Promoting Successful Restoration through Effective Monitoring in the Chesapeake Bay Watershed

Prepared for the National Fish and Wildlife Foundation
Washington, DC

TIDAL WETLANDS

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FINAL
July 1, 2011

Introduction and Acknowledgements

The National Fish and Wildlife Foundation (NFWF) funds a variety of projects aimed at achieving restoration goals for the Chesapeake Bay and watershed. In order to use their restoration funds most cost-effectively, NFWF seeks scientifically-based criteria for identifying projects with the highest potential for success and monitoring successful outcomes. This chapter is one of many being developed to generate monitoring metrics for restoration and management projects that include: 1) tidal wetlands; 2) non---tidal wetlands; 3) streams; 4) “green” stormwater management (under the direction of Allen Davis, UMCP); 5) agricultural and forest management (under the direction of Brian Benham and Gene Yagow, VA Tech); and 6) stewardship and social marketing (under the direction of Gene Yagow and Erin Ling, VA Tech).

Web-based reviews were conducted to seek expert feedback on the literature review, metrics and recommendations provided in this report. We are grateful to the experts who were generous with their time in the review process: David Burdick (Univ. of New Hampshire), Christopher Craft (Indiana Univ.), Keryn Gedan (SERC), Tom Jordan (SERC), Evamaria Koch (UMCES – Horn Point Lab), Terry McTigue (NOAA), J. Court Stevenson (UMCES – Horn Point Lab). We thank Mandy Chesnutt (NFWF), Ben Hillier (Chesapeake Research Consortium, Inc.) and the University of Maryland Center for Environmental Science for their assistance in arranging the web-based reviews.

Tidal Wetlands – Implementation Verification, Monitoring, and Adaptive Management

This document is intended to guide selection of metrics for verifying implementation of tidal wetland restoration and for monitoring site development and ecological outcomes within a monitoring program being developed by the National Fish and Wildlife Foundation (NFWF). The goals of the monitoring program are to demonstrate the potential benefits of restoration, promote adaptive management, and enhance understanding of effective restoration techniques. Metrics have been selected on the basis of a literature review that identified which metrics had evidence that they captured meaningful ecological or environmental outcomes and expert guidance. A *meaningful* outcome was defined as the restoration of desirable ecosystem processes and functions (e.g., nutrient cycling or sediment accretion) which are considered some of the best indicators of a system's ability to produce a stream of beneficial outcomes (e.g., enhanced fish habitat, water quality improvements) and to sustain them into the future.

The metrics require a range of measurement approaches from the simple to the specialized. Therefore, it is not expected that all restoration projects would implement the full range of metrics. Rather, the selected metrics are meant for use by both community organizations and professionals.

This report is organized as follows:

1. Discussion of links between metric selection and project goals
2. Description of implementation verification metrics
3. Description of classes of monitoring metrics used to support functional outcomes and goals
4. Tables with suggested monitoring metrics and a prioritized list
   Table 4. Tidal Wetland Monitoring Metrics
   Table 5. Prioritized Sets of Recommended Metrics
5. Appendix A: Scientific support for monitoring metrics

Project Types

The monitoring metrics described here are generally appropriate for evaluating restoration of a range of sub-tidal and intertidal systems with varying salinities (salt marsh, brackish marsh, and freshwater tidal wetland). The primary focus of NFWF funding is active restoration of upland and emergent vegetation, with submerged aquatic vegetation considered as a desirable indirect outcome. Specific project types include:

<u>Living Shorelines</u> - Restoration, protection and enhancement of the natural shoreline using soft or non-structural stabilization techniques such as vegetative plantings and sand fill, or 'hybrid' techniques that combine vegetative planting with low rock sills and sometimes oyster reefs (adapted from NOAA 2006).

<u>Tidal marsh restoration</u> - Restoration of hydrologic processes (e.g., through removal of obstructions or drainage devices) and/or revegetation of existing wetland habitat, usually through plantings of grasses or shrubs.

<u>Tidal marsh enhancement</u> - Enhance habitat through removal of debris, fill materials (e.g., silt) and invasive species.

Metric Selection to Support Project Goals

Choosing and interpreting an appropriate set of monitoring metrics will depend on project goals. Tidal wetland and living shoreline restoration projects often have multiple goals, but primary goals often include preventing shoreline erosion and providing habitat benefits for wetland-dependent species or species that require the beach (e.g., terrapin turtles), mudflats, and/or the nearshore shallow water environment (including commercial and recreational fisheries). Other goals may include improving regional water quality, improving aesthetics, and enhancing access for recreational use. To promote these goals, practices need to restore numerous environmental processes that include: wave or storm surge attenuation, nutrient and sediment retention, and the specific habitat functions necessary to support nekton (fish and macro-crustaceans), birds, herpetofauna, and small mammals.

Often, restoration success towards multiple goals is judged in terms of whether the project achieves, "… *a self-sustaining habitat that in time can come to closely resemble a natural condition in terms of structure and function.*" (Turner and Streever 2002, as cited in Thayer et al. 2003). However, the landscape context of a tidal wetland or living shoreline can limit what is possible to achieve at a given location and projects may, therefore, need to balance goals with site constraints. In some cases, sites may be designed to fulfill a narrower set of goals, such as nutrient, sediment, and carbon sequestration, in a location where full restoration of natural dynamics and habitat is not possible. These sites can still be considered successful for a narrow set of goals.

Another consideration when setting restoration goals is that goals can conflict with one another and in such cases, metric selection and interpretation will need to be adjusted to reflect priorities. For example, shoreline restoration projects can have difficulty simultaneously maximizing both erosion control and habitat objectives because habitat may be best served by restoration approaches that allow for some risk of shoreline erosion. To manage this conflict, restoration practitioners have increasingly moved to *hybrid* restoration approaches that combine structural elements such as breakwaters, which aim to reduce erosion, with vegetation planting and soft shorelines to support habitat. The need for structural components to stabilize a tidal wetland or shoreline restoration is largely determined by the wave energy at the site and can be estimated based on sediment characteristics or size and depth of the adjacent water body and boat activity (e.g., MDNR 2005). Structural elements can limit the ability to restore some natural dynamics, therefore functions may need to be traded off in order to achieve the primary project goal. These tradeoffs will be reflected in the selection and interpretation of monitoring metrics.

The literature review was used to link metrics to the functional outputs that they measure (Table 1) in order to promote selection of metrics that match general goals such as habitat for characteristic species assemblages. We selected three general functional goals to represent NFWF's priorities for tidal wetlands: 1. Nutrient and sediment retention and removal; 2. Shoreline protection; 3. Vital habitat for characteristic species assemblages . However, for more specific goals, such as restoration of habitat for a specific species, the project design and monitoring metrics will need to be tailored to those specific outcomes, usually with the help of subject area experts. In addition, metrics may be excluded if the project could not reasonably be expected to change that condition. For example, if plantings are the focus of the restoration, then tidal regime is not likely to change as a result of the project activities.

Because system processes interact in complex ways, a suite of monitoring metrics, used together, is often the best approach for understanding progress towards goals and to evaluate any tradeoffs between goals.

Table 1. Selected Monitoring Metrics and Correspondence to Project Goals (based on literature)

Category	Metric	Nutrient & sediment retention / removal	Shoreline protection	Vital Habitat
Hydrologic	Tidal regime (range, inundation duration, velocity)	X		X
	Hydrologic connectivity	X		X
Geomorphic	Elevation	X	X	X
	Slope		X	X
	Topographic complexity	X	X	X
	Area (by physical zone), Edge complexity	X		X
	Sedimentation rates	X	X	X
Biota	Vegetation cover & density	X	X	X
	Canopy complexity			X
	Vegetation species richness			X
	Invasive plant species cover	X		X
	Invertebrate assessments			X
	Species use (fauna)			X
	Breeding success			X
Physico-Chemical	Pore water salinity and pH			X
	Surface water quality (T, DO, chla, TSS, N, P, contaminants)	X		X
	Denitrification potential	X (N only)		
	Soil properties (Grain size, OM, BD)	X	X	X
	Nutrient retention / removal	X		

Implementation Verification Metrics

The purpose of implementation verification metrics is to confirm that the proposed project was executed according to planned design and such metrics are typically included as part of an engineering contract. Verification metrics will vary by type of project and may include both structural and non-structural elements (Table 2). Verification will generally involve comparing design drawings to field implementation and a checklist may be created, specific to the project design, to ensure all key design elements have been followed. Any purposeful deviations from designs should be explained and justified prior to verification of implementation.

Table 2. Implementation Verification Metrics for Tidal Wetlands

Metric Category	Metric	Description
Structural	Built features (during construction)	Sills, groins, breakwaters, or other built elements have photos or site inspections to document that design elements were followed by contractors (e.g., appropriate depth was excavated, filter cloth was installed)
	Built features (post-construction)	Built elements match design in extent, placement, and type of material
	Topography	Site slope matches design
	Natural structures	Oyster reefs, coir logs, or other natural structural elements meet all design specifications
Non-Structural	Vegetative plantings	Verify that specified planting was conducted through photo documentation or on-site inspection
	Area of vegetated and non-vegetated areas	Measure/estimate area of all marsh zones including non-vegetated areas such as mudflats and beaches. Use of GIS, Google maps or other appropriate software is desirable for documenting vegetation cover and the locations of all project elements.

