Evaluating Urban Wetland Restorations: Case Studies for Assessing Connectivity and Function*

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Abstract

Restoration of urban intertidal wetlands such as the Hackensack Meadowlands of New Jersey typically involves the return of tidal flow to diked or gated land, the removal of dredge spoils to lower elevations, and/or the replacement of invasive plant species (e.g., *Phragmites australis*) with preferred marsh plants. Restoration of preferred vegetation and hydrology is expected to net an overall improvement in habitat quality for fishery and wildlife species. Common metrics have been identified for evaluating the functional success of restoration on individual sites in urban wetlands. We argue, however, that alternative, larger-scale metrics are needed in order to monitor and evaluate the success of restoring functional connectivity to the patchwork of wetlands that compose urban estuarine systems. We present here a literature review of measurements that have been used in wetland restorations throughout the United States to assess restoration success of ecological functions at the ecosystem and/or landscape scale. Our goal is to stimulate discussion of alternative metrics to be included in future and ongoing assessments of urban restoration sites, especially those in the Meadowlands.

Key words: Hackensack Meadowlands, landscape, restoration, salt marsh

Introduction

Functional assessment of undisturbed wetland systems is an intricate task, and assessment of urban wetland systems can be even more complex. As discussed by Ehrenfeld (2000) and Baldwin (2004), urban habitats are generally physically and biologically different from nonurban systems in a number of ways. First, urban systems are often subject to different climate and air quality than nonurban systems (for example, warmer temperatures, lower wind speeds, and higher concentrations of nutrients and toxicants). Physical alteration of wetland habitats, such as ditching and diking, is also common in urban habitats. In addition, the species pool in urban habitats is often limited in its seed-dispersal capabilities or mutualistic interactions, such as pollination, and the possible range of habitat types is often limited. Finally, wetlands, especially small isolated patches, may play different roles for wildlife in urban habitats than their nonurban counterparts. Specifically, while isolated wetlands in nonurban areas may have lower species richness and be underutilized by wildlife, similar habitats in an urban setting may provide an oasis used by a wide variety of species (Ehrenfeld, 2000).

* Published online December 30, 2004

The Hackensack Meadowlands, located in northeastern New Jersey, provide a prime example of these differences. This wetland complex has been dramatically affected by urbanization during the last 200 years: The hydrology has been so altered that this once freshwater-brackish system is now brackish to saline. The roughly 7,000-hectare (17,300-acre) marsh complex is traversed by railroads and highways and has been subject to human intervention ranging from heavy industry and landfills to sports complexes and residential developments. It includes sites contaminated with a variety of toxicants (Sipple, 1971; Roman, Niering & Warren, 1984; Ehrenfeld, 2000), including over 200 known or suspected hazardous waste sites, among which are three Superfund sites. There are also numerous combined sewer overflows, which cause continued degradation of the Meadowlands environment (Thiesing & Hargrove, 1996). As a result of the intensive land use and related habitat degradation in the area, numerous restoration projects are being implemented, primarily to restore hydrology and replace the *Phragmites*-dominated ecosystem with a more diverse blend of vegetation in the interest of providing higher-quality habitat for fishery resources and other wildlife (New Jersey Meadowlands Commission [NJMC], 2004). The urban nature of the Meadowlands presents a challenge in identifying reference sites for gauging restoration success. The existing brackish to saline habitat is itself a product of urbanization, and therefore, undisturbed analogous sites for this habitat are not available nearby to serve as references. Because of this lack of suitable reference sites and the fact that restoration in the Meadowlands is targeted on ecosystem-scale improvements, there is a need to develop landscape-scale metrics for monitoring restoration progress and assessing wetland function.

The challenge of finding ways to measure restoration success on such a large scale is not restricted to the Hackensack Meadowlands; national symposia have been called to evaluate landscape-scale wetland assessment and management (e.g., the Association of Wetland Managers symposium "Landscape Scale Assessment and Management," Nashua, New Hampshire, October 20–23, 2003). As described by Kentula (2000) and the National Research Council (NRC, 2001), a fundamental goal of wetland restoration is that site-specific improvements relay to connected ecosystems. Wetland restoration, enhancement, and creation are regularly undertaken in this country and others to compensate for losses due to development or other habitat degradation. In the United States, federal and state regulatory programs require mitigation or compensation for certain types of disturbances and ecological injury with the ultimate goal of retaining or restoring the ecosystem services provided by aquatic habitats. However, despite the no-net-loss requirements of the federal Clean Water Act and the restoration components of CERCLA (the Comprehensive Environmental Response, Compensation, and Liability Act, also known as Superfund) and RCRA (the Resource Conservation and Recovery Act), wetlands are still being lost at a significant rate (NRC, 2001), and no metrics are being collected universally to demonstrate the contribution of restored wetlands to larger ecosystem and landscape functions. While contiguity and large size are commonly recognized as positive influences on the likelihood of restoration influencing the larger landscape, small isolated wetlands may also be important, especially for maintenance of regional biodiversity (e.g., rare plants; Zedler, 2003). Connectivity, or the degree to which the landscape patches interact, is difficult to measure but is a vital element of wetland sustainability.

