CHAPTER 1: INTRODUCTION TO VOLUME TWO

INTRODUCTION

Coastal habitats provide ecological, cultural, and economic value. They act as critical habitat for thousands of species, including numerous threatened and endangered species, by providing shelter, spawning grounds, and food (Mitsch and Gosselink 2000). They often act as natural buffers, providing ecological, social, and economic benefits by filtering sediment and pollution from upland drainage thereby improving water quality, reducing the effects of floodwaters and storm surges, and preventing erosion. In addition to these ecosystem services, healthy coastal habitats provide many human values including opportunities for:

- Outdoor recreation and tourism
- Education
- Traditional use and subsistence lifestyles
- Healthy fishing communities, and
- Obtaining other marketable goods

Therefore, healthy functioning coastal habitats are not only important ecologically, they also support healthy coastal communities and, more generally, improve the quality of human lives. Despite these benefits, coastal habitats have been modified, degraded, and removed throughout the United States and its protectorates beginning with European colonization (Dahl 1990). Thus, many coastal habitats around the United States are in desperate need of restoration and subsequent monitoring of restoration projects.

WHAT IS RESTORATION MONITORING?

The science of restoration requires two basic tools: the ability to manipulate ecosystems to recreate a desired community and the ability to evaluate whether the manipulation has produced the desired change (Keddy 2000). The latter is often referred to as restoration monitoring.

For this manual, restoration monitoring is defined as follows:

> "*The systematic collection and analysis of data that provides information useful for measuring project performance at a variety of scales (locally, regionally, and nationally), determining when modification of efforts are necessary, and building long-term public support for habitat protection and restoration*."

Restoration monitoring contributes to the understanding of complex ecological systems (Meeker et al. 1996) and is essential in documenting restoration performance and adapting project and program approaches when needs arise. If results of monitoring restored coastal areas are disseminated, they can provide tools for planning management strategies and help improve future restoration practices and projects (Washington et al. 2000). Restoration monitoring can be used to determine whether project goals are being met and if mid-course corrections are necessary. It provides information on whether selected project goals are good measures for future projects and how to perform routine maintenance in restored areas (NOAA et al. 2002). Monitoring also provides the basis for a rigorous review of the pre-construction project planning and engineering.

Restoration monitoring is closely tied to and directly derived from restoration project goals. The monitoring plan (i.e., what is measured, how often, when, and where) should be developed with project goals in mind. If, for example, the goal of a restoration project is to increase the amount of fish utilizing a coastal marsh, then measurements should be selected that can quantify progress toward that goal. A variety of questions about sampling techniques and protocols need to be answered before monitoring can begin. For the fish utilization example, these may include:

- Will active or passive capture techniques be used (e.g., beach seines vs. fyke nets)?
- Where and when will samples be taken?
- Who will conduct the sampling?
- What level of identification will be required?
- What structural characteristics such as water level fluctuation or water chemistry will also be monitored and how?
- Who is responsible for housing and analyzing the data?
- How will results of the monitoring be disseminated?

Each of these questions, as well as many others, will be answered with the goals of the restoration project in mind. These questions need to be addressed before any measurements are taken in the field. In addition, although restoration monitoring is typically thought of as a 'post-restoration' activity, practitioners will find it beneficial to collect some data before and during project implementation. Pre-implementation monitoring provides baseline information to compare with post-implementation data to see if the restoration is having the desired effect. It also allows practitioners to refine sampling procedures if necessary. Monitoring during implementation helps insure that the project is being implemented as planned or if modifications need to be made.

Monitoring is an essential component of all restoration efforts. Without effective monitoring, restoration projects are exposed to several risks. For example, it may not be possible to obtain early warnings indicating that a restoration project is not on track. Without sound scientific monitoring, it is difficult to gauge how well a restoration site is functioning ecologically both before and after implementation. Monitoring is necessary to assess whether specific project goals and objectives (both ecological and human dimensions) are being met, and to determine what measures might need to be taken to better achieve those goals. In addition, the lack of monitoring may lead to poor project coordination and decreased efficiency.

Sharing of data and protocols with others working in the same area is also encouraged. If multiple projects in the same watershed or ecosystem are not designed and evaluated using a complementary set of protocols, a disjointed effort may produce a patchwork of restoration sites with varying degrees of success (Galatowitsch et al. 1998-1999) and no way to assess system-wide progress. This would result in a decreased ability to compare results or approaches among projects.

CONTEXT AND ORGANIZATION OF INFORMATION

In 2000, Congress passed the *Estuary Restoration Act (ERA), Title I of the Estuaries and Clean Waters Act of 2000*. The ERA establishes a goal of one million acres of coastal habitats (including those of the Great Lakes) to be restored by 2010. The ERA also declares that anyone seeking funds for a restoration project needs to have a monitoring plan to show how the progress of the restoration will be tracked over time. The National Oceanic and Atmospheric Administration (NOAA) was tasked with developing monitoring guidance for coastal restoration practitioners whether they be academics, private consultants, members of state, Tribal or local government, non-governmental organizations (NGOs), or private citizens, regardless of their level of expertise.

To accomplish this task, NOAA has provided guidance to the public in two volumes. The first, *Science-Based Restoration Monitoring of Coastal Habitats, Volume One: A Framework* *for Monitoring Plans Under the Estuaries and Clean Waters Act of 2000 (Public Law 160-457)* was released in 2003. It outlines the steps necessary to develop a monitoring plan for any coastal habitat restoration project. *Volume One* briefly describes each of the habitats covered and provides three matrices to help practitioners choose which habitat characteristics may be most appropriate to monitor for their project. Experienced restoration practitioners, biologists, and ecologists as well as those new to coastal habitat restoration and ecology can benefit from the step-by-step approach to designing a monitoring plan outlined in *Volume One*.

Volume Two, *Tools for Monitoring Coastal Habitats* expands upon the information in *Volume One* and is divided into two sections **Monitoring Progress Toward Goals** (Chapters 2-14) and **Context for Restoration** (Chapters 15-18). The first section, Monitoring Progress Toward Goals includes:

- Detailed information on the structural and functional characteristics of each habitat that may be of use in restoration monitoring
- Annotated bibliographies, by habitat, of restoration-related literature and technical methods manuals, and
- A chapter discussing many of the human dimensions aspects of restoration monitoring

The second section, Context for Restoration includes:

- A review of methods to select reference conditions
- A sample list of costs associated with restoration and restoration monitoring
- An overview of an online, searchable database of coastal monitoring projects from around the United States, and
- A review of federal legislation that supports restoration and restoration monitoring

The Audience

Volumes One and *Two* of *Science-Based Restoration Monitoring of Coastal Habitats* are written for those involved in developing and implementing restoration monitoring plans, both scientists and non-scientists alike. The intended audience includes restoration professionals in academia and private industry, as well as those in Federal, state, local, and Tribal governments. Volunteer groups, non-governmental organizations, environmental advocates, and individuals participating in restoration monitoring planning will also find this information valuable. Whereas *Volume One* is designed to be usable by any restoration practitioner, regardless of their level of expertise, *Volume Two* is designed more for practitioners who do not have extensive experience in coastal ecology. Seasoned veterans in coastal habitat ecology, however, may also benefit from the annotated bibliographies, literature review, and other tools provided.

The information presented in *Volume Two* is not intended as a 'how to' or methods manual: many of these are already available on a regional or habitat-specific basis. *Volume Two* does not provide detailed procedures that practitioners can directly use in the field to monitor habitat characteristics. The tremendous diversity of coastal habitats across the United States, the types and levels of impact to them, the differing scales of restoration activities, and variety of techniques used in restoration and restoration monitoring prevent the development of universal protocols. Thus, the authors have taken the approach of explaining *what one can measure during restoration monitoring, why it is important*, and *what information it provides* about the progress of the restoration effort. The authors of each chapter also believe that monitoring plans must be derived from the goals of the restoration project itself. Thus, each monitoring effort has the potential to be unique. The authors suggest, however, that restoration practitioners seek out the advice of regional experts, share data, and use similar data collection techniques with others in their area to increase the knowledge and understanding of their local and regional habitats. The online database of monitoring projects described in Chapter 17 is intended to facilitate this exchange of information.

The authors do not expect that every characteristic and parameter described herein will be measured, in fact, very few of them will be as part of any particular monitoring effort. A comprehensive discussion of all potential characteristics is, however, necessary so that practitioners may choose those that are most appropriate for their monitoring program. In addition, although the language used in *Volume Two* is geared toward restoration monitoring, the characteristics and parameters discussed could also be used in ecological monitoring and in the selection of reference conditions as well.

MONITORING PROGRESS TOWARDS GOALS

The progress of a restoration project can be monitored through the use of traditional ecological characteristics (Chapters 2 - 13) and/or emerging techniques that incorporate human dimensions (Chapter 14).

THE HABITAT CHAPTERS

Thirteen coastal habitats are discussed in twelve chapters. Each chapter follows a format that allows users to move directly to the information needed, rather than reading the whole text as one would a novel. There is, however, substantial variation in the level of detail among the chapters. The depth of information presented reflects the extent of restoration, monitoring, and general ecological literature associated with that habitat. That is, some habitats such as marshes, SAV, and oyster reefs have been the subject of extensive restoration efforts, while others such as rocky intertidal and rock bottom habitats have not. Even within habitats there can be considerable differences in the amount of information available on various structural and functional characteristics and guidance on selecting parameters to measure them. The information presented for each habitat has been derived from extensive literature reviews of restoration and ecological monitoring studies. Each habitat chapter was then reviewed by experts for content to ensure that the information provided represented the most current scientific understanding of the ecology of these systems as it relates to restoration monitoring.

Habitat characteristics are divided into two types: structural and functional. Structural habitat characteristics define the physical composition of a habitat. Examples of structural characteristics include:

- Sediment grain size
- Water source and velocity
- Depth and timing of flooding, and
- Topography and bathymetry

Structural characteristics such as these are often manipulated during restoration efforts to bring about changes in function. Functional characteristics are the ecological services a habitat provides. Examples include:

- Primary productivity
- Providing spawning, nursery, and feeding grounds
- Nutrient cycling, and
- Floodwater storage

Structural characteristics determine whether or not a particular habitat is able to exist in a given area. They will often be the first ones monitored during a restoration project. Once the proper set of structural characteristics is in place and the biological components of the habitat begin to become established, functional characteristics may be added to the monitoring program. Although structural characteristics have historically been more commonly monitored during restoration efforts, measurements of functional characteristics provide a better estimate of whether or not a restored area is truly performing the economic and ecological services desired. Therefore, incorporating measurements of functional characteristics in restoration monitoring plans is strongly encouraged.

When developing a restoration monitoring plan, practitioners should follow the twelve-step process presented in *Volume One* and refer to the appropriate chapters in *Volume Two* (habitat and human dimensions) to assist them in selecting characteristics to monitor. The information presented in the habitat chapters is derived from and expands upon the *Volume One* matrices (*Volume One* Appendix II).

Organization of Information

Each of the habitat chapters is structured as follows:

1. Introduction
    a. Habitat description and distribution
    b. General ecology
    c. Human impacts to the habitat
2. Structural and functional characteristics
    a. Each structural and functional characteristic identified for the habitat in the *Volume One* matrices is explained in detail. Structural and functional characteristics have generally been discussed in separate sections of each chapter. Occasionally, some functions are so intertwined with structural characteristics that the two are discussed together.
    b. Whenever possible, potential methods to measure, sample, and/or monitor each characteristic are introduced or readers are directed to more thorough sources of information. In some cases, not enough information was found while reviewing the literature to make specific recommendations. In these cases, readers are encouraged to use the primary literature cited within the text for methods and additional information.
3. Matrices of the structural and functional characteristics and parameters suggested for use in restoration monitoring
    a. These two matrices are habitat-specific distillations of the *Volume One* matrices
    b. Habitat characteristics are cross-walked with parameters appropriate for monitoring change in that characteristic. Parameters include both those that are direct measures of a particular characteristic as well as those that are indirectly related and may influence a particular characteristic or related parameter. Tables 1 and 2 can be used to illustrate an example. The parameter of salinity in submerged aquatic vegetation is a direct measure of a structural characteristic (salinity, Table 1). In addition, salinity is related to other structural characteristics such as tides and water source. Salinity is also related to functional characteristics such as biodiversity and nutrient cycling and may be appropriate to include in the monitoring of these functions as well (Table 2). Experienced practitioners will note that many characteristics and parameters may be related to one another but are not shown as such in a particular matrix. The matrices are not intended to be all inclusive of each and every possible interaction. The matrices provided and the linkages illustrated are only intended as starting points in the process of developing lists of parameters that may be useful in measuring particular characteristics and understanding some of their interrelationships.
    c. Some parameters and characteristics are noted as being highly recommended for any and all monitoring efforts as they represent critical components of the habitat while others may or may not be appropriate for use depending on the goals of the individual restoration project.
4. Acknowledgement of reviewers
5. Literature Cited

Three appendices are also provided for each habitat chapter. In the online form of *Volume Two,* these appendices download with the rest of the habitat chapter text. In the printed versions of *Volume Two*, each chapter's appendices are provided on a searchable CD-ROM located inside the back cover. Each appendix is organized as follows:

Appendix I - An Annotated Bibliography
a. Overview of case studies of restoration monitoring and general ecological studies pertinent to restoration monitoring
b. Entries are alphabetized by author

Parameters to Monitor the Structural Characteristics of SAV (excerpt)

Parameters to Monitor	**Biological**	Habitat created by plants	**Physical**	Sediment grain size[1]	Topography / Bathymetry	Turbidity	**Hydrological**	Tides / Hydroperiod	Water sources	Current velocity	Wave energy	**Chemical**	Nutrient concentration	pH, salinity, toxics, redox, DO[2]
Chemical														
Salinity (in tidal areas)								●	●					●

Table 1. Salinity is a parameter that can be used to directly measure a structural component of submerged aquatic vegetation habitats (Chemical/salinity). It is shown with a closed circle indicating that it highly recommended as part of any restoration monitoring program, regardless of project goals. A circle for salinity is also shown under the **Tides/Hydroperiod** and **Water source** columns as salinity levels are related to these structural characteristics as well. (Entire table can be found on page 9.39.)

Parameters to Monitor the Functional Characteristics of SAV (excerpt)

Parameters to Monitor	**Biological**	Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	**Chemical**	Supports nutrient cycling	Modifies chemical water quality	Modifies dissolved oxygen
Chemical														
Salinity (in tidal areas)								❍				❍		

Table 2. Salinity is related to the functions of **Supporting high biodiversity** and **Supporting nutrient cycling**. It is shown here with an open circle, denoting that it may be useful to monitor if monitoring of these functions is important to the goals of the restoration project. (Entire table can be found on page 9.40.)

[1] Including organic matter content.
[2] Dissolved oxygen.

Appendix II - Review of Technical and Methods Manuals

These include reviews of:

a. Restoration manuals
b. Volunteer monitoring protocols
c. Lab methods
d. Identification keys, and
e. Sampling methods manuals

Whenever possible, web addresses where these resources can be found free of charge are provided.

Appendix III - Contact information for experts who have agreed to be contacted with questions from practitioners

As extensive as these resources are, it is inevitable that some examples, articles, reports, and methods manuals have been omitted. Therefore, these chapters should not be used in isolation. Instead, they should be used as a supplement to and extension of:

- The material presented in *Volume One*
- Resources provided in the appendices
- The advice of regional habitat experts, and
- Research on the local habitat to be restored

WHAT ARE THE HABITATS?

The number and type of habitats available in any given estuary is a product of a complex mixture of the local physical and hydrological characteristics of the water body and the organisms living there. The ERA Estuary Habitat Restoration Strategy (Federal Register 2002) dictates that the Cowardin et al. (1979) classification system should be followed in organizing this restoration monitoring information. The Cowardin system is a national standard for wetland mapping, monitoring, and data reporting, and contains 64 different categories of estuarine and tidally influenced habitats. Definitions, terminology, and the list of habitat types continue to increase in number as the system is modified. Discussion of such a large number of habitat types would be unwieldy. The habitat types presented in this document, therefore, needed to be smaller in number, broad in scope, and flexible in definition. The 13 habitats described in this document are, however, generally based on that of Cowardin et al. (1979).

Restoration practitioners should consider local conditions within their project area to select which general habitat types are present and which monitoring measures might apply. In many cases, a project area will contain more than one habitat type. To appropriately determine the habitats within a project area, the practitioner should gather surveys and aerial photographs of the project area. From this information, he or she will be able to break down the project area into a number of smaller areas that share basic structural characteristics. The practitioner should then determine the habitat type for each of these smaller areas. For example, a practitioner working in a riparian area may find a project area contains a *water column, riverine forest, rocky shoreline*, and *rock bottom*. Similarly, someone working to restore an area associated with a tidal creek or stream may find the project area contains *water column, marshes, soft shoreline, soft bottom*, and *oyster beds*. Virtually all estuary restoration projects will incorporate characteristics of the water column. Therefore, all practitioners should read *Chapter 2: Restoration Monitoring of the Water Column* in addition to any additional chapters necessary.

Habitat Decision Tree

A Habitat Decision Tree has been developed to assist in the easy differentiation among the habitats included in this manual. The decision tree allows readers to overcome the restraints of varying habitat related terminology in deciding which habitat definitions best describe those in their project area. Brief definitions of each habitat are provided at the end of the key.

1. a. Habitat consists of open water and does not include substrate (**Water Column**)
   b. Habitat includes substrate (go to 2)
2. a. Habitat is continually submerged under most conditions (go to 3)
   b. Habitat substrate is exposed to air as a regular part of its hydroperiod (go to 8)
3. a. Habitat is largely unvegetated (go to 4)
   b. Habitat is dominated by vegetation (go to 7)
4. a. Substrate is composed primarily of soft materials, such as mud, silt, sand, or clay (**Soft Bottom**)
   b. Substrate is composed primarily of hard materials, either of biological or geological origin (go to 5)
5. a. Substrate is composed of geologic material, such as boulders, bedrock outcrops, gravel, or cobble (**Rock Bottom**)
   b. Substrate is biological in origin (go to 6)
6. a. Substrate was built primarily by oysters, such as *Crassostrea virginica* (**Oyster Reefs**)
   b. Substrate was built primarily by corals (**Coral Reefs**)
7. a. Habitat is dominated by macroalgae (**Kelp and Other Macroalgae**)
   b. Habitat is dominated by rooted vascular plants (**Submerged Aquatic Vegetation - SAV**)
8. a. Habitat is not predominantly vegetated (go to 9)
   b. Habitat is dominated by vegetation (go to 10)
9. a. Substrate is hard, made up materials such as bedrock outcrops, boulders, and cobble (**Rocky Shoreline**)
   b. Substrate is soft, made up of materials such as sand or mud (**Soft Shoreline**)
10. a. Habitat is dominated by herbaceous, emergent, vascular plants. The water table is at or near the soil surface or the area is shallowly flooded (**Marshes**)
    b. Habitat is dominated by woody plants (go to 11)
11. a. The dominant woody plants present are mangroves, including the genera *Avicennia*, *Rhizophora*, and *Laguncularia* (**Mangrove Swamps**)
    b. The dominant woody plants are other than mangroves (go to 12)
12. a. Forested habitat experiencing prolonged flooding, such as in areas along lakes, rivers, and in large coastal wetland complexes. Typical dominant vegetation includes bald cypress (*Taxodium distichum*), black gum (*Nyssa sylvatica*), and water tupelo (*Nyssa aquatica*). (**Deepwater Swamps**)
    b. Forested habitat along streams and in floodplains that do not experience prolonged flooding (**Riverine Forests**)

Water column - A conceptual volume of water extending from the water surface down to, but not including the substrate. It is found in marine, estuarine, river, and lacustrine systems.

Rock bottom - Includes all wetlands and deepwater habitats with substrates having an aerial cover of stones, boulders, or bedrock 75% or greater and vegetative cover of less than 30% (Cowardin et al. 1979). Water regimes are restricted to subtidal, permanently flooded, intermittently exposed, and semi-permanently flooded. The rock bottom habitats addressed in *Volume Two* include bedrock and rubble.

Coral reefs - Highly diverse ecosystems, found in warm, clear, shallow waters of tropical oceans worldwide. They are composed of marine polyps that secrete a hard calcium carbonate skeleton, which serves as a base or substrate for the colony.

Oyster reefs - Dense, highly structured communities of individual oysters growing on the shells of dead oysters.

Soft bottom - Loose, unconsolidated substrate characterized by fine to coarse-grained sediment.

Kelp and other macroalgae - Relatively shallow (less than 50 m deep) subtidal and intertidal algal communities dominated by very large brown algae. Kelp and other macroalgae grow on hard or consolidated substrates forming extensive three-dimensional structures that support numerous plant and animal communities.

Rocky shoreline - Extensive littoral habitats on high-energy coasts (i.e., subject to erosion from waves) characterized by bedrock, stones, or boulders with a cover of 75% or more and less than 30% cover of vegetation. The substrate is, however, stable enough to permit the attachment and growth of sessile or sedentary invertebrates and attached algae or lichens.

Soft shoreline - Unconsolidated shore includes all habitats having three characteristics: (1) unconsolidated substrates with less than 75% aerial cover of stones, boulders, or bedrock; (2) less than 30% aerial cover of vegetation other than pioneering plants; and (3) any of the following water regimes: irregularly exposed, regularly flooded, irregularly flooded, seasonally flooded, temporarily flooded, intermittently flooded, saturated, or artificially flooded (Cowardin et al. 1979). This definition includes cobble-gravel, sand, and mud. However, for the purpose of this document, cobble-gravel is not addressed.

Submerged aquatic vegetation (SAV; includes marine, brackish, and freshwater) - Seagrasses and other rooted aquatic plants growing on soft sediments in sheltered shallow waters of estuaries, bays, lagoons, rivers, and lakes. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Marshes (marine, brackish, and freshwater) - Transitional habitats between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water tidally or seasonally. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Mangrove swamps - Swamps dominated by shrubs (*Avicenna, Rhizophora*, and *Laguncularia*) that live between the sea and the land in areas that are inundated by tides. Mangroves thrive along protected shores with fine-grained sediments where the mean temperature during the coldest month is greater than 20º C; this limits their northern distribution.

Deepwater swamps - Forested wetlands that develop along edges of lakes, alluvial river swamps, in slow-flowing strands, and in large coastal-wetland complexes. They can be found along the Atlantic and Gulf Coasts and throughout the Mississippi River valley.

They are distinguished from other forested habitats by the tolerance of the dominant vegetation to prolonged flooding.

Riverine forests - Forests found along sluggish streams, drainage depressions, and in large alluvial floodplains. Although associated with deepwater swamps in the southeastern United States, riverine forests are found throughout the United States in areas that do not have prolonged flooding.

THE HUMAN DIMENSIONS CHAPTER

The discussion of human dimensions helps restoration practitioners better understand how to select measurable objectives that allow for the appropriate assessment of the benefits of coastal restoration projects to human communities and economies. Traditionally, consideration of human dimensions issues has not been included as a standard component of most coastal restoration projects. Most restoration programs do not currently integrate social or economic factors into restoration monitoring, and few restoration projects have implemented full-scale human dimensions monitoring. Although some restoration plans are developed in an institutional setting that require more deliberate consideration of human dimensions impacts and goals, this does not generally extend to the monitoring stage. It is becoming increasingly evident, however, that decisions regarding restoration cannot be made solely by using ecological parameters alone but should also involve considerations of impacts on and benefits to human populations, as well. Local communities have a vested interest in coastal restoration and are directly impacted by the outcome of restoration projects in terms of aesthetics, economics, or culture. Human dimensions goals and objectives whether currently available or yet to be developed should reflect societal uses and values of the resource to be restored. Establishing these types of parameters will increase the public's understanding of the potential benefits of a restoration project and will increase public support for restoration activities.

While ecologists work to monitor the restoration of biological, physical, and chemical functional characteristics of coastal ecosystems, human dimensions professionals identify and describe how people value, utilize, and benefit from the restoration of coastal habitats. The monitoring and observation of coastal resource stakeholders allows us to determine who cares about coastal restoration, why coastal restoration is important to them, and how coastal restoration changes people's lives. The human dimensions chapter will help restoration practitioners identify:

1) Human dimensions goals and objectives of a project
2) Measurable parameters that can be monitored to determine if those goals are being met, and
3) Social science research methods, techniques, and data sources available for monitoring these parameters

This chapter includes a discussion of the diverse and dynamic social values that people place on natural resources, and the role these values play in natural resource policy and management. Additionally, some of the general factors to consider in the selection and monitoring of human dimensions goals/objectives of coastal restoration are presented, followed by a discussion of some specific human dimensions goals, objectives, and measurable parameters that may be included in a coastal restoration project. An annotated bibliography of key references and a matrix of human dimensions goals and measurable parameters are provided as appendices at the end of this chapter. Also included, as an appendix, is a list of human dimensions research experts (and their areas of expertise) that you may contact for additional information or advice.

The final four chapters of this manual are designed to provide readers with additional information that should enhance their ability to develop and carry out strong restoration monitoring plans. Chapter 15 reviews methods available for choosing areas or conditions to which a restoration site may be compared both for the purpose of setting goals during project planning and for monitoring the development of the restored site over time. Chapter 16 is a listing of generalized costs of personnel, labor, and equipment to assist in the development of planning preliminary cost estimates of restoration monitoring activities. Some of this information will also be pertinent to estimating costs of implementing a restoration project as well. Chapter 17 provides a brief description of the online review of monitoring programs in the United States. The database can be accessed though the NOAA Restoration Portal (http://restoration.noaa.gov/). This database will allow interested parties to search by parameters and methodologies used in monitoring, find and contact responsible persons, and provide examples that could serve as models for establishment or improvement of their own monitoring efforts. Chapter 18 is a summary of the major United States Acts that support restoration monitoring. This information will provide material important in the development of a monitoring plan. A Glossary of many scientific terms is also provided at the end of the document.

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CHAPTER 10: RESTORATION MONITORING OF COASTAL MARSHES

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INTRODUCTION

Coastal marshes are characterized as having erect, rooted, herbaceous plants that extend above the water surface (Figure 1). They are extremely productive systems that provide an abundance of food for wildlife that directly access the marsh and exporting large amounts of organic matter to estuaries and other coastal systems. Coastal marshes also provide a variety of feeding and breeding needs for invertebrates, fish, and other wildlife. The characteristics of the marsh vegetation determines the quality and quantity of habitat available to these animals (Adam 1990; Wilcox 1995). The high stem density typical of marsh vegetation provides excellent cover for invertebrates such as crustaceans, snails, worms, and insect larvae, allowing them to feed on algae and on one another while escaping predation from larger fish and wading birds (Havens et al. 1995; Harrel et al. 2001). If plant stems are too dense, however, even small animals may be restricted. Fish use marshes during high water periods to feed, spawn, and as nursery habitat (Keast et al. 1978; Boesch and Turner 1984; McIvor et al. 1989; Jude and Pappas 1992; Wilcox and Meeker 1992; Yozzo and Diaz 1999). Canada geese and some ducks feed on the tender shoots of emergent vegetation[4] (Prince et al. 1992). Wading birds and songbirds migrate along routes through highly productive coastal marshes, using the habitat as temporary feeding areas or as seasonal destinations (Weeber and Vallianatos 2000). The vertical structure provided by emergent plants provides perching areas for birds (Brawley et al. 1998) and allows snails and other animals to escape high water levels (Hamilton 1977). Although many species of mammals such as mink, otter, deer, and raccoons use coastal marshes for feeding and refuge, others such as nutria and muskrats are completely dependent upon them to provide the majority of their habitat needs (Evans 1970; Weller 1981; Wilcox and Meeker 1992).

Coastal marshes also support a host of human uses. They have tremendously high productivity

Figure 1. Emergent vegetation such as arrow arum (*Peltandra virginica*) is a characteristic feature of marshes. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

[1] 2205 Commonwealth Boulevard, Ann Arbor, MI 48105.
[2] 1305 East West Highway, Silver Spring, MD 20910.
[3] 646 Cajundome Boulevard, Lafayette, LA 70506.
[4] Geese can also negatively impact marsh revegetation efforts by feeding on young plants requiring that freshly planted areas be fenced off or otherwise protected from geese.

providing food and cover for a variety of commercially important species such as shrimp, crabs, crayfish, and a variety of finfish (Keefe 1972; Beck et al. 2003). They protect coastlines from erosion by buffering the energy of waves and currents (Möller et al. 2002). Coastal marshes can also temporarily store floodwater and absorb the impact of storm surges thereby protecting shoreline development from erosion (Zedler et al. 1986). They protect downstream and estuarine water quality by accumulating sediments and absorbing or transforming nutrients (Valiela et al. 1978; Heath 1992; Krieger 2003). Marsh sediments can also retain toxic chemicals and heavy metals providing additional estuarine water quality protection (Krieger 2003).

Coastal marsh habitats are dynamic and complex environments. At any one time, they may be wet or dry, aerobic or anaerobic[5], fresh or salty (Wiegert and Pomeroy 1981). The information presented in this chapter has been compiled from extensive literature reviews and input from experts in the fields of salt, brackish, and freshwater (including Great Lake) coastal marsh restoration and ecology. Although there are significant differences across the United States and its protectorates in some structural and functional characteristics and in the species that occupy these marsh types (as will be discussed), many characteristics between these systems are similar enough that they may be discussed together. Each section of this chapter will open with a general discussion of a particular structural or functional characteristic of coastal marshes. Specific examples from salt, brackish, and/or freshwater marsh will then be presented to add more detail for each particular habitat type that may not be generally applied to the others. Each section will conclude with recommendations on different sampling techniques or resources that can be used in monitoring restoration projects.

TYPES OF COASTAL MARSHES

Coastal salt, brackish, and freshwater marshes form a continuum from the ocean coasts inland (Figure 2). In tidal areas, changes in rainfall, river flows, and storm events can change the vegetation communities from freshwater to brackish or brackish to salt marsh and vice versa over time. When designing a restoration project and monitoring program in these areas it will be important for practitioners to have an understanding of each marsh type, how each type relates to one another, and how large physical processes influence the various plant and animal communities. In coastal areas that are not subject to such changes in salinity, such

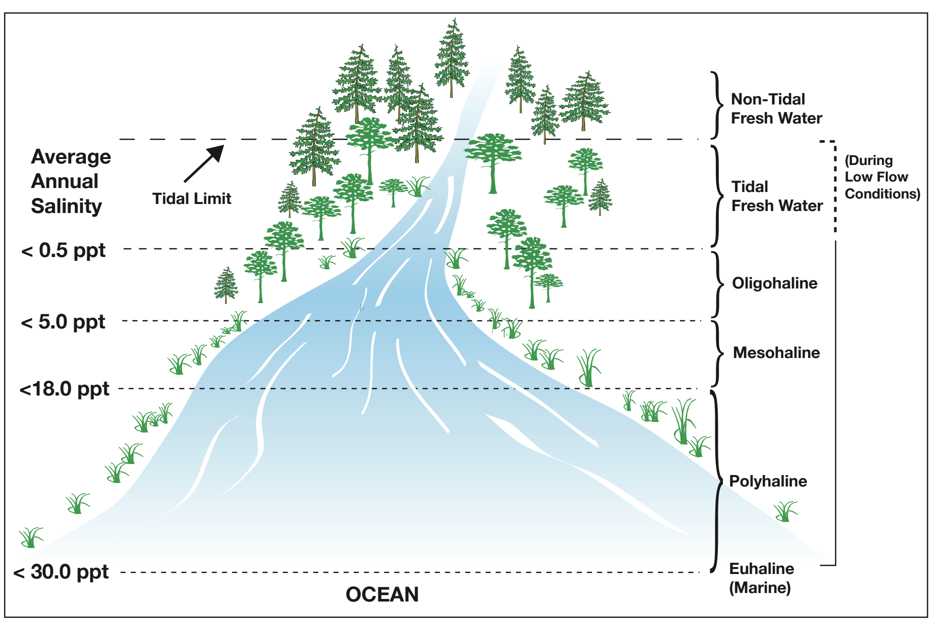


Figure 2. One method of classifying coastal marshes is by salinity. Salinity levels in parts per thousand (ppt) are shown on the left side of the graphic. The corresponding class of marsh is given on the right. The polyhaline and mesohaline marshes are referred to here as salt marshes. Oligohaline marshes are referred to as brackish. Maken from Odum et al. 1984.

[5] With or without oxygen respectively.

		Salinity Gradient		
		Fresh	Brackish	Salt
Hydrologic Regime	Tidal	• Ocean coasts • Gulf of Mexico	• Ocean coasts • Gulf of Mexico	• Ocean coasts • Gulf of Mexico
	Non-tidal	• Great Lake coastal marshes		

Table 1. Coastal marshes can be broken down into eight general classes based on salinity and hydrologic regime. Although, individual marshes may not fall neatly into these categories they are useful for introducing general marsh characteristics. Non-tidal, floating mat marsh communities may also be present along the northern coast of the Gulf of Mexico.

as Great Lakes coastal marshes, restoration practitioners can focus on a single marsh type.

For purposes of description, coastal marshes have been organized into several categories based on salinity and tidal regime (Table 1). Tidal salt, brackish, and freshwater marshes can be found on both ocean coasts of the United States and the northern shores of the Gulf of Mexico. The ocean and Gulf of Mexico have significant differences in tidal range and other characteristics that affect marsh ecology and will be further separated in some of the discussions below. Non-tidal, freshwater marshes occur along the shorelines of the Great Lakes. Non-tidal, floating mat marshes can also be found along the northern coast of the Gulf of Mexico. Much more is known about salt marshes than tidal freshwater marshes (Odum et al. 1984) or non-tidal coastal marshes, particularly those in the Great Lakes, which have only recently drawn the attention of researchers. Significant numbers of non-tidal freshwater, brackish, and salt marshes also occur in various inland portions of the United States. These, however, fall outside of the head-of-tide jurisdiction of the Estuaries Restoration Act of 2000[6] and are not discussed herein.

Salt Marshes

Salt marshes include all coastal marshes with salinities between 5.0 and 18.0 ppt[7] (Figure 2). The plant species in these ecosystems are mainly grasses, sedges, and other perennials tolerant of salty water and salty sediments. Salt marshes make up about 70% of all coastal marshes in the United States (Chabreck 1988). They occur along the intertidal shores of bays and estuaries on the ocean coasts and northern coast of the Gulf of Mexico (Chabreck 1988; Mitsch and Gosselink 2000). They are predominantly found, however, on the eastern and southern coasts of the United States, as the steep topography of the Pacific coastline is not favorable to extensive marsh development (Seliskar and Gallagher 1983; Chabreck 1988). Two subcategories of salt marshes often form on the Atlantic coast of the United States, high marshes and low marshes. High marshes form above the mean water level, low marshes occur below mean water level. Tidal ranges in the Gulf of Mexico are not large enough to create distinct high and low marshes (Odum 1988). The semidiurnal tidal ranges of the Pacific Northwest are also not conducive to high and low marsh development.

Brackish Marshes

Brackish marshes contain a mixture of salt and freshwater and are found farther inland than salt marshes in sounds, rivers, and tidal creeks. Brackish marshes can also be referred to as oliogohaline (salinities between 0.5 and 5.0 ppt - Figure 2). The plants and animals found in brackish marshes are a mix of both fresh

[6] The impetus for the publication of these documents.
[7] Parts per thousand.

and saltwater species able to tolerate periodic tidal flooding and associated changes in salinity levels (Cowardin et al. 1979). The vegetative communities within brackish marshes are determined by the relative contribution of fresh- and saltwater. Vegetative community shifts can occur in brackish systems as the result of either higher than normal, or lower than normal annual rainfall. In some cases, if brackish marshes receive additional freshwater input, it can promote the growth of invasive species such as the common reed (*Phragmites australis*, hereafter *Phragmites)* that may outcompete local plant species and dominate the vegetation community, changing some of the characteristic structure and function of brackish marshes (Able and Hagan 2000).

Freshwater Marshes

Freshwater marshes are found along the margins of the Great Lakes or within river systems that discharge to an ocean or the Gulf of Mexico but have water and soil salinities below 0.5 ppt (Odum et al. 1984). Extensive tracts of tidal freshwater marshes often develop in areas with a major source of freshwater, a high tidal amplitude (i.e., > 0.5 m), and a basin morphology that constricts and magnifies tides in upstream portions of the estuary (Odum et al. 1984). In the United States, these conditions occur most often along the coasts of the Atlantic Ocean and Gulf of Mexico. The bulk of the material presented here concerning freshwater tidal marshes is taken from studies conducted on those coasts. Freshwater tidal marshes do occur on the Pacific coast, especially in the region of San Francisco Bay and in the Columbia River, but they are relatively rare in comparison and are not as thoroughly studied as those on the eastern and southern coasts. Non-tidal coastal freshwater marshes are found along the fringes of the Laurentian Great Lakes[8]. These are not exposed to regular lunar tides but are subject to random water level fluctuations caused by seiches[9] as well as seasonal and annual changes in lake level.

HUMAN IMPACTS TO MARSHES

Coastal marshes of all types are subject to a wide variety of natural disturbances and impacts including:

- Fire
- Herbivory
- Deposition of organic debris
- Salt water intrusion
- High (and variable) soil salinity in tidal areas
- Low nutrient availability in internal marsh areas
- Anaerobic soils
- Hurricanes, and
- Burial with excess sediments (Bertness and Ellison 1987; Titus 1988; Adam 1990; Flynn et al. 1995; Guntenspergen et al. 1995; Nyman and Chabreck 1995; Allison 1996; Taylor et al. 1997; Valiela et al. 1998)

Fluctuating water levels can also stress plants by inducing:

- Temperature shock
- Changes in photoperiod
- Mechanical stress from waves and currents, and
- Deposition of sediments on the surface of leaves (Adam 1990)

In general, coastal marshes have adapted over time to these stressors and, barring sudden

[8] Non-tidal freshwater marshes may be found in other areas of the US as well. These systems, however, fall outside of the jurisdiction of the Estuary Restoration Act of 2000 and, as such, are not specifically addressed here. Many of the structural and functional characteristics of these systems may, however, still apply for restoration monitoring purposes.

[9] Wind-driven tides. They often have the effect of piling water up on the down wind side of the lake. Once winds stop blowing water sloshes back and forth throughout the basin creating water level fluctuations on either end.

vertical land moves caused be earthquakes or tsunamis, are generally able to rebound after a year or more depending on the type and level of impact.