Monitoring metrics

The purpose of monitoring metrics is, primarily, to evaluate whether the biophysical functions of the site have been restored and to suggest when adaptive management is needed to realize a project's full potential. Adaptive management may include enhancing site maintenance, repeating some restoration activities (e.g., replanting vegetation), or modifying design elements (e.g., site topography, plant species). (See Broome and Craft 2009 for discussion of adaptive management approaches.) The metrics were developed with the assumption that sites have been pre-screened to promote successful restoration. The importance of appropriate site selection for ensuring project success cannot be overemphasized, since site constraints (Table 3) will largely drive what is possible to achieve in a given project and landscape condition. For example, connections to aquatic ecosystems will affect whether some types of biota are able to make use of the site.

The guidance provided here is intended to be the basis of a more detailed sampling design that specifies appropriate analytical techniques, frequency and areal extent of monitoring. The ability to demonstrate statistically significant results requires that data collection follows appropriate techniques such as collecting replicated random samples. Such detailed plans should be developed through consultation with local professionals who can adapt these recommendations to project goals, site conditions and resource availability.

The monitoring metrics are intended to be used both before and after project implementation and may supplement data used to pre-screen locations. **Reference sites are needed** to be able to establish whether measured values for a site exhibit the characteristic spatial and temporal variability necessary to produce desired outcomes (White and Walker 1997). Further, reference sites provide a means to distinguish short-term fluctuations in environmental condition (e.g., drought, storms) from restoration effects and to generate metric expectations under long-term or regional drivers of change, such as sea level rise. Ideally, reference sites will be monitored simultaneously with project sites to provide the best opportunities to evaluate project success. However, if resources are not available to sample reference sites, it may be possible to use regional databases to evaluate monitoring results. For example, the NERR system is establishing reference sites for regional use. More information about selecting reference sites and using regional databases can be found in Merkey (2005).

Table 3. Restoration Site Constraints and Opportunities for Tidal Wetlands

Disturbance level in near-shore zone	*Potentially unsuitable locations include those with: structures in the water (causeways), heavy boat traffic, local sources of pollution (sewage outflows), intensive development, agriculture, clear-cutting, or mining activities.*
Tidal control structures	*Reversible hydrological modifications create suitable opportunities for restoration. In particular, opportunities to restore hydrologic connectivity between marsh and open water and to promote water flow over the whole marsh (rather than just through culverts) promotes nutrient and sediment trapping.*
Invasive species	*Risks from invasive species vary by restoration goal. Phragmites can limit restorability of diverse plant and bird communities but appears to have neutral or positive effects on water quality and nekton usage; risk may be managed through hydrological controls. Nutria may limit project success due to high herbivory (check with Maryland Dept. of Natural Resources or other agency for areal distribution).*
Fetch / sediment type	*Low energy environments (marked by minimal fetch and fine grained sediment) are generally more suitable for natural tidal restoration, but design modifications can extend the range of suitable exposure conditions.*
Sensitive elements (in the direction of sediment drift)	*Downstream beaches, sand bars, and SAV beds may be harmed by erosion control projects.*

A secondary purpose of collecting monitoring data across sites is to develop standardized data sets that can be used to track cumulative restoration progress over time, learn from problems encountered, and test hypotheses regarding which aspects of location, design, and approach contribute to restoration success. To promote this goal, **basic project implementation information should be recorded to assist comparisons** such as condition prior to restoration and restoration actions taken. Relevant information includes: latitude and longitude, elevation, maximum water depth within footprint, upslope and adjacent land uses, historic use of site (e.g., if it has been farmed, used as a boat launch, etc.), presence of tidal restrictions, current deviations from natural conditions (fill, structures, drainage devices, non-native invasive plant cover) and other relevant characteristics.

The recommended monitoring metrics for tidal wetlands are shown in Table 4 and are broken down into three categories: Hydrology and Geomorphic, Biota, and Physico-Chemical, which require different monitoring approaches. The selected metrics were considered the most promising because the current literature (or, in a few cases, well-accepted ecological theory) suggests that they are either *valid proxies for* or *direct measurements of* functional outcomes. Metrics are either structural, meaning that they quantify spatial conditions and patterns, or functional, meaning that they quantify dynamic processes. An easy way to distinguish the two is that structural metrics can be meaningfully evaluated at a point in time (e.g., the number of native plant species per unit area), while functional metrics require multiple measurements over time to generate meaningful measures and thus have *rate* units (e.g., oxygen consumption per unit area per unit time). Functional metrics ensure that fluxes and dynamics that influence various life stages of biota are evaluated in relation to changing hydrologic conditions within a wetland. Most of the metrics in Table 4 are structural proxies for functions, however, tidal regime, sediment accretion, and denitrification potential are direct functional measures.

The table provides a brief description of the metrics, recommendations for measurement techniques and some information about metric interpretation and use in adaptive management. These metrics are intended to be measured in each of the representative marsh habitats or zones using transects or stratified sampling of the entire project. For all metrics except the hydrologic, replicate samples within each zone will be needed to conduct statistical analyses of change and to compare the restoration site to reference conditions. Sources of guidance for sampling techniques and measurement protocols are listed in the table,but project teams should consider **matching sampling protocols to existing monitoring sites** (e.g., at national refuge sites), if those sites will be used as reference sites.

Hydrologic and Geomorphic Metrics

For wetlands, restoring characteristic hydrologic variability (timing, magnitude and duration of wet and dry cycles) is generally considered the most important condition for success of all other processes and endpoints (Mitsch and Gosselink 1993, Zedler 2000). For example, a review of salt marsh restoration found that rapid recovery of vegetation was associated with “lower elevations, greater hydroperiods, and higher soil water tables” (Warren et al. 2002). In addition, recolonization of vegetation and *nekton* (fish and macro-crustaceans) can occur quickly (< 1 year) following hydrologic reconnection between adjacent habitats (Neff 2002, Roman et al. 1984). Therefore, establishing appropriate tidal regime, surface flow over marsh (vs. in culverts), and connectivity to open water is a path to restoring multiple functions. **The hydrologic metrics are considered the most critical indicators of project success since they are the best leading indicators that the site will regain all or part of natural functioning (Table 4).**

Biota

Monitoring the restoration of biotic functions typically relies heavily on vegetation metrics since they are relatively easy to measure and serve as indicators of multiple functional qualities. Establishment of characteristic vegetation can suggest whether a marsh is likely to provide refuge and food or to mediate many physical and chemical conditions necessary to provide habitat (Table 4). However, vegetation metrics can be difficult to interpret early in a restoration trajectory since plant cover is known to exhibit high variability in young marshes and initial vigor of vegetation can be followed by later decline (Craft et al. 2003, Garbutt and Wolters 2008, Matthews et al. 2009). Nonetheless, vegetation cover, diversity and structural complexity can all suggest future outcomes for a variety of functions and therefore are an important and cost-effective component of monitoring.

Although, much more difficult to measure, direct measurements of animal use is more satisfying for determining whether habitat goals have been achieved. Ideally, animal use metrics (Table 4) will do more than show that species have visited the site and, instead, demonstrate that a site is enhancing the vigor or enlarging the population of a target species. For this reason, we differentiate between metrics that support habitat and those that provide population support. However, usage by animals is extremely difficult to apply to adaptive management, since many species will respond to landscape conditions that are beyond the scope of any given restoration project. Therefore, restoring *potential* habitat function, as measured by structural proxies, may be all that can be demonstrated in the short-term. Multiple types of bioassessments are suggested in Table 4, but, at the most basic level, collecting species lists will provide useful data for calculating a variety of metrics for understanding site restoration trajectories.

Physico-Chemical

The condition of soils and surface or pore water in tidal areas will reflect site hydrodynamics, history and regional stressors. Therefore, these metrics are leading indicators of future success and are helpful for use in adaptive management, such as understanding why plants may not be thriving (Table 4). Many metrics in this category, particularly water quality metrics within open surface waters, may not be responsive to restoration practices. However, monitoring of pore water and surface water that has limited tidal connectivity is important for understanding whether processes that support multiple desirable outcomes have been restored including: tidal regime, nutrient cycling, water infiltration and aquatic habitat.

