh (Stuart Farm, New Hampshire) indicated that functions controlling vertical marsh growth could be attained, whereas little to no elevation increase at another (Drakes Island Marsh, Maine) indicated the hydrologic restoration was inadequate (Boumans et al. 2002, this issue). We included such measures as additional (i.e., optional) variables because they tend to be more costly to measure than the core structural variables or are project-specific regarding sampling choices and restoration goals. Both characteristics limit the potential for uniform application on a regional scale.

Some marsh functions and values may recover more quickly than others, and the rate of change for any given variable may not be uniform. For example, most fish species appear to use the restored marsh immediately (Simenstad & Thom 1996; Burdick et al. 1997; Dionne et al. 1999; Roman et al. 2002, this issue), but the reestablishment of anadromous populations may require many years (Gray et al. 2002, this issue). Invasive species provide another example. *Lythrum salicaria* was eliminated within a year from one tidally restored marsh (Burdick et al. 1997), but 6 years or more may pass before *P. australis* is reduced to an acceptable level (Rozsa 1995). The height of *P. australis* declined 1 year after the restoration of more natural tidal hydrology at Argilla Marsh, Massachusetts, but it took 3 years before a statistically significant decline in cover occurred (R. Buchsbaum, unpublished data).

The protocol we describe here provides a foundation for a regional monitoring network of restored and reference marshes. Consistent application of the protocol to a large number of local projects will facilitate development of regional performance curves for assessment of tidal restoration throughout the Gulf of Maine. Although the protocol was developed for Gulf of Maine systems, it can be adapted for examining the response of coastal marshes in other regions to tidal restoration.

Once this approach is implemented across a representative range of marsh types and locations throughout the Gulf of Maine, it will be possible to determine the appropriate frequency and duration of monitoring. Ultimately, comparisons of standard monitoring variables between populations of restored and reference sites can be used to identify the best indicators of restored marsh functions and to suggest regionally applicable success criteria (performance standards) for restoration projects. It may also be possible to establish a range of reference values characterizing natural tidal wetland systems in the region (Brinson & Rheinhardt 1996). This information will be valuable for evaluating the effectiveness of tidal marsh restoration in the Gulf of Maine and for guiding future restoration efforts.

Acknowledgments

This article is based on a monitoring protocol that was published and distributed in the Gulf of Maine region (Neckles & Dionne 2000; full report available at http://www.pwrc.usgs.gov/resshow/neckles/gpac.htm). The regional protocol was developed at a workshop sponsored by the Global Programme of Action Coalition for the Gulf of Maine, the Commission for Environmental Cooperation, the Laudholm Trust, and the Wells National Estuarine Research Reserve. We thank N. Bayse for coordinating the workshop and A. Banner, J. Catena, R. Cook, T. Diers, S. Fefer, C. Foote-Smith, A. Hanson, K. Hughes, R. Milton, K. Ries, L. Roberts, P. Shelley, J. Taylor, D. Thompson, and L. Winter for assistance in planning and running the workshop. We also thank the workshop participants, whose input forms the basis of this approach. Finally, we extend particular thanks to Si Simenstad, Blaine Kopp, and two anonymous reviewers, whose thorough and insightful reviews significantly improved the manuscript.

LITERATURE CITED

Bedford, B. L. 1999. Cumulative effects on wetland landscapes: links to wetland restoration in the United States and southern Canada. Wetlands **19:**775–788.

Boumans, R. M. J., and J. W. Day. 1994. Effects of two Louisiana marsh management plans on water and materials flux and short-term sedimentation. Wetlands **14:**247–261.

Boumans, R. M. J., D. M. Burdick, and M. Dionne. 2002. Modeling habitat change in salt marshes after tidal restoration. Restoration Ecology **10:**543–555.

Brinson, M. M., and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. Ecological Applications **6:**69–76.

Burdick, D. M., M. Dionne, R. M. Boumans, and F. T. Short. 1997. Ecological responses to tidal restorations of two northern New England salt marshes. Wetlands Ecology and Management **4:**129–144.