Human-induced impacts are, however, often more difficult for marshes to recover from and can lead to complete loss of entire marshes. Common human impacts to coastal marshes in the United States include:

- Urban development
- Road construction
- Industrial and agriculture run-off
- Conversion to upland
- Logging
- Damming
- Diking, and
- Ditching (Seliskar and Gallagher 1983; Gosselink 1984; Odum et al. 1984; Page et al. 1995; Maynard and Wilcox 1997; Portnoy and Giblin 1997; Portnoy 1999; Hester and Mendelssohn 2000; Williamson and Morrisey 2000)

Early changes in land cover from forested to agriculture caused large sediment and nutrient inputs to coastal marshes. Later conversion to urban land uses further increased nutrient inputs through wastewater discharge (Chapman 1973). Pollution resulting from urban runoff from bridges, roads, industrial areas, farms, lawns and, golf courses (pesticides and fertilizers) has also been a major impact to coastal marshes (Hester and Mendelssohn 2000; Stewart et al. 2000; Lougheed et al. 2001).

Regional Examples

In many southern states, tidal freshwater areas have been diked for use in agriculture. Many of these dikes remain intact and are still used for rice production or management of the marsh for waterfowl (Odum et al. 1984). Along the gulf coast of Louisiana marsh losses have been attributed to:

- Saltwater intrusion from sea level rise and canal construction
- Decreases in nutrient input and sediment deposition due to construction of dams and flood control levees
- Dredging of gas and oil exploration canals and associated spoil bank creation, and
- Erosion by waves along exposed shorelines (Turner 1997; Day et al. 2000; Day et al. 2001; Gosselink 2001; Turner 2001)

Tidal freshwater marshes on the east coast were also originally altered by the conversion of adjacent forested areas to agriculture (Odum et al. 1984). That changed the amount of runoff and sediments entering the marshes. In the Great Lakes basin, most coastal marsh losses have been due to diking and drainage for agriculture (Jude and Pappas 1992; Edsall and Charlton 1997).

The Impact of Diking

Tidal marshes that have been diked and drained pose special problems for restoration[10]. Soils in diked and drained marshes are constantly aerated, increasing the decomposition of soil organic matter. Compaction and subsidence of the sediment surface and changes in sediment chemistry such as decreases in pH can also occur and impact plant growth (Portnoy 1999). As a result, tidal marshes that have been diked for several decades may have elevations much lower than the original elevation at mean sea level. In these cases, dikes cannot simply be breached to re-introduce tidal flushing of the system to re-create the marsh. The area would become open water instead. Efforts must first be undertaken to increase the substrate elevations closer to mean sea level for appropriate marsh communities to develop (Pezeshki et al. 1992; Wilsey et al. 1992; Wagner 2000).

[10]See Restoration Ecology volume 10 issue 3, an entire volume dedicated to dike-breaching restoration projects.

An additional problem with restoring marshes that have been diked for long periods of time is that, due to increased oxygen supply, soil chemistries can be drastically altered. Large concentrations of nutrients such as ammonium, phosphate, and iron may suddenly become mobilized from the soil upon reflooding and removed from the marsh with tidal flushing. These effects, however, will likely be short term and may enhance the growth of marsh plants (mobilization without flushing) but may also lead to nutrient enrichment in downstream areas (Portnoy and Giblin 1997).

Many of the impacts mentioned above have completely altered the structural and functional characteristics of marshes. For example, when marshes are channeled, diked, leveed, or dredged, fish become isolated from historic spawning and nursery habitats. Material export as well as nutrient and sediment dynamics are also disrupted (Wilcox 1995; Lathrop et al. 2000). Streams that once fed marshes with sediments and nutrients are often diverted around diked marshes and their material load is then deposited directly into downstream water bodies, reducing water quality. Dams for mills, irrigation, and flood control have also cut off normal tidal exchange altering sedimentation rates, nutrient inputs, and water exchange (Gosselink 1984). These changes, in turn, affect other aspects of water chemistry such as salinity and oxygen concentration and can reduce the diversity of vegetation communities (Odum et al. 1984; Reed and Rozas 1995). Changes in the dominant vegetation community of the marsh can lead to changes in the animal communities that use them as well (Adam 1990; Wilcox and Meeker 1995).

Sea Level Rise

Rising sea levels, in conjunction with shoreline stabilization and diking of tidal marshes, have serious implication for the future of coastal marshes, and salt marshes in particular. Armoring the coastline with riprap or sea walls to protect urban or residential development impacts coastal marshes by directing the erosive energy of waves downward, eroding away plants, less mobile animals, sediments, and seed banks, thus reducing the possibility of vegetation to regenerate naturally (Tsai et al. 1998; Davis and Streever 1999). As sea levels rise in response to global climate change and more coastal development is threatened, the extent of this problem will likely increase. In addition, as sea levels rise areas that are salt marshes today may become replaced by seagrass habitats or open water (DeLaune et al. 1983a). Brackish and freshwater marshes will be replaced with more salt-tolerant marsh species as salt marshes move inland (Boesch et al. 1994; Baldwin and Mendelssohn 1998). If dikes, abundant in many coastal areas, are not breeched to allow for tidal exchange and the movement of salt marshes inland, salt marshes may disappear from some coasts completely. This would have disastrous consequences on estuarine-dependent species and waterfowl populations, as well as on many other economically important species that use them (Park et al. 1993).

Invasive Species

One of the largest and most difficult to address impacts humans have had on coastal marshes is the introduction of invasive species. Through a variety of intentional and unintentional means, humans have introduced new plant and animal species wherever they have traveled. Plant and animal species new to an area may cause problems in the community by outcompeting native species. Several terms for these organisms have been used (‘non-native’, ‘exotic’, ‘invasive’) and are often used interchangeably. Some literature will, however, draw distinctions between these categories. ‘Non-native’ species are plants or animals that were not historically found in a particular area. They may be from a different state, coast, or country. ‘Exotic’ refers to those species historically not found in the

United States. These most often arrive in ballast water from ships or through other unintended mechanisms such as escaping from cultivation, aquaculture, fishing bait, or aquariums (Wilcox 1989; Mills et al. 1993). Some, such as carp (*Cyprinus carpo*), have been intentionally introduced (Mills et al. 1993). Only a small percent of species that enter an area ever cause any major problems in their new environment (Lodge 1993a; Lodge 1993b; Williamson 1996). 'Invasive species', on the other hand, may be non-native, exotic, or even native plants that for some reason suddenly spread uncontrollably through an area to the detriment of other species.

Some common examples of invasive species that cause problems in coastal marshes include plants such as:

- Smooth cordgrass (*Spartina alterniflora*) (native on the east coast, invasive on the west)
- *Phragmites*
- Japanese dodder (*Cuscuta japonica*)
- Pepperweed (*Lepidium latifolium*)
- Purple loosestrife (*Lythrum salicaria*)
- Hybrid cattail (*T.* x *glauca*)
- Chinese tallow (*Sapium sebiferum*), and
- Reed canary grass (*Phalaris arundinacea*)

Animals can also be invasive. Some notable examples include:

- Zebra mussels (*Dreissena polymorpha*)
- Nutria (*Myocastor coypus*)
- Common marsh periwinkle (*Littorina irrorata),* and
- Asian swamp eels (*Monopterus albus*)

The effects of *Phragmites* and purple loosestrife are briefly described below to illustrate the impact invasives can have on restoration monitoring programs.

Figure 3. Large stands of *Phragmites* in tidal areas can indicate conditions of reduced tidal exchange. Photo by Louis Kane, Barnstable County, MA. Photo from the NOAA Photo Library. http://www.photolib.noaa.gov/habrest/r0011812.htm.

Phragmites

Phragmites is a common invader of brackish and freshwater coastal marshes (Figure 3 - Windham and Lathrop 1999; Able and Hagan 2000). It is a tall, perennial grass that grows at or above mean water level in freshwater and brackish marshes (Ailstock et al. 2001). It spreads into new areas by wind- and water-borne seeds and vegetative fragments carried on construction equipment. Once established, it grows extensive networks of runners along the sediment surface and spreads quickly. Although *Phragmites* is native to North America (see review in Chambers et al. 1999), it has recently begun to form extensive, monospecific stands in wetlands throughout the United States, limiting plant species richness (Chambers et al. 1999), impacting wildlife habitat (Weinstein and Balletto 1999; Weinstein et al. 2000; Teal and Weinstein 2002; Currin et al. 2003), and altering nutrient cycling dynamics (Meyerson et al. 1999).

The conversion of dominant marsh vegetation from one vegetation type to another can change how fish and other animals use the marsh. Due to its large size and high stem density compared to other types of marsh vegetation, *Phragmites* can restrict the movements of fish and crustaceans into feeding areas (Roman 1978), thus limiting secondary productivity. In a study comparing the interaction of fish and crustacean use of smooth cordgrass and *Phragmites* dominated brackish marshes in southern New Jersey, researchers found that the abundance of mummichogs

(*Fundulus heteroclitus*) and spotfin killifish (*Fundulus luciae*) was significantly greater at smooth cordgrass sites than in *Phragmites* marshes. Blue crabs (*Callinectes sapidus*) and grass shrimp (*Palaemonetes* spp.) were also more abundant in smooth cordgrass dominated areas, whereas the non-native Harris mud crab (*Rhithropanopeus harrisii)* was most abundant within *Phragmites* dominated areas. *Phragmites* also negatively affected larval and small juvenile fish but showed little or no affect on larger fish and crustacean populations (Able and Hagan 2000), possibly because these larger animals are restricted from marsh surfaces by other factors such as hydroperiod.

Differences in the type and amount of macroinvertebrates have also been observed between smooth cordgrass and *Phragmites* dominated brackish marshes in the Mullica River (0-17 ppt salinity) in southern New Jersey (Angradi et al. 2001). Total macroinvertebrate density and mean taxa richness were significantly greater in the smooth cordgrass marsh compared to the *Phragmites* marsh. The relative abundance of the three most abundant taxa was also lower in the *Phragmites* marsh. Dense stands of *Phragmites* have been shown to lower bird species richness by excluding wading birds and facilitating the replacement of marsh specialists with generalist bird species (Benoit and Askins 1999). Dense *Phragmites* stands can also greatly diminish resting, feeding, and breeding areas for migratory waterfowl (O'Shea, cited in Chambers et al. 1999). Compared to saltmeadow cordgrass (*Spartina patens*) and salt grass (*Distichlis spicata*) communities, *Phragmites* has significantly greater live aboveground biomass than the other two species (Windham and Lathrop 1999). Soil salinities, water level, and microtopography are also all significantly lower in the *Phragmites* stands (Windham and Lathrop 1999). These results imply that water quality and nutrient cycling functions between these marshes may be different as well.

Some argue, however, that *Phragmites* is not all bad. Despite the list of affects on animals given above, other research has found no significant difference in the utilization of *Phragmites* versus smooth cordgrass marshes in terms of abundance or biomass, nor between the total number of species using the two marsh types (Meyer et al. 2001). One study of marsh nekton in Delaware Bay also suggests that *Phragmites* may actually be an important component of the estuarine food web (Wainright et al. 2000). Dense stands of *Phragmites* also do not seem to have a significant impact on the density, diversity, and productivity of insects in freshwater marshes (Ailstock et al. 2001). Due to its large size, *Phragmites* stores large amounts of nitrogen in its stems and leaves. Slow decomposition of these structures contributes to the accumulation of organic matter in marsh soils (Ailstock et al. 2001) and potentially high sedimentation rates (Harrison and Bloom 1977). In comparison to cattails, a plant *Phragmites* often replaces in freshwater and brackish marshes, *Phragmites* stores more nitrogen and accumulates greater amount of detritus in marsh soils. Detrital communities are somewhat negatively affected by this change but not necessarily enough to warrant control of *Phragmites* (Findlay et al. 2002). These characteristics, coupled with a strong root structure that holds wetland sediments in place (Ailstock et al. 2001), have caused *Phragmites* to be viewed favorably in some locations such as portions of coastal Louisiana where, as the result of physical or biological stressors, few other plants will grow (Stevenson et al. 2000).

Purple loosestrife

Purple loosestrife is a tall emergent plant with showy purple flowers. It was brought to the United States in the mid to late 1800s (Stuckey 1980), quickly spread across the continent, and is now found in all of the lower 48 states (Blossey et al. 2001). Purple loosestrife provides little to no food or cover value for most wildlife (Rawinski

Figure 4. Purple loosestrife dominates this marsh. Photo courtesy of Bernd Blossey, Cornell University. http://www.invasive.org/

1982) and can form dense, monospecific stands (Figure 4), displacing native vegetation to which animals are adapted (Wilcox 1995). Purple loosestrife produces an abundance of seeds that stay viable in the seed bank for several years (Rawinski 1982). Several methods of controlling it have been tried including hand pulling, flooding, and herbicide treatments, all with little success (Wilcox 1995). Recent experiments with biologic control, however, have shown promise at significantly weakening established plants without damaging other more desirable species[11] (Stamm-Katovich et al. 2001; Hoey 2002).

Careful selection of restoration project goals concerning the removal of invasives is particularly important. If, for example, the goal of a particular project is the simple reduction of purple loosestrife, a variety of methods to do so might temporarily work (Morrison 2002). If the goal of the restoration is to improve species richness, however, then simple removal of purple loosestrife alone may not be sufficient as removal alone may create a niche in the marsh plant community for another pest species, such as reed canary grass to invade (Morrison 2002).

These examples of purple loosestrife and *Phragmites* illustrate the point that both the positive and negative qualities of invasive species need to be taken into consideration when setting restoration and monitoring projects goals. In some areas where nothing else will grow due to severely altered hydrology, subsidence, or some other disturbance, invasive species such as *Phragmites* may be the best bet to get vegetation established and restore at least some marsh functions until the disturbance can be brought under control, if at all (Stevenson et al. 2000). In other areas where the establishment of a greater diversity of native plant species is possible and desirable, then efforts to control the spread of invasives should be undertaken.

[11] http://www.npwrc.usgs.gov/resource/1999/loosstrf/loosstrf.htm.

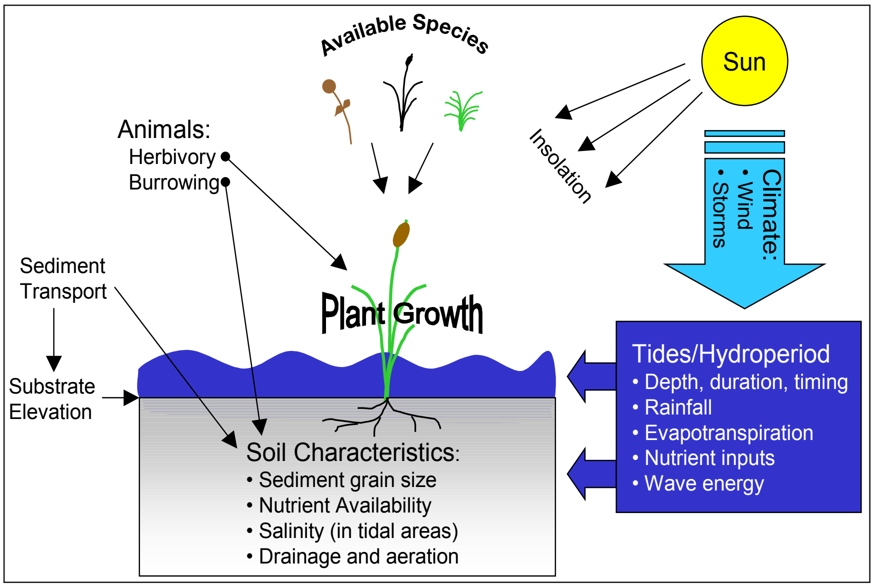
STRUCTURAL CHARACTERISTICS OF COASTAL MARSHES

Coastal marshes of the United States occur across a wide range of climatic conditions and in a variety of physical settings. All of them, however, share several important structural and functional characteristics that make them 'marshes.' Characteristics such as water velocity and source, tidal regime or hydroperiod, wave energy, sediment grain size, soil nutrient content, and substrate elevation and topography largely determine which particular plant species are able to grow in any given area (Figure 5). These factors, and others described in this chapter, represent the fundamental structural characteristics that allow a marsh plant community to develop. In addition to determining which plant species will grow, many of the functions that marshes perform are dependent upon these structural characteristics as well.

Structural characteristics are often manipulated during restoration projects to bring about changes in function. Therefore, structural characteristics should be considered when developing a restoration monitoring program, particularly in the short-term. For example, a goal of a restoration project may be to reintroduce tidal flooding to a diked coastal marsh in order to facilitate nutrient transformation, thus helping protect estuarine water quality. The ability of a marsh to perform this function depends, in large part, upon the elevation of the substrate relative to mean water level. Water level fluctuations that periodically inundate and expose the soil surface are also needed for higher nutrient transformation rates to occur. Quite often, however, the soils of diked marshes have subsided and/or been compacted so that substrate elevations are much lower than when the marsh was originally diked. Thus, the substrate elevation must be raised, or water levels increased slowly over time. Otherwise the relationship between water level and sediment elevation will not be appropriate for the marsh to perform the desired function. Marsh elevation and water level fluctuations will need to be monitored prior to, during, and immediately after project implementation to determine whether or not the marsh will be capable of performing the desired functions or if additional adjustments in sediment elevation will be needed.

The structural characteristics of coastal marshes determine which plant species are able to grow

Figure 5. Some of the structural and functional characteristics that influence plant growth. These characteristics and others are explained throughout the chapter as they relate to restoration monitoring. Graphic by David Merkey, NOAA Great Lakes Environmental Research Lab.



and influence a variety of functions performed by coastal marshes as well. Coastal march structural characteristics are broken into four categories, any or all of them may be monitored as part of a restoration project. These characteristics are:

Biological
- Habitat created by plants

Physical
- Acreage of marsh
- Sediment
  - Grain size
  - Organic content
  - Sedimentation
- Bathymetry/topography
  - Elevation and microtopography
  - Slope geomorphology

Hydrological
- Climate
- Tides/hydroperiod
- Water sources
- Current velocity
- Wave energy

Chemical
- Nutrient concentration
- Salinity, toxics, redox, DO

Each of these and its relevance to coastal marsh ecology and restoration monitoring is explained below.

BIOLOGICAL

Habitat created by plants[12]

The emergent, herbaceous vegetation that characterizes coastal marshes provides the bulk of the physical habitat used by fish, birds, invertebrates, and mammals (Adam 1990; Wilcox 1995). Characteristics of the plant community include:

- Stem density
- Plant height
- Species composition
- Percent cover, and
- Amount of edge to open water

All affect how, and which, animals use marsh habitats (Gosselink 1984; Zimmerman and Minello 1984; Browder et al. 1989; Wilcox and Meeker 1992; Wilcox 1995; Teal and Howes 2001). For example, the abundance of epibenthic[13] invertebrates is significantly higher in vegetated marshes with 80% or more plant cover than areas with less cover (Scatolini and Zedler 1996). Although, the mere presence of vegetation is often enough to increase the number and diversity of animal species that inhabit a particular area (Wilcox 1995 and literature cited therein). Which plant species are present, their growth form, decay rate, stem density, height, and interspersion with open water and other habitats also determine the type, quality, and amount of habitat marshes provide.

Marsh vegetation can be divided into two categories, persistent and non-persistent, based on the speed with which it is decomposed and nutrients cycled back into the system (Cowardin et al. 1979). Persistent marsh plants are those that are visible above the sediment surface throughout the year (Figure 6). Non-persistent marsh plants are those that decompose quickly when the plants die, leave no evidence aboveground outside of the growing season (Odum and Heywood 1978). They may also not be apparent during large parts of the year or even portions of the growing season. Wild rice, for example, can grow up to 3 m tall and dominate marsh vegetation communities in midsummer where no vegetation was even apparent in late spring (Odum 1988).

On the Atlantic and Pacific coasts of the United States, high marshes are often dominated by

[12]This section describes some of the characteristics of coastal marsh plant communities and methods that can be used to monitor them. Examples of how animals use plant communities are discussed in the *Functional Characteristics of Coastal Marshes: Habitat* section below.

[13]Living on the surface of the sediment.


Figure 6. Cattails (*Typha spp.)* are an example of persistent vegetation. These two photos were taken of the same marsh in summer and spring of the following year. Photos by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

persistent vegetation and low marshes by non-persistent (Odum 1988; Khan and Brush 1994). Tidal ranges in the Gulf of Mexico are not large enough to create distinct high and low marshes, nor are high and low marshes found in the non-tidal Great Lakes. Marshes in these areas can be made up of persistent or non-persistent vegetation or a mix of the two depending on the particular species present, water depth, and characteristics of the substrate. Whether a marsh is dominated by persistent or non-persistent species has implications for how wildlife use the marsh, certain water quality and nutrient cycling functions as well as the type and timing of sampling that can be done as part of monitoring.

The relationship that different types of marshes have with other habitats also affects the habitat function of coastal marshes. Salt and freshwater marshes differ in their relationship with submerged aquatic vegetation (SAV) habitats[14]. In freshwater areas, SAV is a common component of marshes in deeper areas and large SAV habitats often occur adjacent to marshes (Figure 7). Salt marshes, on the other hand, generally lack dense beds of SAV in adjacent, shallow subtidal areas (Yozzo and Smith 1998). This difference changes the way animals use marsh habitats. Estuarine animals such as mummichogs often stay in salt marshes during low tide by sheltering in pools (Yozzo and Smith 1998). In freshwater areas, animals tend to leave the marsh completely and move to adjacent SAV habitats (Rozas and Odum 1987b; Rozas and Odum 1987a; Yozzo and Smith 1998). As these areas provide similar levels of protection from predation and food availability as marshes do without the added stress of high salt concentrations and potential desiccation (Yozzo and Smith 1998).

Salt marshes

Although salt marshes may have a very high number of algal species within them, the diversity of vascular species is quite low compared to freshwater marshes (Wiegert and Pomeroy 1981). Some of the common dominant plant species of estuarine salt marshes along the Atlantic coast and the coast of the Gulf of Mexico include:

Smooth cordgrass
Saltmeadow cordgrass
Big cordgrass (*S. cynosuroides*), and
Black needlerush (*Juncus roemerianus*)

On the Pacific coast, California cordgrass (*Spartina foliosa*) is the dominant species with:

Salt grass
Sea blite (*Suaeda californica*), and
Arrow grass (*Triglochin maritima*)

[14]See Chapter 9: Restoration Monitoring of Submerged Aquatic Vegetation.

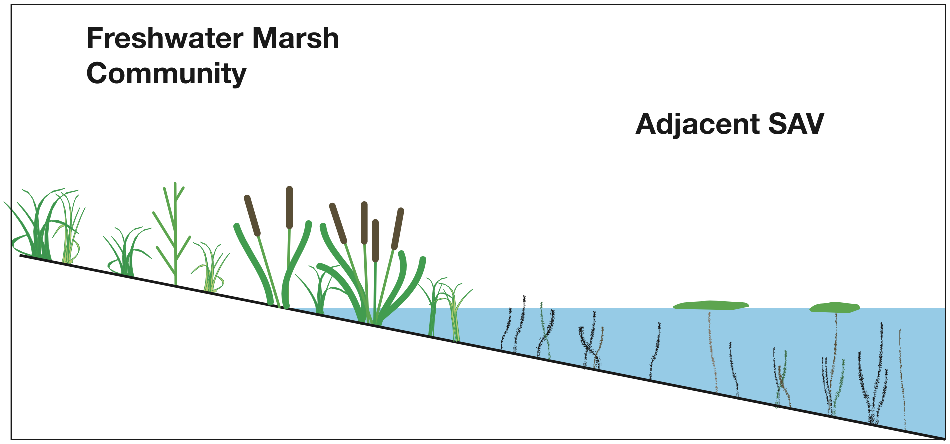


Figure 7. In freshwater areas, SAV grows adjacent to and sometimes within marsh communities. Modified from Maynard and Wilcox 1997.

(Cowardin et al. 1979; Seliskar and Gallagher 1983; Adam 1990 and literature cited therein)

Other common species of salt marshes include:

Saltwort (*Batis maritima*)
Pickelweed, and
Salt marsh plantain (*Plantago maritima*) (Cowardin et al. 1979; Adam 1990)

These plants and the various forms of algae found in salt marshes provide organic matter that supports a host of invertebrates, fishes, and resident and migratory birds (Kwak and Zedler 1997). Smooth cordgrass seeds and rhizomes, for example, are consumed by birds such as ducks, geese, and shore birds (Vivian-Smith and Stiles 1994). When plants die, leaves and stems settle on the sediment surface where they are broken down by bacteria and fungi. This detritus[15] is then eaten by bottom dwelling scavengers such as worms, fish, and crabs (Darnell 1967; Odum 1980).

Of the species listed, smooth cordgrass is the most important species in salt marshes of the eastern United States. Two growth forms are commonly found throughout its range. A tall form that can grow up to 3 m tall is found along tidal creeks and in low marsh areas. A short form, normally 10-40 cm tall, grows on upper levees and in pans between tidal creeks (Adam 1990). The short form is stunted from a general lack of available nutrients in upper levees and pans (Shea et al. 1975). Smooth cordgrass is not native to the west coast and is considered an invasive species there.

Seedling survival in salt marshes is extremely low (~5% - Allison 1996). The successful establishment and expansion of salt marshes is therefore dependent upon the few individuals that do survive, spreading by vegetative growth. Huge sections of marsh can in fact be made up of single, interconnected clones (Miller and Egler 1950; Ranwell 1964; Redfield 1972; Neiring and Warren 1980; Hartman 1988). Unlike freshwater marshes that have large, diverse seed banks, the seed banks of salt marshes have generally low density of seeds and low diversity of species (Hartman 1988). This is due, in part, to the dominance of these habitats by long-lived perennial species (Hopkins and Parker 1984).

Brackish marshes

Some plant species of tidal brackish low marshes include:

Marshhay cordgrass (*Spartina patens*)
Bulrushes (*Scirpus* spp.)
Salt grass (*Distichlis spicata*)
Salt meadow cordgrass
Spikerushes *(Eleocharis* spp.)
Broad-leaved cattail (*Typha latifolia*)
Narrow-leaved cattail (*T. angustifolia*)
Black rush (*Juncus roemerianus*)

[15]The mix of decayed plant material and nutrient-rich microorganisms.

Pickerelweed (*Pontederia cordata*)
Three-cornered grass (*Scirpus olneyi*)
Smooth cordgrass (*Spartina alterniflora*)
Widgeon-grass (*Ruppia maritima*)
Phragmites, and
Southern wild rice (*Zizaniopsis miliacea*) (Cowardin et al. 1979; Adam 1990)

Plant species found in brackish high marshes also often include smooth cordgrass and saltmeadow cordgrass (Adam 1990). On the northwest Pacific coast, Lynbei's sedge (*Carex lyngbei*) is also a common dominant species of brackish marshes (Seliskar and Gallagher 1983). Of the species listed, marshhay cordgrass is the most important species in brackish marshes of the Atlantic Ocean and Gulf of Mexico (Chabreck 1970). This species makes up over 24 percent of the vegetative composition and almost doubles the values for its nearest competitor, smooth cordgrass in coastal brackish marshes in Louisiana (Chabreck 1970).

Freshwater marshes

On the coasts of the Atlantic Ocean, Gulf of Mexico, and in the Great Lakes, freshwater marshes with persistent vegetation are often dominated by:

Narrow-leaved cattail
Sedges (Family Cyperaceae)
Phragmites, and
Southern wild rice

On the Pacific Coast, cattail (*T. domingensis*) and the California bulrush (*Scirpus californicus*) are common dominants. There are also a variety of broad-leaved persistent emergents common to these systems such as:

Purple loosestrife
Dock (*Rumex* spp.), and
Waterwillow (*Decodon verticillatus*) (Cowardin et al. 1979)

Freshwater marshes with non-persistent vegetation often include species such as:

Arrow arum (*Peltandra virginica*)
Wild rice (*Zizania aquatica*)
Pickerelweed
Arrowheads (*Sagittaria spp*.), and
Smartweeds (*Polygonum* spp.)

Due to lower levels of environmental stress, freshwater wetlands have a much greater diversity of species than salt or brackish water marshes (Odum et al. 1984). In tidal areas, this diversity is derived in part from a large, diverse seed bank with an abundance of annual species (>85% of the seed bank - Leck and Graveline 1979; Parker and Leck 1985; Leck and Simpson 1987). In coastal marshes of the Great Lakes, however, the seeds of perennial species tend to be more dominant (Keddy and Reznicek 1982). The large seed bank diversity of freshwater marshes may make construction and restoration easier as there may not be as great a need for planting if the hydroperiod can be manipulated to allow germination from the seedbank to occur (Odum 1988).

Potential variability

Coastal marsh plant communities can be very dynamic. Seasonal and annual changes in climate and large, coastal storms play an important role in these dynamics. The vegetation of salt and brackish marshes, for example, is adapted to a range of soil salinities that can change as a result of differences in climate-driven freshwater flows (Zedler et al. 1986). The vegetation of freshwater marshes, on the other hand, is adapted to and dependent upon periodic, water level fluctuations also related to climate (Keddy and Reznicek 1986; Wilcox 1995; Wilcox and Meeker 1995). Hurricanes and changes in land use practices can completely alter marsh vegetation communities from salty to fresh and vice versa (Clark and Patterson 1985).

Freshwater marshes, in particular, exhibit considerable changes in vegetation both seasonally and from one year to the next (Odum et al. 1984; Odum 1988; Leck and Simpson

1995; Wilcox et al. 2002). A common pattern is for broadleaved emergents to dominate in the spring and early summer. By late summer, grasses and other herbaceous vascular plants come to dominate (Odum 1988; Yozzo and Diaz 1999). Because of the inter-annual variability of Great Lake's water levels, the marshes that are directly dependent on them also vary from year to year. If water level changes from one year to the next, slight differences in species composition may result. If water level changes are more drastic, entire habitats may change from marsh to upland or submerged aquatic vegetation depending on the direction of the change (Wilcox et al. 2002).

Sampling and Monitoring Methods

Some parameters that have been suggested for use in monitoring restoration (revegetation) projects include species composition, percent survival over time, percent cover relative to wetland area, rate of expansion, ratio of vegetation to open water, and percentage of gaps that have grown in with vegetation (Levine and Willard 1990). Stem density and plant health/survival are also commonly measured parameters in restoration monitoring projects. Measurements should be conducted quarterly for the first year, and in the early summer and early fall of the following two years (Levine and Willard 1990). Monitoring at a high frequency soon after implementation of the restoration helps ensure that plants are successfully germinating and becoming established. If they are not, adaptive management strategies may be identified and implemented to assist the process (Thayer et al. 2003). Additional monitoring should also take place after large storms as, in certain coastal areas, these can be extremely stressful on marshes (Levine and Willard 1990).

Numerous sampling and measurement methods are available to evaluate plant communities in marshes. Examples of remote sensing and line intercept methods are presented below but a variety of other methods exist such as quadrat sampling that allows for calculation of plant density and % cover. Practitioners should choose among available techniques based on a number of factors such as the size/accessibility of their project area, the type of technique(s) previously used in their area (the data from which might be used for comparison), the particular aspect of plant community that will be measured (aerial extent, productivity/biomass, species richness/diversity/etc.), and the particular statistical question(s) to be answered. Therefore, a statistician should be consulted during the planning stages of a restoration project to help practitioners determine appropriate sampling strategies and techniques for their restoration project. The second appendix of this chapter, *Appendix II: Review of Technical Methods Manuals* provides additional resources on sampling and planning issues.

Remote sensing - Remote sensing, in the form of aerial photographs or satellite imagery, can be a very effective tool for monitoring changes in the characteristics of marsh vegetation such as % cover, dominant species, plant health, productivity, and biomass over very large areas (Gross 1987; Thomson et al. 1999; Shuman and Ambrose 2003; Berberoglu et al. 2004). Satellite imagery can also be gathered at regular intervals during a growing season and used to derive estimates of primary productivity for a whole marsh (Hardisky et al. 1984; Gross 1987). Remote sensing data is most useful when it has been ground-truthed by physically sampling plots that have been remotely sensed. This allows for a greater degree of certainty when interpreting remotely sensed data and verifies that what is seen in the imagery is what is actually present on the ground (Windham and Lathrop 1999).

Line intercept - Line intercept sampling is a measurement of plant communities along straight lines (usually a tape measure, cord, or length of rope). Lines are laid out over a gradient such as upland to open water and any plant that touches the line is recorded. The number of replicate lines needed depends, in part, on the complexity and size of the marsh being studied. This method of sampling can be used to quantify both the distribution and abundance of plant species within a marsh. The placement of permanent stakes or other markers to identify the beginning and end of the line may be used if particular areas are to be resampled over time[16]. In Laguna Atascosa National Wildlife Refuge in southern Texas, the line intercept method was used to analyze the change in plant species over time in salt and brackish marshes (Judd and Lonard 2002). Each marsh was sampled using three line transects in 1996 and 1999 to compare plant species variation between transects, years, and marshes. Although no difference in species diversity was noted from one sample time to the next, the vegetation was clearly zoned along an elevation gradient. Studies such as this can be used to help identify which plant species should be planted where during a marsh restoration.

PHYSICAL

The physical characteristics of marshes such as the size of the marsh, sediment grain size and organic content, and topography/bathymetry are separated from the hydrologic characteristics of marshes discussed in a later section. Marsh size is included as a physical characteristic as it determines the limits of the area under study, how much habitat is available to wildlife, and helps identify all of the potential inputs to the system. Soil characteristics such as grain size and organic content direct the types of restoration strategies that can be considered. Marsh topography/bathymetry determine marsh plant community distribution and marsh function. Although many hydrologic characteristics of marshes are ‘physical’ in nature, they are important enough to warrant a separate discussion.

Size

In general, large marshes with many different vegetation communities provide higher quality habitat for a larger number of species than do smaller, less complex wetlands (Hemesath and Dinsmore 1993; Merendino and Davison 1994). This is particularly true for birds as very few species use marshes as small as 0.10 ha. The number of bird species dramatically increases with marsh size, particularly in the 1 to 5-ha range (Watts 1992). That does not mean that smaller marshes are unimportant. Small marshes provide critical amphibian habitat, maintain landscape-level diversity, and provide recruits to new marsh areas following disturbance (Semlitsch and Bodie 1998). If a large, diverse, productive marsh is severely disturbed or degraded, smaller marshes, even inland ones, scattered throughout the landscape could escape the disturbance and provide seed sources and wildlife to recolonize the larger wetland. In addition, some animals and birds require large continuous blocks of a single habitat type that are at least as large as their territorial range. The amount of flood/storm water a marsh is able to retain is also size related. Larger marshes can store larger volumes of flood/storm water than smaller marshes thus increasing the amount of flooding protection provided to downstream areas.

Sediment

Sediments are brought into coastal marshes by river flows, tides, and storms carrying marine deposits (Meade 1969; Chabreck 1988). The grain size of marsh sediments and their associated nutrient content is dependent upon the:

- Parent material
- Method of transport
- The geologic and hydrologic characteristics of the marsh itself

[16]If particular areas are to be sampled in this manner, care must be taken to ensure that sampled areas do not become impacted (i.e. trampled) by repeated site visits.

- Current velocity
- Plant density
- Water volume
- The area over which sediment spreads, and
- Watershed characteristics such as size, geology, and discharge (Seliskar and Gallagher 1983; Cahoon and Reed 1995; Cahoon et al. 1996; Leonard 1997; Pasternack and Brush 2002).

Freshwater marshes typically have soils deposited by river flow from upland sources. These tend to be a mix of clays, silt, and fine organic matter with some sand and can be quite variable depending on the characteristics of the watershed (Meade 1972). Salt and brackish marsh soils consist of silt, sand, or clay derived from both upland sources and marine deposits (Redfield 1972; Nixon and Oviatt 1973).

Three characteristics of sediments important to restoration monitoring are grain size, organic matter content, and the rate of accretion or sedimentation. Each is a key structural component of marshes that will often need to be monitored closely after the implementation of restoration projects. As will be discussed below, sediment grain size affects nutrient availability (Hausenbuiller 1972; Andrieux-Loyer and Aminot 2001; Koch 2001; Jahnke et al. 2003; Steiger and Gurnell 2003). Sediment organic content affects the ability of a restored marsh to act as a nutrient sink and the use of sediments as benthic habitat (Cole and Weigmann 1983; Craft 2000). Sedimentation rates that are too high or too low can alter the elevation of the substrate or bury the seed bank and lead to changes in vegetation communities (Jurik et al. 1994; Wang et al. 1994).

Grain size

Marsh vegetation obtains a majority of its nutrients from sediments (DeLaune et al. 1981). Plant productivity and biomass is therefore related to soil nutrient content (Broome et al. 1975; DeLaune and Pezeshki 1988). Sediment grain size also has direct effects on nutrient levels available to marsh plants. Different grain sizes such as clay (below 0.002 mm), silt (0.002 to 0.05 mm), sand (0.05 to 2.0 mm), and gravel (above 2.0 mm) supply different levels of nutrients and support different plant communities (Hausenbuiller 1972; Andrieux-Loyer and Aminot 2001; Koch 2001; Jahnke et al. 2003; Steiger and Gurnell 2003). Fine sediments, such as silts and clays, have greater nutrient content than do coarse, sandy soils. This is due in part to the increased surface area to volume ratio of fine sediments compared to larger particles (Andrieux-Loyer and Aminot 2001; Pasternack et al. 2001; Steiger and Gurnell 2003). This effect can be offset, however, by the poor drainage that fine sediments suffer from (Clarke and Hannon 1967; Clarke and Hannon 1969). Fine-grained, poorly drained, waterlogged soils can be low in oxygen. This negatively affects plant growth and has a variety of other effects on sediment chemistry that will be discussed in the section on *Chemistry: dissolved oxygen and redox potential* below (Long and Mason 1983; Portnoy 1999).

Soil bulk density[17] can also be used as an indicator of the relative amount of mineral sediment (Hatton et al. 1983) and has been related to the amount of aboveground plant biomass in salt (DeLaune and Pezeshki 1988) and brackish marshes (Nyman et al. 1994). Soils with higher bulk density typically contain higher concentrations of phosphorus, an important nutrient to marsh plants (Patrick and DeLaune 1976).