Wetland acreage and function continue to be lost, and finding out why is made more difficult by the lack of effective postconstruction monitoring and adaptive management of wetland mitigation and restoration processes (Race & Fonseca, 1996; Zedler, 2000). Regulations typically require only limited evaluation of created or restored wetlands, with an emphasis on rapid-assessment methodologies, such as the Wetland Evaluation Technique (WET) or the Habitat Evaluation Procedure (HEP). With their focus on vegetation-related parameters such as plant height, percentage cover, and invasive species (see Craft, Reader, Sacco & Broome, 2003; Zedler, 2000), these correlative methodologies are good for rapid, qualitative screening of basic trends and for predicting the likelihood that a function is occurring. However, they don’t allow us to examine key large-scale interactions, such as nutrient retention or the dynamics of wildlife metapopulations), and their qualitative data are difficult to feed into models of adaptive management. Thus, while rapid-assessment methodologies are useful for broad oversight of the three basic wetland parameters (soil, water, and vegetation), they are of little use in assessing the participation of a given restored wetland in larger ecosystem services or functions. Achieving this functional connectivity is, after all, the goal of most wetland restoration and creation projects, both urban and "pristine" (Morgan & Short, 2002).

The time frame of current monitoring protocols also limits their use in landscape-scale assessments. Postrestoration monitoring is often only conducted for three to five years after construction. There is increasing awareness that this period of time is too short to adequately gauge the development of many important ecosystem attributes (Siegel, Laska, Hatfield & Hartman, unpublished data). Numerous studies have indicated that ecosystem attributes such as soil organic carbon, soil nitrogen, and biological communities require at least 5 to 25 years (or much more) to achieve relative equivalence with natural reference systems (Craft et al., 2003; Craft et al., 1999; Zedler, 2000; Warren et al., 2002). Moreover, establishment and measurement of larger-scale landscape interactions may take many more years to achieve (Zedler, 2001). As it stands today, monitoring is often conducted in a vacuum, so to speak, with little consideration given to the role of a specific site in the larger ecosystem context (Zedler, 2003).

Longer monitoring and better metrics for assessment of landscape-scale functions are especially important in patchy urban settings, where restoration may take a substantially different trajectory than that taken in more contiguous, nonurban sites. Furthermore, due to their ecological importance in disturbed landscapes, urban wetlands may contribute more at the landscape scale than independent wetlands in less disturbed settings (Callaway & Zedler, 2004). Thiesing (2001) and Zedler (2001), among others, have called for improved assessment of wetland functions at the landscape scale, but very few studies have developed techniques for large-scale assessment. Our objective is to present an outline of the common metrics of compliance success (i.e., achievement of restoration goals as set forth by a regulatory agency) in current use and to review alternative methods for assessing wetland functional progress. By reviewing published studies of creative monitoring techniques throughout the U.S., it is our goal to provide a general overview of possible means for improving the methods used in judging success in urban wetland creation and restoration.

We propose that ideal metrics for measuring urban restoration success at the landscape level have the following attributes:

- Metrics should have low spatial and temporal variability (outside of recognized gradients);
- Metrics should be measured regularly (at least annually);
- Metrics should quantitatively predict or measure a critical ecosystem function;
- Data should fit into an adaptive measurement strategy.

We recognize that not all metrics will have all these attributes, but a composite of improved metrics will allow for improved prediction and management of connectivity and function. Further, we recognize that metrics are chosen for more than scientific reasons and that the choices may affect the interpretation of restoration outcomes, a thorny issue to resolve in the restoration community.

Current Metrics of Compliance Success

Thiesing (2001) provides an excellent overview of the methods currently used to evaluate compliance success in wetland restoration and creation. She classifies the methods into four approaches: 1) inventory and classification, 2) rapid assessment protocols, 3) data-driven assessment models, and 4) bioindicators. While the approach implemented at a given site is generally specified by the regulatory agency overseeing the project, multifunction rapid assessment is the most common one used. Data collection for rapid assessment is usually a ranking for a given wetland function (e.g., high–medium–low) based on field observations or data (e.g., vegetation cover) specifically collected for compliance success. Below, we list common measurements for compliance success and review how they may be incorporated into a larger composite metric of landscape success.