Table 4. Tidal Wetlands Monitoring Metrics

Category	Metric	Measured variables	Timing and Frequency	Area	Main functions or processes supported	Performance Measures	Adaptive Management
Hydrologic	Tidal regime	Tidal range	Soon after project installation and annually or as needed to inform adaptive management; Continuously for 2 weeks during a period that includes a neap and spring tide	Representative marsh zones	- Nutrient cycling / denitrification - Erosion control and sediment retention - Habitat - Nekton, Reptiles, Birds - Food web support	-Tidal range matches reference conditions -No routine overtopping of breakwaters or sills (overtopping is expected during storms)	Consider whether channel widening is needed to enhance connectivity
		Inundation duration	Soon after project installation and annually or as needed; Continuous (or high-frequency) monitoring over representative months in all seasons	Representative marsh zones		Inundation duration matches reference conditions	Consider whether channel widening or other modification is needed to restore appropriate range
		Maximum surface flow velocity	Soon after project installation; Midway between high and low tides as tide velocity approches its maximum on a flood tide; compare multiple tidal cycles when winds are not significant	At a minimum - measure the downstream entrance to the channel; Multiple points along channel or across marsh channels may be needed	- Habitat (fish may not migrate out if velocity is too high) - Shoreline protection	- Currents should be below 0.5 m/sec to allow fish passage (Eberhardt et al. 2010).	Consider whether channel widening is needed to reduce velocities
	Hydrologic connectivity	Number and width of open channels connecting to surface water bodies; Extent of surface flow over marsh	Soon after project installation at seasonally low tide and annually or as needed; measure over 1-2 full tidal cycles	Comprehensive assessment of project edges	- Habitat - Nekton (by providing passageways between feeding/refuge areas and waterbodies) - Nutrient cycling - Sediment trapping	- Connectivity is maintained through time but may vary over tidal cycles - Extent of sheet flow fulfills design specifications	- Channel or structural changes may be needed to enhance connectivity (e.g., channel dredging or widening)

Geomorphic	Elevation maintenance	Marsh level wrt sea level through time (ideally measured with established control points or benchmarks)	Measured >1 year post planting and annually thereafter	Representative marsh zones	- Nutrient cycling / denitrification - Erosion control and sediment retention - Habitat - Food web support	-Stable elevation within all marsh zones; or matches reference site -Elevations that are higher in tidal spectrum will be more resilient	Additional fill material or physical structures to retain sediment may be needed if marsh elevation is declining
	Slope maintenance	Slope (depth profile) on seaward side of marsh	Measured >1 year post planting and annually thereafter	Transect(s) perpendicular to shoreline, from foot of escarpment (if present) to a seaward point beyond project footprint	- Erosion control and sediment retention - Habitat - Food web support	-Stable slope through time that matches design specifications or reference conditions; variability in slopes is expected -Gentle slopes (1-3%) within the intertidal zone support a greater area for intertidal marsh vegetation, but steeper slopes can enhance wave dampening. Design should be appropriate for setting. -No bank erosion at base -Amount of erosion/deposition is appropriate to local conditions and distributed across slope profile	Substantial erosion suggests the need for improved physical structure; substantial movement of groin structures suggests the need for maintenance or redesign
	Topographic complexity	Surface roughness at	Measured >1 year post planting and	Representative marsh zones	- Nutrient cycling and denitrification	Variability matches reference conditions	- Additional structures or

	(Fine-medium scale spatial variation in elevation and physical patches)	fine scales; Spatial interspersion of microhabitats at medium scales (e.g., hummocks or mounds, pools, swales, snags)	annually thereafter	from subtidal to upland.	- Habitat - Food web support - Water storage	and is maintained or increases through time	plantings may be needed to promote variability
	Area of wetland physical zones: beach, mud flat & marsh zones including SAV beds (as appropriate)	Total and % Area; (Edge complexity - only if aerial images or GIS data are available)	Measured >1 year post planting and annually thereafter	All zones	- Habitat - Food web support - Erosion control and sediment retention - Nutrient cycling	- Stable area over time - Proportions of physical zones similar to reference site - Edge complexity matches or approaches reference conditions	- Changes in structures, sediment elevation or additional plantings may be needed to alter proportions of physical zones or promote edge complexity
	Sediment Accretion	Depth of sediment or material deposited over time (e.g., using feldspar markers).	For feldspar markers - Spread material after project completion and measure annually; For SET may need to wait several years for reliable measurements and frequency of measurement may be on the order of every 5 years	Replicate samples within representative marsh zones; SET -need at least 3 for good information and replicates within zones of large projects	- Erosion control and sediment retention (but not net erosion or elevation considering all factors such as subsidence)	Sediment accretion in the range of 0.2 - 1 cm per year in mid and upper marsh	- Exposed roots can suggest sediment dynamics are affecting plant viability indicating the need for enhancing sediment sources or reducing wave energy - Excessive wind-borne sediments may be controlled with sand fences and establishing upland vegetation - %OM and bulk density (described below) may be used to separate accretion of mineral sediments

							from undecomposed organic matter to better understand accretion.
Biota	Vegetative cover & density	- Abundance of plants over a defined area measured as stem density - Vegetated marsh width - perpendicular to shoreline (if not measured under area) - % Bare ground	> 1 year post-restoration at peak vegetation, annually to assess persistence through time	Replicate samples within representative marsh zones or entire site, if small	- Nutrient cycling / denitrification - Erosion control and sediment retention - Water retention and infiltration (high marsh) - Habitat - Food web support	- % cover matches reference conditions and interannual variability is decreasing over time - % bare ground decreases through time (in areas that are intended to be vegetated)	- Physical factors, such as elevation, salinity, pH, grain size, %OM, should be checked before replanting; species should be matched to salinity - SAV may not be supported by all salinity regimes - High levels of wrack may explain some vegetation loss - Herbicide control of invasive non-natives may be appropriate, depending on goals and landscape setting - If herbivory is extreme, control of herbivores with fencing, hunting or trapping may be appropriate
	Canopy complexity	Structural complexity of the vegetation layers, including variations in form, height and age	> 1 year post-restoration at peak vegetation, annually to assess persistence through time	Replicate samples within representative marsh zones or entire site, if small	- Habitat - Birds	- Complexity matches habitat requirements of target species, or - Complexity is similar to reference conditions or is increasing through time	- Targeting plantings of species with alternative growth forms may be appropriate
	Vegetation	-Number of	> 1 year post-	Replicate	- Habitat	- Richness,	- Physical factors,

	species richness / community composition	plant species (weighted by abundance) - List of species, labeled by preferred salinity regime (fresh, brackish, salt) and coefficient of conservation (rare, tolerant, etc.)	restoration at peak vegetation, annually to assess persistence through time	samples within representative marsh zones or entire site, if small; quadrats along transects; fixed quadrats/sites	- Food web support	abundance, presence approaches reference conditions	such as elevation, salinity, pH, grain size, %OM, should be checked before replanting; species should be matched to salinity - Herbicide control of invasive non-natives may be appropriate, depending on goals and landscape setting - Species may be selected by their ability to resist sea level rise; in some high energy settings, high marsh species may persist longer than low marsh species; in other settings, low marsh vegetation can facilitate higher accretion rates
	% Non-native plant species	Relative abundance of non-native species relative to native (e.g., % cover)	> 1 year post-restoration at peak vegetation; annually to assess persistence through time	Replicate samples within representative marsh zones or entire site, if small	- Nutrient cycling / denitrification - Erosion control / sediment stabilization - Habitat - Food web support	Depends on goals: - Non-native species may be effective at intercepting nutrients and controlling erosion: high % non-native is acceptable - Non-native species may prevent the establishment of habitat for some species and alter food webs: low % non-natives is desirable	-Tidal regime can be a factor in controlling invasives; Phragmites may be promoted by short inundation duration - Herbicide control of non-native invasive species may be warranted, depending on goals and landscape setting

	Invertebrate bioassessments	- Diversity - Abundance - Species list (may be used to construct IBI) - % area covered by reef builders (oysters, clams and worms)	Every few years in late winter or early spring (by summer many organisms will have been eaten)	Replicate samples within representative marsh zones or entire site, if small	- Habitat - Food web support	-Approaching reference conditions -Increasing number of filter feeders (vs. oligochetes) because these are more accessible food for fish	- Evaluate topographic complexity
	Species use - nekton	Abundance / density / species richness measured with nets, traps, etc. - Species list	Annual surveys; During slack high tide during spring migration of diadromous fish and in summer	Replicate samples within representative creeks or surface waters; density dependent sampling	- Habitat - Nekton, Birds - Food web support	Approaching reference conditions or increases through time	- Evaluate hydrologic connectivity conditions
	Species use - birds	Abundance / density / species richness measured with field surveys (e.g., point counts) - Species list	Annual surveys; During breeding season and migration periods of target species (e.g., waterfowl, waders and shorebirds); during winter if overwintering habitat is being targeted; multiple days are preferred	Visible use within and adjacent to wetland in representative sites in large marshes, or from best vantage point, if small	- Habitat - Birds - Food web support	Signs of use and increasing use through time	
	Species use - herpefauna and mammals	Abundance / density / species richness measured with field	Annual surveys; During peak abundance, as appropriate; multiple days are preferred	Representative sites in large marshes, or from best vantage point if small	- Habitat - Reptiles, Mammals, Birds - Food web support	Signs of use and increasing use through time	

		surveys - Species list					
	Breeding success - birds, reptiles & mammals	Nests, breeding pairs, offspring of target species - Species list	Annual surveys during breeding season; multiple days are preferred	Representative sites in large marshes, or from best vantage point if small	- Population support - target species	Number of young and survival rate matches reference condition	- Predator control is sometimes used to enhance nest success
Physico-Chemical	Pore water and surface water salinity and pH	Dissolved salts (parts per thousand) and pH; surface water salinity only measured in impounded marshes	Pore water and pH at regular intervals throughout marsh growing season (at least 3 times per year) at low tide; surface water salinity measured a few times in late summer close to sunrise	Replicate samples within surface waters and/or representative marsh zones	- Useful for adaptive management - Nutrient cycling - Habitat - nekton (surface water) - Food web support	- Salinity matches reference conditions and gradients support marsh zonation (if applicable) - pH matches reference conditions	- Salinity issues should be addressed through hydrologic manipulations; - pH can be a problem with tidal wetland restorations using dredged material and lime additions can be adjusted to reach reference conditions
	Surface water quality (impounded marshes only)	In-situ: Temperature, chla, turbidity	Regular intervals throughout marsh growing season (at least 3 times per year)	Replicate samples within surface waters under the influence of the project	- Habitat - Nekton - Food web support	- Conditions consistent with reference sites; no localized areas of excessive temperature (e.g., >30 C) or algal concentration, or low DO (<3 mg/l), attributable to the project (e.g., behind breakwaters or in impounded marshes)	- Poor water quality may need to be addressed by improving connectivity to external water bodies (e.g., channel/culvert creation, deepening or widening)
		Lab analysis: TN, TP, contaminants of concern, coliforms	Regular intervals throughout marsh growing season (at least 3 times per year)	Replicate samples within surface waters in or adjacent to project	- Useful for adaptive management - Habitat - nekton - Food web support	Nutrient or contaminants do not exceed tolerance of sensitive design elements (e.g., SAV)	
	Denitrification	Dentrification	Soon after installation	Replicate	- Nutrient cycling /	- Denitrification	- Additions of organic