Sampling

Sediment grain size or bulk density can be monitored to determine if the rooting medium for emergent plants is adequate for establishment and/or if sedimentation rates are keeping pace with coastal subsidence for the long-term survival of the marsh. Sediment grain size can

[17]The dry weight of the sediment per unit of volume.

be measured directly by drying and sifting samples through a series of different sized sieves or indirectly through measuring bulk density. It is generally low (e.g., 0.2 to 0.3 g/cm^3) for sediments with high organic matter content and high (e.g., 1.0 to 2.0 g/cm^3) for sediments with high mineral content. These and other methods to measure sediment characteristics are reviewed by Poppe et al. (2003).

Organic content

Sediment organic matter comes from two sources: upland drainage (more important in freshwater marshes than salt marshes) and from marsh plants. The dead leaves, stems, seeds, roots, rhizomes, and other parts of marsh plants lay in or on the sediment where animals, bacteria, and fungi break them down. This material can then be worked into the sediments by burrowing animals or covered over with new mineral sediments deposited from storms or upland drainage. The amount of plant material in the soil depends upon the plant community, frequency and duration of flooding, and the magnitude of tidal and other surface water currents, as well as the burrowing activity of benthic organisms (Chabreck 1988). As such, the amount of organic matter in the soil generally increases inland from the sea (Chabreck 1970). For example, freshwater marshes tend to have higher organic content than brackish or salt marshes (Odum 1988 and literature cited therein). Percent organic matter for tidal freshwater marshes ranges between 20% and 70% with a mean of 35%, though much variability between and within sites should be expected (Odum 1988). In addition, in marshes that have distinct high and low marsh communities, high marshes tend to have higher amounts of sediment organic matter than low marshes (Khan and Brush 1994). This is partially due to the increased exposure to wave energy low marshes are subject to, as well as an increased frequency of inundation (Whigham and Simpson 1975; Gosselink et al. 1977). Marshes in protected bays or behind barrier beaches may accumulate thick deposits of organic sediments, while open marshes in wave exposed areas typically have little sediment organic matter (Keddy 1985; Burton et al. 2002).

Many of the chemical functions marshes provide such as nutrient cycling and retention and conversion of metals and pesticides as well as some habitat functions are affected by the amount and type of organic matter in the sediment (Simpson et al. 1978; Cole and Weigmann 1983; Orson et al. 1992; Khan and Brush 1994). Marshes with higher amounts of sediment organic matter retain greater amounts of nutrients and metals than marshes with lower concentrations of sediment organic matter (Simpson et al. 1978; Khan and Brush 1994). Benthic invertebrates such as worms (polychaetes and oligochaetes) and midge larvae (chironomids) are also strongly related to amount of organic matter in the sediments (Cole and Weigmann 1983; Moy and Levine 1991; Craft 2000). These invertebrates are also important sources of food for bottom feeding fish and shrimp (Weisberg and Janicki 1990; Swenson and McCray 1996).

The amount of organic matter deposited in marsh soils can vary over time. This is particularly true in coastal marshes of the Great Lakes. During years with low lake levels, barrier beaches may form over the outlets of some marshes, limiting exchange of water with the lake, fostering the accumulation of organic sediments. During prolonged high water levels, these protective structures may erode and organic sediments might wash away (Wilcox 1995). Thus the ability of a Great Lake coastal marsh to function as a sink or source of organic material and nutrients to the associated lake varies from year to year depending on the water level fluctuations of the lake and its affect on marsh geomorphology and hydrologic characteristics. The amount of organic matter also changes in salt marshes over time but over much longer time scales. Young marshes accumulate sediments, organic matter, and the nutrients and contaminants adhered to them. As the marsh ages, these materials are exported out of the marsh. Thus the ability of a marsh to act as a source or sink depends upon the age of the marsh as well (Leendertse et al. 1996). As with natural marshes, organic matter content will vary with restored marshes according to marsh type and the age of the restoration project (Craft 2000).

Sampling

A common method of measuring soil organic matter involves freeze drying the samples, then grinding them and applying hydrochloric acid (HCl) overnight to remove any calcium carbonate. The samples are then dried at 70˚C to remove any water and weighed. They are then dried at 550˚C for 1.5 hr to burn off all of the soil organic matter (Davies 1974). Samples are allowed to cool and then re-weighed. The difference in weights is the amount of organic matter in the soil. Although this method is widely used in laboratories, it may require a significant investment in equipment. Smaller, less expensive chemical methods are also available from environmental and aquaculture suppliers that can provide similar results (Queiroz and Boyd 1998). Bulk density can also be used to determine the amount of organic and inorganic matter in sediments (DeLaune et al. 1983b).

Accretion[18]

Sea level rise, natural subsidence, and changes in land use have increased mean water level in many coastal marshes, making it more difficult for emergent vegetation to survive (Hatton et al. 1983; Baldwin et al. 1996). The continued existence of coastal marsh habitat depends on whether the substrate can maintain an elevation above relative sea level. The annual increase in marsh elevation, referred to as accretion, is accomplished through a combination of processes including mineral sedimentation and organic matter production. While mineral sediment supply has long been considered the primary control of vertical marsh accretion and marsh stability (Hatton et al. 1983; Baumann et al. 1984), several other factors can also influence the accretion of coastal marsh soils including pulsed storm events (Reed 1992), local subsidence (DeLaune et al. 1983b), and the oxidation and compaction of organic matter (DeLaune et al. 1990). These processes link soil formation to the stability of marsh wetlands. The conversion of marshes to open water habitats can occur where accretion is less than the relative rise in water level causing excessive flooding and marsh loss.

Soil formation and accretions are controlled by the contribution of biomass production and the loss of organic matter through decomposition. An increase in accretion can occur by either an increase in belowground plant production or by a decrease in decomposition rate; either of which increases the accumulation of organic matter in marsh soils. The balance between these two processes is controlled by a myriad of factors including mineral sediment and nutrient supply, freshwater delivery, and hydroperiod (Mendelssohn et al. 1983; Mendelssohn and McKee 1988; Reed and Cahoon 1992). The interactions of these factors are very complex and can vary spatially across a coastal landscape.

Deposition of sediment on the marsh surface can only occur when the marsh is flooded and requires both the availability of suspended sediment and the opportunity for that sediment to be transported by floodwaters over the marsh (Reed 1989). Freshwater tidal marshes, for example, often occur where the highest rates of sediment deposition are found (Meade 1972). These marshes often act as sedimentation basins, protecting downstream water bodies from turbidity and other problems associated with sediment deposition. The high stem density of emergent vegetation also contributes to sedimentation on the marsh surface by slowing water velocity and allowing suspended sediments to fall out of suspension.

[18]Sedimentation rate is equal to accretion minus erosion.

Too much sediment, however, can also be a problem as water level/substrate elevation relationships are altered and existing sediments are smothered. These changes in sediment type and substrate elevation can lead to changes in marsh vegetation communities. Heavy inputs of sediments from agricultural areas can create mudflats along shorelines, creating habitat for annual, freshwater, pioneer species such as nodding smartweed (*Polygonum lapathifolium*), bur-marigold (*Bidens cernuus*), and soft stem bulrush (*Scirpus validus*) and smothering the perennial species that may have once dominated the area (Minc 1997). Heavy sediment inputs can also alter the physical and chemical characteristics of the substrate, further impacting vegetation communities. Wild rice, for example, grows best in rich, organic deposits and once dominated some coastal marshes in the Great Lakes. Sediment-laden runoff from agricultural areas, however, has covered over the original organic deposits and eliminated wild rice habitat (Minc 1997).

Variability in Sedimentation Rates

There can also be considerable variation in sedimentation rates (Harrison and Bloom 1977). Characteristics of the plant community, distance from creek channels and inlets, frequency and severity of storms, and water level fluctuations can all affect the amount of sediments deposited in the marsh (Roman et al. 1997; Boorman et al. 1998; Pasternack and Brush 2002). The amount of sediments delivered to a marsh from upland sources can also be quite variable over time (McManus 2002). Hurricanes and large storms can cause tremendous amounts of erosion in the low marsh (Ranwell 1961) and can greatly increase sedimentation in the high marsh (Stumpf 1983). A major flood in 1936 and Hurricane Agnes in 1972, for example, accounted for half of the sediment deposited in the upper Chesapeake Bay between 1905 and 1975 (Schubel and Hirschberg 1978). The type of marsh also affects sedimentation patterns. High marshes tend to accumulate and retain sediments better than low marshes (Craft et al. 1993). These sources of potential variability will need to be accounted for when developing a restoration monitoring plan requiring measurement of sedimentation rates.

The Role of Algae

Although studies often focus on the role of vascular plants in increasing sedimentation in marshes, algae can also play a crucial role (Adam 1990). Algae (particularly diatoms) are often the first plants to colonize and stabilize newly exposed mudflats. These microscopic plants produce large amounts of mucus-like material that holds loose sediments together, eventually allowing vascular plants to colonize the area (Coles 1979).

Sampling

Various methods have been employed to measure the rate of vertical accretion in coastal marshes. Commonly used techniques involve the use of a 'marker layer' of brick dust, feldspar, or some other easily identifiable substance spread along the soil surface. In some cases, natural markers such as a layer of sand deposited by a particular storm can also be used. Once the marker layer is deposited, sediment cores can be taken to measure the rate of accretion over time (Adam 1990 and literature cited therein). Stakes can also be driven into the sediment for shorter-term studies. High current velocities, however, may lead to scour around the stake and complicate measurements using this technique (Adam 1990). Accretion can also be determined by measuring the concentration of radioactive materials such as Pb-210[19] at specific depths in the soil (French et al. 1994; Cochran et al. 1998; Anisfeld et al. 1999; Brenner et al. 2001).

When measuring rates of accretion, infrequent measurements over longer periods of time may be more informative than repeated measurements at short time intervals. Frequent, short-term measurements tend to show a more complicated

[19] A naturally occurring radionuclide supplied to marshes from the atmosphere.

picture of highly variable sedimentation and accretion rates over time. This is particularly true in lower marshes, due to the increased time of inundation. Short-term measurements may also over estimate accretion as they do not allow for sediments to settle and consolidate (Adam 1990).

Bathymetry/Topography[20]

The topography and bathymetry of marsh sediments, in relation to water level, influences the types of plants and animals that live in the marsh. Changes in topography through erosion, subsidence, or sediment deposition, even of a few centimeters (microtopography), can alter plant and animal communities and plant productivity (Adam 1990; Morris et al. 1990; Morris 2000). This is because each plant species is adapted to germinate and grow under a specific tidal regime or hydroperiod as it relates to water depth (van der Valk and Davis 1978; Keddy and Reznicek 1982). Changes in sedimentation rates, water level fluctuations of the Great Lakes, sea level rise, and subsidence of coastal areas can all change the depth of water to the substrate and thus change the vegetation community (Hatton et al. 1983; Wilcox and Whillans 1989; Adam 1990; Wilcox and Meeker 1995; Minc 1997; Baldwin and Mendelssohn 1998). The topographic diversity of marsh sediments also increases the diversity of the plant community. All other things being equal, marshes with uniform substrate elevations should have a much more uniform vegetative community with lower species diversity than a marsh with more topographic diversity. The presence of channels in the marsh also increases the ratio of edge to area and allows greater access to the marsh surface by fish and crustaceans, thus increasing the habitat value of the marsh (Rozas et al. 1988). In addition to elevation, microtopography, and channels, other ecologically important characteristics of marsh topography for monitoring include pans, slope and geomorphology.

In any restoration project involving planting or seeding, careful measurement of depth to substrate, substrate elevation, and topographic diversity will need to be done in order for the proper plant species to be selected. During the planning stages of any restoration projects requiring earth moving or the use of dredge material, soil engineers will compare the size of the project area with the source area to determine a settlement curve prior to restoration activity. Practitioners may still need to monitor substrate elevations and topographic diversity for a period after implementation and before planting to determine if the planned-for elevations have been achieved. Once sediments have settled into place and final elevations of the marsh substrate are known, final selections of plant species can be made and placed in the field.

Elevation and microtopography

Mean water level, as it relates to elevation of the marsh surface, is one of the most important factors affecting marsh productivity (Morris et al. 2002). Mean water level determines the frequency and duration of flooding of marsh soils. In salt marshes, mean water level (sea level) also determines soil salinity. The frequency and duration of flooding and soil salinity directly impact the health and productivity of marsh vegetation (Phleger 1971; Morris 1995). For example, changes in mean sea level from year to year as small as 5-10 cm have been shown to greatly impact the productivity of smooth cordgrass marshes on the east coast of the United States (Morris et al. 1990; Morris 2000). Increases in relative mean sea level through subsidence of coastal areas or increases in actual sea level through global warming can be potentially problematic for salt marsh restoration efforts. While the processes of subsidence and erosion constantly decrease

[20]Unless otherwise noted, the discussion of topography and bathymetry as it relates to wetland geomorphic features has been developed using Keough, J. R., T. A. Thompson, G. R. Guntenspergen and D. A. Wilcox. 1999. Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19:821-834.

marsh surface elevations, healthy marshes with adequate sediment inputs are able to constantly modify marsh elevations toward equilibrium with mean sea level (Morris et al. 2002). Other topography-related factors that affect plant growth include soil salinity, soil aeration and drainage, sediment grain size, and nutrient availability (Gray and Bunce 1972).

Small changes in topography (microtopography) on the marsh surface are extremely important in maintaining plant species diversity and providing refuge areas for juvenile animals. Since each plant species is adapted to growing within a certain depth or elevation, small changes in the vertical structure of marsh substrates such as depressions or mounds can greatly increase the diversity of the plant community (Werner and Zedler 2002). Fish and invertebrates commonly use pools of open water on the marsh surface to wait out low tides and escape predations while hummocks created by different vegetation types make excellent hiding spaces for these animals during high water levels (Havens et al. 1995).

Pans

Pans are a characteristic feature of coastal salt marshes. They are slight depressions in the marsh surface often located between tidal channels. Seawater from high spring tides can become trapped in these areas and, over the growing season, become increasing salty as the water evapotranspirates away. These high salinity conditions limit seedling germination and plant growth. Without precipitation or additional tidal flooding, salt concentrations in pans may reach levels high enough to kill marsh plants and form a salt crust over the soil surface, limiting future recolonization of the area (Figure 8 - Adam 1990).

Marsh Creeks[21]

Water channels through a marsh are important corridors for water, materials, and animals to move from the marsh to open water areas and back (Mitsch and Gosselink 2000). Water carrying suspended and dissolved material moves downstream during periods of low water levels and inland with tides and seiches. Marsh creeks also facilitate the draining of the marsh during low tide, a process essential to the survival of many marsh plant species (Teal and Weinstein 2002). The more channels a marsh has also increases the exchange of animals, nutrients, sediments, and other materials between the marsh and downstream water bodies (Figure 9). Animals such as fish and shellfish find refuge in creeks during low water levels and then enter marshes to forage during times of high water levels (Weinstein 1979; Rozas et al. 1988; Laffaille et al. 2001; Hampel et al. 2003; Teo and Able 2003b; Teo and Able 2003a). In fact, most of the shrimp, crabs, and fish that use salt marshes are found within 5 meters of open water or marsh creeks so they can quickly return to lower areas at low tide (Minello et al. 1991; Peterson and Turner 1994).

A dense network of creeks maximizes the amount of marsh edge that can be accessed by animals increasing the use of marshes for feeding, breeding, and nursery purposes (Kneib 1994; Minello et al. 1994; Minello and Rozas 2002; Whaley and Minello 2002). The exact effect of animals' use of marsh creeks to access the marsh surface is also dependent upon the:

- Marsh slope
- Elevation
- Tidal dynamics
- Vegetation type and density
- Sediment grain size, and
- Drainage characteristics of the sediment (Minello et al. 1994)

Studies comparing natural versus constructed marshes in southern California also suggest that the creek characteristics most important in determining fish use of coastal marshes are:

[21] Often referred to as 'tidal creeks' in tidal marshes. The more generic 'marsh creeks' term is used here to include creek channels flowing through non-tidal Great Lake coastal marshes.

Figure 8. A salt crust (white areas) has formed on the soil surface of this tidal marsh pan on Whidbey Island, Washington. The vegetation in the pan has also turned red in response to salinity stress. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

Figure 9. An aerial view of the meandering tidal creeks and extensive pristine marshes in North Inlet Estuary North Inlet - Winyah Bay National Estuarine Research Reserve, South Carolina. Creeks such as these increase the amount of edge habitat and allow fish and other animals access to the marsh surface during high water levels. Photo from the NOAA National Estuarine Research Reserve Collection.

- Water depth
- Temperature
- Dissolved oxygen
- Channel width
- The presence of smaller creeks, and
- Salinity (in tidal areas) (Zedler et al. 1997; Williams and Zedler 1999)

Slope

Since each plant species is adapted to a certain depth of water, the slope of the marsh surface can also influence plant communities. In freshwater marshes, differences in slope dictate the width of various vegetation zones as plant species adjust spatially in response to water level fluctuations. In salt marshes, differences in the slope can also influence salinity levels that dictate plant zonation (Dreyer and Niering 1995). This is more often an issue in high marshes where tidal waters may become trapped in poorly drained areas[22]. In tidal areas that are poorly drained or lack sufficient groundwater or fresh, surface water flows to flush sediments, salts brought in with the tide can accumulate

[22]Practitioners should also ensure that selected elevations and slopes will actually be inundated long enough that marsh vegetation will grow instead of upland or scrub-shrub species.

in the sediment through evapotranspiration (Valiela et al. 1978; Adam 1990; Thibodeau et al. 1998; Mitsch and Gosselink 2000). As soil salinities increase, plant productivity diminishes and fewer and fewer species are able to tolerate the increasingly saline conditions (Zedler et al. 1999; Mitsch and Gosselink 2000). Increasing the slope of and creating channels through a marsh to help salt water drain out during low tide can help minimize this problem (Zedler et al. 1999).

Geomorphology

Geomorphology is the study of the physiographic features of the earth's surface. By understanding the shape of a particular feature on the landscape and how it was formed, insights can be gained regarding the functions that area can perform (Valiela et al. 1978; Odum et al. 1979). Geomorphic features are determined based on the:

- Shape and geologic history of an area
- Degree of protection from wave energy, and
- Amount of hydrologic exchange with their receiving water body

These basic structural characteristics are outlined in Figure 10 for three different types of coastal wetlands: open wetlands, drowned river mouths, and protected wetlands (Roy 1984; Keough et al. 1999).

Open Coastal Wetlands

Open coastal wetlands are located directly on the shores of lakes, bays, or the open ocean (Figure 11). They and their associated marsh habitats are subject to more wave energy and hydrologic exchange than drowned river mouths or protected wetlands. Open marshes are chemically and hydrologically directly connected to the water body they discharge into. They may also have upland water sources such as small streams. They typically do not have as much sediment organic matter accumulated as drowned river mouths or protected wetlands. Plants and animals that live in open marshes must be tolerant of daily water level fluctuations from tides or seiches and higher rates of erosion caused by waves and ice.

Drowned River Mouths

Drowned river mouths were formed during the last ice age when water levels of the Great Lakes and oceans were much lower than they are today. As the lakes and oceans rose to present levels, deep river valleys filled with sediments creating linear wetland complexes dominated chemically and hydrologically by both the rivers moving through them and their receiving body of water (Figure 12). Many of the estuaries in the United States such as the Chesapeake and Delaware Bays on the east coast, Coos and Siletz Bays in Oregon, and those in the Great Lakes such as Muskegon Lake in Michigan are drowned river mouths. Marshes of drowned river mouths are usually long, linear, and run perpendicular to the coast. Unlike open or protected marshes, drowned river mouths are heavily influenced by physical and chemical processes of both the river and the receiving body of water. During periods of low flow or the presence of a barrier beach, retention time of water in the marsh is increased, and sediments and nutrients are held in the marsh as well (Reeder and Mitsch 1989). During severe storm events or high water levels, protective structures can be eroded away reducing retention time of water and flushing accumulated sediments, nutrients, and organic matter out of the marsh.

Protected Wetlands

Protected wetlands and associated marshes are located behind some sort of barrier (often an island) that protects them from the full force of waves coming off a water body (Figure 13). Barriers for protected marshes, as well as those occasionally associated with drowned river mouths, can be completely isolating or can be open to allow some hydrologic exchange with the receiving body of water. The extent of the barrier has direct effects on the accumulation

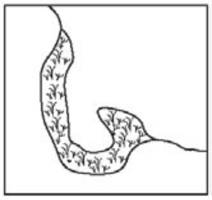
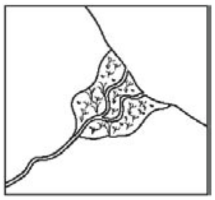
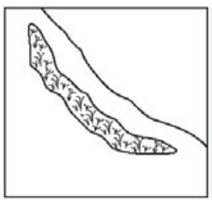
Type	Physical	Hydrologic	Biological	Chemical
Open 	Variable inorganic substrate (clay to gravel). Thin to non-existent organic substrate. Moderate to high wave climate. Low rate of sediment supply. Gentle offshore and underlying-surface slopes. May or may not have offshore bars of sand to gravel.	Direct surface-water connection to the receiving body of water. Ground-water flow-system directly influenced by elevation of receiving body of water.	Plant morphometry adapted to hydraulic stress. Vegetation aligned with shoreline bars and dunes. Vegetation sensitive to wave climate and protective dunes, ridges, bars, and points. Plant species preferring inorganic substrates. Stray estuarine fauna. Biota tolerant of ice action.	Strongly influenced by constituents of the receiving body of water. Low turbidity. Vegetation may isolate nearshore water from mixing with the receiving body of water.
Drowned River 	Variable inorganic substrate (clay to gravel). Variable thickness of organic substrate. Low to moderate wave climate. Low to moderate rate of sediment supply from coast and river.	Direct surface-water connection to river and the receiving body of water. Ground-water flow-system influenced by elevation of the receiving body of water and the river. Many local flow systems. Seiches transmitted upstream.	Plants and animals of riverine, lagoonal, and coastal habitats. Mud-flat annuals, and plants preferring organic sediments. Warm-water fish. Biota tolerant of flooding and high turbidity.	Upstream-downstream gradient in water constituents caused by seiches mixing of river water with water from the receiving body of water and reversal of currents. Variable turbidity.
Protected 	Uniform inorganic substrate (sand to gravel). Thick organic substrate. High rate of sediment supply to shoreline.	May or may not have a surface-water connection to receiving body of water. Ground-water flow-system may or may not be influenced by the elevation of the receiving body of water. Many local flow systems.	Peatland vegetation is often present in northern areas. Ridges and swales show successional patterns. Warm-water fish in lagoons. Plants preferring organic substrates.	Organic matter may dominate water chemistry if limited riverine inflow. High water temperatures in summer. Ground-water seepage may cause temeprature gradients. Low turbidity. Ground water may dominate chemistry where inputs are high.

Figure 10. Three main types of coastal wetland geomorphology: open, drowned river mouth, and protected. The specific type of geomorphic feature a marsh is part of has direct effects on the physical hydrological, biological, and chemical characteristics of the marsh. Modified from Keough et al. 1999).

Figure 11. Braddock Bay, an open embayment on the shore of Lake Ontario. Photo courtesy of Doug Wilcox, United States Geological Survey.

Figure 12. Beaver Creek, a drowned river mouth marsh in the Great Lakes. Photo courtesy of Doug Wilcox, United States Geological Survey.

of organic matter, water chemistry, and other physical and biological characteristics as well by altering the flow and retention time of water through the marsh. If the barrier is complete, it may isolate them from tides, seiches, and other water level fluctuations of the receiving body of water. In the Great Lakes, the extent of the barrier can change from year to year with lake level fluctuations, thus changing many of the structural and functional processes within the marsh.

Sampling

Traditional methods for obtaining topographic information in enough detail for plant studies requires detailed field surveys of marshes. Although they provide definitive information of marsh topography for baseline information, field surveys can be costly and time-consuming and, depending on the variability in sedimentation and erosion in the marsh, the expense may not be warranted on a repeated basis. Newer technologies using aerial and satellite remote sensing or hand-held global positioning systems (GPS) may provide information in

Figure 13. South Colwell Pond, a barrier protected marsh on the shores of Lake Ontario. Photo courtesy of Doug Wilcox, United States Geological Survey.

sufficient detail for monitoring purposes. These technologies have been successfully demonstrated in mapping coastal topography (Blomgren 1999; Van de Kraats 1999; Parker et al. 2001; Brock et al. 2002; Ozesmi and Bauer 2002). Other geomorphic features of marshes such as tidal creeks and barrier beach formation can be monitored during site visits or with aerial photography. Aerial photography has the added benefit of creating a comparable physical record of changes in the marsh over time (Weinstein et al. 2001).

HYDROLOGICAL

As long as there is a direct, open connection between a marsh and its receiving body of water, the hydrological characteristics of the marsh will be dominated by the hydrodynamics[23] of the receiving basin, be it a Great Lake, open ocean, or the Gulf of Mexico. This occurs even when the marshes and open water bodies are not directly adjacent to one another. Because of this relationship, marshes are very dynamic places and the specific location of the habitat can move spatially over time. A strong storm surge that brings saltwater upstream coupled with low flushing potential can replace freshwater marshes with brackish and salt marsh habitats or remove marshes entirely. Increases in the water level of the Great Lakes can also push freshwater marsh habitats inland, replacing them with submerged aquatic vegetation (SAV) or open water habitats. During periods of high precipitation in headwater areas coupled with little storm activity at sea or during low water-level periods of Great Lakes, freshwater marshes may expand farther downstream (Zedler et al. 1986; Maynard and Wilcox 1997).

The Role of Climate

The particular species of plants growing in a marsh are ultimately dependent upon climate and can thus be quite variable over time. Vegetation communities in Great Lakes and tidal freshwater marshes are adapted to and dependent upon periodic, natural water level fluctuations (Keddy and Reznicek 1986; Wilcox 1995; Wilcox and Meeker 1995). These water level fluctuations are brought about by changes in long-term climate patterns and short-term freshwater flows (droughts and flooding). In salt and brackish marshes, soil salinity is the mechanism responsible for most changes in vegetation communities[24] (Zedler et al. 1986). Soil salinity is, in turn, dependent upon tidal exchange and upon the climate-related factors of freshwater flows and storm activity. Thus soil salinity can also be highly variable over time (Zedler et al. 1986).

With all of this variability coastal marshes can be extremely stressful environments for plants and animals. In addition to periodic water level fluctuations caused by seiches, tides, storm surges, and differences in soil salinity in coastal areas, marshes are often exposed to the erosive energy of waves and ice (in northern climates). These physical stresses, however, also help to create diversity in the plant and animal communities of marshes (Odum et al. 1984). Therefore, hydrologic characteristics such as tidal regime, hydroperiod, water velocity, water sources, and wave energy are important structural characteristics of marshes that need to be taken into consideration when preparing restoration project goals and monitoring plans (Wilcox et al. 2002).

Tides/Hydroperiod

Tidal regime and hydroperiod refer to the depth, duration, frequency, and timing of inundation. Tidal regime commonly refers to the pattern of these water level fluctuations in ocean and Gulf coast areas. Hydroperiod is commonly used for Great Lake or other freshwater habitats.

[23]Vertical water level fluctuations.

[24]Changes in salt marsh vegetation also occur in relation to changes in sea level but these effects are seen over much longer periods of time Clark, J. S. and W. A. Patterson, III. 1985. The development of a tidal marsh: Upland and oceanic influences. *Ecological Monographs* 55:189-217.

Water level fluctuations vary by region and on daily, seasonal, and on annual/decadal cycles, driven by changes in climate. Tidal regime and hydroperiod are the most important factors in determining the dominant vegetation and habitat found in a given area (Keddy and Reznicek 1986; Chabreck 1988; Wilcox 1995; Wilcox and Meeker 1995; Baldwin et al. 2001). Therefore, they are strongly suggested as parameters to be measured during any restoration monitoring program.

Tides have a variety of effects on coastal marsh vegetation and influence a variety of physiographic, chemical, and biological processes including transport, deposition, and erosion of mineral and organic sediments, flushing of toxins, and controlling sediment salinity, pH, and redox[25] potential (Mitsch and Gosselink 2000). During spring high tides, the entire surface of even the high marsh can be inundated and low marshes are completely submerged for the duration of the tide (Adam 1990). This changes the amount and quality of light available for photosynthesis. Once tides recede, they often leave a coating of sediment on plant leaves that may further limit photosynthesis and productivity if not washed off by rain (Adam 1990). As tides rise and fall, marsh plants are also exposed to the erosive forces of waves action and tidal currents. Well-established vegetation, with a developed system of roots or rhizomes, is usually able to tolerate the extra stress of tidal currents on sediments but the combined stress of high water levels and increased wave action can lead to erosion (Adam 1990). Germinating seedlings and young plants without well-developed root systems are particularly vulnerable to erosion during these times (Adam 1990).

Tidal marshes can be salty, brackish, or fresh depending on the relative inputs of seawater and upland freshwater to them. Freshwater tidal marshes develop where incoming tides prevent the continued flow of freshwater downstream so river flows pile up. Once the tide subsides, downstream flow of freshwater can continue. This phenomena has been noted as far as 80 km (50 miles) inland from the coast (Mitsch and Gosselink 2000) and occurs most readily in areas where there is a diurnal tide greater than 0.5 m, a flat gradient from the ocean inland, and enough precipitation or river flow to maintain salinities below 0.5 ppt (Odum et al. 1984). These conditions are more commonly found along the Atlantic Ocean and Gulf of Mexico than the Pacific coast of the United States (Odum et al. 1984). Seiches are wind-driven water level fluctuations that occur in tidal areas of the Gulf of Mexico, large bays, and other large open bodies of water on the ocean coasts as well as in the non-tidal coastal marshes of the Great Lakes (Wax et al. 1978; Muller and Willis 1983; Herdendorf 1990; Bedford 1992; Trebitz et al. 2002). By temporarily raising and lowering water levels and moving water in and out of marshes, seiches have many of the same characteristics and functions as tides without the regularity (Bedford 1992).

The hydrodynamics of coastal marshes can be divided into three types corresponding to their geographic location: *Tidal - Ocean Coasts, Tidal - Gulf Coast,* and *Non-tidal Great Lakes*. Due to significant regional differences, the type and timing of tides and hydroperiod will be described for each location.

Tidal: ocean coasts

Tides on the ocean coasts can be as large as 3 meters or more (Chabreck 1988 and literature therein). Regional subclasses of tidal ranges can be identified and used to allow practitioner to anticipate conditions they may encounter (Shafer and Yozzo 1998). Tides on the North Atlantic coast (Eastport, Maine to Cape May, New Jersey) experience the largest tidal range (>3 m). Tides in the Mid-Atlantic region (Cape May to Virginia Beach, Virginia) range from 1 to 2 m. While tides in marshes of the South Atlantic coast can be broken into two classes,

[25]Stands for 'oxidation-reduction' potential. This influences nutrient cycling and other chemical processes in marsh sediments and will be discussed in greater detail with other chemical characteristics of coastal marshes below.

a microtidal with tides less than 0.5 m and a macrotidal class with tidal ranges between 1 to 2 m depending on characteristics of the estuary. The Pacific coast can be broken into two subclasses. The South Pacific (Baja Peninsula to Cape Mendocino, California) has a tidal range of 1 to 2 m. The North Pacific (Cape Mendocino to southeastern Alaska has moderate (1 – 2 m) to large (> 3 m) tidal ranges. Along the Pacific northwest, daily and semi-daily tides result in two unequal high and low tides per day (Oceanographic Institute of Washington 1977). The highest tides occur in the Pacific northwest in the fall and winter when plants are dormant (Seliskar and Gallagher 1983).

In areas with tides of ~0.7 meters or more (Simpson et al. 1983; Baldwin et al. 2001), two distinct vegetation zones can be found; a high marsh, with saturated soils that may be shallowly inundated for up to 4 hours and a low marsh, inundated for a longer period of time and to a greater depth (Chapman 1960). The transition line between high and low marsh is roughly equal to the elevation of the mean water level. These differences in the depth, duration, and timing of flooding affect not only the plants but other marsh functions such as decomposition, nutrient cycling, and heavy metal retention as well (Simpson et al. 1978; Khan and Brush 1994)[26]. Accurate measurement of basin topography and the elevation and duration of tides must be a part of any pre-restoration planning in order for selection of appropriate plant species for revegetation projects.

Tidal regime will also influence the sampling times and selection of other characteristics to be monitored, to ensure that appropriate comparisons are made. For example, nitrogen levels in tidal freshwater marshes can range from barely detectable levels at low tide to nearly 120 µg per L at high tide (Simpson et al. 1978). Similar patterns have also been found for phosphorus and dissolved oxygen concentrations. If accurate comparisons of nutrient levels in a marsh are to be made over time, then samples will need to be taken at the same point in the tidal pattern and over a range of tidal cycles as well.

Tidal: Gulf of Mexico

The hydrology of marshes along the northern Gulf of Mexico is dominated by rivers in the winter and spring and by shallow tides in the fall (Stern et al. 1986). Seasonal wind patterns are also an important influence on marsh hydrodynamics. This is due to the small tidal range (often < 0.5 m), shallow marsh depth, and low elevation of Gulf coast marshes (Marmer 1954; Stern et al. 1986; Shafer and Yozzo 1998). High Mississippi River flows in the late winter and spring, followed by steady winds from the south and east during the summer (Muller and Willis 1983; Gosselink 1984), raise water levels in the estuaries and marshes (Wax et al. 1978). By late summer, river flows typically subside and in the late fall and early winter winds come predominantly from the north, pushing water out of the coastal marshes (Muller and Willis 1983; Gosselink 1984). Although these patterns are the predicted ideal, actual water level fluctuations in the Gulf of Mexico are heavily influenced by changes in weather patterns and can be quite variable (Gosselink 1984).

Changes in seasonal hydrodynamics are reflected in seasonal changes in nutrient concentration (Stern et al. 1986; Stern et al. 1991), suspended solids within the marshes (Stern et al. 1986), and in vegetation communities (Mitsch and Gosselink 2000). Suspended sediment and nutrient values are highest during high river flows in the winter and spring and decrease in the summer as river flows subside (Hem 1970; Dunne and Leopold 1978). Due to low topographic relief[27] and differences in the timing and frequency of inundation, coastal

[26]See Chapter 2 for a broader discussion of tidal processes.

[27]An exception occurs where natural levees have formed along the bayous. During spring overbank flooding events, heavier sediments drop out as floodwaters leave river channels, forming levees (ridges) parallel to the waterway. These features form definite elevational gradients within coastal Louisiana with high ground adjacent to bayou and low ground on the opposite, marsh side of the ridge.

marshes along the northern Gulf of Mexico do not exhibit the high and low marsh zonation commonly found in coastal marshes along the Atlantic Ocean (Shafer and Yozzo 1998) and are much more diverse. Vegetation species in the area are also commonly adapted to salt and freshwater conditions, making separation of plant communities along a salinity gradient challenging (Shafer and Yozzo 1998).

Non-tidal: Great Lake coastal marshes

Great Lakes coastal marshes are subject to short-term (i.e., daily) and long-term (i.e., annual or decadal) changes in water level. Seiches move sediments, nutrients, and organic material back and forth throughout the marsh-lake system and can mix lake water far into coastal marshes (Figure 14 - Bedford 1992). Particularly strong seiches have even been shown to reverse the flow of connecting channels between the lakes (Derecki and Quinn 1990). Since they are caused by weather patterns, seiches do not occur at regular intervals nor develop to consistent depths, as do lunar tides. Since seiches can stress germinating plants (Fenner 1985; Lenssen et al. 1998; Middleton 1999), water levels need to be monitored to ensure successful plant establishment.

Long-term, climate-driven changes in water-levels of the Great Lakes also have an effect on coastal marshes (Keddy and Reznicek 1986). As Figure 15 illustrates, during years when lake levels are high, marsh vegetation is pushed inland. During low-water years, marsh vegetation expands out toward the lake (Mitsch 1992; Wilcox et al. 2002). Great Lakes coastal marsh communities are composed, almost exclusively, of species tolerant of these variable water level fluctuations (Odum 1988; Maynard and Wilcox 1997). The plant species of coastal marsh seed banks can be extremely diverse, allowing a different plant community to germinate in response to whatever hydrologic conditions exist (Keddy and Reznicek 1982). Restoration project goals and monitoring programs need to account for these long-term changes in lake water levels since an area that was planned and planted as emergent marsh one year might be too dry to maintain emergent vegetation, or completely inundated and dominated with submersed aquatic vegetation, the next.

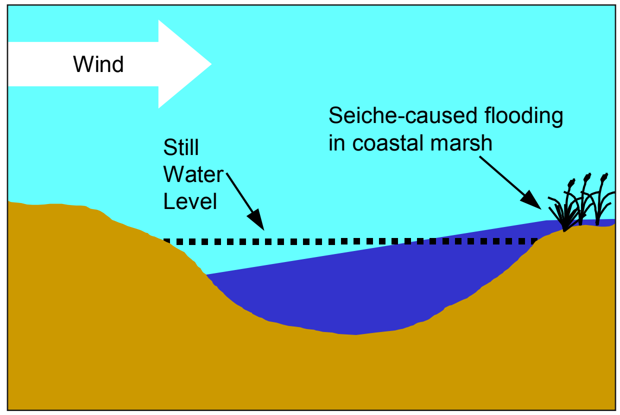


Figure 14. A seiche causing high water levels in a coastal marsh. If the wind were still or blowing the opposite direction, water levels would be lowered in the marsh. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

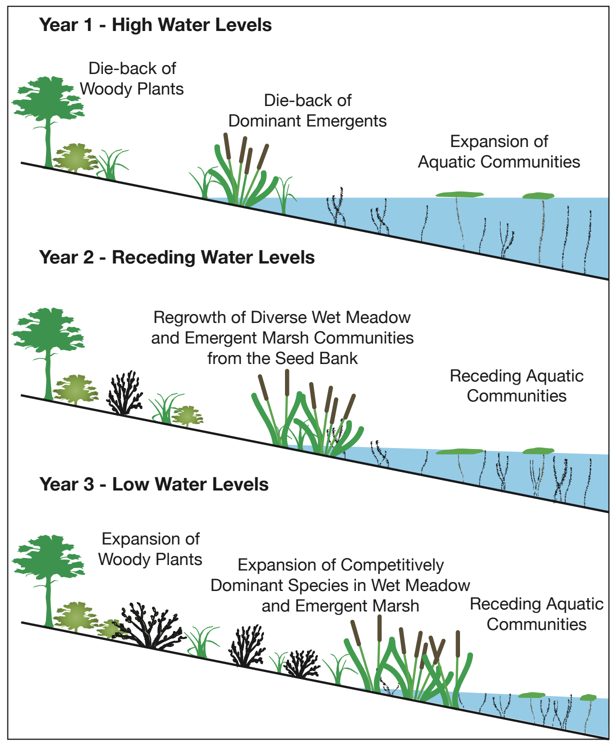


Figure 15. Simplified diagram of water-level fluctuation effects on coastal marsh vegetation communities of the Great Lakes. Modified from Maynard and Wilcox 1997.