Vegetation Cover and Composition

Vegetation cover and composition are the most common monitoring metrics used in most restoration projects. Indeed, they are the sole field-based metrics for many projects, particularly those driven by 404 permits (i.e., permits issued under the Clean Water Act). Factors such as percentage survival, percentage cover, and the presence of target species are relatively easy to assess in a single site visit. Monitoring vegetation cover and composition is useful because it provides a general idea of whether a restoration or construction project is establishing vegetation as expected or required. Regular vegetation monitoring can potentially help identify problems, such as low plant survivorship or the presence of invasive species, early in a project and allow for corrective action. In the New Jersey Meadowlands, for example, annual vegetation sampling in the Harrier Meadow wetland enhancement area is helping prevent *Phragmites* invasions by allowing modifications in planting and hydrologic patterns (Hicks & Hartman, 2004). In contrast, vegetation monitoring of the Eastern Brackish Marsh restoration site was limited to the first few years of vegetation establishment (1989–91), after which *Phragmites* returned as the dominant species (Laska, personal observation).

However, vegetation in and of itself can be misleading. Percentage cover and the presence of any one species, including invasive species, cannot fully determine how an ecosystem is functioning (Zedler, 2001). Measuring the fertilization of plants in their early stages of establishment may also give a false assessment of future vegetation sustainability (Zedler, 2001). Furthermore, vegetation biomass and structure, while providing a rough index of macrophyte primary production, are not always correlated with larger-scale functions such as fisheries habitat, trophic support, etc. (Weinstein, Balletto, Teal & Ludwig, 1997; Weinstein & Kreeger, 2000). Monitoring for the presence of invasive plant species (e.g., *Phragmites australis*, *Lythrum salicaria*, *Arundo donax*) is a necessary part of any wetland restoration or construction project, as invasives thrive in disturbed habitats and may limit floral and faunal recovery. While monitoring for invasive species is generally a site-specific process, the invasion pressure is a function of propagule density in the surrounding landscape. Evaluating the rate of return of *Phragmites* is critical in Meadowlands habitat, where more than 5,000 acres are dominated by this species (see Weinstein, Guntenspergen, Keough & Litvin, 2003, for additional commentary on *Phragmites* removal in New Jersey).

Wildlife Species Composition

The recovery of animal populations is often the focal goal of restoration (e.g., the northern harrier, *Circus cyaneus*, in Laska, Baxter & Graves, 2003; the California clapper rail, *Rallus longirostris obsoletus*, in Zedler, 1998), but typically monitoring efforts are minimal at best and often don't occur at all unless directly required by the overseeing regulatory agency. More than 225 species of birds occur in the Meadowlands (Kiviat & MacDonald, 2002), indicating great potential for avian responses to restoration efforts there. Generally, bird diversity or population attributes are good indicators of habitat quality (Croonquist & Brooks, 1991; Bryce, Hughes & Kaufmann, 2002); therefore, monitoring avian population responses to or habitat uses of restoration sites can be a valuable tool in evaluating restoration success (Neckles, 2002). The effectiveness of these evaluations increases when attributes are properly compared temporally (such as current versus prerestoration conditions) or spatially (restored site versus reference site over multiple years). Animal populations are rarely (if ever) in equilibrium (Wiens, 1984) and thus are extremely variable between years. Animal populations from fish to mammals must be monitored for at least five to ten years to account for high interannual variability (Elzinga, Salzer, Willoughby & Gibbs, 2001). Even with eight years of demographic study, Petranka, Murray, and Kennedy (2003) were unable to assess the response of two key amphibians to a wetland restoration in North Carolina.

Despite the difficulties in monitoring animal populations, though, they are one of the best landscape-scale indicators. This is true for both fully mobile vertebrate animals that use multiple habitats within an urban watershed and benthic invertebrates that are motile only in early life stages.

Water- and Soil-Quality Parameters

Monitoring of parameters such as salinity, pH, nutrient concentration, dissolved oxygen, and temperature can also help to identify major problems like nutrient overload, lack of dissolved oxygen, or high or low salinity and enable corrective action.