	potential	enzyme activity (DEA) assay	and annually thereafter; Upper 15-20 cm of soil/substrate throughout marsh,	samples within representative marsh zones	denitrification - Food web support	potential rates match or approach reference conditions or are within expected ranges of variability for similar systems); increasing rates over time; - Spatial variability in denitrification potential values throughout marsh is similar to reference conditions	material may enhance rates - Rates can take a long time to reach reference conditions (see Broome and Craft 2009, Table 1)
	Soil characteristics	Grain size distribution or texture, % Organic matter, Bulk density	Measured >1 year post restoration and annually thereafter or as needed to inform adaptive management	Replicate samples within representative marsh zones	- Useful for adaptive management - N and P cycling and burial - Food web support (OM promotes infauna) - Water infiltration (high marsh) - Carbon sequestration	- % sand, silt and clay match or approach reference conditions - OM is increasing through time - Bulk density is close to reference conditions	- Low OM may limit plant growth; additions of organic matter may improve soil properties and nutrient cycling - Bulk density and grain size are markers of whether appropriate hydrodynamics have been restored and can thus suggest need for modified design or structures; bulk density also reflects organic matter content
	Nutrient retention / removal	N and P burial rates	Every few years	Replicate samples within representative marsh zones	- N and P cycling and burial	-N and P content of accreted material increases through time to approach reference conditions	Rates can take a long time to reach reference conditions (see Broome and Craft 2009, Table 2).

Table 4 (cont). Tidal Wetlands Monitoring Metrics - Protocols

Category	Metric	Basic measurement protocols	Additional and/or advanced measurement protocols
Hydrologic	Tidal regime	-Electronic water level data loggers are preferred. See: Neckles and Dionne, 1999, p 7. http://www.pwrc.usgs.gov/resshow/neckles/Gpac.pdf -For a simple protocol using gauges, see: Carlisle et al, 2002, Chapter 9, p 9-1 to 9-8. http://www.mass.gov/czm/smchapter9.pdf; If measurements are taken for short time periods, they should be taken during periods without wind	
		-Use electronic water level data loggers to capture change through time (see equipment manufacturer's manual for further information).	-Professional sampling techniques are described in US Army Corps of Engineers 2009. http://el.erdc.usace.army.mil/wrap/pdf/tnwrap05-2.pdf
		-Depending on site characteristics, a portable velocimeter may be most appropriate (e.g., www.marsh-mcbirney.com, has technical details for the type of equipment used) and methods are described at USGS 2011: http://ga.water.usgs.gov/edu/streamflow2.html -A simple technique that may be applicable to tidal channels is described in Gibbons et al. 1994, Chapter 5. http://www.ecy.wa.gov/programs/wq/plants/ management/joysmanual/5float.html	
	Hydrologic connectivity	-Use mapping or GIS analysis. For example protocol, see: Collins et al, 2008, p 43 to 45, but only consider % transect with flowing water. http://www.cramwetlands.org/documents/ 2008-09-30_CRAM%205.0.2.pdf	-Conventional surveying techniques may be used to map and quantify elements of hydrologic connectivity.
Geomorphic	Elevation maintenance	-Conventional survey techniques are most reliable; for discussion of appropriate datum usage, see: Brophy, 2009, p 19 to 20.	-For advanced methods using sediment erosion tables (SETs), see: U.S. Army Corps, 2009, p 7-B-4 to 7-B-6. http://www.evergladesplan.org/pm/program_docs/qasr.aspx and Cahoon and Lynch 2003 http://www.pwrc.usgs.gov/set/

	Slope maintenance	Slope can be measured over small ranges using two stakes, string, a line level, and a measuring tape. For example: http://www.extension.umn.edu/distribution/naturalresources/DD6982.html	-For better results, use conventional surveying techniques.
	Topographic complexity (Fine-medium scale spatial variation in elevation and physical patches)	-Visual assessment. For example protocol for fine-medium scale variability, see: Collins et al, 2008, p 71 to 74. http://www.cramwetlands.org/documents/ 2008-09-30_CRAM%205.0.2.pdf. -Note that overall project diversity will be addressed through area by area of wetland physical zones and hydrologic connectivity metrics	-Conventional surveying techniques offer a more quantitative assessment. For a detailed example, see: Moser et al, 2007. http://mason.gmu.edu/~cahn/Publication/Moser%20and%20Ahn-MTvege%202007.pdf -Fine-scale variability can also be assessed using GIS analysis, as in: Diefenderfer et al, 2008, p 345.
	Area of wetland physical zones: beach, mud flat & marsh zones including SAV beds (as appropriate)	-Use ground surveys, aerial imagery, and/or GIS analysis to capture important cover types. For example protocol, see: Collins et al, 2008, p 65 to 70. http://www.cramwetlands.org/documents/ 2008-09-30_CRAM%205.0.2.pdf -Google maps or Google Earth may be an easy way to monitor changes in area using their imagery (if available) and measurement tools -Aerial imagery of salt marshes is available from VIMS (http://web.vims.edu/bio/sav/maps.html)	-If using GIS, consider measuring edge complexity of interface between water and vegetated areas (e.g., fractal dimension) -Can apply side scan sonar and/or acoustic sounder systems for SAV assessment. -SAV cover estimates from aerial photos may be verified by ground-truthing if necessary. See: U.S. EPA, 2006, p 18-9 to 18-13. http://water.epa.gov/type/oceb/nep/upload/2007_04_09_estuaries_monitoruments_manual.pdf
	Sediment Accretion	-Feldspar markers are most appropriate for small sites with low erosion potential. For explanation of feldspar markers, see: U.S. Army Corps, 2009, p 7-B-2. http://www.evergladesplan.org/pm/pm_docs/qasr/ qasr_2009/qasr_2009_app_07-b.pdf	-For extensive overview of soil and substrate sampling method options see: U.S. Army Corps, 2009, p 7-B-1 to 7-B-4. http://www.evergladesplan.org/pm/pm_docs/qasr/qasr_2009/qasr_2009_app_07-b.pdf For additional details on SET and marker horizons: Cahoon and Lynch 2003. http://www.pwrc.usgs.gov/set/

Biota	Vegetative cover & density	-Appropriate methods depend on complexity of site and project goals. Fixed transects offer advantages for detecting change in highly variable sites and are recommended. Aerial images, taken annually, are also recommended if available. -Aerial imagery may be available from VIMS (http://web.vims.edu/bio/sav/maps.html) For example of site selection and sampling protocols, see: -Peet et al. 1998; http://cvs.bio.unc.edu/methods.htm -Carlisle et al, 2002, Chapter 4. http://www.mass.gov/czm/smcomplete.pdf -Niedowski, 2000, p 55 to 59. http://www.edc.uri.edu/restoration/html/resource/nymarsh.pdf -Can be supplemented by time-series photos (example: http://picturepost.unh.edu)	-For additional methods for selecting monitoring sites, see: -Vasey et al, 2002. www.wrmp.org/docs/protocols/Tidal%20Marsh%20Vegetation.doc
	Canopy complexity	-See sampling protocols under "Vegetation Cover." -Measurement methods depend on the species present and project objectives. -Height variation can be measured with protocols in Niedowski 2000, p. 59. -Supplemental measurements are available in Peet et al. 1998. http://cvs.bio.unc.edu/methods.htm -Photos may be used to assign and document a relative structural complexity score (see Marsden et al, 2002 for techniques developed for forests)	Keer and Zedler 2002 provide more quantitative measurement approaches.