Sampling

The patterns in climate and water level described above highlight the need for restoration monitoring to occur for more that a single season or year and in comparison to reference sites[28] whenever available. A monitoring project that only samples water level fluctuations for one year after project implementation might conclude that changes in suspended sediment and nutrient concentrations were a result of restoration activities. These changes may, however, be the result of regional hydrologic patterns unaffected by a particular restoration activity. Only through monitoring for multiple years after restoration implementation, as well as at appropriately selected reference sites can one separate the effects of the restoration activity from the background affect of large-scale, non-restoration related hydrologic patterns.

Tide tables for most of the United States and its protectorates are available from the National Oceanic and Atmospheric Administration (NOAA) at http://tidesonline.nos.noaa.gov/. If the restoration site is reasonably close to a currently monitored site, measuring tidal- or hydroperiod as part of the restoration monitoring may not be necessary (U.S. EPA 2001). The United States Geological Survey (USGS) also operates a series of gaging stations on rivers throughout the United States. Historical and real-time data on hydroperiod and characteristics of the watershed for many of these sites are available at http://water.usgs.gov/waterwatch/. Smaller, coastal rivers may not have a gaging station and may require that restoration practitioners implement another methods to collect this information. In addition, the tidal regime experienced within a marsh is not necessarily the same as that of the open ocean or coasts. The geomorphology of the estuary or individual marsh can magnify or dampen the tidal range. Funnel shaped estuaries tend to magnify the tidal range while restrictions such as barrier beaches can lessen tidal ranges (Adam 1990). An initial set of measurements to compare NOAA- or USGS-recorded tidal regimes with those actually measured in the marsh would dispel most uncertainty in using these less expensive, publicly available data.

A variety of manual and electronic gages are commercially available in different lengths and measurement intervals. Manual gages, also called staff gages, can be attached to metal poles driven into the substrate. Water levels are simply read off the gage during site visits (Figure 16). Electronic gages, however, can be set up and left in place to continually record water level fluctuation, thus recording data that would otherwise be missed by manual sampling alone. Monitoring wells can also be installed for measuring the depth of water below the soil surface (Sprecher 2000). Regardless of the type of equipment used to monitor water level, the precise location of where it is placed should be surveyed or determined with a GPS so that the exact elevation and location is known. This will allow for the construction of detailed maps showing the relationship between plant species and water level patterns.

Care should also be taken when selecting the placement of gauges and other equipment to be left in the field over extended periods of time. Equipment should be placed where it is hidden from the general public to avoid random vandalism but where those taking measurements can still readily find it. The use of a Geographic Positioning System (GPS) could facilitate this in areas without readily available landmarks. Equipment also needs to be protected from damage caused by animals. Large animals such as deer may rub on equipment dislodging it, and even smaller animals can chew on and damage plastic fixtures as well. If damage from animals is a persistent problem, monitoring equipment may need to be fenced off for protection.

[28]See Chapter 15 for a discussion on the selection of reference sites.

Figure 16. An extra length of gage is being added to this pole to measure higher water levels. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

Water Velocity

The velocity of water moving through a marsh directly affects a variety of coastal marsh functions including primary productivity, erosion protection, provision of benthic habitat, and sediment deposition. The velocity of water, ideally moving as sheet flow, affects the ability of water to carry suspended particles (i.e., sediment) and dissolved nutrients (Margalef 1968). Faster currents have more energy and are able to carry larger sediment loads and particle sizes than slower moving water. As flood- or tidewaters spread out over a marsh, its velocity slows and much of the suspended sediment is deposited on the marsh surface. If wetland substrates are saturated long enough, they become anaerobic and the phosphorus bound to the sediment particles becomes soluble in water[29]. Thus, the soluble phosphorus can then be taken up by plants contributing to primary productivity. The availability of nitrogen, a nutrient soluble under aerobic and anaerobic conditions, is also affected by water velocity. If nitrogen rich water is constantly flushed through a marsh system, then there should always be enough nitrogen available for plant production. If, however, water moves slowly through a marsh, the nitrogen carried in the water might be used up, eventually limiting plant production in the more downstream portions of the marsh. If velocities are too high, marsh sediments may be eroded away. High velocities can also carry large sediment loads that can smother benthic habitats and bury plants, thus destroying marsh habitats instead of enriching them. Moving water also tends to have higher oxygen concentrations than stagnant water (Sparling 1966), this also benefits the plants and animals that live in the marsh.

Renewal rate

An important hydrologic parameter related to velocity is the renewal rate of water moving through a marsh. The renewal rate is a measure of the frequency water is replaced. It is dependent upon water depth, volume, frequency of inundation, and velocity (Margalef 1968). Although extremely important, renewal rate can be difficult to measure. In some cases, a useful surrogate may be the ratio of marsh to watershed area. Water in a large marsh with a small watershed should have a low renewal rate. Low renewal rates foster increased nutrient uptake by plants, biochemical transformation by microbes, and retention of nutrients in and build up of sediment organic matter (Eger 1994; Raisin and Mitchell 1995). Structures related to basin geomorphology, such as barrier beaches, can decrease renewal rates, thus increasing the

[29]Under aerobic (oxygenated) conditions, phosphorus is bound to sediment particles.

uptake and transformation of nutrients while protecting water quality of other coastal areas (Heath 1992).

Monitoring sheet flow and renewal rate before and after a restoration project is critical when setting project goals and determining whether or not they are being achieved. If, for example, the goal of a restoration project is to remove nutrients from the water column to protect downstream water quality, then having a slow water velocity[30] and low renewal rate through the marsh is important. If, on the other hand, the goal of a project is to increase biomass production then a higher flow rate of water through the marsh might be important so that plant productivity is not limited. The goal of preserving downstream water quality by restoring marsh in a high velocity area will have only limited effectiveness.

Sampling

A variety of manual and automated methods are commercially available for use in determining water velocity within and around vegetated areas. Equipment costs range from tens to several hundreds of dollars depending on whether you use low-tech, manual methods that measure flow at one point and time or hi-tech electronic meters that can be left in place for many weeks or months. Careful consideration of the project goals and data required to assess them needs to take place before any equipment is purchased. Local or regional experts can assist in this process and should be consulted as to the precise method and equipment that could or should be used in any given location.

Water Sources

The sources of water to the marsh need to be understood early in the restoration plan development phase. If they are not, then parameters selected for monitoring may be poorly chosen or altogether inappropriate for the monitoring effort. In addition, it may be that factors upstream from the marsh are directly responsible for impacting the health of the marsh. Any restoration effort within the marsh itself that does not account for upstream impacts will have limited value or success. By understanding the sources and timing of water entering the marsh, restoration practitioners will be better able to address impacts to their specific system and select parameters that best track the progress of their restoration effort over time.

Water quality and quantity from various sources can have direct effects on a variety of marsh functions. Water source determines nutrient concentration, toxin load, oxygen saturation, and suspended sediment load (Margalef 1968). The chemical concentration and physical nature of water entering coastal marshes is influenced by:

- Tidal regime (as previously discussed)
- Amount of groundwater entering the system
- Regional climate
- Geology
- Surface water flow, and
- Human inputs (Valiela et al. 1978; Mitsch and Gosselink 2000).

The precise combination of factors delivering water to a marsh dictates what parameters are measured as part of a restoration monitoring project.

Groundwater

The type of substrate groundwater moves through before it enters a stream, river, or coastal marsh and how long it has been in contact with mineral soil determines the type and concentration of minerals dissolved in it (Langmuir 1997; Seelbach and Wiley 1997). Water that passes through limestone or dolomite typically has higher dissolved ion concentrations

[30] Although increased retention time does increase nutrient uptake, retention times that are too long or conditions of persistent non-flowing, stagnant water can be harmful to plants and decrease nutrient uptake.

(e.g., calcium and magnesium) and a more neutral pH (~7.0) than water that has passed through less soluble rock such as granite or sandstone (Langmuir 1997). Groundwater can also provide marshes with significant amounts of soluble nutrients such as nitrate (NO_3) and dissolved organic nitrogen (DON) (Valiela et al. 1978; Page et al. 1995; Tobias et al. 2001).

In brackish and salt marshes, groundwater discharge can also play a significant role in controlling the distribution of soil salinities (Thibodeau et al. 1998; Tobias et al. 2001; Gardner et al. 2002). Groundwater is freshwater and discharge through marsh sediments can moderate pore water salinities (Tobias et al. 2001). Although the relative amount of groundwater discharge to a marsh can change seasonally (Tobias et al. 2001), it is often higher in areas with porous soils and steep topography compared to flatter, less porous areas (Bedient and Huber 1992). Marshes adjacent to upland forests have also been shown to have higher rates of groundwater discharge and lower pore water salinities than those adjacent to other types of land cover (Thibodeau et al. 1998; Gardner et al. 2002). In marshes without strong enough groundwater discharge to flush sediments, evapotranspiration can concentrate salts in the sediment pore water (Thibodeau et al. 1998).

Sampling

Monitoring of groundwater discharge requires the installation of a series of nested piezometers or hydraulic potentiomanometers throughout the marsh and adjacent upland areas (Winter et al. 1998; Sprecher 2000). Once installed, these should be monitored on a regular basis. The exact frequency of which depends upon the goals of the restoration and monitoring effort (Shaffer et al. 2000). This level of effort may not be necessary for many marsh restoration projects, particularly those without pore water salinity problems. Regardless of whether or not groundwater discharge is actually measured, an understanding of the relative quantity of groundwater entering a system and the underlying geology through which water has passed before entering a river or marsh will be important to consider when choosing species for planting and chemical parameters to monitor.

Climate

Changes in weather and climate can alter the quality and quantity of freshwater entering a marsh (Dunton et al. 2001). Increases in precipitation create increases in surface water flow that dilute concentrations of chemicals such as salinity, nutrients, toxics, and other dissolved ions (Valiela et al. 1978; Page et al. 1995). On a seasonal basis, waters that enter freshwater marshes tend to have low chemical concentrations in the spring when precipitation is high and snowmelt (in northern or mountainous areas) is entering rivers. In the summer and fall, precipitation tends to lessen, decreasing the overall amount of water entering marshes and increasing the chemical concentrations (Hem 1970; Dunne and Leopold 1978). During droughts, the concentration of chemicals in the water also increases and tidal areas may experience increased salinity (Wicker 1980). Hypersaline conditions may result that can stress or kill salt marsh plants (Zedler et al. 1986).

Sampling

Regional climate information can be obtained from the National Oceanic and Atmospheric Administration (http://www.noaa.gov/climate.html or http://weather.gov) or other regional climate stations such as airports. If there are no public weather stations in the vicinity of the restoration project an inexpensive climate station or rain gauge can be used to obtain local precipitation and temperature data. Incorporating short-term precipitation data within the longer-term record will help practitioners better understand the results of chemical analyses taken as part of a monitoring program.

Geography

There are several geographic effects that impact the quantity and quality of water entering coastal marshes. Most are not parameters that will be routinely monitored as part of a restoration project but they need to be accounted for in order to accurately interpret collected chemistry data. Watershed size and slope, soil texture, underlying geology, upstream land use, and cover types all have direct impacts on the quantity and quality of water entering from upland sources (Seelbach and Wiley 1997). Watershed size and slope affect the timing and amount of freshwater discharged from upland sources into the marsh (Dunne and Leopold 1978; Newson 1994). Soil texture and underlying bedrock also affect the timing and delivery of water to the marsh as well as the suspended and dissolved content of the water that affects plant communities and species composition (Minc 1998).

Coastal position is another aspect of geography that affects water source. Along coastal areas where significant upwelling occurs, deep-ocean, nutrient-rich water may enter estuaries through gravitational mixing[31]. These nutrients may then be available for use in estuarine tidal salt marshes (Proctor et al. 1980). Nutrient input from the oceans is likely to be greatest during seasonal upwelling events, while nutrient input from upland sources will be greatest during peak seasonal runoff and after large storm events (Seliskar and Gallagher 1983).

Surface water flow

By definition[32], all estuaries have a combination of upland water mixed with water from the receiving body, be it a Great Lake, ocean, or Gulf of Mexico. Upland surface water flows bring to estuaries and their marshes not just freshwater but sediments and nutrients as well (Valiela et al. 1978; Page et al. 1995; Mitsch and Gosselink 2000). In general, high river flows carry large amounts of suspended material such as sediments and low concentrations of dissolved material such as salt and nutrients. Low flows carry smaller suspended loads and higher concentrations of dissolved material (Hem 1970; Dunne and Leopold 1978; Lerberg et al. 2000). These patterns can be reversed, however, in watersheds with large amounts of disturbance such as construction or active agriculture that allow sediments and nutrients to be eroded during storms, carried in a river, and deposited in downstream marshes (Wolman 1967; Omernik 1977). The diversion of freshwater flows through the use of dikes, dams, levees, and shipping canals can alter the amount of these materials deposited into coastal marshes (Gosselink 1984; Ambrose and Meffert 1999; Wilson et al. 2001) directly impacting marsh plant and animal communities (Gosselink 1984; Adams et al. 1992; Wortmann et al. 1998; Montagna et al. 2002).

The amount of surface water flow can be highly variable over time. Seasonal or annual patterns of flooding and drought and individual storms can dramatically alter the chemistry of coastal marshes which in turn influences patterns of plant growth (Zedler et al. 1986; Herdendorf and Krieger 1989; Stern et al. 1991). In a long-term study of the influence of flooding and drought on salt marsh vegetation in southern California, Zedler et al. (1986) found that overall increases in freshwater flow increased the productivity of California cordgrass. Decreases in freshwater flow during droughts increased soil salinities through evapotranspiration and decreased overall productivity (as measured by the total stem lengths per area).

The duration and timing of freshwater flows also influence how increases in productivity are measured (Zedler et al. 1986). Productivity in California cordgrass, as measured by total stem length per area, can be related to the season and length of time soil salinities are lowered, not to the absolute lowest salinity reached. High freshwater flows in the winter and spring, when plants are actively growing, leads to increases

[31]See Chapter 2: Restoration Monitoring of the Water Column for a discussion of gravitational mixing in estuarine systems.

[32]See Volume One for a definition of ‘estuaries’.

in stem length. High freshwater flows later in the growing season are too late to increase individual growth and instead stimulated vegetative reproduction, increasing overall plant (stem) density (Zedler et al. 1986).

Sampling

Information on the quantity and timing of surface water flows can often be obtained from USGS gaging stations located throughout the United States. Real-time data from some stations is available on-line at http://waterdata.usgs.gov/nwis/rt. Data from more remote locations may be obtained by contacting regional USGS offices. Where data from gaging stations are not available, shallow monitoring wells can be outfitted with electronic devices to continuously record water levels. Manual flow meter measurements can also be taken to provide similar data for restoration monitoring efforts.

Human inputs

The particular types of human land use upstream from a marsh can directly affect the timing, delivery, and chemical and physical composition of the water entering a marsh (Marsh 1978) and, therefore, the success of a restoration project. This will also affect the parameters selected for a monitoring effort. Runoff from agricultural land may carry pesticides, herbicides, increased sediment loads, high nutrient concentrations, and bacterial contamination. Runoff from urban landscapes may have elevated temperatures, increased sediment loads, as well as high concentrations of hydrocarbons and other contaminants washed off of parking lots and streets. Sewage treatment plants, for example, may also discharge high concentrations of nutrients and bacteria during overflow events to be carried into downstream marshes. Urban and agricultural land uses also alter hydrology by getting the runoff into streams and rivers faster than forested cover types (Omernick 1977). Forested land also tends to contribute less sediment and nutrients to downstream areas and slows the discharge of water during and after storms. Land use information can often be obtained from local watershed councils or planning agencies. If these resources are not available aerial photography can be used to assess the amount and location of various upstream land uses.

Wave Energy

Wave energy has many impacts (positive and negative) on marsh vegetation. Waves can alter the composition of marsh substrates (Minc 1998) and redistribute reproductive structures such as buds and tubers (Foote and Kadlec 1988). Wave energy can resuspend and move seeds once buried in shallow sediments to new locations where they can germinate (Kelly and Bruns 1975). Thus, seed banks in areas of higher wave energy are not only a source of propagules in the immediate area but to surrounding areas as well (Foote and Kadlec 1988). Excessive amounts of wave energy can, however, damage and uproot marsh plants (Jupp and Spence 1977).

In tidal areas with high and low marsh communities, low marshes are subject to greater wave action and erosion potential than high marshes (Chapman 1960). As a result, marsh sediments exposed to waves such as in low or coastal open marshes typically have very little organic matter (Burton et al. 2002). Any organic matter produced is transported out of the marsh to other adjacent systems, leaving mineral substrates behind (Keddy 1985; Burton et al. 2002). By resuspending and redistributing sediments, altering sediment grain size, and removing most of the organic matter, wave energy effectively changes the sediment nutrient content[33] and primary productivity (Kadlec 1962; Wilson and Keddy 1985).

Terracing of marsh restoration projects, as demonstrated at the Sabine National Wildlife Refuge in coastal Louisiana (Castellanos 2003),

[33]The relationship between sediment grain size and nutrient availability was discussed in a previous section of this chapter.

can be an effective technique for reducing wave energy and protecting adjacent upland areas and the marsh itself (Underwood et al. 1991). Earthen terraces planted with smooth cordgrass were used to disrupt the fetch across open water and mimic natural deltaic sedimentation patterns (Figure 17). The combination of transplanted vegetation along with shallow terracing prevented shoreline erosion by reducing wave energy and creating areas for sediment deposition to occur. The combined effect had a greater affect on reducing wave energy than simply transplanting smooth cordgrass alone (Underwood et al. 1991). The terraces effectively reduced the rate at which open water areas within the marsh were widening due to erosion and allowed for the reestablishment of marsh in an area that had been converted to open water.

Restoration projects using fences constructed of recycled Christmas trees have also been shown, in some cases, to be effective at reducing wave energy, increasing sediment deposition, and enhancing revegetation efforts in desired areas. These structures, however, are very susceptible to damage from storms and heavy boat traffic and need to be monitored to maintain proper functioning condition (Boumans et al. 1997).

Sampling and Measuring Methods

Wave energy can be determined by measuring the height and period of waves. Wave height and period can be directly measured using a wave buoy (Smith 2002). Wave buoys are weather stations that are fixed within the marsh and left in place to record information about tidal currents. Wave height, direction, and period can also be measured using electronic sensors placed on the sediment surface. The goal of monitoring wave energy is to determine the shear stress at the sediment surface. Shear stress is the effect that waves have on marsh sediments. This is more important to coastal marsh processes than wave height alone, as not all surface wave energy affects the sediment (Sanford 1994). A more detailed discussion of different measurement techniques and the effect of wave energy on sediments and plant communities in coastal areas can be found in Chapter 9: Restoration Monitoring of Submerged Aquatic Vegetation, Appendix IV.

CHEMICAL

Sources of water to the marsh determine what nutrients and chemicals are present in sediment

Figure 17. Two of the newly planted earthen terraces can be seen in the fore- and background of this photo. Terraces are only a few feet wide but that is sufficient to reduce wave energy and allow smooth cordgrass to become established, further reducing wave energy in the marsh. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

pore water and in what quantity. In salt and brackish marshes, most plant nutrients such as calcium (Ca), magnesium (Mn), potassium (K), sulfate (SO_4^-) are derived primarily from sea water, while silicon (SiO_2), phosphate (PO_4^-), iron (Fe), Zinc (Zn), and copper (Cu) are derived from upland, freshwater sources. Nitrogen (N) is in approximately equal proportions in seawater and freshwater although considerable local variation may occur (Mitsch and Gosselink 2000). The amount of the other chemicals listed above depends, in part, on physical characteristics of the soil and the relative contribution of salt and freshwater to the marsh.

Tidal freshwater marshes receive the majority of their chemicals from upland river flows (Stern et al. 1991). As freshwater flows vary seasonally, so too does the amount of nutrients carried to marshes by stream flow (Stern et al. 1991; Page et al. 1995). The concentration of nutrients and other chemicals in the sediment can also vary seasonally (Stern et al. 1991; Thompson et al. 1995).

Coastal marshes of the Great Lakes receive their waters from both upland sources and the lakes themselves. The hydrologic, nutrient, and sediment characteristics of Great Lakes coastal marshes are, however, dominated by storms that add pulses of each to marshes over time (Herdendorf and Krieger 1989). As such, concentrations of nutrients and other chemicals in Great Lakes coastal marshes are highly variable (Krieger 1989).

Pore water chemical characteristics considered important structural characteristics of coastal marshes and that may be of use when designing and implementing a monitoring plan include:

- Nutrient concentration
- Salinity
- Dissolved oxygen, and
- Redox potential

Temperature can also affect primary production and plant species composition but is not considered a primary structural characteristic. Extreme heat in shallow areas with black sediments, however, can lead to metabolic stress, reducing primary productivity. Marshes in colder climates or that receive large amounts of cold, groundwater discharge may also experience reduced productivity (Wilcox 1995).

Nutrient Concentration

The emergent plants that dominate marshes obtain the majority of their nutrients from the soil and low nutrient supply can result in reduced plant growth (Valiela and Teal 1974; Paludan and Morris 1999; Tyler et al. 2003). Excess nutrients from industrial, agriculture, wastewater, and other chemical inputs can increase plant growth and may alter the species composition of marsh plant communities (Pennings et al. 2002). The type and concentration of nutrients available for plants to use depends on the sediment grain size, organic content of the soil, and hydrologic characteristics of the marsh such as water source and the duration of flooding.

Nitrogen and phosphorus are the two nutrients that most often control plant growth in coastal marshes. Nitrogen availability often limits plant growth in salt and brackish marshes (Valiela and Teal 1974; Van Wijnen and Bakker 1999; Tyler et al. 2003), whereas freshwater marshes tend to be phosphorus limited (Howarth 1988; Hecky et al. 1993). Phosphorus can, however, also become limiting in salt marshes if there is:

- An overabundance of nitrogen (Cargill and Jefferies 1984)
- A lack of soil organic matter (Van Wijnen and Bakker 1999)
- A relatively low clay[34] content (Froehlick 1988; de Olff et al. 1997; van Wijnen and Bakker 1997), or
- A lack of iron (King et al. 1982)

[34]Particularly gibbsite or other clays with natural oxide coatings. Pure clays such as kaolinite have limited ability to bind with phosphate (Froehlick, P. N. 1988. Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. *Limnology and Oceanography* 33:649-668).

Compared to freshwater marshes there is often much more phosphorus available to plants in salt and brackish marshes (Froehlick 1988; Roden and Edmonds 1997). Increased nutrient levels, on the other hand, can increase primary productivity and change (often decrease) species abundance and community structure (Reader 1978).

Nitrogen[35]

Nitrogen is found in a variety of forms in marsh waters and soils: elemental, inorganic, organic, and total *Elemental* nitrogen (N_2) is abundant in the atmosphere but it is not usable by plants. Elemental nitrogen is, however, 'fixed' into *inorganic* forms by humans and certain types of bacteria and blue green algae into nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). These forms of nitrogen are then usable by plants. Vascular plants and algae take up these forms of nitrogen and use them to make amino acids and other biologically useful compounds. *Organic* nitrogen, as is often measured in marsh sediments and surface waters, is all of the nitrogen that is bound up with organic matter such as leaves, stems, roots, and dead animals or dissolved in the water column. Organic nitrogen plus all of the other forms together are referred to as *total* nitrogen.

The type(s) of nitrogen that is (are) monitored as part of a monitoring program will depend upon the:

- Inputs to the marsh
- Sediment grain size
- Amount of organic matter present in the soil
- Types of bacteria present, and
- Oxidation/reduction state of the sediments (see discussion of *Dissolved Oxygen and Redox* below)

Nitrate (NO_3^-) and nitrite (NO_2^-) are the oxidized forms of N and are found in aerobic sediments and in thin layers around the roots of healthy plants. Nitrate is the more abundant form of the two. Ammonium (NH_4^+) is the reduced form of nitrogen and is often the most abundant form of nitrogen in anaerobic marsh soils after total N. Both NO_3^- and NH_4^+ can be used by vascular plants although NO_3^- is generally the preferred form. Algae can use either of these forms and NO_2^- as well. When a marsh is 'nitrogen limited' at least one of these biologically available forms is lacking even though there may be abundant organic or total nitrogen present.

Phosphorus

Under aerobic conditions phosphorus is bound to iron and organic matter in the soil (Dolan et al. 1981). As sediments become anaerobic with inundation, phosphate (also referred to as orthophosphate, PO_4^-) becomes soluble and is released from the sediment (Mortimer 1941; Mortimer 1942). Phosphate is the only form of phosphorus that can be used by plants. Phosphate dissolved in pore water, together with phosphorus still bound to soil particles and organic matter is referred to as total phosphorus.

The process of phosphate becoming soluble and available to plants can be greatly enhanced by the presence of sulfate (SO_4^-) as sulfate competes with phosphate to bind with iron in the sediment (Roden and Edmonds 1997). Rates of phosphate release from the soil in the presence of sulfate can be five times greater than without it (Caraco et al. 1990). Sulfate is abundant in marine coastal areas but comparatively scarce in freshwater marshes. It is partly through the presence of sulfate that salt marshes are not phosphorous limited as compared to freshwater marshes (Odum 1988; Roden and Edmonds 1997).

Sampling and Monitoring Methods

There are a variety of ways to sample and measure the nutrient content of marsh sediment

[35]Unless otherwise cited, APHA (1999) and Mitsch and Gosselink (2000) have been used to develop this section. They are cited here, instead of liberally throughout the text.

pore waters. Syringes can be used to collect water at very specific depths. Monitoring wells can also be placed at different depths although they are not as precise at sampling at specific depths as syringes. If monitoring wells are used, wells should be within the depth of the rooting zone of marsh plants and pumped clear of water at least twice before the sample is collected to ensure that the water collected for analysis has not been modified by contact with the atmosphere (see discussion on the effects of dissolved oxygen on water chemistry below). A third method to sample pore waters involves the collection of sediment cores. Once taken, cores can be transported to a laboratory for dissection by depth and pore water extracted by centrifuging the sample. Portable labs can be used for quick analysis of nutrients in the field, but if precise measurements are required samples should be analyzed in a controlled laboratory environment. In addition, sandy sediments have greater drainage capacity and likely exhibit a greater variability of nutrient concentrations than clayey soils (Zedler and Lindig-Cisneros 2000). Thus marshes with sandier sediments or marshes subject to greater variability in water sources may require more frequent sampling to determine nutrient concentrations and availabilities.

Salinity

Salinity influences plant zonation and animal use of coastal marshes (Weinstein 1979; Adams et al. 1992; Wortmann et al. 1998; Mitsch and Gosselink 2000; Gelwick et al. 2001; Montagna et al. 2002; Bart and Hartman 2003). Each plant and animal species is adapted to living within a certain range of salinities and will use the various portions of a coastal marsh that have salinities within their specific tolerance (Weinstein 1979). Some plants and animals are tolerant of greater changes in salinity than others (Howes et al. 1986 and literature cited therein). Any change outside of the salinity range to which a plant or animal is adapted will cause stress. High salinity, for example, interferes with ammonium uptake in salt marsh plants, requiring them to expend more energy to incorporate nutrients; energy that could otherwise be spent on growth (Whitney et al. 1981). In response to salinity stresses, plants and animals that cannot migrate will decrease productivity (Weinstein 1979; Howes et al. 1986). Salinity stresses may be so great that plants, or animals that cannot migrate, will die.

The salinity level in salt and brackish marshes ranges from the salinity of the open ocean water (35 ppt) to almost freshwater (0.5 ppt). Occasionally, localized hypersaline conditions (> 35 ppt) can also occur with negative impacts on salt marsh vegetation. Salinities over 100 ppt have been recorded in coastal marshes in Texas during the summer months due to low freshwater inflow and high rates of evaporation (Montagna et al. 2002). Freshwater marshes have salinities below 0.5 ppt and salinity therefore, is typically not an issue in freshwater marshes. The amount of salt in any particular area depends upon the:

- Salinity of the flooding estuarine water
- Tidal elevation
- Climate as measured by:
    - Temperature
    - Evaporation, and
    - Rainfall
- Sediment grain size
- Specific evapotranspiration rate of local plant species (Gallagher 1980), and
- Freshwater inputs from groundwater and surface water (Odum et al. 1984).

Soil salinities in high marshes tend to vary over the growing season. As previously mentioned, seawater brought into the marsh by high spring water levels can get trapped in depressions (pans) between tidal creeks and evaporate away leaving higher concentrations of salt deposited in and on the soil. Soil salinities in low marshes tend to be more uniform throughout the year as these lower marsh areas are more frequently inundated and salts do not get concentrated through evapotranspiration (Beeftink 1965; 1977).

Measuring and Monitoring Methods

A variety of electronic meters for measuring salinity based on conductivity or density of the water sample (APHA 1999) are commercially available and range in price from tens to several hundreds of dollars. When purchasing a salinity meter, practitioners should note that most meters are designed for use within a given range of salinity. Use outside of this range will result in the collection of incorrect data if salinity levels are below that for which the meter is designed or permanent damage to the meter if salinity levels are too high.

Dissolved Oxygen and Redox

Bacteria in the soil preferentially use oxygen during the breakdown of organic matter. Once marsh soils are flooded, any oxygen in the soil is quickly used up. Bacterial communities then use a sequence of other chemicals in the soil as they continue to break down soil organic matter (see Figure 18 under Redox below). Many of these reactions are considered characteristic functions of marshes and will be discussed in a later section of this chapter. A few, however, have direct affects on plant growth and can be considered structural characteristics. These are briefly described here.

The amount of oxygen in marsh soils affects a host of chemical reactions related to nutrient availability, transformation, and uptake as well as the availability of toxic compounds in the soil. While low oxygen levels have been shown to directly limit plant productivity (Howes et al. 1986; Mitsch and Gosselink 2000), a host of associated factors brought about by anaerobic conditions can also limit plant growth. Anaerobic conditions can lead to increased levels of carbon dioxide (CO_2), and increased availability to plants of:

- Manganese (Mg)
- Boron (B)
- Copper (Cu)
- Lead (Pb)
- Mercury (Hg)
- Zinc (Zn), and
- Sulfide (S^{2-})
- Aluminum (Al)

All of these are toxic to plants in high concentrations (Long and Mason 1983 and literature cited therein). Under anaerobic conditions, nitrate (NO_3^-) is also converted to ammonia (NH_4^+). Some plant species have specific requirements for nitrate over other forms of nitrogen and thus suffer under anaerobic conditions (Long and Mason 1983). Marsh plants can, however, transport oxygen down to the roots where it diffuses out to the sediments creating a thin, oxygen-rich layer around roots where ammonia is converted to nitrate and taken up by plants (Howes et al. 1986 and literature cited therein; Chen and Barko 1988). This process is dependent upon the growth of healthy marsh plants. If plants are stressed from other factors, oxygen transport to the sediments may be limited (Howes et al. 1981). The burrowing of benthic invertebrates such as crabs and polychaetes can also increase the oxygen concentration of the sediment, thereby increasing plant productivity (Montague 1982; Bertness 1985).

One of the main problems associated with changing oxygen concentrations in marsh sediments is the formation of sulfide in salt and brackish marshes. Sulfate (SO_4^-) is abundant in seawater. When sulfate comes in contact with anaerobic marsh soils, bacteria reduce it to sulfide. Under anaerobic conditions sulfide bonds with iron to form insoluble pyrites and is thus removed from the water column. If there is not enough iron present hydrogen sulfide (H_2S) is formed. This is extremely toxic to marsh plants (Linthurst 1979). It also inhibits nitrogen cycling and uptake (Mendelssohn 1979; Morris 1980; Howes et al. 1981; King et al. 1982) and thus limits plant productivity. In addition, when tides or water levels recede and expose the soil to the atmosphere, hydrogen sulfide combines with oxygen to form sulfuric acid (H_2SO_4). This dramatically lowers soil pH and has been linked to the death of marsh plants (Cooper 1974; Mitsch and Gosselink 2000) and fish when areas are reflooded and the acid is leached from the soil (Soukup and Portnoy 1986). These conditions are more common in pans between tidal creeks than on creek banks. Creek banks tend to be much more well drained than pans and sulfide is continually washed away (King et al. 1982). In poorly drained pans, these acidic conditions will, however, remain until marsh soils are again inundated and the sulfuric acid is flushed from the system.

Redox

As previously mentioned, when soils are inundated most of the available oxygen is quickly used up as soil microbes break down organic matter. When the available oxygen has been depleted, bacteria need to use different chemicals in place of oxygen to make energy. As each new chemical is used up in the soil different bacterial communities are able to continue the decomposition process by using a different chemical. After oxygen is used up, nitrate is used first, followed in order by magnesium, iron, sulfate, and finally carbon dioxide (Mitsch and Gosselink 2000). Measuring the duration of inundation, however, to infer these chemical concentrations in the soil would require near constant water level measurements. Even when these data are available the rates at which these chemicals are used differs between marshes due to differences in microbial communities, the amount of organic matter, and relative amounts of each of the chemicals listed. By measuring the oxidation-reduction (redox) potential of the marsh soil practitioners get an indirect measure of the duration of inundation and a direct measure of which chemical forms are likely to be present in the soil.

Redox (also referred to as electronic potential or Eh) is measured in millivolts (mV) and can have positive or negative numbers, marsh soils range from +400 to -400. Highly oxygenated, upland soils have Eh values between +700 and +400 mV (Mitsch and Gosselink 2000). As soils are flooded and microbes use up oxygen this value begins to drop. At approximately +400 mV oxygen depletion begins and phosphate (PO_4^-), once attached to sediments, starts to become soluble and is then available for plants to use (Figure 18). At ~250 mV, soil oxygen has been depleted and bacteria begin to convert nitrate (NO_3^-) to ammonium (NH_4^+). At ~200 mV, manganic magnesium (Mn^{4+}) is converted to the manganous form (Mn^{2+}). Once NO_3^+ and Mn^{4+} are used up, ferric iron (Fe^{3+}) is converted to ferrous iron (Fe^{2+}), sulfate (SO_4^{2-}) to sulfide (S^{2-}), and finally carbon dioxide (CO_2) to methane (CH^4) (Mitsch and Gosselink 2000). Many of these chemicals are nutrients that are used directly by plants or that modify the nutrient cycling function of marshes.

As redox potential is related to duration of inundation there is also a relationship with soil depth. Deeper soils are inundated longer and typically have lower Eh values. Redox potential should therefore be measured at various depths within the root zone. Probes to measure redox potential, oxygen concentration, and pH can be purchased from commercial vendors or even made in a lab (Howes et al. 1981; Faulkner et al. 1989; Swerhone et al. 1999).

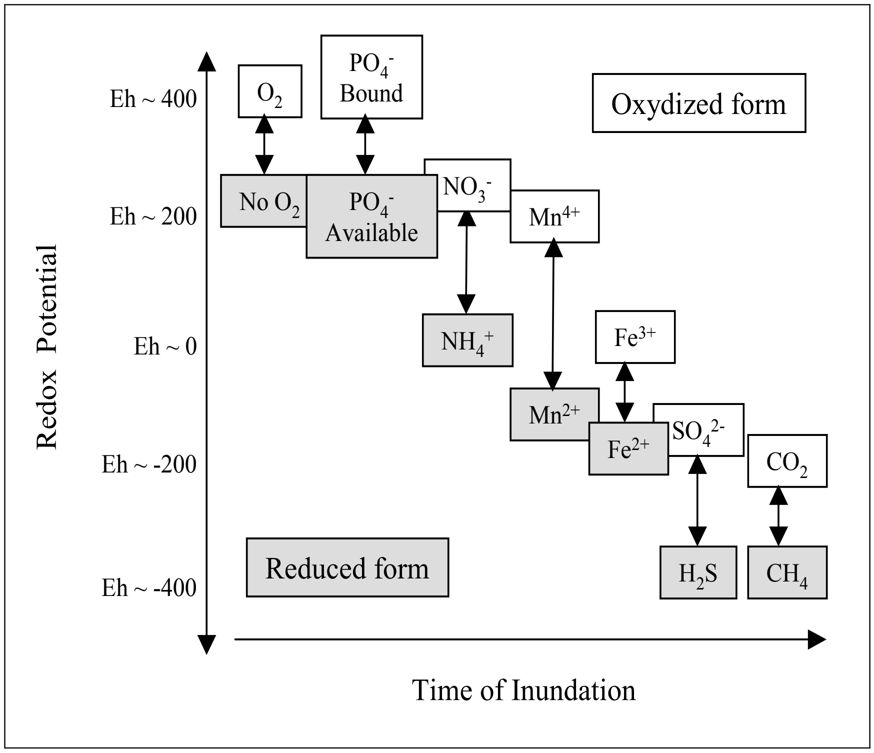


Figure 18. Redox potential of marsh soils changes with the duration of inundation. The longer soils are inundated, the lower the redox potential the soil has as bacteria reduce various chemicals during decomposition of soil organic matter. This process plays an important role in nutrient cycling processes and determines which nutrient forms are available for plants to use. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

FUNCTIONAL CHARACTERISTICS OF COASTAL MARSHES

The goal of many restoration projects, either directly or indirectly, is to restore function(s) to a degraded area, hopefully to a level comparable with reference standards[36]. Functions are things that marshes or other habitats do, whether or not humans derive any social or economic value from them. Temporary storage of flood and storm water is something that often occurs in marshes. If the marsh happens to be in an area where performance of this function prevents or minimizes flood damage to homes and businesses downstream, then a value can be placed on this function. The information provided in this section is organized around common functions of coastal marshes instead of values since values change from place to place and over time based on the needs and desires of the local community[37]. The functions of coastal marshes include:

Biological
- Contributes to primary productivity
- Provides habitat

Physical
- Alters sedimentation rate
- Reduces erosion potential and wave energy
- Temporary flood and storm water storage

Chemical
- Modified water quality
- Supports nutrient cycling

These and the parameters that can be used to monitor them are discussed below.