Unfortunately, these factors are not usually measured continuously and can be extremely variable over the course of even a day. Results also depend on season, precipitation, tidal amplitude, etc. As such, mean values of these factors do not provide a predictable or linear measure of conditions (Ayers, Kennen & Stackelberg, 2001). Soil chemistry can also be highly variable at the submeter scale due to small microtopographic differences. While these physiochemical parameters are fundamental to achieving restoration goals, monitoring them is only valuable when they are 1) measured together, as a suite of parameters; 2) replicated spatially in accordance with background levels of variability; and 3) replicated temporally across important gradients of time (day, tide, season, year).

Hydrology

Tidal inundation, tidal prism, water velocity, and seasonal hydrologic patterns can be monitored to ensure that a site is complying with the regulatory definition for wetland hydrology. Detailed hydrologic studies and/or hydrogeomorphic classification (HGM) are time-consuming and rarely included in long-term monitoring plans. An HGM model was recently completed for multiple sites within the New Jersey Meadowlands (see McBrien, 2003), and it will allow quantification, and thus comparison, of key hydrologic parameters between reference and restored sites. HGM models are developed iteratively (i.e., through repeated processes) with validation from field data and so are better refined and more objective than rapid assessment models. However, they are still based on comparisons with undisturbed reference wetlands, which may be outperformed by urban wetlands in functions such as pollutant retention (due to higher incidence of pollutants in urban areas). Further, although they are highly useful for determining the physical underpinnings of a marsh restoration, HGM models are not particularly useful for assessing the role of the wetland within the larger landscape.

Proposed Metrics of Functional Progress

Extensive research by both the scientific community and government agencies involved in the wetland permitting process has demonstrated that the current system of wetland mitigation and monitoring is failing to accomplish the no-net-loss goals set forth by the Clean Water Act (Race & Fonseca, 1996; NRC, 2001). This failure is due not only to the shortage of disturbed wetland acres being replaced but also to the inadequacies of currently applied monitoring techniques. With these techniques, it’s difficult to identify whether functional success has been achieved at a particular restoration site. It is also difficult to assess how restoration of one parcel influences other parcels within the landscape. Here, we review a number of metrics that have been used in the assessment of wetland functionality in ecosystem or landscape contexts.

Wildlife Assemblage and Abundance

Bird Populations

Siegel et al. (unpublished data) are monitoring avian habitat use at Meadowlands restoration sites both before and after restoration across multiple years and seasons, providing one of the few direct comparisons of wildlife responses to restoration at a landscape scale in the region. The researchers present results of pre- and post-restoration monitoring of avian communities at two tidal marshes in the

Meadowlands, Harrier Meadow and Mill Creek Marsh. Both sites were dominated by *Phragmites australis* at the beginning of the restoration effort. Restoration efforts included creating more open-water areas and upland islands, reducing invasive species, regrading to create new emergent marsh habitat, and increasing connectivity of more diverse habitats. The sites were surveyed for avian usage for at least one year prior to restoration and during a five-year postrestoration monitoring phase (Feltes & Hartman, 2002). By comparing the changes in each of these sites, as well as the differences between them, the monitoring demonstrated a significant increase in avian species richness in habitats that had been restored and presumably a relationship between type of restored habitat and avian guild. These results also indicate a tangible benefit to urban intertidal wetland restoration for avian communities in the Meadowlands.

Fish Populations

While fish productivity is often challenging to quantify, many large restoration projects have used them as indices of landscape function and restoration success. In Delaware Bay, New Jersey, a long-term study of fish response to a 10,000-acre wetland restoration has been ongoing for seven years (Weinstein et al., 2000; Grothues & Able, 2003). In this study, a broad variety of ecological patterns were quantified to demonstrate that multiple trophic levels of fish were able to breed, grow, move, and behave in similar ways in both restored and reference marshes. The researchers' methods included tracking juvenile fish movements and isotopic signatures (of carbon, nitrogen, and sulfur) in fish to determine whether the food chain had been altered by restoration. At four sites in Oregon's Salmon River estuary, researchers assessed the rate and pattern of juvenile chinook salmon (*Oncorhynchus tshawytscha*) by measuring fish density, available prey resources, and diet composition using a chronosequence approach (Gray, Simenstad, Bottom & Cornwell, 2002). Dikes had been removed from three of the sites at different times between 1978 and 1996; the fourth site was an undiked reference site. The study revealed differences in measured factors between the four sites but indicated that early habitat functionality was attained within two to three years after dike removal in the restored estuaries.