	Vegetation species richness / community composition	-See sampling protocols under "Vegetation Cover." -Calculation methods depend on the species present and project objectives. Species lists may be sufficient, or various diversity metrics may be used to consider both number of species and relative abundance (such as Shannon diversity) -Consider whether richness metric should be limited to native species only, based on project objectives. -Consider labeling by coefficient of conservation (As discussed in Andreas et al, 2004, p 1 to 8. Available from: http://www.epa.state.oh.us/) -For calculating simple metrics, see: Carlisle et al, 2002, p 4-8 to 4-12. http://www.mass.gov/czm/smchapter4.pdf	-Floristic Quality Assessment Index (FQAI) can be a useful community metric. See: U.S. EPA, 2002a, p 13 to 18. http://water.epa.gov/type/wetlands/upload/2008_12_23_criteria_wetlands_10Vegetation.pdf - For an example of Floristic Quality Assessment Index (FQAI), see: Andreas and Lichvar, 1995. http://el.erdc.usace.army.mil/wetlands/pdfs/wrpde8.pdf
	% Non-native plant species	-See measurement protocols under "Vegetation Cover." -For calculating simple metrics, see: Carlisle et al, 2002, p 4-9 to 4-12. http://www.mass.gov/czm/smchapter4.pdf -For example protocol that targets a specific invasive (Phragmites australis), see: Niedowski, 2000, p 67 to 72. http://www.edc.uri.edu/restoration/ html/resource/nymarsh.pdf	
	Invertebrate bioassessments	-Metrics that assess diversity, richness or the Index of Biotic Integrity (IBI) require common sampling and species analysis techniques. -For a thorough example of field protocols, data entry and analysis, see: Carlisle et al, 2002. Chapter 5. http://www.mass.gov/czm/smchapter5.pdf	-For IBI, sample analysis and calculation is best done by professionals. -For a discussion of invertebrate IBI see: U.S. EPA, 2002c. http://water.epa.gov/type/wetlands/upload/2008_12_23_criteria_wetlands_9Invertebrate.pdf -For field methods appropriate for the Chesapeake Bay, benthos see: Chesapeake Bay Benthic Monitoring Program 2005. http://www.baybenthos.versar.com/DsgnMeth/FieldLab.htm

	Species use - nekton	-Appropriate methods depend on species present but all values need to be corrected by area sampled (density) or sampling effort (CPUE, catch per unit effort). -For example protocols, see: -Carlisle et al, 2002, p 6-1 to 6-14. http://www.mass.gov/czm/smchapter6.pdf -Neckles and Dionne, 1999, p 15 to 17. http://www.pwrc.usgs.gov/resshow/neckles/Gpac.pdf	
	Species use - birds	-For an example of measurement protocol and data analysis, including calculating richness, see Carlisle et al, 2002. http://www.mass.gov/czm/smchapter7.pdf -For another simple example protocol, see: Niedowski, 2000, p 61. http://www.edc.uri.edu/restoration/html/resource/nymarsh.pdf.	-For comprehensive discussion of monitoring options, see: Conway, 2005. www.fws.gov/bmt/documents/marshbird_monitoring_protocol.pdf
	Species use - herpefauna and mammals	-Appropriate methods depend on species present. -For general information, see: Thayer et al, 2005, p 10.55 to 10.58. http://coastalscience.noaa.gov/documents/rmv2/WholeDocument.pdf -For basic amphibian monitoring protocols, see Timmermans, 2001, p 5. http://www.bsc-eoc.org/mmpreport2002.html. Also, U.S. EPA, 2003, p 20, 66 to 68. http://water.epa.gov/type/wetlands/upload/2008_12_23_criteria_wetlands_14Casestudies.pdf. -For general mammal survey methodologies, see: U.S. EPA, 1990. http://water.epa.gov/type/wetlands/assessment/mamm.cfm	-For comprehensive discussions of reptile/amphibian sampling options, see: -Hutchens and DePerno, 2009. -U.S. EPA, 2002b. http://water.epa.gov/type/wetlands/upload/2008_12_23_criteria_wetlands_12Amphibians.pdf
	Breeding success - birds, reptiles & mammals	-Count nests, breeding pairs, and/or offspring. For Birds, see Carlisle et al. 2002, Chapter 7. http://www.mass.gov/czm/smchapter7.pdf	-For examples of advanced methods, see: Erwin and Beck, 2007. http://www.pwrc.usgs.gov/prodabs/pubpdfs/6904_Erwin.pdf.

Physico-Chemical	Pore water and surface water salinity and pH	-Salinity is easily measured with a manual refractometer. - pH is measured with pH sensitive papers or standard meters -For an example pore-water sampling protocols and salinity analysis methods, see: -Neckles and Dionne, 1999, p 10. http://www.pwrc.usgs.gov/resshow/neckles/Gpac.pdf -Carlisle et al, 2002, p 8-1 to 8-10. http://www.mass.gov/czm/smchapter8.pdf	-For information on advanced pore water sampling methods, see: U.S. Army Corps, 2009, p 7-A-17 to 7-A-22. http://www.evergladesplan.org/pm/pm_docs/qasr/qasr_2009/qasr_2009_app_07-a.pdf
	Surface water quality (impounded marshes only)	-In situ measurements with electronic meters (such as those manufactured by Hydrolab or YSI) are easiest. If meters are not available, alternative techniques are described in U.S. EPA, 2006. http://water.epa.gov/type/oceb/nep/upload/2007_04_09_estuaries_monitoruments_manual.pdf -For DO, see: p 9.1 to 9.13. -For turbidity, see: p 15.1 to 15.11. -For temperature, see p 13.1 to 13.5. -If Chl*a* will be measured in a lab. Use standard water sampling techniques (Described in US EPA 2006, chapters 6 and 7).	
		-These metrics should be analyzed in a lab. For proper sample collection techniques, see: U.S. EPA, 2006, chapters 6, 7, 10, and 17. http://water.epa.gov/type/oceb/nep/upload/2007_04_09_estuaries_monitoruments_manual.pdf	
	Denitrification potential	-Assay must be done in a laboratory and soil samples must be properly handled; -For example sampling method and discussion, see Bruland et al, 2006. http://www.ctahr.hawaii.edu/brulandg/publications/Bruland06Wetlands.pdf.	-For laboratory methods, see Groffman, 1999.

	Soil characteristics	-For general soil sampling guidelines, see U.S. EPA, 2008, p 15 to 17. http://water.epa.gov/type/wetlands/upload/ 2008_12_23_criteria_wetlands_18Biogeochemical.pdf -For discussion of bulk density, see: U.S. EPA, 2008, p 23 to 24. http://water.epa.gov/type/wetlands/upload/ 2008_12_23_criteria_wetlands_18Biogeochemical.pdf -Soil organic matter should be analyzed in a lab. Basic protocols are described in Niedowski, 2000, p 60. http://www.edc.uri.edu/restoration/ html/resource/nymarsh.pdf -To assess grain size, see methods in Gee and Gauder, 1986.	-For a comprehensive review of soil sampling techniques, see: U.S. Army Corps, 2009, chapter 7. http://www.evergladesplan.org/pm/pm_docs/qasr/qasr_2009 /qasr_2009_chap_07.pdf
	Nutrient retention / removal	-Verifying net nutrient removal by wetlands requires quantifying incoming and outgoing nutrient flows via surface and subsurface water, which is an involved process for most tidal wetlands. -Where such measurements are not possible, soil and sediment accumulation rates may be used with other analyses to indicate nutrient removal by the site. N and P content of accreted material can be estimated in a lab (see sampling protocols under Sediment Accretion and Soil Characteristics).	- See US EPA 2008 for general discussion of soil sampling and analysis techniques used. - See Craft et al. 1991 for techniques to relate analysis results to total nitrogen storage. - See Jordan et al. 2003 for example of a comprehensive approach to verifying nitrogen and sediment retention and removal in wetlands receiving unregulated flows.

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Prioritized Sets of Recommended Metrics

Resources will limit total monitoring effort at a site and goals will suggest which metrics are most useful to measure. However, to promote data collection that allows restoration to be tracked and compared at multiple sites, we recommend a "primary" set of metrics that can be used to evaluate core system features and processes within and across sites. To supplement the primary metrics, a "secondary" set of metrics is proposed that provides options for measuring goal-driven outcomes, such as restoration of a particular species or ecosystems. Table 4 provides information on how such metrics may be effectively measured but some aspects of measurement and the interpretation of metric results will need to be tailored to project goals. Many metrics are not useful unless they can be sampled at a sufficient number of locations throughout the marsh and at sufficient frequency. Therefore, monitoring effort may be more effective if a few metrics are intensively sampled rather than many metrics being superficially sampled, particularly for larger sites. See Table 4 for further descriptions of metrics listed here.

Table 5. Recommended Monitoring Metrics

Primary Metrics – Required by all projects and represent core structure & functions	
1.	Tidal range
2.	Inundation duration
3.	Sediment accretion
4.	% Vegetation cover by species (classified by native status)
5.	Area and diversity of marsh zones or project elements (Emergent and submerged vegetated areas, beach, mudflat, bare areas, and channels)
6.	Surface water salinity (impounded marshes only)
Secondary Metrics – Dependent on project goals	
1.	Hydrologic connectivity
2.	Current velocity in channels
3.	Topographic complexity
4.	Canopy complexity
5.	Invertebrate diversity, abundance, % area covered
6.	Species use – nekton use and density
7.	Species Use – birds, reptiles, mammals
8.	Surface water quality measured in situ (Temp, DO, chla, turbidity in impounded marshes)
9.	Surface water quality measured in lab (nutrients, contaminants, coliforms)
10.	Pore water salinity and pH
11.	Soil characteristics (% organic matter, grain size, bulk density)
12.	Denitrification potential

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Appendix A. Evidence-Based Review of Performance Measures for Assessing Tidal Wetland Restoration Projects

In this chapter, we examine the scientific evidence supporting the use of various metrics for evaluating the functional performance of tidal wetland restoration projects. Salt marshes and living shorelines generate a variety of processes that promote restoration goals or protecting shorelines and restoring water quality and vital habitat, such as: wave or storm surge attenuation, nutrient and sediment trapping, and habitat provision, particularly for nekton (fish and macro-crustaceans), birds, and amphibians. The relationships between performance metrics (listed in Table 4-1) and the ability to site to generate these and other functions are discussed below and the strength of the evidence is summarized in Table 4-2. We indicate which metrics offer the strongest support for specific goals since metric selection and interpretation is guided by restoration project goals.