BIOLOGICAL

Contributes to Primary Productivity

Coastal marshes are extremely productive ecosystems. Tidal freshwater marshes have been shown to have net primary productivity ranges between 566 to 2,311 g/m^2 per year. Net productivity for brackish marshes are similar at 216 to 2,270 g/m^2 per year and salt marshes typically range between 830 and 2,900 g/m^2 per year[38] (Whigham et al. 1978; Mitsch and Gosselink 2000 and literature cited therein), although values as high as 8,000 g/m^2 per year have also been measured in salt marshes on the southern coastal plain of the United States (Mitsch and Gosselink 2000). These values put marsh productivity on par with tropical rainforests and intensively managed agricultural areas (Teal and Teal 1969; Whigham et al. 1978).

Marsh productivity is largely controlled by water depth, salinity (in tidal areas), and proximity to marsh creeks (Mendelssohn et al. 1982). High marshes also tend to exhibit greater productivity than low marshes. This may be related to the greater amounts of organic matter, higher nutrient concentrations, and differences in hydrology between high and low marshes. In high mashes, since wave and tidal energy is lower, plants can allocate less of their energy to belowground processes such as root production and maintenance and more to aboveground growth. In freshwater areas, for example, broad-leaved, low marsh plants, such

[36]Sites or conditions that represent project goals (Brinson, M. M. 1993. A hydrogeomorphic classification for wetlandspp. U.S. Army Corps of Engineers Technical Report WRP-DE-4., Army Corps of Engineers, Vicksburg, Mississippi.). See also Chapter 15 of this volume.

[37]For a detailed discussion of the human dimensions values or benefits associated with coastal restoration see Chapter 14.

[38]Net primary productivity estimates for Great Lakes coastal marshes could not be found for comparison but probably vary widely based on differences in latitude and nutrient availability between the lakes as well as inter-annual differences in vegetation communities due to cyclical water level fluctuations.

as arrow arum and pickerelweed, allocate more energy to belowground rhizomes than to above ground stems and leaves. Freshwater, high marshes tend to be dominated by tall, grass-like perennials such as *Phragmites* and *Typha* and annuals that also exhibit greater aboveground productivity compared to the smaller low marsh species (Whigham et al. 1978; Doumele 1981). Marsh age also has an effect on marsh primary production and plant species composition. Younger marshes generally have lower productivity and accumulate organic matter and nutrients while older marshes tend to have higher rates of productivity and export nutrients and organic matter (Tyler et al. 2003).

Algae

In addition to the productivity of vascular plants, algae also contribute a significant portion of the overall marsh productivity, particularly in autumn and winter when vascular plants are dormant and grazers are less abundant (Zedler et al. 1978; Pomeroy et al. 1981; Adam 1990). Algae also decompose quickly due, in part, to their simple cell structure and are eaten more readily by fish and invertebrates than vascular plants (Polderman 1979). Thus, algae can play a significant role in nutrient cycling within the marsh as well (Adam 1990). There is strong evidence that the secondary productivity of coastal marshes is equally, if not more, dependent upon algae as a primary food source than detritus derived from vascular plants (Haines 1977; Thayer et al. 1978; Haines 1979; Haines and Montague 1979; Hackney and Haines 1980)

Detritus

Less than 10% of the production of vascular plants in coastal marshes is actually consumed by herbivores. The vast majority of biomass produced by vascular plants enters the food web through the detrital pathway (Figure 19 - Teal 1962; Pfeiffer and Wiegert 1981). As marsh vegetation dies and becomes incorporated in the marsh sediments, bacteria and fungi begin the process of decomposition. Bacteria, fungi, and the associated detritus are then fed upon by benthic animals such as nematodes and polychaetes (Kruczynski and Ruth 1997). Although these infauna[39] can be spatially and temporally patchy they can be an important food source for juvenile fish and crustaceans (Nixon and Oviatt 1973; Bell and Coull 1978; McTigue and Zimmerman 1998). They may also be sufficiently abundant to provide an important role in the secondary productivity of coastal marshes (Kreeger and Newell 2000).

Although direct grazing on marsh vascular plants is not the dominant way energy from the vascular plants enters the food chain, some species have been shown to consume large quantities of live vegetation. For example, the heavy marsh crab (*Sesarma reticulatum*) has been known to graze tall, creek side stands of cordgrass down to the ground (Kraeuter and Wolf 1974).

Sampling Methods

There are two main strategies for estimating productivity: sample once during the growing season or sample at multiple times throughout the year (Whigham et al. 1978). Sampling plants to estimate primary productivity is usually done during the time of peak growth for each species in the marsh. Unlike salt marshes that can be veritable monocultures, freshwater marshes tend to have very diverse vegetation communities, meaning that no single sample period will adequately capture the overall rate of productivity for the whole marsh for the year. Seasonal patterns of species dominance in freshwater marshes necessitate that multiple sample times be used (Whigham and Simpson 1975; Doumele 1981; Pickett et al. 1989). Perennials dominate in the early spring, die back and are then replaced by a succession of annuals with a few additional perennials that reach peak biomass later in the year (Whigham et al. 1978). Comparing productivity over longer periods of time in highly dynamic systems such as Great Lakes coastal marshes, where the entire

[39]Small invertebrates that live in the top few centimeters of the sediment.

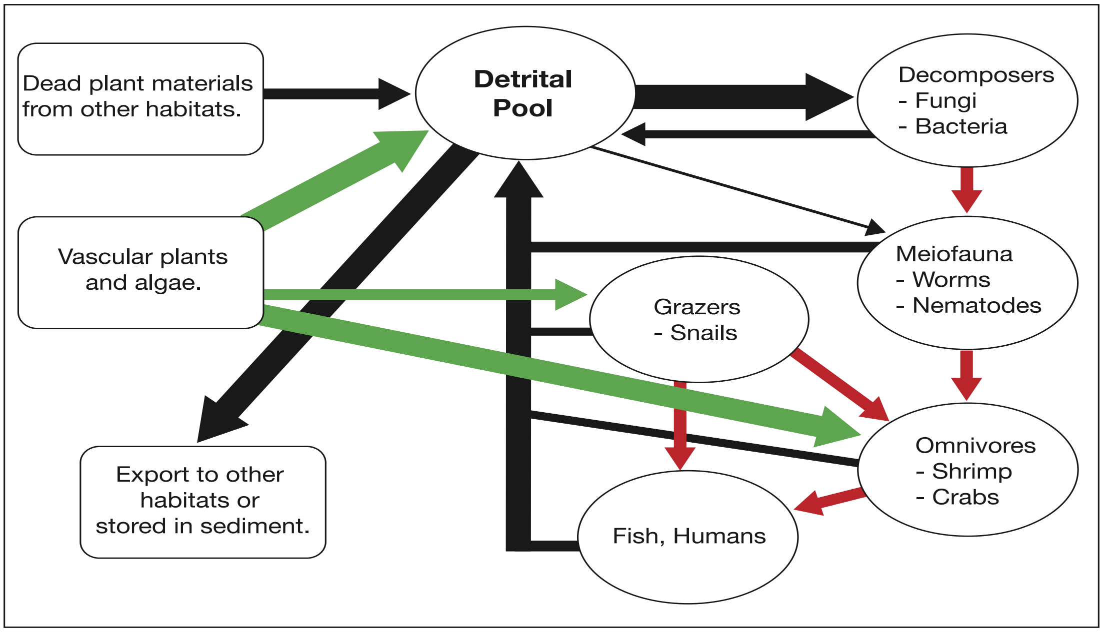


Figure 19. An example of a marsh food web. Green arrows represent the flow of live plant material, black arrows represent dead plant and animal material, red arrows represent predation. Although arrows are sized to represent relative amounts, exact amounts of energy moving from one component to the next will vary among individual areas. Graphic by David H. Merkey, NOAA Great Lakes Environmental Research Laboratory.

vegetation community may differ from year to year, is even more complicated.

A variety of techniques have been explored to measure marsh productivity. These include the simple measurement of plant height, harvesting of live peak standing crop, and more complicated procedures that account for growth, mortality, and decomposition (Keefe 1972; Kirby and Gosselink 1976; Linthurst and Reimold 1978; Shew et al. 1981; Long and Mason 1983; Gibson et al. 1994; Thursby et al. 2002). One common measurement often used is aboveground peak biomass production. Aboveground biomass production is, however, a good measure of just that, aboveground biomass production (de la Cruz 1978; Whigham et al. 1978). It is not a good measure of overall productivity because it does not account for belowground production, herbivory, or leaf mortality during the growing season. Aboveground biomass measurements may, in fact, underestimate overall productivity by 50 to 90 percent (Long and Mason 1983 and literature cited therein). It also leads to difficulties in comparing perennials to annuals and high marshes to low marshes as these vegetation types allocate plant productivity in different ways (i.e., aboveground vs. belowground).

In addition, plants respond to poor conditions by increasing growth and allocating energy to organs that acquire the most strongly limiting resource (Bloom et al. 1985). For example, marsh plants appear to put more energy into root production under unfavorable soil conditions (such as low nutrient availability - Mitsch and Gosselink 2000), perhaps because unfavorable soil conditions require more root surface to obtain the nutrients that are available and service each unit of aboveground biomass (Good et al. 1982). Without accounting for these shifts in relative production and not including belowground production, practitioners may inaccurately evaluate conditions of nutrient limitation.

If primary productivity is related to restoration project goals and is a desirable monitoring parameter, sampling techniques should be coordinated with other biomass monitoring efforts in the region to ensure comparability of data. Regional ecologists and botanists can also help by identifying peak productivity times based on species composition and vegetation dynamics of the restored system. The positives, negatives, and basic assumptions underlying a variety of standard techniques are also reviewed in Long and Mason (1983).

Provides Feeding, Breeding, and Nursery Areas

Coastal marshes provide feeding areas, breeding grounds, and protection for many species of animals such as:

- Fish (Vince et al. 1976; Kneib 1986; Bry 1996)
- Crustaceans and other invertebrates (Heck and Thoman 1981; Christy 1982; Christy 1983; Zimmerman and Minello 1984; Kneib and Knowlton 1995; McTigue and Zimmerman 1998)
- Birds (Weller and Spatcher 1965; Craig and Beal 1992; Prince et al. 1992; Brawley et al. 1998)
- Reptiles (Hurd et al. 1979; Gosselink 1984; Adamus et al. 2001), and
- Mammals (Magwire 1976a; Gosselink 1984; Ford and Grace 1998)

The tremendous diversity of microhabitats provided by marsh vegetation and small changes in topography provide animals with a range of habitats to exploit. The type and number of species, the abundance of individuals, and community composition may be useful parameters in restoration monitoring depending on the goals of the project.

What brings all of these animals into marshes is the high rate of primary and secondary productivity and protection from predators (Moy and Levine 1991 and literature cited therein; Teo and Able 2003b). The abundance of primary producers such as aquatic plants, epiphytes and periphytes, and benthic algae growing in the marsh, and phytoplankton growing in the water column provide animals with food, either directly through grazing or through the detrital food web. Leaf litter from upland sources and other inputs from the adjoining estuary supplement these food sources as well (Kreeger and Newell 2000). All of this organic matter leads to high rates of secondary productivity as various marsh omnivores and carnivores feed upon herbivores and one another.

Various amounts of information are available for the animal communities of salt-, brackish, and freshwater coastal marshes. Some groups such as the invertebrates are particularly well studied in salt marsh communities but not as well understood for freshwater areas. Other types of animals such as amphibians are more abundant in freshwater marshes than in saltwater areas. Thus an equal treatment of all animal types for each habitat across the entire United States and its protectorates is not possible even if it were within the scope of this document. Presented here is an introduction to the available information on the ecological role that some invertebrates, fish, birds, reptiles, amphibians, and mammals play in coastal marshes and how these organisms may be sampled in restoration monitoring. Although examples of how plants, animals, hydrology, water quality, and chemistry are related to one another are provided, practitioners interested in using animal communities to monitor restoration projects are strongly encouraged to follow up the reading of this section with resources in the literature cited and the chapter appendices.

Invertebrates

Invertebrates are a very broad and diverse group making up over 95% of known species of animals (Ruppert et al. 2003). A few of the myriad of possible examples include:

Segmented worms (Phylum Annelida) such as:
- Oligochaetes (Class Oliogchaeta)
- Bristle worms (Class Polychaeta), and

Leaches (Class Hirunidae)
Molluscs (Phylum Mollusca) such as:
Snails (Class Gastropoda), and
Oysters and clams (Class Pelecypoda a.k.a. bivalves)
Arthropods (Phyllum Arthropoda) such as:
Crustaceans (Superclass Crustacea)
Amphipods (Order Amphipoda),
Shrimp, crabs, and crayfish (Order Decapoda), and
Isopods (Order Isopoda), and
Insects (Class Insecta), such as:
Dragonflies and damselflies (Order Odonata)
True bugs (Order Hemiptera), and
True flies (Order Diptera)
Midges (Family Chironomidae)
Mosquitoes (Family Culicidae) (Davis et al. 1990)

In all of their forms, invertebrates form the link in the marsh food web between primary producers, decaying organic matter, and vertebrate predators such as fish, birds, and mammals including humans.

The positive and negative aspects of using some types of invertebrates (e.g., insects) in restoration and ecological monitoring of marshes has been covered in a thorough review by Batzer et al.[40] (2001). There are a number of taxonomic groups that respond well to environmental stressors, making them useful indicators of degradation. Invertebrates are also ubiquitous in marsh habitats making comparison from one marsh to another possible. The sampling of marsh invertebrates is also relatively straightforward, although the taxonomy of species can be somewhat difficult for some groups (e.g., chironomids).

Some of the disadvantages of using invertebrates are that species/impact relationships have not been worked out for many species. Abundance from one marsh to another and within-site patchiness can also vary greatly requiring a large sample size for accurate comparisons to be made. Collection of invertebrate data can be time-consuming compared to other types of wetland data such as plants and birds. Since many restoration projects already have tight budgets and monitoring of invertebrates can be time-consuming and expensive, their use should be carefully considered in conjunction with project goals (Brown and Batzer 2001).

Nonetheless, invertebrates can be very useful for indicating the rate at which restored marshes mature as invertebrates exhibit a variety of means for colonizing new habitats (Wissinger 1999). Adult dragon- and damselflies and the true bugs, for example, can fly from one wetland area to another to lay eggs in newly available habitats. Monitoring efforts will likely find these animals quickly after a restoration project has been implemented. Aerial colonizers such as these have been found in abundance only six months after some projects have been completed (Cramer 1998). Other invertebrates that colonize more slowly, such as molluscs (Wissinger et al. 2001), worms, and crustaceans, may take several years to reach abundance and diversity levels similar to reference sites.

Salt and Brackish Marshes

The invertebrate communities of salt marshes are particularly well studied in comparison to freshwater marshes. This is partially due to the economic importance of shellfish fisheries in marine coastal areas. An important difference, however, in the invertebrate communities on Atlantic and Gulf of Mexico coasts compared to Pacific coasts is that macroinvertebrates, particularly snails and crabs, are lacking in Pacific coastal marshes (Seliskar and Gallagher 1983). Infauna are, however, three times more abundant in Pacific coastal marshes compared to those on the east coast (Levin et al. 1998). Three groups of salt marsh invertebrates are discussed below: benthic macroinvertebrates, benthic infauna, and molluscs.

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[40]The EPA publication *Methods for evaluating wetland condition: developing an invertebrate index of biological integrity for wetlands*, 57 pp. EPA-822-R-02-019, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. also lists several advantages to using invertebrates in monitoring restoration efforts. This report and other wetland assessment materials can be found at: http://www.epa.gov/waterscience/criteria/wetlands/

Benthic Macroinvertebrates

Shrimp - The largest shellfish fisheries in the United States are for brown shrimp (*Farfantepenaeus aztecus*) and white shrimp (*Litopenaeus setiferus)* in the northern Gulf of Mexico (Zimmerman et al. 2000). Marshes play a more important role in the life cycle of shrimp in the Gulf of Mexico than in Atlantic coastal areas due to the longer duration of flooding Gulf coast marshes experience in the spring and summer giving shrimp greater access to the marsh surface (McTigue and Zimmerman 1998). In estuaries of the Gulf of Mexico, young brown shrimp are found in higher abundance in vegetated areas compared to mudflats or soft bottom habitats (Zimmerman et al. 2000 and literature cited therein). While juvenile white shrimp, are also found in and around coastal marshes, their linkage to the marsh surface is not as strong. Juvenile brown shrimp move into coastal marshes from late February to early April to feed on benthic infauna (particularly polychaetes) while juvenile white shrimp arrive in estuarine areas in late May or June to feed mostly on plant matter (Gosselink 1984; Minello et al. 1994; McTigue and Zimmerman 1998 and literature cited therein). Grass shrimp (*Palaemonetes* spp.) on the other hand, are year-round residents of coastal salt marshes, consuming smaller types of infauna (meiofauna[41]) than do brown shrimp (Bell and Coull 1978; Watts 1992).

Crabs - As with seasonal populations of commercially important shrimp, densities of blue crabs (*Callinectes sapitus*) can be almost ten times higher in vegetated versus non-vegetated habitats (Zimmerman et al. 2000). The high density of shrimps and crabs is due in part to the protection marshes provide from fish and other invertebrate predators (Zimmerman et al. 2000 and literature cited therein). Shrimp and crab are much more abundant near marsh edges than in interior portions of a marsh (Baltz et al. 1993; Minello et al. 1994; Minello and Rozas 2002). Marsh edges have less dense, albeit taller, vegetation than internal marsh areas. This allows invertebrates to burrow during the day and escape predation (Fuss 1964; Minello et al. 1987; Wilson et al. 1987).

Crabs have a special relationship with salt marsh plant communities and the density of crab burrows along the edges of marshes can be quite high. The Atlantic fiddler crab (*Uca pugnax*) is often found only in areas dominated by the tall form of smooth cordgrass as burrows cannot be maintained in soft, unvegetated sediments and root mats in the short form of cordgrass are too dense to burrow through (Bertness 1985). Burrowing by crabs increases plant productivity by increasing aeration of the soil during low tides (Clarke and Hannon 1967; Montague 1982; Bertness 1985). Although crabs are not found equally in all marshes, other burrowing animals may have similar effects on soil characteristics and plant growth (Adam 1990).

Benthic Infauna

Infauna are small invertebrates that burrow and live in the top few centimeters of the sediment (McCann and Levin 1989). These include various types of insect larvae, small crustaceans, and benthic infauna such as nematodes, worms (polychaetes and oligochaetes), and meiofauna, all of which are an important link in the detritus-based food web of coastal marshes (Levin et al. 1998 and literature cited therein). Infauna feed on dead algae and plant material in the soil and are in turn eaten by larger crustaceans and fish (Tenore et al. 1982; McTigue and Zimmerman 1998). Their burrowing through the soil also increases the porosity and aeration of the soils which benefits plants (Levin et al. 1998).

Infauna are dependent upon the presence of a certain amount of organic matter in the soil. As a result, they are often found in lower densities in created marshes with lower amounts of soil organic matter compared to natural reference sites (Matthews and Minello 1994). There are a variety of other factors that also influence

[41]A diverse group of microorganisms approximately 0.042mm and 1mm in size.

the composition and abundance of infaunal communities. These include:

- Sediment grain size
- Soil nutrient content
- Macro-organic matter
- Oxygen availability
- Hydroperiod (as it relates to desiccation)
- Sedimentation rates
- Disturbance, and
- Root density (Broome et al. 2000 and literature cited therein; Zedler and Lindig-Cisneros 2000)

These differences along with differences in marsh age bring about differences in the density, species composition, and diversity of infaunal communities (Goldberg 1996; Levin et al. 1998; Broome et al. 2000 and literature cited therein).

Molluscs

Snails such as the salt marsh snail (*Melampus bidentatus*) and periwinkle snails (*Littoraria irrorata*) graze on algae and are in turn eaten by crabs, fish, and some waterfowl and wading birds. Periwinkle snails often move up the stems of smooth cordgrass in advance of the incoming tide (Hamilton 1977) presumably to avoid predation from blue crabs (Warren 1985). Snail densities are often higher in areas where smooth cordgrass plants are tall or dense or where predators are less abundant (Lewis and Eby 2002).

Tidal Freshwater

The literature on invertebrate communities of tidal freshwater communities has been reviewed by Yozzo and Diaz (1999)[42]. Most of the information has been derived from studies conducted in the northeast and mid-Atlantic regions of the United States and the Columbia River on the west coast. Compared to the salt marshes, the invertebrate communities of tidal freshwater marshes are poorly understood and typically have lower species diversity. One reason for lower diversity is that only those freshwater organisms tolerant of a wide range of environmental conditions and resistant to disturbance and pollutants can dominate tidal areas. Yozzo and Diaz (1999) provide lists of taxa for some areas and include detailed discussions of the different types of organisms that inhabit marsh sediments, the water column, and those that are associated directly with different types of vegetation communities. These lists might be useful to practitioners trying to identify organisms or determine which types of taxa might be most useful for them to monitor depending on restoration project goals.

Non-tidal Freshwater

Invertebrate communities in coastal marshes of the Great Lakes have only recently come under consideration and are not well understood (Krieger 1992). More recent efforts have, however, begun to shed light on these organisms (Cardinale et al. 1997; Burton et al. 2002) and their possible use in biological assessment (Burton and Uzarski 2000; Kashian and Burton 2000; Wilcox et al. 2002). Programs that use invertebrates to monitor Great Lakes marsh restoration must also monitor water level fluctuations and the associated changes in vegetation community. As previously stated, long-term water level fluctuations of the lakes (e.g., inter-annual patterns of highs and lows) have tremendous effects on these plant communities (Keddy and Reznicek 1986). Since it is the plants that provide the habitat for invertebrates (Krieger 1992), changes in vegetation community may have tremendous effects on the invertebrates that can live in a particular area. Any changes in invertebrate community observed after a restoration project may have little to do with the act of restoration itself and may be due to variable lake levels influencing vegetation communities (Wilcox et al. 2002). The use of appropriately chosen reference sites will help elucidate the differences in restoration-induced changes in invertebrate community versus those associated with natural variation and lake level fluctuation.

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[42]See summary in Appendix I of this chapter.

Sampling

A variety of methods to sample invertebrate communities are available. Rozas and Minello (1997) have reviewed the literature on methods to estimate nekton, including decapod crustaceans, in shallow habitats and Merritt and Cummins (1996) provide a review of gear that can be used for sampling insects and other smaller invertebrates. A few examples include:

- Corers
- Plankton nets
- Sweep nets
- Drop nets, and
- Small fyke nets

The selection of gear and sample design will depend upon the goals of the monitoring efforts and characteristics of the habitat. For example, a study of five marshes on the Swan Coastal Plain showed that invertebrate community composition collected with sweeps and tows was higher than collected with cores. Cores were not able to catch rapid swimming species such as hemipterans or less abundant species (Cheal et al. 1993). Plankton tows were used mainly when the time available for sorting species was restricted. This is because these samples were sediment-free and generally gave similar results to those obtained with sweeps. Plankton tows, however, cannot be used in areas with dense vegetation present. Sweeps appeared to be the most useful method for a large classification study as they collected more species and resulted in the best discrimination amongst marshes (Cheal et al. 1993). Recommendations on gear and sampling strategy can be found in the resources listed in the second appendix of this chapter, a *Review of Technical Methods Manuals*.

Fish

Coastal marshes provide important spawning, nursery, forage areas, and shelter for a wide variety of fish species (Vince et al. 1976; Keast et al. 1978; Gosselink 1984; Jude and Pappas 1992; Wilcox 1995; Craig and Crowder 2000 and literature cited therein). The particular species of fish present as well as how and when they use the marsh depends, in part, on whether the marsh is tidal (fresh-, brackish, or salt water) or non-tidal (freshwater Great Lake).

Tidal marshes

Tidal marsh communities are made up of a complex and variable mix of freshwater species tolerant of low salinity conditions, estuarine residents, juveniles of anadromous species or adults on spawning runs, marine juveniles using marshes as nursery areas, and marine transients (Odum et al. 1984). Some estuarine species such as killifish (*Fundulus* spp.), bay anchovy (*Anchoa mitichilli*), and the tidewater silverside (*Menida beryllina*) are commonly found foraging in freshwater tidal marshes (McIvor and Odum 1988; McIvor et al. 1989). Other estuarine fishes such as Atlantic croaker (*Micropogonias undulates*) and red drum (*Sciaenops ocellatus*) enter marshes to feed on juvenile brown shrimp (Minello and Zimmerman 1983). Commercially important anadromous fish such as herring (*Alosa* spp.), salmon (*Oncorhynchus* spp.), and striped bass (*Morone saxatilis*) use marshes as spawning and nursery areas before maturing and returning to the open ocean (Congleton and Smith 1976; Levy et al. 1979; Odum 1984; Miller and Simenstad 1997). Three families, cyprinids (minnows, carp, and shiners), centrarchids (sunfish, crappies, and bass), and ictalurids (catfish), spawn and complete their entire life cycle only in freshwater areas (both tidal and non-tidal) (Odum 1984).

The mummichog is an important resident fish of salt marshes on the East (*Fundulus heteroclitus)* and Gulf (*F. grandis)* coasts and is commonly studied for its role in marsh ecosystems (Teal 1962; Nixon and Oviatt 1973). Mummichogs use marshes for feeding, breeding, and refuge from predation (McIvor and Odum 1988; Rozas and Reed 1993; Able and Hagan 2000; Able et al. 2003) and are often found migrating between the marsh surface, marsh creeks, and small pools in response to tidal patterns (Weisberg and Lotrich 1982; Teo and Able 2003b). Mummichogs and banded killifish (*Fundulus diaphanous*) have been shown to enter marshes with almost empty stomachs on the high tide and leave almost full on the low tide (Rozas et al. 1988). While in the marsh, mummichogs feed on copepods, amphipods, insects, algae, and detritus (Fell et al. 2000). Once they leave the protection of the marsh surface, mummichogs are preyed upon by striped bass (Tupper and Able 2000), Atlantic croaker (Nemerson 2001), and flounder. Thus, this species serves as an important ecological link between the productivity of the marsh surface and commercially important estuarine species.

Non-tidal Marshes

In Great Lakes, northern pike (*Esox lucius*), long nose gar (*Lepisosteus osseus*), and bowfin (*Amia calva*) make extensive use of marsh habitats for feeding and spawning. Other species such as gizzard shad (*Dorosoma cepedianum*), carp (*Cyprinus carpio*), suckers (*Catostomus* spp.), and perch (*Perca* spp.) can be found seasonally in abundance in coastal wetlands (Jude and Pappas 1992). Though these species are not strictly dependent on coastal marsh habitats, the high productivity of freshwater marshes makes them efficient places to forage (Herdendorf 1992).

Seasonality

There is a strong seasonal component to fish use of coastal marshes, particularly in tidal areas. Anadromous and semi-anadromous fishes spawn early and their young begin using the marsh as a nursery area in the spring. Winter-spawning marine fishes also use freshwater marshes as nursery areas at this time. Later in the spring and summer as waters warm, freshwater species also begin to spawn in the marsh. Resident killifishes spawn in midsummer. In tidal freshwater marshes of the mid-Atlantic the greatest number of individuals and species are found in the summer and fall (Odum et al. 1984).

Effects of Hydroperiod

Hydroperiod and vegetation communities create opportunities and constraints to fish use of coastal marshes. The duration and depth of flooding are closely linked to marsh elevation and tidal regime (Rozas 1995). Fish can only access high marshes during high water periods or high tides. This means that shorter hydroperiods will limit the ability of estuarine fish to access marsh habitats (Teo and Able 2003b). While fish move into marshes on the high tide to feed and escape predation (Vince et al. 1976; Craig and Crowder 2000 and literature cited therein), patterns of fish movement at low tide often differ depending on the availability of adjacent SAV habitats (Rozas and Odum 1987b). In freshwater areas, where SAV is more likely to be adjacent to marshes, fish and crustaceans move out of the marsh into SAV during low tide (Yozzo and Smith 1998). In salt marshes where dense beds of SAV are not commonly as closely associated with marshes, fish and crustaceans stay in the marsh when possible. They are, however, restricted to deeper pools and channels, making them subject to predation from larger individuals and birds (Yozzo and Smith 1998 and literature cited therein). During neap tides, high marsh areas may not flood at all and are entirely unavailable for fish use (McIvor et al. 1989). These effects of hydrodynamics on fish use of marsh surfaces would also be present in Great Lakes marshes subject to large seiches. In addition, long-term water level fluctuations (e.g., 30 year patterns of highs and lows) that dramatically alter plant communities can have tremendous effects on the fish communities (Wilcox et al. 2002).

Response to Restoration

Fish can quickly colonize restored marshes if provided access through water level fluctuation, creek channels and other structures that provide 'edge' habitat, and the presence of sufficient vegetation to protect them from predation (Williams and Zedler 1999; Zedler and Lindig-Cisneros 2000; Roman et al. 2002). Just one to two years after implementation of a restoration project fish abundance, density, species richness, average size, and community composition can equal that of natural, reference marshes (Able et al. 2000; Roman et al. 2002). This does not mean that full functioning of the marsh has been restored as factors such as fish growth and survival may also need to be evaluated depending on the goals of the restoration project. In addition, the complete transformation of a fish community in restored marshes to one resembling a reference condition does not follow a linear trajectory. Although some utilization can be seen in a relatively short period of time, it may take several years (i.e., >15 years, Minello and Webb 1997) for restored communities to completely reflect those of reference marshes (Dionne et al. 1999).

Sampling

A myriad of techniques and equipment are available for sampling fish populations and each has biases toward sampling or missing different types and sizes of fish (Able and Hagan 2000). If sampling of fish is to be incorporated as part of restoration monitoring very specific questions about the goal of the project and the timing of sampling need to be answered before fieldwork is conducted (Rozas and Minello 1997). Pit traps, for example, cannot provide information on the relative abundance of animals occupying the marsh at low tide (Talbot and Able 1984; Kneib 1986; Yozzo and Smith 1998). They are only effective for sampling fish and invertebrates that stay in high salt marshes during low tide. Pit traps are also not as effective at sampling animals in high freshwater marshes as animals tend to move out of the marsh on low tide into adjacent SAV areas instead of waiting out low water levels in scattered pools and depressions on the marsh surface (Yozzo and Smith 1998).

Should fish be considered as part of a restoration-monitoring program, hydrologic patterns must be taken into consideration during the planning process. Multiple years of sampling may also be necessary to assess the change in fish communities over time with respect to the effect of restoration activities. Additional factors also need to be taken into consideration including:

- Depth of innundation
- Temperature of the water
- Salinity
- Seasonal shifts in marsh use by different species, and
- Daily behavior patterns

The use of appropriately chosen reference sites may also help differentiate between restoration-induced changes in fish communities and those associated with natural variation due to water level fluctuation, changes in vegetation community, or timing of sampling. Rozas and Minello (1997) provide an extensive review of sampling designs and gear suitable for sampling fish in marsh habitats. Additional resources may be found in *Appendix II: Review of Technical Methods Manuals*.

Birds

Coastal marshes are used for feeding, breeding, roosting, and resting by resident and migrating waterfowl, wading birds, shore birds, gulls and terns, raptors, and perching birds (Gosselink 1984; Odum et al. 1984; Herdendorf 1992). Wading birds such as herons (*Ardea* spp. and *Butorides* spp.) and bitterns (*Ixobrychus exilis* and *Botaurus lentiginosus*) often nest away from coastal marshes but use them to forage for fish and benthic invertebrates (Gosselink 1984; DuBowy 1996). Snowy egrets (*Egretta thula*), greater and lesser yellowlegs (*Tringa melanoleuca* and *T. flavipes*), glossy ibises (*Plegadis falcinellus*), and least and semipalmated sandpipers (*Calidris minutilla* and *C. pusilla*) frequently forage in and around large open pools within marshes

(Brawley et al. 1998). Rails (*Rallus* spp.) and other shorebirds feed on macroinvertebrates and seeds. Endangered and threatened species[43] such as the bald eagle (*Haliaeetus leucocephalus*) and whooping cranes (*Grus americana*), along with more common birds of prey, also use coastal marshes to hunt and nest. Swallows (Family Hirundinidae), flycatchers (Family Tyrannidae), sparrows, finches (Family Fringillidae), juncos (*Junco* spp.), blackbirds (Family Icteridae), as well as many other songbirds and groundbirds also use coastal marshes, particularly freshwater ones, to feed (Mitsch and Gosselink 2000). Dabbling ducks use coastal marshes in the mid-Atlantic region in fall and winter to forage during migrations. Migrant shorebirds, wading birds, and seabirds also use marshes in spring and summer for breeding (Erwin 1996). Migrating birds, such as the long-billed marsh wren (*Telmatodytes palustris*), use high marsh areas above high tide as breeding grounds and feed extensively on the abundant food supplies available in summer and fall in preparation for seasonal migrations (Magwire 1976b; Gadallah and Jefferies 1995). It is partly this diversity that makes birds so useful in monitoring marsh habitats.

The density and species richness of bird populations in coastal marshes is dependent upon an adequate supply of water (Capen and Low 1980), the interspersion of vegetation and open water (Weller and Spatcher 1965), and a diversity of vertical structure brought about by a diversity of vegetation types (Craig and Beal 1992). Up to 90% of all bird species of eastern North America have been observed in coastal marshes of the Gulf of Mexico (Lowery and Newman 1954) and upwards of 280 species use freshwater marshes at some point in their lifecycle (Odum et al. 1984). Dabbling ducks and migratory geese[44] seek out tidal marshes during migrations to feed on the abundant seeds of annual grasses and sedges and upon the rhizomes of perennial marsh plants (Stewart 1962). Waterfowl often use emergent vegetation for cover and nesting and move to adjacent habitats to forage (Prince et al. 1992). Water level fluctuations, characteristic of coastal communities caused either by tides, storms, seiches, or lake level fluctuation, can, however, have serious impacts on waterfowl nesting in marsh habitats either through direct mortality caused by high winds (DuBowy 1996) or drowning of nests during high water periods (Figure 20 - Prince et al. 1992). Waterfowl may prefer the use of diked or isolated inland wetlands for nesting but still use coastal habitats for feeding purposes. In fact, bird diversity may actually be higher in impounded marshes compared to natural marshes. Several bird species, however, such as willets (*Catoptrophorus semipalmatus*), sharptailed sparrow (*Ammodramus caudacutus*), and seaside sparrow (*A. maritimus*) are considered marsh specialists and cannot use impounded habitats. These and other marsh specialists are solely dependent upon salt marshes open to tidal fluctuations for survival (Brawley et al. 1998).

Unlike other groups of animals, waterfowl have been known to graze heavily on marsh vegetation. While many ducks consume only the aboveground portion of marsh plants[45] (Adam 1990), others such as snow geese (*Anser caerulescens*) feed on rhizomes of young grasses and sedges, uprooting large amounts of vegetation in the process (Silby 1981). In some east coast marshes, large flocks of snow geese have been responsible for 'eatouts' in areas up to several square kilometers (Lynch et al. 1947; Smith and Odum 1981). Since the major reproductive mechanism for many marsh plants, such as cordgrass, is through vegetative reproduction of the rhizome, this heavy grazing can severely impact marsh plant communities,

[43] http://endangered.fws.gov/wildlife.html#Species

[44] Resident Canadian geese (*Branta canadensis*) may become a nuisance in marshes by eating newly planted or germinating plants and may need to be controlled.

[45] A notable exception to this generalization is duck potato (*Sagittaria* spp.). Ducks often eat the tubers and rhizomes of this genus.

Figure 20. Although this black bird nest in a Great Lakes marsh is build higher up in vegetation, it is still vulnerable to large changes in water level caused by seiches. Photo by David H. Merkey, NOAA Great Lakes Environmental Research Lab.

efforts to restore them, and the other organisms that depend on coastal marshes.

Measuring and Monitoring Methods

Birds can be one of the easiest types of animals to monitor since they can be measured directly (i.e., counting individuals by sight, sound, or mark and recapture) or through surrogate measures such as the number of nests (Levine and Willard 1990). Aerial surveys and direct counts have been used to estimate bird density and inventory migrant shorebirds (Erwin et al. 1991) and monitor wintering populations (Morrison and Ross 1989). Photographic, video, and sound recording equipment can also be used to build a permanent record of bird usage of an area. Video cameras and aerial photography can also be used to provide estimates of birds as well as a visual record of marsh structural characteristics (Dolbeer et al. 1997). Since many species of birds use marshes solely as foraging areas the amount of time individuals are observed in a marsh can also be used as an indicator of the quality of the habitat and amount of food available.

In 1994, Bird Studies Canada teamed up with Environment Canada and began the Marsh Monitoring Program (MMP). The program has since expanded into the United States and covers areas throughout the Great Lakes basin. The program uses volunteers to assess the health of coastal and inland marshes by monitoring bird and calling amphibian[46] populations and compiles the data together to develop basin-wide trends. The program has tracked the loss of species diversity at the regional scale and has been used to help identify areas where restoration opportunities exist. The protocols used in the MMP could also be used to monitor the progress of restoration projects over time to determine whether or not a restored marsh is providing habitat for marsh dependent birds. The protocols used in the MMP for monitoring birds in coastal marshes can be found on-line at http://www.bsc-eoc.org/mmpbirds.html.

Reptiles and Amphibians

Freshwater reptiles tend to be generalists, not adapted to specific types of freshwater marshes but able to tolerate conditions in a variety of settings (Odum et al. 1984).

[46]Calling amphibians such as frogs are those whose vocalizations can easily be heard. Non-calling amphibians such as salamanders are harder to sample.

Although they are generalists, their presence, absence, or abundance is often noteworthy for restoration monitoring, particularly in the case of endangered species. Amphibians have the added monitoring-related benefit of having a highly permeable skin through which they breathe and transfer water. They are, therefore, likely to be more sensitive to disturbance and contamination than reptiles or other wildlife and useful in restoration or ecological monitoring activities involving contaminated conditions (Weeber and Vallianatos 2000).

Reptiles and amphibians also form an important link in marsh food webs, typically feeding on plants or invertebrates and in turn being fed upon by one another, wading birds, mammals, and fish. Reptiles and especially amphibians are, however, rather rare in salt- compared to freshwater marshes (Gosselink et al. 1979; Zedler 1982), although the diamondback terrapin (*Malaclemys terrapin*) does frequent salt and freshwater tidal marshes along the Atlantic coast to forage for small crabs, snails, ribbed mussels, clams, and fish (Hurd et al. 1979; Montague et al. 1981). Due to the warmer climate, southern portions of the country have greater numbers of reptiles species than northern areas subject to severe winters and sub-freezing temperatures. About 100 reptile species are commonly found in freshwater marshes of the southeast including:

- Water snakes (*Nerodia*)
- Cottonmouths (*Agkistrodon piscivorus*)
- American alligators (*Alligator mississippiensis*), and
- River turtles such as the:
  - Painted turtle (*Chrysemys picta*)
  - River cooter (*Pseudemys concinna*)
  - Florida cooter (*Pseudemys floridana*) (Odum et al. 1984)

Great Lakes coastal marshes also support a variety of snakes and turtles. Herdendorf (1992) compiled a list of 28 species of amphibians and 27 species of reptiles that inhabit the Lake Erie region including the common snapping turtle (*Chelydra serpentina*).