Crooks, S., J. Schutten, G. D. Sheern, K. Pye, and A. J. Davy. 2002. Drainage and elevation as factors in the restoration of a salt marsh in Britain. Restoration Ecology **10:**591–602.

Deegan, L. A. 1993. Nutrient and energy transport between estuaries and coastal marine ecosystems by fish migration. Canadian Journal of Fisheries and Aquatic Sciences **50:**74–79.

Dionne, M., D. Burdick, R. Cook, R. Buchsbaum, and S. Fuller. 1998. Scoping Paper 5: physical alterations to waterflow and salt marshes. Commission for Environmental Cooperation, Montreal, Canada.

Dionne, M., F. T. Short, and D. M. Burdick. 1999. Fish utilization of restored, created, and reference salt marsh habitat in the Gulf of Maine. American Fisheries Society Symposium **22:**384–404.

Elzinga, C. L., D. W. Salzer, and J. W. Willoughby. 1998. Measuring and monitoring plant populations. BLM Technical Reference 1730-1, BLM/RS/ST-98/005+1730. Bureau of Land Management, Denver, Colorado.

Good, R. E, N. F. Good, and B. R. Frasco. 1982. A review of primary production and decomposition dynamics of the belowground marsh component. Pages 139–157 in V. S. Kennedy, editor. Estuarine comparisons. Academic Press, New York.

Gray, A., C. A. Simenstad, D. L. Bottom, and T. Cornwell. 2002. Contrasting functional performance of juvenile salmon habitat in recovering wetlands of the Salmon River estuary, Oregon, U.S.A. Restoration Ecology **10:**514–526.

Hackney, C. T., and A. A. de la Cruz. 1980. In situ decomposition of roots and rhizomes of two tidal marsh plants. Ecology **61:**226–231.

Havens, K. J., L. M. Varnell, and J. G. Bradshaw. 1995. An assessment of ecological conditions in a constructed tidal marsh and two natural reference tidal marshes in coastal Virginia. Ecological Engineering **4:**117–141.

Howard, R. J., and I. A. Mendelssohn. 1999. Salinity as a constraint on growth of oligohaline marsh macrophytes. I. Species variation in stress tolerance. American Journal of Botany **86:**785–794.

Hutto, R. L., S. M. Pletshet, and R. Hendricks. 1986. A fixed-radius point count method for non-breeding and breeding season use. Auk **103:**593–602.

Jacobson, H. A., G. L. Jacobson, Jr., and J. T. Kelley. 1987. Distribution and abundance of tidal marshes along the coast of Maine. Estuaries **10:**126–131.

Kentula, M. E., R. P. Brooks, S. E. Gwin, C. C. Holland, A. D. Sherman, and J. C. Sifneos. 1992. An approach to improving decision making in wetland restoration and creation. EPA/600/R-92/150. U.S. Environmental Protection Agency, Washington, DC.

Kneib, R. T. 1997. The role of tidal marshes in the ecology of estuarine nekton. Oceanography and Marine Biology **35:**163–220.

Kuhn, N. L., and J. B. Zedler. 1997. Differential effects of salinity and soil saturation on native and exotic plants of a coastal salt marsh. Estuaries **20:**391–403.

Kwak, T. J., and J. B. Zedler. 1997. Food web analysis of southern California coastal wetlands using multiple stable isotopes. Oecologia **110:**262–277.

Mendelssohn, I. A., B. K. Sorrell, H. Brix, H.-H. Schierup, B. Lorenzen, and E. Maltby.1999. Controls on soil cellulose decomposition along a salinity gradient in a *Phragmites australis* wetland in Denmark. Aquatic Botany **64:**381–398.

Mitsch, W. J., and J. G. Gosselink. 2000. Wetlands. 3rd edition. John Wiley and Sons, New York.

Morgan, P. A., and F. T. Short. 2002. Using functional trajectories to track constructed salt marsh development in the Great Bay estuary, Maine/New Hampshire, U.S.A. Restoration Ecology **10:**461–473.