Table 4-1. Metrics reviewed for monitoring success of tidal wetlands restoration projects

Hydrology and Geomorphology	Biota	Physical and Chemical
• Tidal regime • Hydrologic connectivity • Elevation • Slope • Microtopographic relief • Large woody debris • Marsh edge complexity • Sedimentation rates	• Abundance / cover / density • Species richness • Community composition • Plant structural complexity • % Non-native species • Indicator species	• Surface water chemistry • Salinity • Denitrification potential • Soil / substrate characteristics

Hydrology and topography

Tidal regime (surface water depth, duration of inundation, tidal range, tidal flushing)

Tidal regime is considered a fundamental characteristic of the hydrologic regime because, in combination with elevation and sediment sources, it influences the full range of physical, chemical and biotic processes (Gedan et al. 2009, Cahoon and Reed 1995, Seybold et al. 2002, Lefor et al. 1987, McKee and Patrick 1988). The percent time that a marsh is flooded due to tidal inundation is a simple metric used to capture one of the most important aspects of tidal regime. Other important and closely related metrics of tidal regime include water depth, tidal range and tidal flushing (methods in Appendix B). Because tidal cycles control many processes in complex ways, duration, frequency or range targets are generally established using reference sites in the region rather than attempting to estimate needs of specific species.

Vital Habitat – Flooding duration is well established as contributing to habitat quality (Burdick et al. 1997, Gedan et al. 2009) by promoting bird nesting success (Greenwood and Macfarlane 2006) and reducing size and % cover of the invasive, non-native *Phragmites* (Niering 1997, Roman et al. 1984). Flooding with duration of less than 4 hours has been associated with *Phragmites* establishment (Seneca and Woodhouse 1985). In addition, enhanced tidal flushing associated with many tidal wetland restorations is thought to promote use by nekton (Rozas 1995) and productivity of adjacent estuarine waters (Niering 1997).

Water Quality (nutrient removal) – Longer water retention time is associated with greater rates of denitrification and phosphorus removal, although salt marshes are known to be both sinks and sources of nitrogen (Jordan et al. 1983, Weinstein and Kreeger 2000, Mitsch and Gosselink 1993, McKellar et al. 2007, Seybold et al. 2002).

Hydrologic connections

Vital Habitat – Hydrologic connections (channels, ponds, and embayments) between restored and natural habitats can enhance abundance of nekton (West and Zedler 2000, Meynecke et al. 2008, Sheaves et al. 2010, Barbier et al. 2010), even when tidal flow remains partially restricted, estuarine nekton communities can be similar to those in fully connected habitats (Ritter et al. 2008). Increased connectivity has been linked to increased bird use of created and restored wetlands (Brusati et al. 2001, DeGraaf et al. 1985) and enhanced seed dispersal and establishment of characteristic plant assemblages (Huiskes et al. 1995, Middleton 1999, Neff and Baldwin 2005, Neff 2002, Morzaria-Luna and Zedler 2007, Hopfensperger et al. 2009, Stromberg et al. 2009).

Topography (elevation, slope, topographic variability)

Elevation, slope and fine-scale variability in elevation (topographic variability) influence multiple processes within salt marshes. Sediment accretion and accumulation of organic matter within wetlands is promoted by lower elevations and slopes and more variable topography (Cahoon and Reed 1995, Pasternack et al 2000, Grismer et al. 2003, Wallace et al. 2005, Torres and Styles 2007).

Vital Habitat – Appropriate elevation is important to nekton access and use of the site (Minello and Webb 1997). Gentle slopes (1-3%) within the intertidal zone support a greater area for intertidal marsh vegetation and fine-scale variability of slopes creates greater diversity of habitat type. Topographic variability enhances plant species richness (Zedler et al. 1999) and aquatic habitat connectivity, it creates pools that serve as oases for transient species (Williams and Zedler 1999, Larkin et al. 2008, Larkin et al. 2009). Further, heterogeneity has been linked to invertebrate health as measured by ability to repair shells (Moody and Aaronson 2007).

Shoreline Protection – Steeper slopes and more variable microtopography have been linked to enhanced wave dampening suggesting enhanced erosion control at certain wave heights (Moeller et al. 1999, 1996).

Large woody debris (LWD)

Vital Habitat – Evidence that LWD promotes habitat quality in tidal marshes is too limited to draw strong conclusions (Simenstad et al. 2003, Hood 2007). However, available research suggests that higher densities of LWD (>2 cm diameter) promotes habitat by serving as a refuge for aquatic species especially epibenthic fish and invertebrates (Everett and Ruiz 1993) and promotes use by small mammals (Bias and Morrison 2006).

Marsh edge complexity (length and density)

Vital (Aquatic) Habitat –The amount of edge between the intertidal vegetated and the intertidal unvegetated areas is thought to generally influence exchange of organisms and promote habitat quality for some species (Minello et al. 1994, Peterson and Turner 1994). Edge habitat is associated with higher concentrations of nekton and is thought to be an area of increased predator-prey interaction (Whaley and Minello 2002, Long and Burke 2007, La Peyre and Birdsong 2008). Length of marsh edge is influenced by topography and plant distribution in the intertidal zone. The sinuosity (curviness) or patchiness of edges creates more marsh edge per unit area (edge density).

Sedimentation (accretion) rates

Vital Habitat, Shoreline protection and Water Quality – Tidal wetlands must achieve sufficient accretion rates to persist (Langland and Cronin 2003) making sedimentation rate a strong leading indicator of wetland resilience. Sediment accumulation is affected by multiple synergistic factors: elevation, tidal exchange, vegetation form and density, and proximity to sources (DeLaune et al. 1983, Cahoon and Reed 1995, Leonard 1997) therefore, accretion rates can suggest whether physical processes are working together to promote marsh resilience. Accretion rates must be judged appropriately with respect to elevation. For example, high marshes in Chesapeake Bay appear to lose sediment but maintain elevation through accumulation of organic matter (Stevenson et al. 1985).

Vegetation

Establishment of appropriate vegetation is one of the most common measurements of wetland success since vegetation provides refuge and food, and mediates many physical and chemical conditions in marshes. However, cover is known to exhibit high variability in young marshes and initial vigor of vegetation can be followed by later decline, making interpretation of short-term results difficult (Craft et al. 2003, Garbutt and Wolters 2008, Matthews et al. 2009).

Vegetative Cover (stem density, % cover, width of vegetation)

Vital Habitat – The effect of vegetation cover on habitat quality appears to be highly species dependent. A major review of salt marsh restoration found that percent cover does not necessarily correlate with overall use by birds or fish but can be important for some species (Warren et al. 2002). Studies on particular bird species or guilds have suggested that upland vegetation density promotes bird use and abundance within tidal wetlands (e.g., Havens et al. 2002, Mills et al. 1991). In restored prairie potholes (where bird species can be similar to tidal wetlands), *waterfowl* species richness was more heavily influenced by wetland area than vegetation characteristics, but *total species* richness and *breeding bird* species richness were influenced more by vegetation characteristics (Van Rees-Siewert and Dinsmore 1996).

Higher stem density is not necessarily better for supporting fish within emergent vegetation, but can protect invertebrates that use marshes as refuge from predatory fish. Thick, widely spaced stems create a marsh surface more accessible to predatory fish (Teal, 1986) and intermediate levels of density can protect small fish from large fish. Thus, variable marsh densities support different sizes or life stages of fish (Orth et al. 1984).

Water quality (sediment removal) and Shoreline protection - Vegetation stem density promotes sediment deposition by slowing water to allow particle settling, attracting particles to stems, and preventing resuspension of fine grains (Nixon 1982, Yang et al. 2008). Vegetation also provides friction that dampens erosive potential of waves (Coops et al. 1996). While target stem densities vary by species, denser beds of grasses such as *Spartina alterniflora* are generally expected to be more effective at sediment trapping and wave attenuation (Leonard and Luther 1995, Leonard et al. 2002, Leonard and Croft 2006, Gleason et al 1979). Marshes with *S. alterniflora* have been demonstrated to reduce wave energy on the order of 26% per m of vegetation at the seaward edge or up to 63% at 7 m inside the marsh edge (Fonseca and Cahalan 1992, Morgan et al. 2009).

The research on the wave dampening effects of *Spartina* demonstrates that much of the effect occurs close to the marsh edge, suggesting that there are diminishing returns to increasing width. However, other research suggests wider marshes (as measured by extent of vegetation between upland and seaward edges) are more effective at dampening wave energy (Knutson 1982) and that marsh slope and water depth also play an important, but complex, role in determining wave dampening ability (Morgan et al. 2009, Moeller et al. 1996, 1999). In contrast, some recent research has challenged the belief that vegetation is responsible for binding soil to prevent erosion and instead suggests that soil type is the only statistically significant factor in determining resistance to erosive waves (Feagin et al. 2009).