The common snapping turtle has one of the largest distributions of any turtle in North America, from Canada to the Gulf of Mexico, east of the Rocky Mountains (Dillon 1998). Despite this wide range, individual turtles rarely, if ever, leave their home marsh (Froese 1974; Brown et al. 1994). The eggs of adult snappers have also been shown to reflect the amount and type of contaminants that a particular turtle has been exposed to throughout the year (Pagano et al. 1999). Thus, where populations of snapping turtles are abundant enough to support sampling, analysis of turtle eggs can be used to build a long term record of changing levels of contamination in coastal marshes (SOLEC 2003).

Due to seasonal and daily activity cycles, amphibians and reptiles may present a logistical complication to monitoring efforts. Most hibernate in the winter, sometimes at a distance from the marsh they typically use in the summer (Cagle 1942; Cagle 1950; Gibbons 1970; Ernst 1971; Ernst 1976). Daily activity cycles are dependent upon air and water temperature (Cagle 1942; Ernst 1971; Ernst 1976) with some species having both minimum and maximum temperatures required for activity. This highlights the need for monitoring efforts to be repeated over time to ensure that an accurate representation of any change in population or species diversity is captured over time.

When setting project goals and selecting monitoring characteristics for marsh restoration projects it should be noted that reptiles and amphibians typically have a much smaller migratory range than birds or even mammals. If direct seeding of the animals is not a part of a restoration activity and there are no other marshes in the area from which these animals can colonize a restored area, then populations of these animals may take many years to become established if at all.

Sampling

The Marsh Monitoring Program (MMP) has been monitoring bird and calling amphibian populations of coastal and inland marshes in the upper Midwest since 1994 (see section on monitoring birds above). As the ecological monitoring protocols the MMP has developed for birds can be modified for restoration monitoring purposes, so too could the protocols for amphibians. The MMP's simple protocols can be found on-line at http://www.bsc-eoc.org/mmpfrogs.html. Results of ecological monitoring done through the MMP, more detailed descriptions of sampling protocols, and contact information can also be found at http://www.bsc-eoc.org/mmpreport2002.html.

Mammals

Freshwater marshes have higher numbers and diversity of mammals than salt marshes (Seliskar and Gallagher 1983; Gosselink 1984). This is due in part to the lack of freshwater for drinking in salt marsh habitats (Seliskar and Gallagher 1983) with only precipitation, dew, and food juices to provide small mammals with enough freshwater (Magwire 1976a). While some species of mammals that commonly use coastal marshes are also found in upland habitats, such as raccoons (*Procyon lotor*) and white tailed deer (*Odocoileus virginianus*), others are completely dependent on freshwater marsh habitats for food, shelter, and nesting areas. River otters (*Lutra canadensis*), marsh rabbits (*Sylvilagus palustris*), marsh rice rats (*Oryzomys palustris),* mink (*Mustela vison*), nutria, and muskrats (*Ondatra zibenthicus*) may spend their entire lives in marshes (Gosselink 1984; Odum et al. 1984; Mitsch and Gosselink 2000). For additional information on specific species and their use of coastal marshes readers are referred to Odum et al. (1984) who compiled a list of 45 mammal species common to freshwater tidal marshes along the east coast and to Herdendorf (1992) who lists 20 mammal species common to Great Lakes coastal marshes.

Nutria

Herbivores such as nutria and muskrats tend to be much more important (and potentially detrimental) to the structure of plant communities and associated marsh morphology than are predators or other herbivores such as deer and rabbits (Odum et al. 1984). Nutria, an invasive species now common throughout wetlands of the southeastern United States, and muskrats prefer the roots and rhizomes of marsh plants to eating just the leaves (Figure 21). These are the

Figure 21. A nutria in a marsh in southern Louisiana. Photo courtesy of the Louisiana Department of Wildlife and Fisheries.

plant parts that hold marsh substrates in place. When these animals forage for and remove them, sediments can then be easily resuspended and may be washed away by storms or tidal action (Lynch et al. 1947). The aggressive foraging of nutria in particular has been known to severely impact marsh vegetation to such an extent that it may not be able to regenerate naturally (Ford and Grace 1998).

Muskrats
Similar to nutria, when muskrat populations get too high they can 'eat out' marsh vegetation making it harder for the vegetation to re-establish (Weller 1981). When muskrat populations are small, however, their foraging activity is actually beneficial to the overall habitat function of the marsh. By opening gaps in the vegetation, increasing the interspersion of vegetation to open water, and increasing the topographic diversity of the marsh substrate, muskrats increase the diversity of the overall marsh habitat (Weller 1981). The topographic diversity created by muskrat feeding stations creates additional structural diversity to the marsh substrate. This topographic diversity coupled with the control of dominant species and increase in light availability can lead to a greater variety of plant species colonizing a marsh and an increase in plant species diversity. In addition, some types of wildlife can benefit as well. Wading birds can use the open spaces created by muskrats for foraging and waterfowl can use muskrat feeding stations as nesting spots, safe from raccoon predation (Weller 1994).

Restoration efforts in the presence of high herbivore populations may require precautions such as the use of protective tubes around seedlings or fenced enclosures to limit herbivory (Llewellyn and Shaffer 1993; Myers et al. 1995), a technique often used to exclude or reduce impacts of geese. Planted areas should also be monitored regularly to assess the damage caused by herbivores so corrective actions may be taken before too much damage has occurred.

PHYSICAL

Sedimentation

The functional characteristics of sedimentation and methods to monitor sedimentation rates were covered previously with the discussion of sediment as a structural characteristic.

Reduces Erosion Potential and Wave energy

Coastal marshes protect adjacent upland areas from the erosive energy of waves and coastal storms (Möller et al. 2002). Marshes reduce the height and erosive power of waves through a combination of shallow depths causing shoaling and breaking of waves and from frictional losses due to high stem densities (Brampton 1992). Marshes are, in fact, able to reduce wave energy to the extent that little if any erosive energy remains at the landward limit of the wave. This protects shorelines from erosion and allows for the significant reduction in the cost and extent of coastal defenses in areas with healthy marshes (Wayne 1976; Knutson et al. 1982; Leggett and Dixon 1994; King and Lester 1995; Möller et al. 2002). In one study a swath of marsh only 6 meters wide in front of a coastal dike reduced wave energies enough that the dike necessary to protect inland areas from flooding and erosion could be halved in size (6 m tall instead of 12) at a significant reduction in construction and upkeep costs (King and Lester 1995). Several factors influence the ability of marshes to attenuate wave energy. These include meteorological conditions, tidal currents, spatial and seasonal changes in vegetation community, and the viscosity of the substrate (Möller et al. 2002).

Sampling

Sampling methods suitable for monitoring the wave energy affecting coastal marshes was covered in the discussion of waves as a structural characteristic earlier in this chapter.

Temporary Flood and Storm Water Storage

Marshes are transitional areas between permanent open water and uplands and are well adapted to changes in water level. The combination of basin geomorphology, topography, high vegetation stem densities, and interspersion of vegetation with open water contributes to water moving slowly through the marsh as sheet flow. Depending on the cycle of inundation and drydown, marsh sediments can also hold significant amounts of floodwaters. The slowing of water through sheet flow and holding water in the soil temporarily stores flood and storm water, thus helping to reduce flooding in downstream areas. Areas that are prone to flooding could be maintained as marsh so they continue to perform this function, preventing costly insurance payments for flood damage to buildings and agricultural fields in other areas. The function of floodwater storage can be measured by obtaining data on water level fluctuation over short (i.e., hourly) time intervals.

Sampling

Methods suitable for measuring the flood and stormwater storage functions of coastal marshes are covered in the section on the structural characteristic of Tides/Hydroperiod.

CHEMICAL

Coastal marshes perform a variety of chemical functions that help protect estuarine water quality. Marshes retain or transform nutrients, toxic chemicals, and metals (Khan and Brush 1994; Mitsch and Wang 2000; Krieger 2003). They also provide areas for sedimentation to occur, helping to preserve water clarity (Krieger 2003). Many of these functions are dependent upon sedimentation rates and water velocity (Heath 1992 and literature cited therein) but other factors such as the relative age of the marsh are also important (Leendertse et al. 1996; Tyler et al. 2003).

Modifies Water Quality and Supports Nutrient Cycling

Water quality, as measured by nutrient content, temperature, salinity, and the presence of toxic chemicals, has direct effects on primary productivity and species composition of coastal marshes (Weller 1995; Wilcox 1995; Stewart et al. 2000; Lougheed et al. 2001). Coastal marshes in turn modify the quality of water that passes through them (Klopatek 1978; Simpson et al. 1978; Stern et al. 1991; Khan and Brush 1994; Krieger 2003). The ability of individual marshes to retain or transform nutrients and pollutants depends on a variety of factors including:

- Hydrology (residence time and water depth)
- Sediment grain size
- Percent organic matter in the sediment
- Resident microbial community, and
- Age of the marsh (Heath 1992 and literature cited therein)

In a comparison of inland marshes with coastal marshes Heath (1992) found that inland marshes (particularly depressional marshes) are generally better at serving as nutrient sinks (Richardson 1989). This is primarily due to longer retention time of water. As water stays in a marsh soluble and reactive forms of N and P are taken up by plants, bound to sediments and organic matter, or converted into inactive forms before being released to receiving bodies of water or dissipated into the atmosphere (Heath 1992 and literature cited therein). Coastal marshes, on the other hand, typically have much shorter retention times and different hydrodynamics than inland wetlands (Heath 1992). They therefore are not as good at permanently retaining nutrients as inland marshes but often have higher productivity rates due to the constant inflow of new nutrients. Although they do not typically act as long-term sinks for nutrients, coastal wetlands are good transformers of nutrients (Simpson et al. 1978; Whigham et al. 1989), particularly of nitrogen (Teal 1986).

Supports nitrogen cycling

Nitrogen enters coastal marshes through a variety of means and forms. Elemental nitrogen (N_2) from the atmosphere can be fixed by cyanobacteria[47] into forms usable by plants. The amount that this process contributes to marsh nutrient pools varies by season (Whitney et al. 1981) but is generally believed to be a very small part (< 10%) of the total nitrogen inputs to coastal marshes (Wickstrom 1988). The vast majority of nitrogen available to marsh plants comes from a combination of nitrate (NO_3^-) and ammonium (NH_4^+) in the groundwater, in river flows, and from the associated estuary (Bedford 1992; Page et al. 1995; Staver and Brinsfield 1996; Brock 2001). Nitrate is more abundant in oxygenated surface waters and shallow groundwater while ammonium concentrations tend to be higher in oxygen-poor sources such as deeper groundwater, particularly when there is also dissolved carbon present to act as an energy source for bacteria that convert nitrate into ammonium. Organic nitrogen can also enter marshes through surface water inputs but is not readily available for uptake by plants.

Once nitrate enters marsh soils, it is quickly taken up by plants for growth or denitrified by bacteria in the sediment (Barko et al. 1986; Wickstrom 1988). A very simplified diagram of the nitrogen cycle in marsh soils is provided in Figure 22. As plants and animals die and decompose in the anaerobic marsh soils, ammonium is produced (Buchanan and Gibbons 1974). Available ammonium is then assimilated by microbes or released to the surrounding pore water (Hardy and Holsten 1973). In freshwater marshes the ammonium released into the pore water is bound to oxygenated sediments where it is eventually used by other groups of bacteria and converted back into nitrate (Watson et al. 1981). Once converted to nitrate, it is once again available to

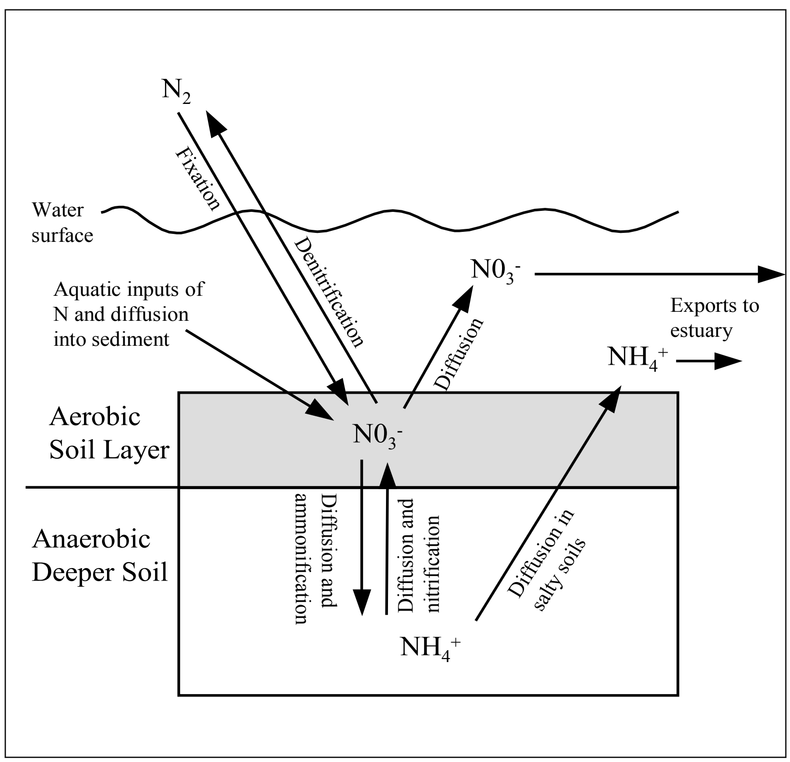

Figure 22. Simplified version of the nitrogen cycling function of marshes. Nitrogen (nitrate) enters aerobic marsh sediments where it diffuses into anaerobic sediments and is changed to ammonium by bacteria. Ammonium then diffuses back up to aerobic sediments to repeat the process or, under salty conditions ammonium will diffuse through to the water column for export out to the estuary. A variety of additional cycles involving algal and vascular plant uptake of the different forms of nitrogen vof organic nitrogen to inorganic forms (NO_3^- and NH_4^+) could also be illustrated to add further complexity to the diagram. Graphic by David H. Merkey, NOAA/Great Lakes Environmental Research Laboratory.

[47]Blue-green algae.

plants or converted to elemental nitrogen (N_2) by yet another group of bacteria and released to the atmosphere (Jeter and Ingraham 1981).

In the sediments of salt and brackish marshes ammonium and nitrate are not retained in the sediment for eventual use by bacteria. Due to the influence of salts, sulfide, and other chemicals present in seawater, many of the nutrient cycling functions of freshwater marshes are significantly different than those of salt and brackish marshes (Heath 1992). Salts in the soil prevent ammonia from binding to sediment surfaces (Gardner et al. 1991; Seitzinger et al. 1991). These chemicals instead move from the soil to the water column where they may be transported out of the marsh (Seitzinger 1988). Through this mechanism, nitrate is transformed into ammonium as it passes through the marsh.

Supports phosphorus cycling

The cycling of phosphorus is much less complex than that of nitrogen. Phosphorus enters marshes bound to sediments entering the marsh with surface water. As sediments settle out and are buried by additional sediments, they may eventually become anaerobic. As sediments turn anaerobic, phosphate (PO_4^-) becomes soluble and is available for plants to use (Mortimer 1941; Mortimer 1942). As discussed in the structural section above, this process is magnified by the presence of sulfate (King et al. 1982; Roden and Edmonds 1997). In phosphorus-limited freshwater marshes, the high concentration of algae and vascular plants in marshes absorbs most of the available phosphorus so that little makes it out of the marsh where it may impact downstream or estuarine water quality. Most of the available phosphorus is retained within the marsh (Klarer 1988). Marshes that accumulate mineral and organic sediments may also accumulate phosphorus (Khan and Brush 1994). Salt marshes where phosphate is not limiting, however, may actually be a source of phosphorus to the associated estuary (Reimold 1972).

Measuring and Monitoring Methods

Nutrient concentrations of marsh surface and sediment pore water can be monitored directly or indirectly. A common method is to simply go out to the marsh with a sample bottle and bring a sample back to a laboratory for analysis. Short-term increases in nutrient concentration such as those caused by storms may, however, be missed by infrequent manual sampling times. High plant productivity is one surrogate measure of marsh nutrient levels but many other factors also affect macrophyte productivity as well. Phytoplankton type and abundance and chlorophyll concentration can also be good measures of marsh nutrient levels as algae are able to quickly take advantage of high nutrient concentrations and reproduce (Gerloff and Skoog 1954). Many forms of algae are also capable of luxury uptake (Rhee 1973; Tilman and Kilham 1976; Mackerras and Smith 1986). This is the ability to take up excess amounts of phosphorus that the algal cells are not going to immediately use. Monitoring the nutrient concentration within algal cells can be a good indication of recent increases in nutrient concentrations that might be missed by only sampling marsh water.

One of the simplest methods to evaluate the chemistry of water is to measure concentration. The use of simple chemical concentrations of water entering and leaving a marsh with tidal cycles or seiches, however, is inadequate to infer nutrient cycling functions without knowledge of the volume of water being exchanged (Merrill and Cornwell 2000). For example, a high concentration in a small amount of water might represent a much lower total amount of a chemical than a smaller concentration in a large amount of water. That said, calculation of a complete water budget for a marsh can be quite complicated as groundwater exchanges and the influences of storms are difficult to assess (Reed 1989; Orson et al. 1990; Staver and Brinsfield 1996; Murray and Spencer 1997). Intensive, long-term, automated sampling may be required to develop realistic estimates of nutrient cycling and other chemical functions in coastal marshes (Merrill and Cornwell 2000).

Retains Heavy Metals and Other Toxics

Heavy metals and other toxics can have serious detrimental effects on human and wildlife populations. Coastal marshes can protect surface water quality by accumulating and retaining metals dissolved in the water column or attached to sediments (Simpson et al. 1983; Orson et al. 1992). Tidal high marshes with high sediment organic content and high sedimentation rates have greater accumulation and retention of metals than low marshes (Khan and Brush 1994). In areas with high sedimentation rates where accumulated organic material is continually buried, marshes may be important long-term sinks for metals such as lead (Pb), nickel (Ni), copper (Cu), cadmium (Cd), and chromium (Cr), baring any major disturbance (Simpson et al. 1983; Whigham et al. 1989; Orson et al. 1992 and literature cited therein). Sediments of Great Lakes marshes that are rich in silts and clays can retain metals as well (Glooschenko et al. 1981). When present in large quantities, however, metals and toxics can have severe negative impacts on plants and wildlife (de la Cruz 1978) and can potentially work their way up the food chain to impact humans (Wiegert and Pomeroy 1981; Anderson et al. 1998).

The ability of a marsh to act as a sink for nutrients and metals is partly dependent upon the proportion of high marsh to low marsh, as high marshes have higher rates of sedimentation and accumulation of organic matter (Khan and Brush 1994). Due to longer periods of inundation, low marsh soils are more efficient at accumulating nutrients and metals per unit of organic carbon. The amount of sediment and organic matter deposition in high marshes, however, is so much larger compared to low marshes that considerably more nutrients and metals are retained there (Khan and Brush 1994).

Sampling

Monitoring for heavy metals or other toxic compounds such as pcbs and ppbs requires special equipment and may be rather expensive for most restoration efforts. In areas with suspected contamination, however, monitoring of these compounds may be necessary. As with all other chemical characteristics, practitioners should consult the American Public Health Association's *Standard Methods for the Examination of Water & Wastewater* for analytical methods.

PARAMETERS FOR MONITORING STRUCTURAL/FUNCTIONAL CHARACTERISTICS

The matrices of structural and functional characteristics and parameters for restoration monitoring presented below were developed through extensive review of restoration and ecological monitoring-related literature. Additional input was received from recognized experts in the field of coastal marsh ecology. These lists are not exhaustive and are merely intended as a starting point to help restoration practitioners develop monitoring plans for coastal marshes. Additional parameters not in this list, such as those related to human dimensions, may also be appropriate for restoration monitoring efforts. Parameters with closed circle (●) are those that, at the minimum, should be considered in monitoring restoration progress. Parameters with an open circle (❍) may also be monitored depending on specific restoration goals. Information on why these parameters are important for monitoring and how they relate to structural and functional characteristics as well as to one another is found throughout the previous text. Additional information on the ecology of coastal marshes, restoration case studies, and sampling strategies and techniques can be found in Appedix I: *Annotated Bibliography of Coastal Marshes* and Appendix II: *Review of Technical Methods Manuals*.

Parameters to Monitor the Structural Characteristics of Marshes

	Structural Characteristics								
	Biological	**Physical**		**Hydrological**				**Chemical**	
Parameters to Monitor	Habitat created by plants	Sediment grain size	Topography / Bathymetry	Tides / Hydroperiod	Water sources	Current velocity	Wave energy	Nutrient concentration	pH, salinity, toxics, redox, DO[48]
Geographical									
Acreage of habitat types	●								
Biological									
Plants									
Species, composition, and %cover of:									
Herbaceous vascular	●								
Canopy aerial extent and structure	❍								
Interspersion of habitat types	●		●						
Plant height	❍								
Stem density	❍								
Seedling survival	❍								
Hydrological									
Physical									
Shear force at sediment surface						❍	❍		
Sheet flow						❍			
Upstream land use					❍				
Water level fluctuation over time				●	●				
Chemical									
Groundwater indicator chemicals[49]					❍				
Nitrogen and phosphorus								❍	
pH									❍
Salinity (in tidal areas)				●	●				●
Toxics									❍
Soil/Sediment									
Physical									
Basin elevations			●						
Geomorphology (slope, basin cross section)			●	●					
Organic content		●							
Percent sand, silt, and clay		❍							
Sedimentation rate and quality			❍						
Chemical									
Pore water nitrogen and phosphorus								❍	
Pore water salinity (in tidal areas)									❍
Redox potential									❍

[48]Dissolved oxygen.
[49]Calcium and magnesium.

Parameters to Monitor the Functional Characteristics of Marshes

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Geographical																
Acreage of habitat	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Biological																
Plants																
Species, composition, and % cover of:																
Herbaceous vascular	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Invasives			○	○	○	○	○	○								
Interspersion of habitat types		○	○	○	○	○	○	○		○	○	○	○	○		
Plant health (herbivory damage, disease[50])					○											
Plant height	○	○														
Plant weight (above and/or below ground parts)	○	○			○											
Seedling survival[49]												○				
Stem density				○		○		○	○	○	○	○	○			
Animals																
Species, composition, and abundance of:																
Amphibians		○	○	○	○	○	○	○								
Birds		○	○	○	○	○	○	○								
Fish		○	○	○	○	○	○	○								
Invasives		○		○	○	○	○									

[50] If the whole community is destroyed by disease or lack of seedling survival, all vegetation-related functions will be impaired.

Parameters to Monitor the Functional Characteristics of Marshes (cont.)

Parameters to Monitor	Biological: Contributes primary production	Biological: Supports biomass production	Biological: Provides breeding grounds	Biological: Provides nursery areas	Biological: Provides feeding grounds	Biological: Provides refuge from predation	Biological: Supports high biodiversity	Biological: Supports a complex trophic structure	Biological: Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Physical: Alters turbidity	Physical: Reduces erosion potential	Physical: Reduces wave energy	Physical: Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Chemical: Modifies chemical water quality
Biological (cont.)																
Animals																
Species, composition, and abundance of:																
Invertebrates		❍	❍	❍	❍	❍	❍	❍								
Mammals		❍	❍	❍	❍	❍	❍	❍								
Reptiles		❍	❍	❍	❍	❍	❍	❍								
Hydrological																
Physical																
Fetch										❍	❍	❍	❍			
PAR	❍	❍								❍	❍					
Seiche disc depth	❍	❍								❍	❍					
Shear force at sediment surface										❍	❍	❍	❍			
Sheet flow										❍	❍	❍		❍	❍	❍
Trash											❍					
Upstream land use	❍	❍								❍	❍					❍
Water level fluctuation over time			●	●	●	●				●	●	●		●	●	
Chemical																
Groundwater indicator chemicals																❍
Nitrogen and phosphorus	❍	❍									❍				❍	❍
pH																❍
Salinity (in tidal areas)							❍									❍
Toxics			❍	❍	❍											❍

Parameters to Monitor the Functionalv Characteristics of Marshes (cont.)

Parameters to Monitor	Biological: Contributes primary production	Supports biomass production	Provides breeding grounds	Provides nursery areas	Provides feeding grounds	Provides refuge from predation	Supports high biodiversity	Supports a complex trophic structure	Provides substrate for attachment	Physical: Affects transport of suspended/dissolved material	Alters turbidity	Reduces erosion potential	Reduces wave energy	Provides temporary floodwater storage	Chemical: Supports nutrient cycling	Modifies chemical water quality
Soil/Sediment																
Physical																
Basin elevations			❍	❍	❍	❍	❍		❍	❍				❍		
Geomorphology (slope, basin cross section)			●	●	●	●	●		●	●	●	●		●		●
Sediment grain size (OM[51]/sand/silt/clay/gravel/cobble)		❍							❍	❍	❍	❍	❍		❍	❍
Sedimentation rate and quality							❍			❍	❍	❍				
Chemical																
Organic content in sediment		❍			❍		❍	❍		❍	❍				❍	❍
Pore water nitrogen and phosphorus		❍													❍	❍
Pore water salinity (in tidal areas)							❍									
Redox potential								❍							❍	❍

[51]Organic matter.

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APPENDIX I: COASTAL MARSHES ANNOTATED BIBLIOGRAPHY

This annotated bibliography contains summaries of restoration case studies and basic ecological literature. It is designed to provide restoration practitioners with examples of previous restoration projects as well as overviews of papers from the ecological literature that offer more detail than that covered in the associated chapter. Entries are presented from both peer reviewed and grey literature. They were selected through extensive literature and Internet searches as well as input from reviewers. They are not, however, a complete listing of all of the available literature. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information has been included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract'* or *'Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapter. Additional references concerning tidal marsh restoration can be found at http://www.neers.org/main/library/wetbiblio.htm.

Allen, H. H., E. J. Clairain, R. J. Diaz, A. W. Ford, L. F. Junt and B. R. Wells. 1978. Habitat development field investigations-Bolivar Peninsula marsh and upland habitat development site. Galveston: Summary Report. 73. City: United States Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS. Technical Report D-78-15.

This study was conducted to establish salt marsh and upland vegetation on a 2-yr old dredged material deposition site on the Galveston Bays side of Bolivar Peninsula, Texas. Small bulldozers and a rubber tire front-end loader were used for grading and transporting sand. Intertidal planting were in 3 elevation tiers. Various techniques were used for seasonal plantings (e.g., fertilizers and application methods). These techniques are described in this report. Monthly samplings recorded changes in plant height, density, number of stems, number of stressed plants, number of stable plants, the percent foliage cover, vegetative reproduction, number of plants with flowers, seed heads and new growth, and above and below-ground biomass. Before and after the marsh was constructed, fish and aquatic species were sampled. Results showed no significant changes in fish diversity or abundance. In marsh benthos protected by the dike, polychaetes and oligochaetes increased in some species. Bird and mammal usage of the marsh area also increased. Researchers concluded that the salt marsh could be created on dredged material, and could function like a natural marsh.

Allen, H. H. and J. W. Webb, Jr. 1993. Bioengineering methods to establish salt marsh on dredged material. In Laska, S. and A. Puffer (eds.), Coastal Zone 93 in New Orleans, Louisiana, American Society of Civil Engineering, New Orleans, LA.

A low-cost wave stilling device and five transplanting treatments was used to develop a *Spartina alterniflora* marsh along a shoreline in Bolivar Peninsula in the Galveston Bay area, which was exposed to moderate to high wave action. Researchers used two breakwaters, a modified floating tire design (FTB) and a fixed tire design. Transplanting treatments included: single stem, multi-stem clumps, multi-stem clumps wrapped in burlap, multi-stem clumps on 0.5-m intervals in a burlap roll with substrate between, and single stems planted in erosion control fiber mat openings and secured in the substrate. Four test plots of each planting treatment were prepared outside the breakwaters.

Techniques for planting and measuring cover are provided in this publication. Results showed that within two and a half years, there was about 25% cover in three mat plots, two multi-stem plots, and one burlap wrapped multi-stem plot. After four years about 50% of the vegetation cover vanished. *Spartina,* however, dominated at the end of five years.

Barrett, N. E. and W. A. Niering. 1993. Tidal marsh restoration: trends in vegetation change using a geographical information system (GIS). *Restoration Ecology* 1:18-28.

Author Abstract. Adequately evaluating the success of coastal tidal marsh restoration has lagged behind the actual practice of restoring tidally restricted salt marshes. A *Spartina* dominated valley marsh at Barn Island Wildlife Management Area, Stonington, Connecticut, was tidally restricted in 1946 and consequently converted mostly to *Typha angustifolia*. With the re-introduction of tidal flooding in 1978, much of the marsh has reverted to *Spartina alterniflora* . Using a geographical information system (GIS), this study measures restoration success by the extent of geographical similarity between the vegetation of the restored marsh and the pre-impounded marsh. Based on geographical comparisons among different hydrologic states, pre-impounded (1946), impounded (1976), and restored (1988) tidal marsh restoration is a convergent process. Although salt marsh species currently dominate the restored system, the magnitude of actual agreement between the pre-impounded vegetation and that of the restored marsh is only moderate.

Bontje, M. P. 1988. The application of science and engineering to restore a salt marsh, pp. 16-23. In Webb, F. J. Jr. (ed.), Proceedings of the 15th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

This report briefly describes the creation of the *Spartina* marsh and compared the use of a 63-acre man-made *S. alterniflora* marsh by birds, mammals and fish, to a 113-acre *Phragmites communis* (reed) marsh. The *Spartina* marsh was established by removing *Phragmites* using glyphosate, excavating and grading the area by digging wide, gently sloping canals. Excavated material was mounded to form berms for shrubs and trees. Once the surface was at a suitable slope and elevation (0.15 -0.45 ft below MHW), *S. alterniflora* was sow into the substrate and established itself within the first growing season. Birds, mammals, fish and water were sampled for 11 months. Bird counts were made monthly by walking or boating through the study site. Mammals were trapped with bait for 24-hrs each month and their tracks and burrows recorded. Fish were collected bimonthly using seine nets. Results showed significantly greater diversity and abundance of birds in *Spartina* marsh compared to *Phragmites* marsh. Muskrat burrows were more densely populated in *Spartina* marsh than the *Phragmites* marsh. Benthos was also significantly greater and more diverse in the *Spartina* marsh compared to *Phragmites* marsh. In adjacent rivers and creeks, fish diversity was low due to poor water quality.

Bontje, M. P. 1991. A successful salt marsh restoration in the New Jersey meadowlands, pp. 5-16. In Webb, F. J., Jr., (ed.), Proceedings of the 18th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

This article addresses a salt marsh restoration and creation project conducted in Lyndhurst, NJ. In an old dredged material deposition site, *Phragmites australis* had invaded the site. Researchers eliminated the reed (*P. australis*), decreased the elevation of the site to match regular marsh levels, improved drainage across the site, and planted and established *Spartina alterniflora.* Techniques used included the use of glyphosate to eradicate *Phragmites*, by means of two aerial sprayings and one hand spraying of recruits. The ground was cultivated using backhoes and dump trucks. There were 9 acres of salt marsh, 2 acres of tidal channels and 3 acres of upland berms established. The salt marsh drained about 80% at low tide and during high tide, dike and a central ridge submerged. *Spartina alterniflora* was planted in peat pots on 3-feet centers. Results showed no significant plant mortality and successful growth.

Brawley, A. H., R. S. Warren and R. A. Askins. 1998. Bird use of restoration and reference marshes within the Barn Island Wildlife Management Area, Stonington, Connecticut, USA. *Environmental Management* 22:625-633.

Author Abstract. Tidal marshes have been actively restored in Connecticut for nearly 20 years, but evaluations of these projects are typically based solely on observations of vegetation change. A formerly impounded valley marsh at the Barn Island Wildlife Management Area is a notable exception; previous research at this site has also included assessments of primary productivity, macroinvertebrates, and use by fishes. To determine the effects of marsh restoration on higher trophic levels, we monitored bird use at five sites within the Barn Island complex, including both restoration and reference marshes. Use by summer bird populations within fixed plots was monitored over two years at all sites. Our principal focus was Impoundment One, a previously impounded valley marsh reopened to full tidal exchange in 1982. This restoration site supported a greater abundance of wetland birds than our other sites, indicating that it is at least equivalent to reference marshes within the same system for this ecological function. Moreover, the species richness of birds and their frequency of occurrence at Impoundment One was greater than at 11 other estuarine marshes in southeastern Connecticut surveyed in a related investigation. A second marsh, under restoration for approximately ten years, appears to be developing in a similar fashion. These results complement previous studies on vegetation, macroinvertebrates, and fish use in this system to show that, over time, the reintroduction of tidal flooding can effectively restore important ecological functions to previously impounded tidal marshes.

Brown, S. C. and D. P. Batzer. 2001. Birds, plants, and macroinvertebrates as indicators of restoration success in New York marshes, pp. 237-248. In Rader, R. B., D. P Batzer, and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Ongoing losses of wetlands have resulted in dramatically increased efforts at restoration of wetlands, often in an attempt to increase habitat for wildlife. Assessment of the success of these restoration efforts must often be done with severely limited resources and time. We examined the use of birds, plants, and macroinvertebrates as indicators of the success of wetland restoration in shallow marshes in northern New York. Analysis of the taxonomic richness of macroinvertebrates and species richness of plants and birds indicated that restored and natural reference sites were not significantly different. However, in terms of community composition, birds, plants, and macroinvertebrates each has significant differences between restored and natural wetlands. Richness measures for the different groups did not correlate with each other, so each group must be analyzed separately. Plants were the most sensitive measure, and bird sampling required the least effort. Macroinvertebrates should be analyzed when one of the goals of the restoration project is to restore macroinvertebrate diversity or overall food web structure. In these wetlands, no single group of organisms indicates overall success of restoration.

Broome, S. W., E. D. Seneca and W. W. Woodhouse, Jr. 1986. Long-term growth and development of transplants of the salt marsh grass *Spartina alterniflora. Estuaries* 9:63-74.

Author Abstract. The effect of transplant spacings (45, 60, and 90 cm) on establishment of *S. alterniflora* along an eroding shoreline in North Carolina was evaluated and annual biomass production of the planted marsh was compared to a natural marsh. The 45- and 60-cm spacings were more successful for establishment on marginal sites that were near the lower elevation limits of *S. alterniflora*. The 90-cm spacing was adequate where growing conditions were favorable. Measurements of aboveground growth indicated that there were no differences due to spacing by the end of the second growing season. Differences between spacing treatments in belowground dry weight persisted through three growing seasons. Annual aboveground and belowground standing crop of the transplanted marsh and a nearby natural marsh were compared over a ten-year period. During the early years of development, several characteristics of the transplanted vegetation differed from the natural marsh, but these differences diminished with time.

Broome, S. W., E. D. Seneca and W. W. Woodhouse, Jr. 1988. Tidal salt marsh restoration. *Aquatic Botany* 32:1-22.

This document presents techniques used to restore *S. alterniflora* salt marshes in the southeastern U.S. Transplanting is a common method used for restoring vegetation. Young plants were available from nearby, healthy, natural donor marshes, or from nursery stocks. Researchers stated that planting was best done early in the growing season (April-June) and growth monitored and evaluated every two months. Additional information on techniques for restoration and monitoring are described in this paper. Based on results, the site must be at a suitable elevation between MSL and MHW, and have a gentle slope less than 10%. While salt marshes occurred in a variety of substrates, sandy substrates were not considered the most suitable for grass growth because they are relatively nutrient poor. Authors stated that restoration work and replanting be done whenever monitoring reveals any deficiency. In addition documentation should be made of successes and failures in a restoration project with some rationale of why failures occurred in order to prevent future failures.

Broome, S. W. 1989. Creation and restoration of tidal wetlands of the Southeastern United States, pp. 37-72. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

Presented are tidal salt marsh restoration efforts, marsh functions, and evaluations of the project success. The dominant plant species *Spartina alterniflora* is commonly used in salt marsh restoration efforts. The common method used in *Spartina* restoration is transplanting. The project success will depend on careful planning. Restoration practitioners should make observations, measure and prepare notes of the elevation at the study site, water circulation in and out the area, salinity levels, sunlight, whether it is protected from wave action, pests activities and anthropogenic impacts. Monitoring is needed to track trends in success and failures of a project as well as the technique used. Monitoring techniques of plant species used in this study include: aerial dry weight, below ground dry weight, number of stems, number of flowering stems, height of the plant, and basal area (area occupied by stems at ground level). Further information regarding monitoring and restoration techniques is described in this paper.

Chabreck, R. H. 1989. Creation, restoration and enhancement of marshes of the Northcentral Gulf Coast, pp. 125-142. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D.C.

This paper provides information on creating and/or restoring coastal marshes. Factors that are to be considered during the restoration planning process include: location, topography, hydrology, substrate type, salinity, and wind and wave climates are all important factors to be considered in the planning process. Monitoring allows practitioners to determine whether the project is on track as planned and if the level of success accomplished. Site characteristics, dredged material placement, protective measures, plant establishment and growth, and wildlife use are monitored. See article for additional measures that are monitored. Plant establishment is an important factor in marsh creation and restoration because plant abundance and diversity indicate marsh success. Sampling marsh characteristics at the sites is also significant because it provides quantative data needed for research or data analysis of sites. Information collected for data analysis includes number of stems, mean height, number flowering, aboveground biomass and belowground biomass.

Craft, C. 2000. Co-development of wetland soils and benthic invertebrate communities following salt marsh creation. *Wetlands Ecology and Management* 8:197-207.