Invertebrate Populations

Benthic invertebrate populations are common indicators of water quality and for trajectories of succession (Levin, Talley & Thayer, 1996). The Massachusetts Office of Coastal Zone Management developed a macroinvertebrate index to assess the condition of salt marshes both along a gradient of human disturbance and in response to tide restoration (United States Environmental Protection Agency, 2003). However, as with all animals, invertebrates are controlled by top-down and bottom-up forces (predation pressure and food supply, respectively), and this can obscure population differences during the monitoring phase. In a southern California marsh, for example, Talley and Levin (1999) found greater populations of macroinvertebrates in newly restored marshes, so-called "density overshoots." While invertebrates in isolated wetlands and other enclosed water bodies are easily tracked between years and can give strong evidence of restoration success (Dodson & Lillie, 2001), populations of invertebrates in tidal wetlands are difficult to monitor due to constant resuspension and resettlement of their planktonic larval stages. Given these difficulties in interpreting invertebrate populations, we suggest that agencies focus on the wetland function itself: nursery habitat. Intertidal marshes should function as nursery habitat for soft-sediment invertebrates (as well as fish), and rates of infaunal colonization are a quantitative indicator of habitat selection over the course of succession (Mosemen, Levin, Currin & Forder, in press). Placement of sampling devices for key invertebrates within restored and reference wetlands, while accounting for seasonal variability in their dispersal and growth, allows regulatory agencies to count and compare the frequency of settlement and the relative growth rate for these organisms throughout an estuary. For a more detailed understanding of macroinvertebrate population dynamics, Levin (2004) is performing trace-metal analyses of mussel and clam tissue of invertebrate populations in a southern California estuary to determine connectivity (i.e., how many of the invertebrates are coming from afar as opposed to occurring locally, by self-seeding).

Natural Abundance Stable Isotopes

Analysis of the natural abundance of stable isotopes of carbon, nitrogen, and sulfur in organic matter provides a useful and powerful in situ tracer for wastewater nitrogen (N) as well as for trophic relationships (what is eating what). Since isotopes are atoms with the same number of protons but different number of neutrons, the heavy-to-light-isotope ratio (e.g., ^{15}N: ^{14}N) is generally expressed as the per mil (‰) deviation of that sample from the isotopic composition of a reference compound. For example, the natural abundance of ^{15}N ($\delta^{15}N$) in wastewater is generally high, so the nitrogen signature is considered "heavy." This $\delta^{15}N$ can be compared with other pools of nitrogen, in plants or animals, so that one can determine how much nitrogen nutrition these organisms are getting from wastewater. It is known that biologically mediated nitrogen transformations (e.g., trophic assimilation of N) discriminate slightly against molecules containing the heavy isotope of N; when one considers the reaction rates for the different isotopes, the isotopic signatures can be used to determine such data as the source of nitrogen and/or the trophic level of a consumer.

Comparing Trophic Pathways

University of Rhode Island (URI) researchers (Wozniak, Roman, James-Pirril, Wainright & McKinney, 2003) are using $\delta\ ^{13}C$:$\delta\ ^{15}N$ ratios to track the food source of mummichogs (*Fundulus heteroclitus*) and fiddler crabs (*Uca pugnax*) in restored marshes of different ages (e.g., Sachuest Point, Rhode Island, and Hatches Harbor, Massachusetts) and referencing their findings to an undisturbed marsh (Herring River). Both reflect a *Spartina* species–dominated food chain in the reference marsh. However, in the restored marshes, mummichogs and crabs show little evidence of a *Spartina*-dominated diet. The URI researchers and the Center for Coastal Studies (Provincetown, Massachusetts) are developing a multisite model of isotope data from restorations on the eastern seaboard, for comparison between sites and between years in both the restored and reference sites. This approach would be extremely valuable for almost all Meadowlands restoration sites.

Nitrogen Retention

Cole et al. (2004) have reported on the use of $\delta^{15}N$ signatures in identifying sources of N for macrophytes and algae in salt marshes across the U.S. By tracking tissue concentrations of $\delta\ ^{15}N$ over time and comparing the signatures between wetlands at different successional stages, it is possible to determine the N dynamics of different marshes and infer whether a marsh is functioning as a sink for excess bioavailable N, or as a source through N fixation. For example, Cole et al. (2004) found that both developing and historic marshes in the heavily impacted urban watersheds of San Diego County, California, are important sinks for N.

Plant Assemblage and Biomass

Vegetation monitoring is both a site-specific metric and a landscape-scale metric, in that propagules of plant species are dispersed throughout watersheds by air, water, and animals. However, percentage cover and biomass of a given year are less valuable indicators than changes in species composition or nitrogen concentrations over time. Variation in species presence over time can be a simple but useful indicator of ecosystem function, with systematic loss or decline suggesting environmental stress (Zedler, 2001). This is especially true for perennial species, which are the dominant plants in salt marshes.