Water Quality (nutrient removal) – Although the same factors that trap sediments can lead to nutrient removal, vegetation in salt marshes appears to promote nutrient *cycling* rather than retention (Jordan et al. 1983) and total retention has been more closely related to nutrient loads than vegetation density (Spieles and Mitsch 1999).

Vegetation persistence (herbivory, disease)

In addition to snapshot views of vegetation cover, metrics that suggest vegetative cover persistence may be indicators of marsh resilience. For example, extensive herbivory or disease can be a leading indicator of plant die-off and marsh loss (Gedan et al. 2009). In the case of the marsh snail (*Littoraria irrorata)*, populations uncontrolled by predators have been observed to completely denude entire stands of wetland vegetation along the Atlantic coast by facilitating fungal infections (Silliman and Bertness 2002). Similarly, nutria (*Myocastor coypus*) are thought to be an important factor in marsh degradation (Gough and Grace 1998, Colona et al. 2003). While some herbivory is natural and can facilitate use by waterfowl, uncharacteristically heavy herbivory or high disease prevalence suggests a need for adaptive management to prevent vegetation loss.

Vegetation composition (species richness, and dominance)

Vegetation richness can be measured both within representative communities and across communities within the marsh (e.g., with community type ratios).

Vital Habitat – A recent review found, "Although, indicators based on species richness often overestimated wetland performance, indicators based on species composition or dominance were more effective." (Matthews et al. 2009). This work suggested that species richness was not a useful indicator of later success, when measured in the first 5 years after restoration, because species diversity can be driven by disturbance. In this study, restoration "success" was defined by the ability of the wetland to host plant species that are intolerant of degradation rather than a functional outcome. In a study examining much older restored wetlands, Garbutt and Wolters (2008) found that "…even after 100 years, regenerated salt marshes differ in species richness, composition and structure from reference communities." Nonetheless, their review suggested that species richness is able to distinguish restored from natural sites in the long term, but diversity may not develop without assistance.

Water Quality (nutrient removal) – Several studies, conducted under diverse conditions, suggest that diverse community composition will typically accumulate significantly greater biomass, leading to significantly greater N accumulation than single species plantings or non-vegetated habitats (Callaway et al. 2003, Gribsholt et al. 2007, Sullivan et al. 2007).

Vegetative structural complexity

Vital Habitat – Greater canopy complexity (plant shapes and heights including cavities, canopy gaps, and vertical partitioning of vegetative strata) is thought to enhance the potential for support of diverse wildlife (Hammer 1992). Canopy architecture (e.g., as measured with height histograms) has been linked to bird nesting success (Zedler 1993). Structural complexity can vary with plant species diversity, but is not always correlated (Keer and Zedler 2002, Zedler 2000) suggesting the need for a distinct metric to capture structural characteristics.

% Non-native species cover

Vital Habitat – In general, a high degree of invasion by non-native plants is thought to reduce the availability and quality of food for higher trophic levels (Gratton and Denno 2005, Currin et al 2003, Jivoff and Able 2003). Several studies of *Phragmites* suggest that this plant has a detrimental impact on food-web structure, shifting the base of the food web from producer-based to detritus-based and altering trophic linkages (e.g., Currin et al, 2003, Jivoff and Able, 2003, Gratton and Denno, 2005, Topp et al. 2008). Further, Meyerson et al. (2000) and Benoit and Askins (1999) indicated that the tall, dense monocultures resulting from invasion by *Phragmites* altered bird composition relative to un-invaded wetlands; however, because several bird species were able to roost and forage *in Phragmites*-dominated systems, the work indicates that the impacts of non-native vegetation are species-specific. Further, some studies have found that *Phragmites*-dominated wetlands were equivalent to native wetlands in terms of nekton usage (Meyer et al. 2001, Hanson et al. 2002).

Water Quality (nutrient and sediment removal) – The effects of non-native species on wetland sediment dynamics are highly variable. However, several studies suggest that invasion by *Phragmites* is either positive or neutral in terms of effects on sediment trapping (Rooth and Stevenson 2000, Rooth et al. 2003, Leonard et al. 2002). In addition, the plant has been shown to be highly efficient at controlling BOD and removing nitrogen, phosphorus, and heavy metal contaminants from runoff (Adeola et al. 2009, Templer et al. 1998, Otto et al. 1999, Windham 2001, Windham and Meyerson 2003). However, several recent studies have shown that invasive effects on nutrients are difficult to separate from site history and other conditions (e.g., nutrient loads), suggesting that the magnitude of differences between native and non-native invasives may be overestimated (Windham and Meyerson 2003, Ehrenfeld 2003).

Wildlife

Wildlife use

Recent efforts have aimed to use wildlife as indicators of wetland condition (Howe et al. 2007, Price et al. 2007), however, the relationship between wildlife presence and quality of habitat support is not always well understood. Because of long time lags between restoration and site use by higher trophic levels, it is common to assess abundance and diversity of lower trophic levels (i.e., prey species) and other conditions (i.e., water depth) that are consistent with habitat requirements for particular species in order to suggest habitat quality for higher trophic levels (e.g., Brown and Veneman 2001).

Invertebrate assessments (species richness, density, multimetric indices)

Benthic invertebrates are considered sensitive indicators of marsh conditions because they integrate conditions over time, are positioned where they will be exposed to any contaminants or hypoxia present (in bottom sediments), have been shown to change community composition in response to stressors, and are important system components because they support commercially and recreationally important fish and shellfish (Malloy et al.

2007). However, because species assemblages differ geographically and by wetland geomorphic type, multimetric bioassessment tools (e.g., B-IBI) require a great deal of calibration in order to be applicable within the assessment area (Wilcox et al. 2002, Tangen et al. 2003, Batzer et al. 2004, Hanowski et al. 2007, Miller et al. 2008). As a result of the difficulties associated with the interpretation of biotic indices, they may not always be appropriate for project monitoring. When regionally calibrated bioassessments are available, they may be a useful tool for comparing sites across large regions or for comparing communities before and after project implementation.

Vital Habitat – Simple measures of abundance or density through time (e.g., of indicator species or guilds) may represent improving prey availability but must be combined with other metrics to suggest complete habitat support (Beck et al. 2001). For example, prey must not only be present but also accessible to predators. For this reason water depth be considered when evaluating habitat support for birds and fish (Erwin 1983, 1988, Kneib 1993). In addition, metrics that group taxa by functional types may be useful for examining changes in forage food availability to predators. For example, an increasing number of filter feeders (vs. oligochetes) may indicate higher food availability for some fish because oligochetes tend to be less accessible (T. McTigue, pers comm.).

Fish use (abundance, species richness, juvenile densities)

Vital Habitat – Fish usage, measured as abundance or species richness, may indicate restoration of physical characteristics such as water volume, but may not be sensitive to other characteristics of vegetation or marsh condition (Minello and Webb 1997, Williams and Zedler 1999). High densities of juvenile fish are assumed to demonstrate a marsh is serving as a nursery and will lead to adult fish recruitment, but direct evidence for this assumption is weak (Beck et al. 2001).

Bird reproduction and use (fledgling counts, abundance, nests, eggs)

Vital Habitat – Evidence of successful reproduction (e.g., fledgling counts) provides one of the clearest links to habitat success (O'Connell et al. 2007), however, establishment of breeding pairs can take decades (Zedler 1989) and it may be impractical to measure some of the most important species (Wilson et al. 2007). In addition, breeding success in a given year does not necessarily demonstrate that a site is not a population sink over the long term (Donovan et al. 1995). Other metrics such as feeding or migration use, presence of individuals or breeding pairs, may be useful, but have not shown to consistently represent acceptable proxies for habitat support unless population demographics are also considered (van Horne 1983). Further, bird use may be more responsive to broad scale landscape conditions rather than site conditions (O'Connell et al. 2007, DeLuca et al. 2004).

Physical and chemical characteristics of surface water and soil/ substrate

Physicochemical characteristics of surface water

Vital habitat - Poor water quality (low DO, and elevated nutrients, suspended solids and temperature), has been shown to negatively impact fish distribution (Brazner and Beals 1997, Anteau and Afton 2008 Brazner et al. 2007, Trebitz et al. 2007, Reid et al. 1999, Love and May 2007), macroinvertebrate richness, abundance, and community structure (Batzer et al. 2004, Spieles and Mitsch 2000, Stewart and Downing 2008), and vegetative dominance (Lopez and Fennessy 2002, Lougheed et al. 2008). Of all the water quality indicators, dissolved oxygen (DO) may be the best predictor of taxon richness and distribution of macroinvertebrates, amphipods, and fish; several studies have found that low DO is correlated to poor habitat condition (e.g. Henning et al. 2006, 2007, Spieles and Mitsch 2000, Anteau and Afton 2008). However, DO measurements can be difficult to interpret because of high temporal variability. In general, the interpretation of results is often species specific and difficult to relate to outcomes without a long time-series of data. Therefore, physiochemical characteristics of surface water are not generally adequate for measuring restoration outcomes, but may serve as a valuable indicator of local stressors that influence restoration success.

Water Quality – Several commonly measured metrics, including total suspended solids (TSS) and nutrient concentrations (e.g. N and P), are direct indicators of surface water quality. While it is tempting to use these metrics as an indicator of the successful restoration of water quality, instantaneous measurements do not capture temporal variation (e.g. tidal, episodic, or inter-annual; Dodds 2002) and provide no information regarding the ability of a wetland to process nutrients or sediment.