Author Abstract. The development of wetland soil characteristics and benthic invertebrate communities were evaluated in created *Spartina alterniflora* salt marshes in North Carolina ranging in age from 1 to 25 years old. A combination of measurements from different-age created marshes as well as periodic measurements over time on two marshes were used to (1) document rates of wetland pedogenesis, especially soil organic matter, and, (2) explore relationships between soil and benthic invertebrate community development. Soil macro-organic matter (MOM, the living and dead root and rhizome mat), organic C and N increased and bulk density decreased during the 25 years following marsh establishment. The most dramatic changes in bulk density, MOM, C and N occurred within the upper 10 cm of the soil with lesser changes below this depth. Created marshes were sinks for organic C (90–140 $g \cdot m^{-2} \cdot yr^{-1}$) and N (7–11 $g \cdot m^{-2} \cdot yr^{-1}$) but not for P (0–1 $g \cdot m^{-2} \cdot yr^{-1}$). The density of benthic invertebrates (>250 μm) and subsurface-deposit feeding oligochaetes also increased over time on created salt marshes. Invertebrate and oligochaete density were strongly related to MOM content ($r^2 = 0.83–0.87$) and soil organic C ($r^2 = 0.52–0.82$) and N ($r^2 = 0.62–0.84$). These findings suggest that, in created salt marshes, development of the benthic invertebrate community is tied to marsh soil formation, especially accumulation of organic matter as MOM and soil. Field studies that manipulate the quantity and quality of soil organic matter are needed to elucidate the relationship between salt marsh pedogenesis and benthic invertebrate community development.

Dawe, N. K., G. E. Bradfield, W. S. Boyd, D. E. C. Trethewey and A. N. Zolbrod. 2000. Marsh creation in a northern Pacific estuary: Is thirteen years of monitoring vegetation dynamics enough? *Conservation Ecology* 4:12. http://www.consecol.org/vol4/iss2/art12

Author Abstract. Vegetation changes were monitored over a 13-yr period (1982-1994) in the Campbell River estuary following the development of marshes on four intertidal islands. The marshes were created to mitigate the loss of a natural estuarine marsh resulting from the construction of a dry land log-sorting facility. Plant species coverage was measured along 23 permanent transects in planted and unplanted blocks on the constructed islands, and in naturally occurring low-marsh and mid-to-high marsh reference communities on nearby Nunn's Island. Five dominant species, *Carex lyngbyei, Juncus balticus, Potentilla pacifica, Deschampsia caespitosa*, and *Eleocharis palustris* established successfully and increased in cover in both planted and unplanted areas. The planted, unplanted, and Nunn's Island low-marsh sites had similar total plant cover and species richness by the 13th year. Principal components analysis of the transects through time indicated successful establishment of mid-to-low marsh communities on the constructed islands by the fourth year. Vegetation fluctuations on the constructed islands were greater than in the mid-to-high and low-marsh reference communities on Nunn's Island. Results showed that substrate elevation and island configuration were major influences on the successful establishment and subsequent dynamics of created marsh communities. Aboveground biomass estimates of marshes on the created islands attained those of the reference marshes on Nunn's Island between years six and thirteen. However, *Carex lyngbyei* biomass on the created islands had not reached that of the reference marshes by year 13. Despite the establishment of what appeared to be a productive marsh, with species composition and cover similar to those of the reference marshes on Nunn's Island, vegetation on the created islands was still undergoing changes that, in some cases, were cause for concern. On three of the islands, large areas devoid of vegetation formed between years six and thirteen probably a result of water ponding. Adaptive management has allowed us to modify the island configuration through the creation of channels to drain these sites in an attempt to reverse the vegetation dieback. These changes, occurring even after thirteen years, further underscore the need for caution when considering the trading of existing natural, healthy, productive wetlands for the promise of created marshes that may or may not prove to be equal to the natural systems. Where marsh creation is warranted, we recommend that management of created marshes be adaptive and flexible, including a long-term monitoring program that should continue at least until the annual variation in vegetation of the created marsh is similar to that of natural, nearby systems.

Edwards, K. R. and C. E. Proffitt. 2003. Comparison of wetland structural characteristics between created and natural salt marshes in southwest Louisiana, USA. *Wetlands* 23:344-356.

The use of dredge material is a well-known technique for creating or restoring salt marshes that is expected to become more common along the Gulf of Mexico coast in the future. However, the effectiveness of this restoration method is still questioned. Wetland structural characteristics were compared between four created and three natural salt marshes in southwest Louisiana, USA. The created marshes, formed by the pumping of dredge material into formerly open water areas, represent a chronosequence, ranging in age from 3 to 19 years. Vegetation and soil structural factors were compared to determine whether the created marshes become more similar over time to the natural salt marshes. Vegetation surveys were conducted in 1997, 2000, and 2002 using the line-intercept technique. Site elevations were measured in 2000. Organic matter (OM) was measured in 1996 and 2002, while bulk density and soil particle-size distribution were determined in 2002 only. The natural marshes were dominated by *Spartina alterniflora*, as were the oldest created marshes; these marshes had the lowest mean site elevations (< 30 cm NGVD). The six-year-old created marsh (formed in 1996) was higher in elevation (> 35 cm NGVD) and became dominated by high marsh (*S. patens, Distichlis spicata*) and shrub (*Baccharis halimifolia,* *Iva frutescens*) species. The higher elevation marsh seems to be following a different plant successional trajectory than the other marshes, indicating a relationship between marsh elevation and species composition. The soils in both the created and natural marshes contain high levels of clays (30-65 %), with sand comprising < 1 % of the soil distribution. OM was significantly greater and bulk density significantly lower in two of the natural marshes when compared to the created marshes. The oldest created marsh had significantly greater OM than the younger created marshes, but it may still take several decades before equivalency is reached with the natural marshes. Vegetation structural characteristics in the created marshes take only a few years to become similar to those in the natural marshes, just so long as the marshes are formed at a proper elevation. This agrees with other studies from North Carolina and Texas. However, it will take several decades for the soil characteristics to reach equivalency with the natural marshes, if they ever will.

Erwin, K. L., C. M. Smith, W. R. Cox and R. P. Rutter. 1994. Successful construction of a freshwater herbaceous marsh in south Florida, USA, pp. 493-508. In Mitsch, W. J. (ed.) Global Wetlands: Old World and New. Elsevier, Amsterdam.

In 1987, permits were issued for the construction of a correctional facility on a 113 ha site in south Florida. The area contained a mix of pine flatwoods, isolated herbaceous marshes, mesic oak hammocks, and high wet prairies impacted by clearing and cattle grazing. Local hydrology had been altered on-site by a series of berms and ditches and by off-site agricultural pumping. Due to the loss of wetlands during construction, the Army Corps of Engineers (ACE) required on-site, in-kind, one-to-one mitigation. Pre- and post-construction monitoring was required by the ACE permits on both existing and constructed wetlands. Pre-construction monitoring was concluded in October 1987; post-construction monitoring was done in November 1988, September 1989, and September 1990. Measurements included: rainfall, water levels, vegetation, aquatic macroinvertebrates, fish, and wildlife usage.

Rainfall data were obtained from a local county airport located ~12 km from the study site. Water levels were only taken at times of vegetation or macroinvertebrate sampling. Vegetation sampling was done using transects through each major vegetation zone. Species richness and percent cover were measured visually in permanent quadrats located within the major vegetation zones along each transect. Macroinvertebrates were used to assess the wetland's biologic integrity. Macroinvertebrates and fish were reported qualitatively using a D-frame dip net (1-mm mesh size) swept through vegetation and open water within the vegetation sampling station. Use of the wetlands by wildlife was also reported qualitatively; by visual or audible sightings, animal tracks, droppings, nests, burrows, feathers, hair, bones, and reptile skins noted during site visits.

Constructed wetlands met permit success criteria for percent vegetative cover and lack of invasive species after 28 months. Use of the constructed wetlands by macroinvertebrates, fish, and other wildlife was comparable to that at reference sites. Qualitative data are cost effective and often used by regulatory agencies; however, directly equating wetland structure and hydroperiod with wildlife values, percent vegetation cover, and species richness is not well documented in the literature. In response to this lack of information, this wetland has since undergone more rigorous, quantitative sampling of the macroinvertebrate and fish communities to improve performance criteria and determine biological integrity.

Faber, P. M. 1991. The Muzzi marsh, Corte Madera, California: long term observations of a restored marsh in San Francisco Bay, pp. 424-438. In Bolton, H.S. (ed.), Coastal Wetlands. American Society of Engineers, New York.

This article addresses observations made of drainage channel formation, sedimentation, and re-vegetation of the 53-ha portion of the Muzzi Marsh at Corte Madera, California, San Francisco Bay. The Muzzi Marsh was a 81-ha natural coastal marsh that was diked in 1959. The marsh dried out afterward, killing all marsh vegetation. In 1976, an additional 28 ha were diked to retain dredged material, but another 53-ha was opened for tidal circulation by breaching the dikes in two areas. *Salicornia virginica* and *Spartina foliosa* rapidly developed from water born seeds produced by the plants growing on the bayside of the dikes and in the 27-ha natural marsh just to the north of the Muzzi marsh. Data indicated that there was constant competition between *S. virginica* and *S. foliosa* along the MHW elevation. Competition was influenced by yearly rainfall. Results showed that in wetter years *S. foliosa* was more dominant at higher elevations, but during drier years *S. virginica* dominated the lower elevations.

Flynn, K. M., I. A. Mendelssohn and B. J. Wilsey. 1999. The effect of water level management on the soils and vegetation of two coastal Louisiana marshes. *Wetlands Ecology and Management* 7:193-218.

Author Abstract. Wetland degradation and loss is the result of a combination of natural causes and anthropogenic activities and is a serious problem in coastal Louisiana, where approximately 80% of the total US coastal wetland loss since the 1930's has occurred. One method currently used to address this wetland loss problem is structural marsh management, which is the use of levees and water control structures to control hydroperiod. The effects of structural marsh management on two managed marshes in Southern Louisiana (Unit 4 of the Rockefeller Wildlife Refuge and the Fina LaTerre Mitigation Bank) were evaluated by comparing the soils and the dominant emergent marsh vegetation (*Spartina patens*) of the two managed marshes with those of two nearby unmanaged marshes. Soil redox potential, water depth, interstitial water sulfide concentration, salinity, NH4-N and elemental concentrations of Na, K, Ca, Mg, P, Fe and Zn were measured four times during 1989 which was a drawdown year. Net and total CO_2 exchange rate, primary productivity, leaf area, stem density, and live, dead and total aboveground biomass were also measured. The managed marsh at Rockefeller had lower water levels, significantly less reduced surface and 15 cm deep soils and significantly lower interstitial sulfide concentrations and salinity levels. Na, K, Mg and Ca concentrations reflected the same pattern as salinity. Live aboveground biomass, primary productivity and leaf area were 3–4 times greater in the managed marsh. This indicates that marsh management improved soil conditions and provided an environment favorable to more vigorous plant growth. The management scheme at Fina LaTerre was also successful at maintaining lower water levels than in the adjacent unmanaged area. However, surface soils were more reduced and interstitial salinity higher, on average, in the managed marsh indicating generally poorer water circulation. Primary productivity was 50% less and stem density, leaf area, net CO_2 and total CO_2 exchange rates were significantly lower in the managed marsh, compared to the nearby reference marsh. Conditions in the managed marsh indicate that the management scheme was not successful at improving soil conditions when compared to those in the adjacent unmanaged marsh. This study indicates that structural marsh management is not the universal answer to problems faced by Louisiana's coastal wetlands, but may be of value in specific situations.

Fowler, B. K., G. R. Hardaway, G. R. Thomas, C. L. Hill, J. E. Frye and N. A.Ibison. 1985. Vegetation growth patterns in planted marshes of the vegetative erosion control project, pp. 110-120. In Webb, F. J., Jr. (ed.), Proceedings of the 12th Annual Conference on Wetlands Restoration and Creation, Hillsborough Community College, Tampa, FL.

The Vegetative Erosion Control Project studied the success of twenty-four marsh plantings in the Chesapeake Bay system in Virginia. Sites selected were under diverse conditions. Seven sites had low wave energy (average fetch exposure < 1.8km), ten sites had medium wave energy (average fetch exposure from 1.8 to 9.2 km), and seven sites had high wave energy (average fetch exposure > 9.2 km). *S. alterniflora* was planted on 0.5-m centers from MHW to below MSL. *S. patens* were planted above *S. alterniflora*, at a few sites. Practitoners placed about 30-ml of Osmocote fertilizer which has a slow release formula in each hole just before planting. Techniques used are discussed in detail in this paper. Based on results, marshes on low energy shorelines were more productive than those on high-energy shorelines; *S. alterniflora* was more productive in the higher intertidal zone than the lower intertidal zone; and stem densities were greater in marsh areas exposed to greater sunlight and located on the leeward side of the marsh. Additional information on techniques used and recommendations to improve successful establishment of fringe marshes are described in this paper.

Garbisch, E. W., Jr. and L. B. Coleman. 1978. Tidal freshwater marsh establishment in Upper Chesapeake Bay: *Pontedaria cordata* and *Pentandra virginica*, pp. 285-298. In Good, R. E., D. F. Whigham, R. L. Simpson and C. G. Jackson, Jr. (eds.), Freshwater wetlands: ecological processes and management potential. Academic Press, San Diego, CA.

Author Abstract. The effects of tidal elevation, substrate type, and fertilization on the establishment of *Peltandra virginica* and *Pontederia cordata* by seedling and transplanting seedling stock has been determined at a freshwater location in the Upper Chesapeake Bay, Maryland.

Germination percentages ranged from 93% to 5% for *Peltandra virginica* and from 20% to 5% for *Pontedaria cordata* with the higher percentages occurring at the high tidal elevations. The percentages of seedlings that survived the study period averaged ~30% for both species, but the surviving seedlings developed poorly. The establishment of either *Peltandra virginica* or *Pontedaria cordata* by seedling is not considered feasible in unsheltered tidal areas.

No transplanted 1.5-month-old seedlings of *Peltandra virginica* survived at the intermediate and low elevations because of wave stress, debris deposition, and animal depredation. Those surviving at the high elevations did not flower or develop much beyond their stage at the time of planting. Because of the low productivity of 1st year *Peltandra virginica* seedlings, their satisfactory establishment in unprotected tidal environments is not promising. Planting 1st year bulbs or 2nd year seedling stock may yield better results.

The survival of the 3-month-old seedling transplants of *Pontedaria cordata* was relatively high at all elevations and in all substrate types. Both the number of flowering stems and the aboveground standing crop values were significantly greater at the lower tidal elevations. Fertilization effected significant increase in productivity, particularly in sand at the high tidal elevation and peat at the low tidal elevation. Seedling transplants of *P. cordata* became satisfactorily established at all tidal elevations. It is estimated that a tidal *P. cordata* marsh exhibiting a 1st-year aboveground standing crop of 1×10^3 to 4×10^3 kg/ha ca be establishing in the Chesapeake Bay region by planting single seedling transplants on 1- to 0.5-m centers, respectively.

Gulf of Maine Council Habitat Restoration Subcommittee. 2004. Gulf of Maine habitat restoration strategy: Restoring coastal habitat in the Gulf of Maine region, 25 pp., Gulf of Maine Council on the Marine Environment. www.gulfofmaine.org

The Gulf of Maine Restoration Strategy states that habitat restoration is necessary to support aquatic resources in the Gulf of Maine to meet both biological and socioeconomic needs. While restoration projects have already occurred in each of the States or Provinces that share the Gulf of Maine, no formal statement of shared goals or a unified strategy to meet them has been presented. This document lays the groundwork for this by:

- Stating the purpose and scope of regional habitat restoration in the Gulf of Maine
- Identifying habitat types, impacts, and restoration needs, and
- Developing recommendations for enhancing habitat restoration

This report identifies resources of regional significance and promotes habitat restoration that is needed to support the viability of these resources. The strategy presented focuses on four categories of habitats:

(1) Riverine
(2) Intertidal
(3) Subtidal, including nearshore and offshore waters, and
(4) Beaches, sand dunes, and islands

Recommendations provided for the continued success with habitat restoration efforts in the Gulf of Maine include:

- Restore the four coastal marine habitat types identified in this document using a regional strategy to prioritize projects
- Improve our ability to identify habitat restoration sites, focus regional efforts, understand regional trends, and develop effective long-range planning
- Increase development and management capacity in all jurisdictions in the region to make restoration more efficient and effective
- Enhance outreach efforts to federal, state, local governments and the private sector to create a common understanding of the social, economic, and environmental benefits of habitat restoration
- Complete and maintain a database of restoration projects in the region to evaluate progress and ensure accordance with the US National Estuary Restoration Inventory (NERI)
- Refine existing salt marsh monitoring protocols and develop monitoring protocols for other habitats identified in this document

Johnson, G. E., H. L. Diefenderfer, T. J. Berquam, B. D. Ebberts, C. Tortorici and J. D. Wilcox. 2004. Plan for research, monitoring, and evaluation of salmon in the Columbia River Estuary, 133 pp., Pacific Northwest National Laboratory, Richland, WA.

Author Overview. The purpose of this *plan* for research, monitoring, and evaluation (RME) in the Columbia River estuary is to provide a strategic framework to conduct an estuary RME *program*. A formal, integrated RME program does not currently exist; however, it was called for in Action 161 of the Reasonable and Prudent Alternative in the Opinion. Specifically, the estuary RME plan contained herein 1) establishes RME goals and objectives for salmon-related activities in the estuary; 2) develops performance indicators and monitored attributes that are responsive to the objectives; 3) identifies methods to obtain and analyze data on the monitored attributes; and 4) uses project and program level assessments to make recommendations as part of a phased action plan for estuary RME.

Knutson, P. L., J. C. Ford, M. R. Inkeep and J. Oyler. 1981. National survey of planted salt marshes (vegetative stabilization and wave stress). *Wetlands* 1:129-157.

A technique used for evaluating a coastal site's potential for vegetative stabilization based on the site's shoreline characteristics that relate to wave-climate severity was investigated. There were 104 salt marsh plantings in twelve coastal states that were evaluated for this study. The marshes studied were exposed to wind waves, located in brackish and saltwater environments and planted with *S. alterniflora* or *S. foliosa* at least one year prior to the survey. Based on correlation analyses, sediment grain size in the swash zone, longest or average fetch, and shore configuration were good indicators of whether a site is suitable for vegetative stabilization. See publication for additional information on methods used for surveying marsh plants. Results showed an 80% success rate in establishing a fringe marsh when sediment grain size was 0.4mm or less, and an 80% failure when increased. Authors recommended that the site should be at least 6m of intertidal width and be planted over 60% of this area; this should cause sufficient wave dampening to prevent erosion during most of the year. A site evaluation form called the Vegetative Stabilization Site Evaluation Form, was developed to predict the success of *Spartina* planting to control erosion based on observations made.

Kraus, D. B. and M. L. Kraus. 1986. The establishment of a fiddler crab colony on a manmade *Spartina* mitigation marsh, and its effect on invertebrate colonization, pp. 343-348. In Kusler, J. A., M. L. Quammen and G. Brooks (eds.), National Wetland Symposium: Mitigation of Impacts and Losses in Berne, New York. Association of State Wetland Managers, Berne, NY.

A study was conducted to establish fiddler crab populations in a manmade *S. alterniflora* marsh at the Mills Creek mitigation site, and to compare macrobenthos in the manmade marsh to a natural marsh area on Sawmill Creek which. Crabs were collected from the creek and transported to the test sites, with one crab deposited per artificial burrow. Censuses were done of the number of burrows, types of burrows, and crabs observed in the two sites. Benthic macro fauna were sampled at each colony, two control sites, and in a *Phragmites* marsh using a bulb corer to a depth of 10 cm. Details of techniques used in this study can be seen in the article. Results demonstrated that many of the crabs remained in each test site forming two colonies. However, at the end of the study, the fiddler crabs occupied about 42% to 43% of the burrows in the developed marsh. Benthic macroinvertebrates were significantly greater in the developing marsh and natural marsh than the crab colonies or in the *Phragmites* marsh.

LaSalle, M. W., M. C. Landin and J. G. Sims. 1991. Evaluation of the flora and fauna of a *Spartina alterniflora* marsh established on dredged material in Winyah Bay, South Carolina. *Wetlands* 11:191-208.

Author abstract. Approximately 35 hectares of *Spartina alterniflora* marsh has, over a 14-year period, developed naturally on unconfined dredged material placed within the intertidal zone of Winyah Bay, South Carolina. The above- and below-ground vegetative structure, benthic macrofauna, and resident fish and shellfish assemblages of two varying-aged zones (4 and 8 years) of this marsh were evaluated and compared in September 1988. Samples were collected at 10 randomly selected sites along 50-m transect in each marsh. Aboveground vegetative and were assessed from 0.25 m^2. Belowground biomass and sediments were sampled by coring at these sites. Large (1 to 2 cm) macrobenthos were collected only in the 4-year old marsh with Breder traps and block nets.Vegetative structure (stem height, density, percent cover, and biomass) in both zones was within the range reported for natural sites, with a trend toward greater below-ground development with age. The macrofaunal assemblages of both zones were similar in both species composition and numbers of species (17-21 species), with oligochaetes and polychaetes dominating both assemblages. Overall density of macrofauna in the eight-year-old-zone (19,943 individuals per m^2) was significantly greater than that in the four-year-old zone (4,628 individuals per m^2).

Levine, D. A. and D. E. Willard. 1990. Regional analysis of fringe wetlands in the Midwest: creation and restoration, pp. 299-321. In Kusler, J. A. and M. E. Kentula (eds.), Wetland Creation and Restoration: the Status of the Science. Island Press, Washington, D. C.

Levin and Willard provide a brief overview of the history of fringe wetland restoration and creation throughout the Midwest (fringe wetlands are defined as Great Lakes coastal marshes and marshes along inland lakes and reservoirs). They also discuss many of the important ecological characteristics that make up these systems as well as the functions these systems provide such as shoreline protection, fish and wildlife habitat, and water quality protection. They offer recommendations on which site-level characteristics need to be monitored before and restoration/mitigation construction can take place as well as methods for planning successful restoration projects. They recommend that the following steps be included in any restoration/mitigation plan or permit application:

- Justification of location
- Description of site characteristics prior to restoration/mitigation including water level fluctuations, soil type, and elevation
- Clear statement of project goals
- Development of detailed construction plans
- List of target species (to be planted) consistent with project goals
- Long-term management plan
- Complete monitoring plan

Levin and Willard also provide several specific examples of planting techniques, long-term management, monitoring, and mid-course corrections (i.e. adaptive management).

Levin, L. A., D. Talley, T. Talley, A. Larson, A. Jones, G. Thayer, C. Currin and C. Lund. 1997. Restoration of *Spartina* marsh function: an infaunal perspective. In Macdonald, K. B. and F. Weinmann (eds.), Wetland and Riparian Restoration: Taking a Broader View, Proceedings of a Conference, Society for Ecological Restoration International Conference, Seattle, WA.

This study was conducted to investigate factors influencing recovery of restored systems, rates of recovery, and causes for difference in composition between natural marshes and created marshes using sediment dwelling infauna. Researchers examined sediment dwelling fauna functions in salt marshes at two sites in North Carolina and California. Details of techniques used are described in this publication. In North Carolina, organic matter treatments were used at each study site. Results showed reduction in macrofaunal densities and species richness in created marshes compared to natural marshes. Oligochaetes dominated natural marshes and surface deposit feeders dominated created marshes. At the California site, planktrophic organisms were dominant in created marshes compared to natural marshes; and their densities and species richness were greater in the created marsh than natural marsh. Authors concluded that organic treatments should be used to increase *Spartina* growth and support sediment fauna.

Levin, L. A. and T. S. Talley. 2000. Influences of vegetation and abiotic environmental factors on salt marsh invertebrates, pp. 661-707. In Weinstein, M. P. and D. A. Kreeger (eds.), Concepts and Controversy in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Author Abstract. Sediment-dwelling fauna are a ubiquitous component of salt marshes yet we have limited understanding of their roles in marsh functioning and of the environmental conditions that control their distributions and abundances. This paper examines the influence of vegetation (presence, type, density, and biomass) and other environmental variables (marsh age, sediment and porewater properties, elevation, flow, oxygen, and biogenic structures) on salt marsh macrofauna and meiofauna. We review studies from a variety of geographical locations and include new information from systems with adjacent and natural and restored sites in southern California. The influence of environmental factors on faunal assemblages varies with marsh systems, factor intensity or concentration, taxon studied, and with other interacting factors present. We hypothesize a hierarchy of environmental variables in which abiotic properties such as marsh age, elevation and salinity act over large space and time scales, and are most likely to influence the presence or absence of species. Sediment properties (organic matter and particle size) and vegetation presence or type act on intermediate scales affecting macrofaunal abundance and composition. Plant biomass, culms and biogenic structures generated by fauna are patchy and act on small scales, often interacting with flow, to affect distribution and abundance patterns. Resolution of these processes in salt marshes should improve our understanding of controls on invertebrate communities and will ultimately aid in conservation and restoration of salt marsh habitat.

Llewellyn, D. W. and G. P. Shaffer. 1993. Marsh restoration in the presence of intense herbivory: the role of *Justicia lanceolata* (Chapm.) Small. *Wetlands* 13:176-184.

Author Abstract. Research in southern Louisiana over the last decade indicates that large expanses of mudflats are being maintained in an unvegetated state primarily by the rodent nutria (*Myocastor coypus*). At present, there is a dearth of work on managing wetlands in the presence of intense herbivory. The present study was undertaken to elucidate the potential in wetlands restoration of *Justicia lanceolata*, a wetland plant that is resistant to herbivory by nutria. Results from a previous study indicate that *J. lanceolata* is effective at trapping sediments. Furthermore, once it is established and islet elevations are built up, *J. lanceolata* is readily outcompeted by other species of wetland vegetation.

Results from this study indicate that *J. lanceolata* has several other properties that render it amenable for use in marsh restoration in the southeastern region of the USA: (1) thousands of propagules can be obtained from a single *J. lanceolata* islet without mortality to the adult plants; (2) it is resistant to herbivory, perhaps to the extent of being an herbivore repellant; (3) it is resilient with respect to saline storm surges, particularly if followed by a freshwater flushing event; (4) it is well-adapted to flooded conditions.

Lougheed, V. L. and P. Chow-Fraser. 2002. Development and use of a zooplankton index of wetland quality in the Laurentian Great Lakes basin. *Ecological Applications* 12:474-486.

Author Abstract. Recent interest in biological monitoring as an ecosystem assessment tool has stimulated the development of a number of biotic indices designed to aid in the evaluation of ecosystem integrity however, zooplankton have rarely been included in biomonitoring schemes. We developed a wetland zooplankton index (WZI) based on water quality and zooplankton associations with aquatic vegetation (emergent, submergent, and floating-leaf) that could be used to assess wetland quality, in particular in marshes of the Laurentian Great Lakes basin. Seventy coastal and inland marshes were sampled during 1995-2000 these ranged from pristine, macrophyte-dominated systems, to highly degraded systems containing only a fringe of emergent vegetation. The index was developed based on the results of a partial canonical correspondence analysis (PCCA), which indicated that plant-associated taxa such as chydorid and macrothricid cladocerans were common in high-quality wetlands while more open-water, pollution-tolerant taxa (e.g., *Brachionus, Moina*) dominated degraded wetlands. The WZI was found to be more useful than indices of diversity H', species richness) and measures of community structure (mean cladoceran size, total abundance) for indicating wetland quality. Furthermore, an independent test of the WZI in a coastal wetland of the Great Lakes, Cootes Paradise Marsh, correctly detected moderate improvements in water quality following carp exclusion. Since wetlands used in this study covered a wide environmental and geographic range, the index should be broadly applicable to wetlands in the Laurentian Great Lakes basin, while further research is required to confirm its suitability in other regions and other vegetated habitats.

Meyer, D. L., M. S. Fonseca, D. R., Colby, W. J., Kenworthy and G. W. Thayer. 1993. An examination of created marsh and seagrass utilization by living marine resources, pp. 1858-1863. Coastal Zone 93', Vol. 2. In Magoon, O., W. S. Wilson, H. Converseand L. T. Robin (eds.), Proceedings of the 8th Symposium on Coastal and Ocean Management. ASCE, New York.

The authors evaluated fish, shrimp, and crab utilization of planted and natural *Spartina alterniflora* marshes. *S. alterniflora* was planted in 1987 at three dredged material sites in North Carolina with access to channels. The planting method used is described in this publication. Within four years, the marsh developed into a productive vegetative stand habitat. Heterogeneity was added by placing oyster cultch along specific areas of the marsh shoreline. Fishery utilization of the created marshes and nearby natural marsh was examined from 1987 to 1989 using block and fyke nets. Fish density data were done in two years after transplanting. Based on results, average shrimp density was significantly larger in the natural reference marsh than in the planted marshes. Mean crab densities were significantly higher in the natural marsh than in the created marshes. The effect of depositing oyster cultch along the marsh shoreline was examined three months after the cultch placement. The sampling techniques used to collect fauna and perform analysis are described in this article. Oysters, xanthid crabs, amphipods, and other reef organisms occupied the cultch. Overall animal diversity increased in the marsh.

Meyer, D. L., J. M. Johnson and J. W. Gill. 2001. Comparison of nekton use of *Phragmites australis* and *Spartina alterniflora* marshes in the Chesapeake Bay, USA. *Marine Ecology Progress Series* 209:71-83.

Throughout the eastern USA many *Spartina alterniflora* salt-marsh systems are being altered through the invasion of *Phragmites australis*. As a result, substantial declines in the areal distribution of *S. alterniflora*-dominated habitat have occurred in contrast to increases in *P. australis* dominated habitat. While information is scarce on nekton use of *P. australis* marsh, increases in the areal distribution of this species have concerned resource managers. Managers typically view the shift of *S. alterniflora* to *P. australis* marsh as a shift from a biologically diverse and productive marsh to one less biologically diverse and productive. We examined nekton use of *P. australis* marsh relative to *S. alterniflora* marsh with similar geographic location and physical conditions. We found no significant differences ($p > 0.05$) in the utilization of *P. australis* and *S. alterniflora* marsh by nekton in terms of abundance or biomass. Further, no significant difference ($p > 0.05$) in the total number of nekton species was evident between *P. australis* and *S. alterniflora* marsh. We postulate that under similar environmental and physical conditions these marsh types are equivalent in terms of nekton use. It may be necessary to reevaluate current wetland management practices which involve the elimination of *P. australis* in favor of *S. alterniflora* marsh in order to increase nekton use.

Minello, T. J. and J. W. Webb, Jr. 1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. *Marine Ecology Progress Series* 151:165-179.

Author Abstract. We compared densities of nekton and infauna among 5 natural and 10 created (3 to 15 yr in age) salt marshes in the Galveston Bay system of Texas to test whether these marshes were functionally equivalent. Techniques used to evaluate fauna abundance and diversity are described in detail in this publication. Decapod crustaceans dominated the nekton on the marsh surface during both the spring and the fall. Densities of daggerblade grass shrimp (*Palaemonetes pugio)*, the most abundant decapod, were not significantly different among marshes, but the size of these shrimp in created marshes was significantly smaller than in natural marshes. Densities of the marsh grass shrimp (*Palaemonetes vulgaris)* and of three commercially-important crustaceans white shrimp (*Penaeus setiferus)*, brown shrimp (*Penaeus aztecus)*, and blue crab (*Callinectes sapidus*) were significantly lower in created marshes than in natural marshes. Gulf menhaden (*Brevoortia patronus)* were the most abundant fish collected, mainly on nonvegetated bottom adjacent to marsh habitats. Fish densities within vegetation (predominantly gobies and pinfish *Lagodon rhomboides*) were significantly lower in created marshes than in natural marshes. Natural and created marshes, however, did not differ in species richness of nekton. Sediment macro-organic matter and density and species richness of macroinfauna (mainly polychaete worms) were all significantly lower in created marshes than natural marshes. There was a positive relationship in created marshes between marsh age and sediment macro-organic matter, but marsh age was not related to nekton densities. Natural marshes were similar in having low elevations and flooding durations between 74 and 80% of the year; while created marshes were flooded from 43 to 91% of the time. In contrast to marsh age, tidal flooding was often related to nekton densities in marsh habitats. We conclude that marsh elevation and tidal flooding are key characteristics affecting use by nekton and should be considered in marsh construction projects.

Minello, T. J. and J. W. Webb, Jr. 1993. The development of fishery habitat value in created salt marshes, pp. 1864-1865. Coastal Zone '93, Vol. 2. In Magoon, O., W. S. Wilson, H. Converse and L. T. Tobin

(eds.), Proceedings of the 8th Symposium on Coastal and Ocean Management. ASCE, New York.

The Coastal Ocean Program project in Galveston Bay, Texas compared ten created *S. alterniflora* marshes with five natural marshes. The created marshes consisted of transplants on dredged material and aged from three to fifteen years at the time of sampling. A drop enclosure was used to estimate densities of juvenile fishery species within the marsh vegetation. The predominated species were grass shrimp, commercial penaeid, blue crabs, pinfish, and gobies. Results showed that above ground plant biomass was equal or higher in most created marshes than natural marshes while below ground biomass and sediment organic content was lower in created marshes. Also, created marshes supported lower numbers of natant macrofauna, particularly juvenile brown shrimp, white shrimp, and blue crabs. A caging study was also perfomed in the marshes in which the preliminary results indicated that juvenile brown shrimp growth rates were comparable in created and natural marshes, however, survival in cages was significantly lower in created marshes than natural marshes.

Minello, T. J. and R. J. Zimmerman. 1992. Utilization of natural and transplanted Texas salt marshes by fish and decapod crustaceans. *Marine Ecology Progress Series* 90: 273-285.

Author Abstract. Habitat utilization by fish and decapod crustaceans was compared among three transplanted and three natural *Spartina alterniflora* marshes on the Texas (USA) coast during spring 1986. Created marshes had been transplanted on dredged material and were approximately 2 to 5 yr old at the time of sampling. Quantitative drop enclosures (2.6m^2 area) were used to collect juvenile fishes and crustaceans on the marsh surface. Aboveground density and biomass of macrophytes were also measured within these enclosures, and sediment cores were collected to examine sediment macro-organic matter (MOM) and benthic infaunal densities. Transplanted marshes had significantly lower densities of decapod crustacea (primarily daggerblade grass shrimp *Palaemonetes pugio* and juvenile brown shrimp *Penaeus aztecus*) compared with natural marshes. This reduced utilization may have been a response to low densities of benthic food organisms, and densities of decapods were positively correlated with densities of prey in sediment cores. In contrast to the utilization pattern of decapods, densities of fish (dominated by the darter goby *Gobionellus boleosoma* and pinfish *Lagodon rhomboides*) were similar between natural and transplanted marshes. These small fish may rely on salt marshes more for protective cover than for enhanced food resources, and aboveground structure in the transplanted marshes may have adequately provided this function.

Mitsch, W. J. and R. F. Wilson. 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. *Ecological Applications* 6:77-83.

Author Abstract. The creation and restoration of new wetlands for mitigation of lost wetland habitat is a newly developing science/technology that is still seeking to define and achieve success of these wetlands. Fundamental requirements for achieving success of wetland creation and restoration projects are: understanding wetland function; giving the system time; and allowing for the self-designing capacity of nature. Mitigation projects involving freshwater marshes should require enough time, closer to 15-20 yr than 5 yr, to judge the success or lack thereof. Restoration and creation of forested wetlands, coastal wetlands, or peatlands may require even more time. Ecosystem-level research and ecosystem modeling development may provide guidance on when created and restored wetlands can be expected to comply with criteria that measure their success. Full-scale experimentation is now beginning to increase our understanding of wetland function at the larger spatial scales and longer time scales than those of most ecological experiments. Predictive ecological modeling may enable ecologists to estimate how long it will take the mitigation wetland to achieve steady state.

Mitsch, W. J. 2000. Self-design applied to coastal restoration, pp. 554-564. In Weinstein, M. P. and D. A. Kreeger (eds.), Concepts and Controversy in Tidal Marsh Ecology. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Author Introduction. Ecological engineering as the practice and self-design as the theoretical concept may offer the framework in which coastal restoration can take place on a large scale around the world. This paper introduces the concept of ecological engineering, contrasting it with the more familiar term ecosystem restoration. It then focuses on several attempts at large-scale coastal restoration projects that have been undertaken in the USA, describing the scale at which the projects are being developed and the general approaches that are being used. Finally, the paper points out practices that pass the self-design litmus test and those that do not.

Montalto, F. A. and T. S. Steenhuis. 2004. The link between hydrology and restoration of tidal marshes in the New York/New Jersey estuary. *Wetlands* 24:414-425.

Author Abstract. The objectives of this paper are to summarize existing knowledge on the hydrologic characteristics of tidal marshes in the New York/New Jersey (NY/NJ) Estuary, to document the extensive linkages between hydrology and tidal marsh function, to underline their importance in designing restoration projects, and to identify research needs in this area. Hydrologic processes are responsible for the evolution, inter- and intra- marsh variability, and functional value of tidal marshes. Hydrology also controls the movement of materials and organisms between estuaries, wetlands, uplands, and the atmosphere. The importance of hydrology to tidal marsh function is widely recognized by the scientific community. Hydrologic research in tidal wetlands of the NY/NJ Estuary, however, is lacking. Anthropogenic development activities have resulted in drastic losses of tidal wetland value, and restoration is now finally a priority in many of the region's natural resource management plans. The success of tidal marsh restoration efforts depends on how appropriately hydrologic factors and their interdependencies are recognized and incorporated into design; yet, little guidance about how best to restore tidal marsh hydrology is available. There is a need to document better the hydrologic characteristics of existing and historical tidal wetlands, to improve hydrologic modeling capabilities, and to accompany other ecological investigations in tidal marshes with hydrologic documentation.

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

Author Abstract. A growing number of studies have assessed the functional equivalency of restored and natural salt marshes. Several of these have explored the use of functional trajectories to track the increase in restored marsh function over time; however, these studies have disagreed as to the usefulness of such models in long-term predictions of restored marsh development. We compared indicators of four marsh functions (primary production, soil organic matter accumulation, sediment trapping, and maintenance of plant communities) in 6 restored and 11 reference (matched to restored marshes using principal components analysis) salt marshes in the Great Bay Estuary. The restored marshes were all constructed and planted on imported substrate and ranged in age from 1 to 14 years. We used marsh age in a space-for-time substitution to track constructed salt marsh development and explore the use of trajectories. A high degree of variability was observed among natural salt marsh sites, displaying the importance of carefully chosen reference sites. As expected, mean values for constructed site (n = 6) and reference site (n = 11) functions were significantly different. Using constructed marsh age as the independent variable and functional indicator values as dependent variables, nonlinear regression analyses produced several ecologically meaningful trajectories ($r^2 > 0.9$), demonstrating that the use of different-aged marshes can be a viable approach to developing functional trajectories. The trajectories illustrated that although indicators of some functions (primary production, sediment deposition, and plant species richness) may reach natural site values relatively quickly (<10 years), others (soil organic matter content) will take longer.