Vegetation percentage cover is important in terms of determining any glaring soil-related problems limiting plant survival. However, since most relatively successful restorations quickly achieve vegetation coverage, subsequent assessment is more likely to focus on biomass or plant height. One study measured macrophyte biomass and tissue concentrations for three years at 12 Chesapeake Bay tidal marshes varying in postrestoration age between 0 and 17 years (Whigham, Pittek, Hofmockel, Jordan & Pepin, 2002). They found that biomass was highly variable year to year and a poor indicator of marsh restoration over time. By contrast, they found that nitrogen concentration in plant tissue (N retention) was quick to recover, and it was a more stable, consistent indicator of recovery. Zedler (2001) has demonstrated that the accumulation of nitrogen into biomass of newly established tidal wetlands is intimately tied to ecosystem development. Monitoring nitrogen and other nutrients in plant tissue may therefore be a useful metric of wetland recovery following restoration (Whigham et al., 2002).

Soil Parameters

Soil development in wetlands is both autochonous (e.g., organic production) and allochthonous (e.g., sedimentation). Thus, soil metrics are valuable both for determining site-specific production and landscape-scale retention of sediment, including nutrients and pollutants. Finally, soil microbes are at the core of wetland biogeochemical functions, and their activities can be monitored through a variety of new techniques.

Soil Organic Matter Accumulation and Quality

Whereas macrophytic vegetation may reestablish in restored wetlands within 2 to 5 years, nitrogen and carbon pools in soil organic matter may take more than 25 years to approach natural marsh conditions (Broome & Craft, 1998; Craft et al., 1999; NRC, 2001), even with organic amendments. Craft et al. (2003) conducted a detailed analysis of ecological attributes in restored North Carolina marshes and compared the results to adjacent reference sites. Based on a comparison of measured parameters (e.g., soil carbon and nitrogen pools; C:N ratios; benthic invertebrate, algal, and diatom communities; and vegetation), they identified soil organic carbon as an ideal indicator of salt marsh development. Soil organic carbon—also called soil organic matter

(SOM)—was singled out in this study because it correlated well with other measured parameters, and it is predictable, easy to use, and inexpensive (Craft et al., 2003). Overall, soil organic matter is both a cause and result of proper tidal marsh functioning and thus should be considered the key factor for demonstrating ecosystem functionality.

Since it may take 25-plus years for a restored site to reach reference conditions for SOM, we propose modeling a trajectory by which to assess rates of change. This trajectory design should be based on data from analogous, but older, restoration sites (e.g., Eastern Brackish Marsh). For forested wetland restoration, researchers combined soil data from multiple references and restored sites to create a Soil Perturbation Index (SPI), basically a measure of how different the reference soils were from restored soils of various ages (Maul, Holland, Mikell & Cooper, 1999). Using composite data for soil organic matter, total nitrogen, and total phosphorus concentrations, they compared data from restoration sites with the index to estimate progress in soil development.

Sedimentation Rates

Sediment deposition is commonly measured by gauging sediment accumulation upon a feldspar marker horizon (http://www.pwrc.usgs.gov/set/installation/markers.html; Zedler, 2001). Measurement of rates of sediment deposition can be performed simply with a knife and a ruler if 1) the sediments are firm, 2) the surface is free of standing water, and 3) the marker horizon is not deeper than the knife is long. The simplest technique consists of placing a layer of feldspar approximately 0.25 inches in depth in a small plot (~1 m^2) on the sediment surface and returning at various sampling intervals to cut a four-sided plug of sediment; the average depth of sediment on all four sides of the plug will indicate an average sediment accumulation rate in the plot.

Horizon markers indicate rates of marsh buildup and provide the ability to sample the quantity and quality of sediment inputs to the system by keeping them physically separate from the underlying soils. Given the historic problems of remobilization of sediments from multiple development and restoration projects in the Meadowlands, we propose that restorations be required to place a marker horizon within small plots in order to track accumulation over time, thus providing a point from which to measure adverse effects.