Salinity (surface and pore water, and soil salinity)

Vital Habitat – Changes in tidal flux will typically be reflected in surface water salinity, which in turn can alter wetland vegetation type and spatial patterns (Alvarez-Rogel et al. 2007, Greenwood and MacFarlane 2006, 2009, Howard and Rafferty 2006). Therefore, salinity of surface or pore water that compares favorably to reference conditions can suggest that natural hydrologic processes have been restored. Soil salinity strongly affects salt marsh vegetation and uncharacteristic fluctuations can reduce seed germination and inhibit growth (primarily *Spartina alterniflora* and *S. patens*) (Wijte and Gallagher 1996a, 1996b, Noe and Zedler 2000, Zedler et al. 2003) and provide a competitive advantage for *Phragmites* (Chambers et al. 2003).

Denitrification potential (measured with denitrification enzyme activity assay)

Water Quality (nitrogen removal) – The capacity of a wetland soil to remove nitrogen through denitrification, may be quantified using a denitrification enzyme activity (DEA) assay (Smith and Tiedje 1979, Groffman et al. 1999), which measures the conversion of nitrate to dinitrogen gas. Because this method quantifies the activity of denitrifying enzymes produced by microbes present in soil cores, it is broadly applicable and can be used to measure denitrification potential in a variety of wetland types with varying soil and vegetative composition (Flite et al. 2001, Hunter and Faulkner 2001, Merrill and Benning 2006, Ullah and Faulkner 2006, Groffman and Crawford 2003) and in comparing soil properties and denitrification potential between pairs of created, restored and natural wetlands (Bruland et al. 2006). Improvements in wetland functions have been empirically demonstrated among restored wetlands, such as in the application of compost (i.e., enhancing soil organic matter) where an increase in the available N and P and rates of denitrification have been reported (Sutton-Grier et al. 2009). DEA measures the maximum activity of denitrification enzymes present in soil cores and may not reflect actual rates of denitrification in wetland soils under field conditions.

Soil characteristics (organic matter, bulk density / grain size, salinity)

Vital Habitat – Soils characteristics are assessed in restoration to evaluate whether soil development is occurring appropriately to support characteristic organisms since soil qualities are closely associated with nutrient cycling that supports plants and other organisms within wetlands (Craft et al. 2003, Levin and Talley 2002, Cornell et al. 2007, Mitsch and Gosselink 1993). However, some analysis suggests that elevation or habitat type is a stronger control than some soil properties (e.g., organic matter) on plant development (Edwards and Proffitt 2003). In addition, the relationships between soil properties and functions, such as nutrient removal are highly variable (Piehler and Smyth 2011) and likely to change seasonally over time as the soil develops (Gift et al. 2010). Also, soil can take decades to develop to reference conditions (Craft et al. 1999, 2002, 2003, Zedler and Callway 2000). Due to high variability and slow development, organic matter appears to be a weak predictor of functional conditions in the short term, but because of the relationship between soil characteristics and plant vigor, is considered a useful *leading* indicator of restoration success.

Shoreline protection – Soils dominated by fine particles are known to be more cohesive and resist erosion (NRC 2007). Soils with substantial coarse organic matter (associated with the natural marsh interior) have been demonstrated to erode more easily than soils with fine organic matter (associated with natural marsh edge) (Feagin et al. 2009).

Water Quality (nutrient and sediment removal) – Saturated, organic-matter rich soils promote denitrification (Reddy and DeLaune 2008, Jordan et al. 2007, Groffman 1994, Hunter and Faulkner 2001, Clement et al. 2002, Groffman and Crawford 2003, Bai et al. 2005). However, in an extensive review of models currently used to estimate N cycling in wetlands, Stander and Ehrenfeld (2009) concluded that soil moisture and % soil organic matter were inadequate for predicting denitrification rates. However, soils properties associated with anoxic conditions and high organic matter, such as hydric soils, can suggest whether conditions are more likely to support denitrification (Wigand et al. 2004). In addition, developing marsh soils that accumulate fine particles and organic matter (i.e., increased soil organic carbon) have been shown to have increasing denitrification rates (Broome and Craft 2009).

Summary of tidal wetland restoration metrics

Tidal wetlands have naturally high variability (Zedler 1989, Middleton 1999) and restoration sites cannot be expected to show steady improvement towards all goals over time frames of 1-2 years (Broome and Craft 2009, Simenstad and Thom 1996, Streever 2000, Whigham et al. 2002). Some goals may be reached within short time frames (e.g., 5 years) but initial success can sometimes be followed by decline, e.g., of vegetation quality (Matthews 2009). Therefore, most metrics can only be realistically judged in terms of whether sites are making *progress towards* goals such as restoring characteristic natural processes.

Table 4-2. Summary of evidence for tidal wetland monitoring metrics showing effort and cost

Metric	Effort*	Equipment Cost*	Evidence for Strength of Vital Habitat (VH) and Water Quality (WQ) and Shoreline Protection (SP)
Hydrology and Topography			
Tidal regime	Moderate	Moderate	VH: Restoring characteristic flooding magnitude and duration promotes nesting success; deeper water promotes use by diverse nekton WQ: Longer water retention time promotes denitrification and phosphorus removal
Hydrologic connectivity	Low-Moderate	Low	VH: Hydrologic connections between restored and natural habitats can enhance abundance of nekton
Elevation	Moderate	High	VH: Lower elevation regions (appropriate for low marsh) promote sediment accretion and accumulation of organic matter
Slope	Moderate	Low	VH: Gentle slopes (1-3%) within the intertidal zone support a greater area for intertidal marsh vegetation SP: Steep slopes (>3%) can enhance wave dampening
Topographic variability (Fine-scale spatial variation in topography)	Low (if using visual assessment)	Low	VH: Variability enhances plant species richness and creates greater diversity of aquatic habitat types SP: Variability has been linked to enhanced wave dampening
Large woody debris (LWD)	Low	Low	VH: Evidence of the habitat importance of LWD is weak but LWD (>2 cm diameter) is used by epibenthic fish, invertebrates and small mammals
Marsh edge	Low	Low	VH: More marsh edge improves habitat quality for many fish
Sedimentation rates	Moderate	Low	VH & WQ: Sedimentation rate, appropriate for maintaining tidal elevation, is a strong leading indicator of wetland resilience
Biota- Vegetation			
%Cover / density / marsh width	Moderate	Low	VH: % Cover does not necessarily correlate with overall use by birds or fish but can be important for some species; wetland area (rather than cover) may be more important for waterfowl; variable densities of emergent vegetation support different sizes or life stages of fish WQ: Denser beds of *Spartina* are associated with improved sediment trapping; wave dampening effects drop off sharply away from marsh edge, therefore total marsh width may not be important
Herbivory / disease	Moderate - High	Low	VH: Uncharacteristic levels are leading indicators of plant die-off and can indicate need for adaptive management
Species richness / community composition	Moderate - High	Low	VH: High richness measured within the first 5 years may not be indicative of long-term results since disturbance can enhance diversity over the short-term WQ: Diverse community composition enhances nitrogen retention
Canopy complexity	Moderate	Low	VH: Complexity supports diverse bird communities or, at a minimum, particular target bird species

Metric	Effort*	Equipment Cost*	Evidence for Strength of Vital Habitat (VH) and Water Quality (WQ) and Shoreline Protection (SP)
% Non-native species	Low-Moderate	Low	VH: Evidence of harm is mixed for *Phragmites*; effects depend on goals; nekton do not seem to be strongly affected WQ: Harms depend on which species is invading and goals. *Phragmites* generally has neutral or positive effects on water quality
Biota - Wildlife			
Abundance / density / species richness (birds, fish, invertebrates)	Moderate	Moderate - High	VH: In general, the relationship between wildlife presence and quality of habitat support is not well understood. Simple measures of abundance must usually be combined with other metrics to understand relevance
Invertebrate bioassessments	Moderate	Moderate	VH or WQ: Numerous difficulties associated with the interpretation of multi-metric biotic indices suggests they are not always appropriate for monitoring restoration from a functional perspective
Bird fledgling counts, nests / egg abundance	High	Moderate	VH: Evidence of successful reproduction (esp. fledgling counts) provides one of the clearest links to habitat success, however, the metric may be impractical due to long lag times for establishing nests; success must be tracked over the long-term to ensure a site is not a population sink
Physical and Chemical Characteristics			
Surface water chemistry	Moderate	Moderate	WQ: Physiochemical characteristics of surface water are not adequate for measuring restoration outcomes, but may serve as valuable diagnostic tools when used with other indicators
Salinity	Low-moderate	Moderate	VH: Salinity that matches reference conditions can indicate natural hydrologic processes have been restored and that desirable vegetation community is supported
Dentrification enzyme activity (DEA) assay	Moderate	High	WQ: DEA has been shown to provide a reliable measure of denitrification potential but potential rates may not be realized if site conditions are sub-optimal
Soil Organic Matter (SOM), Bulk density / Grain size, Soil Salinity	Low	Moderate	VH: SOM is not a good predictor of vegetation development; elevation appears to be a stronger control SP: Soils with high proportions of very fine grains sizes are more cohesive and resist erosion WQ: Fine grain sizes and high SOM promote conditions appropriate for denitrification

*Effort and cost can vary widely depending on what techniques are used. Therefore, these levels are provided for general guidance only.

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