Neckles, H. A., and M. Dionne, editors. 2000. Regional standards to identify and evaluate tidal wetland restoration in the Gulf of Maine. Wells National Estuarine Research Reserve Technical Report, Wells, Maine.

Neckles, H. A., and C. Neill. 1994. Hydrologic control of litter decomposition in seasonally flooded prairie marshes. Hydrobiologia **286:**155–165.

Niering, W. S., and R. S. Warren. 1980. Vegetation patterns and processes in New England salt marshes. BioScience **30:**301–307.

Pennings, S. C., and M. D. Bertness. 2001. Salt marsh communities. Pages 289–316 in M. D. Bertness, S. D. Gaines, and M. Hay, editors. Marine community ecology. Sinauer Associates, Sunderland, Massachusetts.

Portnoy, J. W. 1991. Summer oxygen depletion in a diked New England estuary. Estuaries **14:**122–129.

Portnoy, J. W., and A. E. Giblin. 1997. Effects of historic tidal restrictions on salt marsh sediment chemistry. Biogeochemistry **36:**275–303.

Reinert, S. E., and M. J. Mello. 1995. Avian community structure and habitat use in a southern New England estuary. Wetlands **15:**9–19.

Roman, C. T., W. A. Niering, and R. S. Warren. 1984. Salt marsh vegetation change in response to tidal restriction. Environmental Management **8:**141–150.

Roman, C. T., R. W. Garvine, and J. W. Portnoy. 1995. Hydrologic modeling as a predictive basis for ecological restoration of salt marshes. Environmental Management **19:**559–566.

Roman, C. T., M. J. James-Pirri, and J. F. Heltshe. 2001. Monitoring salt marsh vegetation. Technical Report, Long-term Coastal Ecosystem Monitoring Program, Cape Cod National Seashore, Wellfleet, Massachusetts.

Roman, C. T., K. B. Raposa, S. C. Adamowicz, M.-J. James-Pirri, and J. G. Catena. 2002. Quantifying vegetation and nekton response to tidal restoration of a New England salt marsh. Restoration Ecology **10:**450–460.

Rozsa, R. 1995. Tidal wetland restoration in Connecticut. Pages 51–65 in G. D. Dreyer and W. A. Niering, editors. Tidal marshes of Long Island Sound: ecology, history and restoration. Connecticut College Arboretum Bulletin 34. Connecticut College Arboretum, New London.

Short, F. T., D. M. Burdick, C. A. Short, R. C. Davis, and P. A. Morgan. 2000. Developing success criteria for restored eelgrass, salt marsh, and mudflat habitats. Ecological Engineering **15:**239–252.

Simenstad, C. A., and J. R. Cordell. 2000. Ecological assessment criteria for restoring anadromous salmonid habitat in Pacific Northwest estuaries. Ecological Engineering **15:**283–302.

Simenstad, C. A., and R. M. Thom. 1996. Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. Ecological Applications **6:**38–56.

Sinicrope, T. L., P. G. Hine, R. S. Warren, and W. A. Niering. 1990. Restoration of an impounded salt marsh in New England. Estuaries **13:**25–60.

Stevenson, J. C., L. G. Ward, and M. S. Kearney. 1986. Vertical accretion in marshes with varying rates of sea level rise. Pages 241–259 in D. A. Wolfe, editor. Estuarine variability. Academic Press, Orlando, Florida.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller, and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program. Open-file series no. 95-01. Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge.

Thom, R. M. 1997. System-development matrix for adaptive management of coastal ecosystem restoration projects. Ecological Engineering **8:**219–232.

Thom, R. M., R. Zeigler, and A. B. Borde. 2002. Floristic development patterns in a restored Elk River estuarine marsh, Grays Harbor, Washington. Restoration Ecology **10:**487–496.

Zedler, J. B. 1996. Coastal mitigation in southern California: the need for a regional restoration strategy. Ecological Applications **6:**84–93.