Microbial Community

Microbial community metabolism, measured as the diurnal fluxes of dissolved oxygen in surface water, is expected to increase over time as a restored wetland develops from a net heterotrophic system to a net autotrophic system (Cronk & Mitsch, 1994). Four years of succession in a restored wetland in Montezuma National Wildlife Refuge, New York, was not sufficient for McKenna (2003) to detect this shift. Following concepts from del Giorgio and Cole (1998), del Giorgio and Newell (Marsh Ecology Research Program, unpublished; R.I. Newell, personal communication) have proposed bacterial growth efficiency (BGE) as a consistent and sensitive indicator of SOM quantity and quality in salt marshes. Another functional approach to biogeochemical processes is through analysis of microbial biochemical products. Specific microbial populations and activities can be assessed with fatty-acid analysis for functional group identification (Ravit, Ehrenfeld & Häggblom, 2003) or enzyme analysis for estimating microbial activity (Prenger & Debusk, 2003). While microbial processes may be highly variable in space and time, they may prove a valuable metric when used for detection of specific wetland functions (e.g., denitrification, sulfate reduction) in a comparative framework between restored and reference sites.

Analysis of Metrics

In Table 1, we review all metrics with the considerations listed earlier. We find that while no metric in and of itself satisfies all monitoring needs, six metrics are relatively inexpensive and together satisfy the needs of measuring at the ecosystem and landscape scales. Basic vegetation indices, coupled with measurement of surface SOM and sedimentation rates, provide quantitative values of key autochthonous and allochthonous processes. In addition, measuring invertebrate colonization and analyzing stable isotopes of key organisms and plants, though time consuming, directly targets processes of habitat production, energy transfer, and nitrogen retention. These alternative metrics, used by other researchers and reported here, are perhaps the most useful new techniques for researchers and regulatory agencies looking to establish relationships between restoration sites and the larger estuarine system.

Of all the metrics reviewed, SOM accumulation is probably the most consistent and meaningful metric of ecosystem function. Intra-annual variability of this metric is minimal, and since SOM is strictly cumulative (unlike, say, the biomass of aboveground vegetation), it generally increases with time. For landscape function, only metrics of mobile elements within the estuary—organisms, isotopes, and sediment particulates—are useful for tracking the interaction between restoration sites and the larger estuarine system. Finally, though no one metric can achieve all monitoring goals, each of the metrics has some inherent value. This is especially true when the goals are specific to a given restoration project, e.g., creating habitat for an endangered species.

Conclusions

Landscape- and ecosystem-scale metrics are important means of assessing urban restoration success in the Hackensack Meadowlands of New Jersey. This is because, as in most urbanized wetland systems, the wetlands there are largely surrounded by human-altered land and affected by human land use, and because restored Meadowland wetlands are potentially isolated from more natural wetland reference areas. Moreover, wetland restoration techniques in general can be improved by knowledge of how restored wetlands contribute to the larger estuarine system.

We suggest that, where possible, simple metrics of ecosystem function (SOM, sedimentation rates) and of landscape connectivity ($\delta^{15}N$ in plant tissues, benthic colonization) be incorporated into annual monitoring plans. We also suggest that landscape-scale monitoring data be incorporated into site-specific assessments. For example, water-quality monitoring in the Meadowlands is relatively extensive; regulators have had to respond to severe pollution distress from immense landfills and unregulated solid-waste dumping, wastewater discharges, sewer discharges from two counties, and haphazard filling for development (Thiesing & Hargrove, 1996). Leveraging data from larger-scale monitoring projects such as this can improve the utility and predictive capacity of monitoring efforts (Holl, Crone & Schultz, 2004).

Acknowledgments

The authors wish to explicitly thank both the editors and reviewers of this manuscript for suggestions that greatly improved its utility. We also thank our colleagues who provided unpublished or gray data and/or graphics for our review of possible alternative metrics, especially Andrew Wozniak and his colleagues (University of Rhode Island) and Marlene Cole (Save the Bay).

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Glossary

Allochthonous: Of or relating to nonindigenous material (e.g., sediment deposits in a river). Opposite of autochthonous (see below).

Autochthonous: Of or relating to material that originated in its present position (e.g., from the decomposition of plants). Opposite of allochthonous (see above).

Autotrophic: Of or relating to autotrophs, organisms capable of synthesizing their own food from inorganic substances using light or chemical energy (e.g., green plants, algae, and certain bacteria).

Bacterial growth efficiency (BGE): The fraction of organic carbon consumed by bacteria that is incorporated into biomass.

Benthic: Of or related to organisms (e.g., protozoa, nematodes) living on the sediment surface under a water column, such as sea or lake bottoms.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA): Enacted in 1980, this law (also known as Superfund) created a tax on the chemical and petroleum industries and provided broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. (Source: www.epa.gov.)

Chronosequence approach: A "space-for-time" substitution used to examine long-term trends in which systems of different ages are compared to determine the trajectory of a metric, instead of monitoring a single system over time.

Combined sewer overflow: The discharge into waterways during rainstorms of untreated sewage and other pollutants via combined sewers carrying both sanitary sewage and storm-water runoff from streets, parking lots, and rooftops.

Dredge spoils: The sediment removed from beneath a body of water during dredging.

Habitat Evaluation Procedure (HEP): A technique developed by the U.S. Fish and Wildlife Service for evaluating and predicting the suitability of changing habitats for species and communities based on ecological principles.

Heterotrophic: Of or relating to heterotrophs, organisms that cannot synthesize their own food and are dependent on complex organic substances for nutrition (e.g., fish, humans).

Horizon markers: Visually distinct substances (such as feldspar) laid down on surfaces of aquatic study areas to measure the vertical accumulation (buildup) of sediment.

Infaunal: Of or relating to infauna, benthic organisms (see above) that dig into the sediment bed or construct tubes or burrows.

Isotopes: Various forms of a chemical element (e.g., carbon) that have different numbers of neutrons and therefore different atomic mass.

Isotopic signatures: Ratios of certain isotopes (see above) that accumulate in organisms and can be used by researchers to profile food webs.

Macroinvertebrate: An animal, such as an insect or mollusk, that lacks a backbone or spinal column and can be seen by the naked eye.

Macrophyte: Water-loving vascular plants (grasses, rushes, shrubs, etc.).

Metapopulation: A group of populations of the same species that exist at the same time but in different places.

Metric: A standard of measurement for estimating or indicating a specific characteristic or process.

Mutualistic: Of or pertaining to mutualism, an interaction between two species that is beneficial to both.

Nitrogen fixation: The transformation of gaseous nitrogen into nitrogenous compounds (e.g., ammonia), usually by way of nitrogen-fixing soil and/or aquatic bacteria.

Planktonic: Of or relating to plankton—tiny aquatic organisms that drift with water movements, generally having no locomotive organs.

Primary production: The rate at which biomass is produced by photosynthetic or chemosynthetic organisms.

Propagule: Any structure that functions in plant propagation or dispersal (e.g., a spore or seed).

Resource Conservation and Recovery Act (RCRA): Enacted in 1976, RCRA (often pronounced "rick-rah") gave the U.S. Environmental Protection Agency control over the generation, transportation, treatment, storage, and disposal of hazardous waste.

Sink: A natural reservoir that can receive energy, species, or materials without undergoing change. Opposite of "source" (see below).

Source: A natural net exporter of energy, species, or materials (see above).

Stable isotope: Any naturally occurring, nondecaying isotope (see above) of an element. Many elements have several stable isotopes. For example, carbon (C) has carbon 12 (^{12}C) and carbon 13 (^{13}C).

Succession: The sequential change in vegetation and the animals associated with it, either in response to an environmental change or induced by the intrinsic properties of the organisms themselves.

Tidal prism: Volume of water that is drawn into a bay or estuary from the ocean during flood tide (i.e., a rising tide).

Trophic: Of or relating to feeding habits or the food relationship between different organisms in a food chain. Organisms can be divided into different trophic levels such as herbivores and predators.

Wetland Evaluation Technique (WET): A water-quality and watershed analytical model developed for the Federal Highway Administration for conducting assessment of wetland functions and values.

Table 1.

	Low spatial and temporal variability	Relative annual cost (ease of use)	Number of annual samples suggested	Indicates landscape connectivity	Indicates ecosystem function
Vegetation cover/composition	Yes	$	3	No	No
Wildlife species composition	No	$$	2	Maybe	Maybe
Water and soil chemistry	No	$$	>30	No	No
Hydrology	No	$$	>30	No	No
Bird population dynamics	No	$$$	2	Yes	Yes
Fish population dynamics	No	$$$	2	Yes	Yes
Invertebrate colonization	No	$$	2	Yes	Yes
Trophic pathways	Yes	$$	1	Yes	Yes
Nitrogen retention	Yes	$$	1	Yes	Yes
Soil organic matter (SOM)	Yes	$	1	No	Yes
Sedimentation rates	Yes	$	1	Yes	Yes
Microbial community	No	$$$$	3	No	Yes

$ 0–$1,000 per year (nearly free, can be performed by volunteers)
$$ $1–10,000 per year (low cost, can be performed by general scientist)
$$$ $10–100,000 per year (high cost, must be performed by wetland scientist)
$$$$ >$100,000 per year (prohibitively expensive, performed by specialist)

Table 1. Overview and comparison of both currently used and alternative metrics.