Moy, L. D. and L. A. Levin. 1991. Are *Spartina* marshes a replaceable resource? A functional approach to evaluation of marsh creation efforts. *Estuaries* 14:1-16.

This study was conducted to compare the functioning of a man-made *Spartina* salt marsh (between ages one to three years) with two adjacent natural marshes. Researchers performed quantifiable measurements on sediment properties, infaunal community composition, and *F. heteroclitus* marsh utilization. Results showed that sediment organic content of the man- made marsh was significantly lower than the natural marshes. *Fundulus* abundance in the man made marsh was significantly lower than in natural marshes indicating that fewer fish were supported by the habitat. *Spartina* stem densities in the man made marsh were significantly lower than the natural marshes. As a result protection or spawning habitat for the fundulids was not suitable. Further details for techniques used are described in this paper. Researchers concluded that the man made marsh ecological functioning was not equivalent to the natural marshes after three years. Authors stated that mitigation could be enhanced by increasing tidal flushing to allow marine organisms additional access to the salt marsh, as well as adding *Spartina* to increase sediment organic-matter content and porosity.

Newling, C. J., M. C. Landin and S. D. Parris. 1983. Long-term monitoring of the Apalachicola Bay wetland habitat development site, pp. 164-186. In Webb, F. J., Jr. (ed.), Proceedings of the 10th Annual Conference on Wetland Restoration and Creation, Hillsborough Community College, Tampa, FL.

Man made cordgrass marshes that occurred in the Apalachicola Bay in an area of dredged material deposition were studied. *Spartina alterniflora* was planted in the intertidal zone, and *Spartina patens* was planted in the supratidal zone. Techniques used included the use of quadrats. Results showed within two growing seasons, all *S. alterniflora* plots began with plants on 1-m centers or less and eventually acheived 100% coverage (using $0.5m^2$). Plants located on larger centers were washed out, or were barely surviving. Similar coverage was found for S. *patens* using $0.25m^2$ quadrats. Within the second year, *Distichillis spicata* dominated in areas between the two cordgrasses. Techniques used are described in this paper.

Six years after the planting, *Scirpus robustus* grew as rapidly as *S. alterniflora* along the landward margin; *S. patens* coverage reduced because of invasive dune type vegetation; vegetation diversity in the dunes and marshes increased to 97 species of plants; plant assemblage was diverse in both manmade and natural marsh sites; and wading birds fed more frequently on vegetation and benthic organisms in the created island.

Poach, M. E. and S. P. Faulkner. 1998. Soil phosphorus characteristics of created and natural wetlands in the Atchafalaya Delta, Lousisiana. *Estuarine, Coastal and Shelf Science* 46:195-203.

Author Abstract. Quantitative comparisons of created and natural wetlands are typically confounded by differences in wetland age, with created wetlands generally younger than their natural counterparts. Observed differences may be attributed to either age differences or to the inability to create wetland functions. The objective of this study was to determine if created dredge-material wetlands and comparably aged wetlands formed by natural deposition in the Atchafalaya Delta have similar sediment phosphorus compositions. Sediment cores were collected on five occasions from elevational strata (low, mid and high) in created and natural wetlands belonging to three age classes (<1-3 years old, 5-10 years old, and 15-20 years old). Sediment phosphorus fractions were determined by sequential chemical extraction. When compared to similarly aged natural wetland sediments: (1) old, created wetland sediments had similar mean phosphorus contents at mid and low elevations, but had lower mean contents at high elevations; and (2) intermediate aged, created wetland sediments had greater phosphorus contents on a per weight basis, but mean contents were lower on a per area basis. At all elevations, the young created wetland had lower phosphorus contents than all other wetlands. Results suggest that dredge sediment used to form the created wetlands in the Atchafalaya Delta is lower in phosphorus than the suspended sediment that forms the natural wetlands. Also, the created wetlands develop natural phosphorus characteristics through time due to sediment deposition during river flooding. In the Atchafalaya Delta, if created wetlands provide the natural flooding cycle, then they begin to develop natural phosphorus characteristics between 10 and 20 years after formation.

Potnoy, J. W. and A. E, Giblin 1996. Biogeochemical effects of seawater restoration to diked salt marshes. *Ecological Applications* 7:1054-1063.

A greenhouse microcosm experiments was conducted to examine biogeochemical effects of restoring seawater to historically diked Cape Cod salt marshes. The peat cores from seasonally flooded and drained diked marshes were water logged with seawater. The porewater chemistry was monitored for twenty-one months. Seawater added to low organic content increases acidic peat from the drained marsh, the pH of the porewater and, alkalinity, PO_4-P, and Fe (II). Increase in cation exchange caused a six-fold increase in dissolved Fe (II) and Al, and a sixty-fold increases in NH_4-N within six months of salination. Re-introducing seasonally flooded diked marshes causes an increase in porewater sulfides to increase affecting re-vegetation success. Restoration of either seasonally flooded or drained diked marshes may encourage large nutrient and Fe (II) releases resulting in primary production and lower oxygen in receiving waters. Some important points mentioned by the authors were that monitoring in diked marshes should occur over a minimum of three years; the common vegetative species in the marsh should be replanted or transplanted; salinity measurements should be taken; sediment testing should be performed; pH levels must be measured; evaluations of adjacent land use should occur; and that nutrient levels must be monitored to determine whether increase in N, SO_4, and PO_4 is due to natural responses or anthropogenic sources. Techniques used in this study are described in detail within the article.

Raposa, K. B. and C. T. Roman. 2003. Using gradients in tidal restriction to evaluate nekton community responses to salt marsh restoration. *Estuaries* 26:98-105.

Author Abstract. Few studies concerning tide-restricted and restoring salt marshes emphasize fishes and decapod crustaceans (nekton) despite their ecological significance. This study quantifies nekton utilization of three New England salt marshes under tide-restricted and restoring conditions (Hatches Harbor, Massachusetts; Sachuest Point and Galilee, Rhode Island). The degree of tidal restriction differed among marshes allowing for an examination of nekton utilization patterns along a gradient of tidal restriction and subsequent restoration. Based on sampling in shallow subtidal creeks and pools, nekton density and richness were significantly lower in the restricted marsh compared to the unrestricted marsh only at the most tide-restricted site (Sachuest Point). The dissimilarity in community composition between the unrestricted and restricted marsh sites increased with more pronounced tidal restriction. The increase in nekton density resulting from tidal restoration was positively related to the increase in tidal range. Species richness only increased with restoration at the most tide-restricted site; no significant change was observed at the other two sites. These patterns suggest that only severe tidal restrictions significantly reduce the habitat value of New England salt marshes for shallow subtidal nekton. This study suggests that the greatest responses by nekton, and the most dramatic shift towards a more natural nekton assemblage, will occur with restoration of severely restricted salt marshes.

Raposa, K. 2002. Early responses of fishes and crustaceans to restoration of a tidally restricted New England salt marsh. *Restoration Ecology* 10:665-676.

Author Abstract. Nekton (fishes and decapod crustaceans) is an abundant and productive faunal component of salt marshes, yet nekton responses to tidal manipulations of New England salt marshes remain unclear. This study examined nekton use of a tidally restricted salt marsh in Narragansett, Rhode Island relative to an unrestricted marsh during summer. In addition, a before-after-control-impact design was used to examine early responses of nekton to the reintroduction of natural tidal flushing. Species richness and densities of *Cyprinodon variegatus, Lucania parva, Menidia beryllina,* and *Palaemonetes pugio* were higher in the restricted marsh compared with the unrestricted marsh. The unrestricted marsh supported higher densities of *Menidia menidia* and *Fundulus majalis*. Mean lengths of *Carcinus maenas* and *P. pugio* were greater in the restricted marsh. Tidal restoration resulted in increased tidal flushing, salinity, and water depth in the restricted marsh. Densities of *Fundulus heteroclitus*, *F. majalis*, and *Callinectes sapidus* were higher after two years of restoration. Density of *L. parva* decreased after restoration, probably in response to a loss of macroalgal habitat. Species richness also decreased after 2 years, from 20.9 species when the marsh was restricted to 13.0 species. Total nekton density did not change with restoration, but shifts in community composition were evident. In this study restoration induced rapid changes in the composition, density, size, and distribution of nekton species, but additional monitoring is necessary to quantify longer-term effects of salt marsh restoration on nekton.

Roberts, T. H. 1991. Habitat value of manmade coastal marshes in Florida. Vicksburg, Mississippi, United States Army Corps of Engineers Waterways Experiment Station. Techinical Report. WRP-REP-2.

This study was conducted to determine the efficiency of marsh creation as mitigation for natural coastal marsh loss along Florida's Gulf and Atlantic coasts. There were four *Spartina* and two *Juncus* natural marshes that ranged in size from 0.20 to 3.2 ha. There were twenty-two manmade marshes between one to ten years in age, seven were one to two years old, six were two to three years old, and six were three to five years old. Researchers collected data on soil substrate texture, particle size and organic content. Vegetation was sampled using stratified random transects with the point-intercept method. Data collected on vegetation included species composition, percent cover, stem density, and height of *Spartina* plants. Below-ground biomass of *Spartina* was measured using 7-cm- diameter cores. Fish were collected using fyke, Breder traps, and a Wegener ring net. Birds were surveyed in each marsh on three consecutive days. Bird-calls were also identified and recorded. Mammals were trapped at each site using Sherman Box and Museum Special Snap traps, one each per station. Detailed methods of the techniques used are presented in the report. Results showed that in manmade marshes, there were no differences observed between the age groups. There was a significant variation in *S. alterniflora* cover with age in the manmade marshes. *S. alterniflora* cover was 80% on a one-year old site and 40% on a two-year old site. Most fish species in natural marshes were found in manmade marshes as well. Details of the results can be seen in the report.

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

Author Abstract. Tidal flow to salt marshes throughout the northeastern United States is often restricted by roads, dikes, impoundments, and inadequately sized culverts or bridge openings, resulting in altered ecological structure and function. In this study we evaluated the response of vegetation and nekton (fishes and decapod crustaceans) to restoration of full tidal flow to a portion of the Sachuest Point salt marsh, Middletown, Rhode Island. A before, after, control, impact study design was used, including evaluations of the tide-restricted marsh, the same marsh after reintroduction of tidal flow (i.e., tide-restored marsh), and an unrestricted control marsh. Before tidal restoration vegetation of the 3.7-ha tide-restricted marsh was dominated by *Phragmites australis* and was significantly different from the adjacent 6.3-ha *Spartina*-dominated unrestricted control marsh (analysis of similarities randomization test, $p < 0.001$). After one growing season vegetation of the tide-restored marsh had changed from its pre-restoration condition (analysis of similarities randomization test, $p < 0.005$). Although not similar to the unrestricted control marsh, *Spartina patens* and *S. alterniflora* abundance increased and abundance and height of *Phragmites* significantly declined, suggesting a convergence toward typical New England salt marsh vegetation. Before restoration shallow water habitat (creeks and pools) of the unrestricted control marsh supported a greater density of nekton compared with the tide-restricted marsh (analysis of variance, $p < 0.001$), but after one season of restored tidal flow nekton density was equivalent. A similar trend was documented for nekton species richness. Nekton density and species richness from marsh surface samples were similar between the tide-restored marsh and unrestricted control marsh. *Fundulus heteroclitus* and *Palaemonetes pugio* were the numerically dominant fish and decapod species in all sampled habitats. This study provides an example of a quantitative approach for assessing the response of vegetation and nekton to tidal restoration.

Sacco, J., E. D. Seneca and T. R. Wentworth. 1994. Infaunal community development of artificially established salt marshes in North Carolina. *Estuaries* 17:489-500.

Author Abstract. In recent years, artificial establishment of *Spartina alterniflora* marshes

has become a common method for mitigating impacts to salt marsh systems. The vegetative component of artificially established salt marshes has been examined in several studies, but relatively little is known about the other aspects of these systems. This study was undertaken to investigate the infaunal community of artificially established salt marshes as a follow up to Researcher Sacco's Ph. D thesis in 1989. Infauna was sampled from pairs of artificially established (AE) salt marshes and nearby natural marshes at six sites along the North Carolina coast. The AE marshes ranged in age from 1 yr to 17 yr. Total infaunal density, density of dominant taxa, and community trophic structure (proportions of subsurface-deposit feeders, surface-deposit and suspension feeders, and carnivores) were compared between the two types of marsh to assess infaunal community development in AE marshes. Overall, the two marsh types had similar component organisms and proportions of trophic groups, but total density and densities within trophic groupings were lower in the AE marshes. Soil organic matter content of the natural marshes was nearly twice that of the AE marshes, and is a possible cause for the higher infaunal densities observed in the natural marshes. Using the same three criteria, comparisons of the natural and AE marshes at each of the six locations revealed varying degrees of similarity. Similarity of each AE marsh to its natural marsh control appeared to be influenced by differences in environmental factors between locations more than by AE marsh age. Functional infaunal habitat convergence of an AE marsh with a natural marsh somewhere within its biogeographical region is probable, but success in duplicating the infaunal community of a particular natural marsh is contingent upon the deveopmental age of the natural marsh and the presence and interaction of site specific factors.

Seabloom, E. W., K. A. Moloney and A. G. van der Valk. 2001. Constraints on the establishment of plants along a fluctuating water-depth gradient. *Ecology* 82:2216-2232.

Author Abstract. We used simulation modeling to investigate the relative importance of current environmental conditions and factors affecting establishment of different plant species on the formation of vegetative zonation patterns. We compared the results from a series of six models that incorporated increasing amounts of information about key factors affecting species' ability to adjust to water-level fluctuations. We assessed model accuracy using aerial photographs taken of a 10-yr field experiment, in which 10 wetlands were flooded to 1 m above normal water level for 2 yr, drawn down for 1 or 2 yr, and reflooded for 5 yr to three different water levels (normal, 10.3 m, 10.6 m). We compared each model's ability to predict relative areal cover of five dominant emergent species and to recreate the spatial structure of the landscape as measured by mean area of monospecific stands of vegetation and the degree to which the species were intermixed.

The simplest model predicted post-treatment species distributions using logistic regressions based on initial species distributions along the water-depth gradient in the experimental wetlands. Subsequent models were based on germination, rhizomatous dispersal, and mortality functions implemented in each cell of a spatial grid. We tested the effect on model accuracy of incrementally adding data on five factors that can alter the composition and distribution of vegetative zones following a shift in environmental conditions: (1) spatial relationships between areas of suitable habitat (landscape geometry), (2) initial spatial distribution of adults, (3) the presence of ruderal species in the seed bank, (4) the distribution of seed densities in the seed bank, and (5) differential seedling survivorship.

Because replicated, long-term data are generally not available, the evaluation of these models represents the first experimental test, of which we are aware, of the ability of a cellular-automaton-type model to predict changes in plant species' distributions.

Establishment constraints, such as recruitment from the seed bank, were most important during low-water periods and immediately following a change in water depth. Subsequent to a drop in water level, the most detailed models made the most accurate predictions. The accuracy of all the models converged in 1–2 years after an increase in water level, indicating that current environmental conditions became more important under stable conditions than the effects of historical recruitment events.

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

Author Abstract. Assessing performance of restored and created wetlands for compensatory mitigation and restoration poses a mismatch between long-term processes and the short-term expediency of management decisions. If they were predictable, patterns in the temporal development of important wetland processes could reduce long-term uncertainty of the outcome of restoration projects. To test our ability to predict long-term trends and patterns in the development of a restored wetland based on the first 7 yr of its development, we analyzed 16 ecosystem functional attributes of the Gog-Le-Hi-Te Wetland, in the Puyallup River estuary, Puget Sound, Washington, USA. This estuarine wetland system was restored to tidal inundation in 1986. Only a few of the 16 ecosystem attributes analyzed showed functional trajectories toward equivalency with natural wetlands, and many were inconclusive or suggested disfunction relative to reference wetlands. Natural variability among reference sites also inhibited our ability to interpret an expected asymptote in developmental trajectories. The ability of wetland managers to assess compensatory-mitigation success over short-term (e.g., regulatory) timeframes depends upon the selection of wetland attributes that can predict long-term trends in the development of the restored/created system. However, we are hampered by a basic lack of long-term data sets describing the patterns, trends, and variability in natural wetland responses to disturbance, as well as natural variability in wetland attributes in presumably mature wetland communities. Ultimately, it may be necessary to supplant our descriptive means of assessing functional equivalency with simple, controlled manipulative experiments or assays, standardized across restoration/mitigation and reference sites.

Sinicrope, T. L., P. G. Hine, R. S. Warren and W. A. Niering. 1990. Restoration of an impounded salt marsh in New England. *Estuaries* 13:25-30.

Author Abstract. The restoration of a 20 ha tidal marsh, impounded for 32 yr, in Stonington, Connecticut was studied to document vegetation change 10 yr after the reintroduction of tidal flushing. These data were then compared to a 1976 survey of the same marsh when it was in its freshest state and dominated by *Typha angustifolia.* Aerial photography examined vegetation by comparing data from a study of the area by Hebard in 1976, with data obtained in 1986. Transects were then evaluated in 1987 and 1988 to determine current coverage by species using the same line intercept method. Currently, *T. angustifolia* remains vigorous only along the upland borders and in the upper reaches of the valley marsh. Live coverage of *T. angustifolia* has declined from 74% to 16% and surviving stands are mostly stunted and depauperate. Other brackish species have also been adversely effected, except for *Phragmites* *australis* which has increased. In contrast, the salt marsh species *Spartina alterniflora* has dramatically expanded, from < 1% to 45% cover over the last decade. Locally, high marsh species have also become established, covering another 20% of the marsh.

Steyer, G. D., C. E. Sasser, J. M. Visser, E. M. Swenson, J. A. Nyman and R. C. Raynie. 2003. A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories in Louisiana. *Environmental Monitoring and Assessment* 81:107-117.

Author Abstract. Wetland restoration efforts conducted in Louisiana under the Breaux Act require monitoring the effectiveness of individual projects, as well as monitoring the cumulative effects of all projects in restoring, creating, enhancing, and protecting the coastal landscape. The effectiveness of the traditional paired-reference monitoring approach has been limited due to difficulty in finding comparable reference sites. A multiple reference approach is proposed that uses aspects of hydrogeomorphic functional assessments and probabilistic sampling. This approach includes a suite of sites that encompass the range of ecological condition for each stratum, with projects placed on a continuum of conditions found for that stratum. Trajectories in reference sites through time are then compared with project trajectories through time. Issues regarding selection of indicators and strata, and determination of sample size will be discussed. The approach proposed could serve as a model for evaluating wetland ecosystems.

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

Author Abstract. Ecological performance of coastal habitat and ecosystem restoration projects is not yet predictable with great certainty. The simple method developed in this paper applies the principles of adaptive management to coastal ecosystem restoration to improve the ability to assess performance and make informed decisions on how to improve performance. The method uses a system-development matrix to assist in identifying the state of the system for which restorative actions were applied. The matrix defines development in terms of structure and function, but can accommodate other performance and development characteristics. Monitoring of the system provides input on the state of the system. Phrases in the matrix provide plausible explanations for the condition of the system and point toward possible actions to be taken. The matrix is applied using examples from community development on dredged material, a seagrass system and tidal marsh system. It is recommended that the matrix be developed by all interested parties during the planning phase. This group can then utilize the matrix for managing the project.

Thom, R. M. 2000. Adaptive management of coastal ecosystem restoration projects. *Ecological Engineering* 15:365-372.

Author Abstract. There is a clear need to apply better and more effective management schemes to coastal ecosystem restoration projects. It is very common for aquatic ecosystem restoration projects not to meet their goals. Poor performance has led to a high degree of uncertainty about the potential success of any restoration effort. Under adaptive management, the knowledge gained through monitoring of the project and social policies is translated into restoration policy and program redesign. Planners and managers can utilize the information from the monitoring programs in an effective way to assure that project goals are met or that informed and objective decisions are made to address both ecological and societal needs. The three main ingredients of an effective adaptive management plan in a restoration project are: (1) a clear goal statement, (2) a conceptual model, and (3) a decision framework. The goal drives the design of the project and helps guide the development of performance criteria. The goal statement and performance criteria provide the means by which the system can be judged. With the conceptual model, the knowledge base from the field of ecological science plays an active and critical role in designing the project to meet the goal. A system-development matrix provides a simple decision framework to view the alternative states for the system during development, incorporate knowledge gained through the monitoring program, and formulate a decision on actions to take if the system is not meeting its goal.

Timmermans, S. T. A. 2001. The Marsh Monitoring Program: 1995 - 2000, Monitoring Great Lakes wetlands and their bird and amphibian inhabitants, 83 pp. Bird Studies Canada, Port Rowan, Ontario, Canada. http://www.bsc-eoc.org/mmpreport2002.html

Partial Executive Summary. Many birds and amphibians frequent and rely heavily on marshes to support their annual life cycle. With continual degradation and loss of marsh habitat, there has long been a recognized need to monitor populations of avian and amphibian species that rely on these sensitive wetland environments. In 1995, a bi-national Great Lakes basinwide effort was launched in a multi-partner effort to establish the Marsh Monitoring Program, a program whose primary goal is to monitor populations of marshbirds and calling amphibians across wetlands in this globally unique and water-rich region. Since 1995, through a unique partnership between Bird Studies Canada, United States Environmental Protection Agency, Environment Canada, Great Lakes United, the Great Lakes Protection Fund, and hundreds of citizen scientists, the Marsh Monitoring Program has succeeded in capturing important and meaningful population and wetland habitat information from hundreds of wetlands throughout the Great Lakes basin.

In 2000, the Marsh Monitoring Program released its first five-year report summarizing information it has gained during its first five years of operation. During this time (and including 2000), the Great Lakes have undergone a dramatic period of water level fluctuation, with the last three years (1997-2000) having undergone relatively dramatic rates of water level decreases. This report provides updated information about numerous avian and amphibian species-specific population trends and how some relate to changes in annual Great Lakes water level changes, at both lake-specific and basin-wide levels. Relations between trends of several avian and amphibian species and trends in lake level changes elucidate how long-term hydrologic dynamics of the Great Lakes may influence bird and amphibian populations occupying and breeding in marshes throughout the basin.

Trends in many species' annual indices, as measured by MMP surveyors, in many instances have been closely related (positively or negatively) to changes in mean annual water levels of Great Lakes. Unique patterns of water level change in Lake Ontario offered an opportunity to assess how species trend responses differed from those of other Great Lakes not under significant anthropogenic operating regimes. Results herein provide an impetus to continue studying these relations and demonstrate a need for additional research to complement and increase our understanding of marshes, their avian and amphibian occupants, and sources of marsh ecosystem health and integrity. The success of the Marsh Monitoring Program demonstrates the value in multi-partner ventures and the need to continue building and strengthening the current partnership that supports this invaluable wetland conservation initiative.

Turner, R. E. and B. Streever. 2002. Bay bottom terracing. Approaches to coastal wetland restoration, pp. 63-76. SPB Academic Publishing, The Hague, The Netherlands.

A project was conducted to create marshes on terraces to support fish and invertebrate species and promote submerged aquatic vegetation in areas protected by terraces. The Schleswick-Holstein method was used to create marshes which involved the use of groins made from stakes and the brushwood to act as breakwaters that protected frequently inundated areas from tidal action. This method was further modified with the construction of Sabine Terracing Project in Calcasieu Lake, LA, in 1990. The Sabine Terracing Project encouraged construction and removal of bay bottom sediment to create terraces. Marsh grass species *S. alterniflora* was planted in these areas. The technique for this method is described in Chapter 6 of this publication. The project was then monitored by the Louisiana Department of Natural Resources since 1990. *S. alterniflora* plugs and sprigs was planted on the terraces and monitored. In ten months, data showed that more than 95% of plugs and over 80% of sprigs survived. After a year, plugs were distibuted over an area with an average width of 1.07m. Within two-years of planting, vegetation was widely distributed over terraces.

Wainright, S. C., M. P. Weinstein, K. W. Able and C. A. Currin. 2000. Relative importance of benthic microalgae, phytoplankton and the detritus of smooth cordgrass *Spartina alterniflora* and the common reed *Phragmites australis* to brackish-marsh food webs. *Marine Ecology Progress Series* 200:77-91.

Author Abstract. We conducted a study to determine the trophic pathways leading to juvenile fish in 2 mesohaline tidal marshes bordering Delaware Bay. The relative roles of the major primary producers in supplying energy, ultimately, to the mummichog *Fundulus heteroclitus* were assessed by measuring the stable isotopic compositions of juveniles (21 to 56 mm total length, TL; most of which were young-of-the-year) and those of macrophyte vegetation, phytoplankton, and benthic microalgae at each site. We collected samples of primary producers and *F. heteroclitus*, the dominant fish species in this and other marshes along the east coast of the USA, in June and August 1997, at 2 study sites (upstream and downstream) within Mad Horse Creek (a *Spartina alterniflora*-dominated site) and Alloway Creek (a *Phragmites australis*-dominated site), for a total of 4 study sites. Our results indicate that *F. heteroclitus* production is based on a mixture of primary producers, but the mixture depends on the relative abundance of macrophytes. In *S. alterniflora*-dominated marshes, C and S isotope ratios indicate that *F. heteroclitus* production is supported by *S. alterniflora* production (ca 39%, presumably via detritus), while in *P. australis*-dominated marshes, secondary production is based upon *P. australis* (73%). To our knowledge, this finding provides the first evidence that *P. australis* may contribute to aquatic food webs in tidal marshes. Benthic microalgae also contribute to the food chain that leads to *F. heteroclitus* in both marsh types, while phytoplankton may be of lesser importance. Benthic microalgal biomass was lower in the *P. australis*-dominated system, consistent with a greater effect of shading in *P. australis*- versus *S. alterniflora*-based creek systems. Based on the difference in nitrogen isotope values between *F. heteroclitus* and the primary producers, the trophic level of *F. heteroclitus* appears to be similar in the 2 marsh types, despite the differing vegetation types. In summary, the relative roles of the primary producers in supplying energy to *F. heteroclitus* varies locally and, in particular, with respect to the type of marsh macrophyte vegetation.

Warren, R. S., P. E. Fell, R. Rozsa, A. H. Brawley, A. C. Orsted, E. T. Olson, V. Swamy and W. A. Niering. 2002. Salt marsh restoration in Connecticut: 20 years of science and management. *Restoration Ecology* 10:497-513.

Author Abstract. In 1980 the State of Connecticut began a tidal marsh restoration program targeting systems degraded by tidal restrictions and impoundments. Such marshes become dominated by common reed grass (*Phragmites australis*) and cattail (*Typha angustifolia* and *T. latifolia*), with little ecological connection to Long Island Sound. The management and scientific hypothesis was that returning tidal action, reconnecting marshes to Long Island Sound, would set these systems on a recovery trajectory. Specific restoration targets (i.e., pre-disturbance conditions or particular reference marshes) were considered unrealistic. However, it was expected that with time restored tides would return ecological functions and attributes characteristic of fully functioning tidal salt marshes. Here we report results of this program at nine separate sites within six marsh systems along 110 km of Long Island Sound shoreline, with restoration times of 5 to 21 years. Biotic parameters assessed include vegetation, macroinvertebrates, and use by fish and birds. Abiotic factors studied were soil salinity, elevation and tidal flooding, and soil water table depth. Sites fell into two categories of vegetation recovery: slow, ca. 0.5%, or fast, more than 5% of total area per year. Although total cover and frequency of salt marsh angiosperms was positively related to soil salinity, and reed grass stand parameters negatively so, fast versus slow recovery rates could not be attributed to salinity. Instead, rates appear to reflect differences in tidal flooding. Rapid recovery was characterized by lower elevations, greater hydroperiods, and higher soil water tables. Recovery of other biotic attributes and functions does not necessarily parallel those for vegetation. At the longest studied system (rapid vegetation recovery) the high marsh snail *Melampus bidentatus* took two decades to reach densities comparable with a nearby reference marsh, whereas the amphipod *Orchestia grillus* was well established on a slow-recovery marsh, reed grass dominated after 9 years. Typical fish species assemblages were found in restoration site creeks and ditches within 5 years. Gut contents of fish in ditches and on the high marsh suggest that use of restored marsh as foraging areas may require up to 15 years to reach equivalence with reference sites. Bird species that specialize in salt marshes require appropriate vegetation; on the oldest restoration site, breeding populations comparable with reference marshland had become established after 15 years. Use of restoration sites by birds considered marsh generalists was initially high and was still nearly twice that of reference areas even after 20 years. Herons, egrets, and migratory shorebirds used restoration areas extensively. These results support our prediction that returning tides will set degraded marshes on trajectories that can bring essentially full restoration of ecological functions. This can occur within two decades, although reduced tidal action can delay restoration of some functions. With this success, Connecticut's Department of Environmental Protection established a dedicated Wetland Restoration Unit. As of 1999 tides have been restored at 57 separate sites along the Connecticut coast.

Webb, J. W., Jr. and C. J. Newling. 1985. Comparison of natural and man-made salt marshes in Galveston Bay complex, Texas. *Wetlands* 4:75-86.

Vegetation of a manmade *S. alterniflora* marsh planted in 1976 on Bolivar Peninsula, Texas, was compared to three natural marshes in the Galveston Bay complex in 1978 and 1979. Methods used included 0.5m^2 quadrats that were randomly placed along elevational transects. From quadrats, researches were able to obtain above-ground biomass analysis on live stem density, dead stem density, stem height, percent cover, and species composition. Below-ground biomass was collected in the same quadrats using about 8-10 cm diameter corers; core depths were 25 and 30 cm. Techniques used are described in detail in this publication. Data collected showed that *S. alterniflora* dominated below the mean high water mark. In the manmade marsh, *S. alterniflora* was significantly greater in 1978 than in natural marshes. At lower elevations below ground biomass was significantly lower in manmade marshes than natural marshes. However, within one-year, below-ground biomass increased in manmade marshes. Authors concluded that above-ground biomass in a two to three year old created salt marsh can be comparable to those in nearby natural marshes.

Weinstein, M. P., J. H. Balletto, J. M. Teal and D. F. Ludwig. 1997. Success criteria and adaptive management for a large-scale wetland restoration project. *Wetlands Ecology and Management* 4:111-127.

Author Abstract. We are using a 20+ year photographic history of relatively undisturbed and formerly diked sites to predict the restoration trajectories and equilibrium size of a 4,050 ha salt marsh on Delaware Bay, New Jersey (USA). The project was initiated to offset the loss of finfishes from once-through cooling at a local power plant. We used a simple food chain model to estimate the required restoration size. This model assumed that annual macrophyte detritus production and benthic algal production resulted in production of finfishes, including certain species of local interest. Because the marsh surface and intertidal drainage system are used by many finfishes and are the focal points for exchange of detrital materials, the restoration planning focused on both vegetational and hydrogeomorphological parameters. Recolonization by *Spartina* spp. and other desirable taxa will be promoted by returning a natural hydroperiod and drainage configuration to two types of degraded salt marsh: diked salt hay (*Spartina patens*) farms and brackish marsh dominated by *Phragmites australis*. The criteria for success of the project address two questions: What is the “bound of expectation” for restoration success, and how long will it take to get there? Measurements to be made are macrophyte production, vegetation composition, benthic algal production, and drainage features including stream order, drainage density, channel length, bifurcation ratios and sinuosity. A method for combining these individual parameters into a single success index is also presented. Finally, we developed adaptive management thresholds and corrective measures to guide the restoration process.

Weller, M. W. 1978. Management of freshwater marshes for wildlife, pp. 267-298. In Good, R. E., D. F. Whigham, R. L. Simpson and C. G. Jackson, Jr. (eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, San Diego, CA.

Author Abstract. Although commonly practiced on wildlife management areas, marsh management is poorly founded in theory and as a predictive science. Major objectives have been to preserve marshes in a natural state and to maintain their productivity. System or community-oriented management techniques are encouraged as most likely to meet diverse public needs, whereas species-specific management is more difficult, costly and limited in application.

The structure of a marsh is a product of basin shape, water regimes, cover, water interspersion, and plant species diversity. Resultant vegetative patterns strongly influence species composition and size of bird populations. Food resources influence mammals as well as birds. Species richness (i.e., number of species) may be the simplest index to habitat quality, although various diversity indices need further evaluation.

Marshes are in constant change, and wildlife species have evolved adaptations of wide tolerance or mobility. Throughout the Midwest, water levels and muskrats (*Ondatra zibethicus*) induce most vegetative change, and pattern of vegetation, muskrat and avian responses are predictable in a general way. This short-term successional pattern in marshes forms a usable management strategy. Various ramifications are discussed that may enhance or perpetuate the most beneficial stages.

Artificial management practices are discouraged as costly and of short-term value whereas systems based on natural successional patterns produce the most ecologically and economically sound results. Public pressures for single-purpose management often increase as management potential increases, but such problems can often be avoided by advance planning and public relations.

Marsh management projects for wildlife have rarely been adequately evaluated because of cost, manpower, and inadequate experimental study areas. Some high priority, management oriented research goals are suggested.

Wilcox, D. A. and T. H. Whillans. 1999. Techniques for restoration of disturbed coastal wetlands of the Great Lakes. *Wetlands* 19:835-857.

Author Abstract. A long history of human-induced degradation of Great Lakes wetlands has made restoration a necessity, but the practice of wetland restoration is relatively new, especially in large lake systems. Therefore, we compiled tested methods and developed additional potential methods based on scientific understanding of Great Lakes wetland ecosystems to provide an overview of approaches for restoration. We addressed this challenge by focusing on four general fields of science: hydrology, sedimentology, chemistry, and biology. Hydrologic remediation methods include restoring hydrologic connections between diked and hydrologically altered wetlands and the lakes, restoring water tables lowered by ditching, and restoring natural variation in lake levels of regulated lakes Superior and Ontario. Sedimentological remediation methods include management of sediment input from uplands, removal or proper management of dams on tributary rivers, and restoration of protective barrier beaches and sand spits. Chemical remediation methods include reducing or eliminating inputs of contaminants from point and non-point sources, natural sediment remediation by biodegradation and chemical degradation, and active sediment remediation by removal or by in situ treatment. Biological remediation methods include control of non-target organisms, enhancing populations of target organisms, and enhancing habitat for target organisms. Some of these methods were used in three major restoration projects (Metzger Marsh on Lake Erie and Cootes Paradise and Oshawa Second Marsh on Lake Ontario), which are described as case studies to show practical applications of wetland restoration in the Great Lakes. Successful restoration techniques that do not require continued manipulation must be founded in the basic tenets of ecology and should mimic natural processes. Success is demonstrated by the sustainability, productivity, nutrient-retention ability, invasibility, and biotic interactions within a restored wetland.

Wilcox, D. A., J. E. Meeker, P. L. Hudson, B. J. Armitage, M. G. Black and D. G. Uzarski. 2002. Hydrologic variability and the application of Index of Biotic Integrity metrics to wetlands: a Great Lakes evaluation. *Wetlands* 22:558-615.

Author Abstract. Interest by land-management and regulatory agencies in using biological indicators to detect wetland degradation, coupled with ongoing use of this approach to assess water quality in streams, led to the desire to develop and evaluate an Index of Biotic Integrity (IBI) for wetlands that could be used to categorize the level of degradation. We undertook this challenge with data from coastal wetlands of the Great Lakes, which have been degraded by a variety of human disturbances. We studied six barrier beach wetlands in western Lake Superior, six drowned-river-mouth wetlands along the eastern shore of Lake Michigan, and six open shoreline wetlands in Saginaw Bay of Lake Huron. Plant, fish, and invertebrate communities were sampled in each wetland. The resulting data were assessed in various forms against gradients of human disturbance to identify potential metrics that could be used in IBI development. Our results suggested that the metrics proposed as potential components of an IBI for barrier beach wetlands of Lake Superior held promise. The metrics for Lake Michigan drowned-river-mouth wetlands were inconsistent in identifying gradients of disturbance; those for Lake Huron open embayment wetlands were yet more inconsistent. Despite the potential displayed by the Lake Superior results within the year sampled, we concluded that an IBI for use in Great Lakes wetlands would not be valid unless separate scoring ranges were derived for each of several sequences of water-level histories. Variability in lake levels from year to year can produce variability in data and affect the reproducibility of data collected, primarily due to extreme changes in plant communities and the faunal habitat they provide. Substantially different results could be obtained in the same wetland in different years as a result of the response to lake level change, with no change in the level of human disturbance. Additional problems included limited numbers of comparable sites, potential lack of undisturbed reference sites, and variable effects of different disturbance types. We also evaluated our conclusions with respect to hydrologic variability and other major natural disturbances affecting wetlands in other regions. We concluded that after segregation of wetland types by geographic, geomorphic, and hydrologic features, a functional IBI may be possible for wetlands with relatively stable hydrology. However, an IBI for wetlands with unpredictable yet recurring influences of climate-induced, long-term high water periods, droughts, or drought-related fires or weather-related catastrophic floods or high winds (hurricanes) would also require differing scales of measurement for years that differ in the length of time since the last major natural disturbance. A site-specific, detailed ecological analysis of biological indicators may indeed be of value in determining the quality or status of wetlands, but we recommend that IBI scores not be used unless the scoring ranges are calibrated for the specific hydrologic history pre-dating any sampling year.

Williams, G. D. and J. B. Zedler. 1999. Fish Assemblage Composition in Constructed and Natural Tidal Marshes of San Diego Bay: Relative Influence of Channel Morphology and Restoration History. *Estuaries*: 22:702–716.

Author Abstract. This study evaluated the use by fish of restored tidal wetlands and identified links between fish species composition and habitat characteristics. We compared the attributes of natural and constructed channel habitats in Sweetwater Marsh National Wildlife Refuge, San Diego Bay, California, by using fish monitoring data to explore the relationships between channel environmental characteristics and fish species composition. Fishes were sampled annually for 8 yr (1989–1996) at eight sampling sites, four in constructed marshes and four in natural marshes, using beach seines and blocking nets. We also measured channel habitat characteristics, including channel hydrology (stream order), width and maximum depth, bank slope, water quality (DO, temperature, salinity), and sediment composition. Fish colonization was rapid in constructed channels, and there was no obvious relationship between channel age and species richness or density. Total richness and total density did not differ significantly between constructed and natural channels, although California killifish (*Fundulus parvipinnis*) were found in significantly higher densities in constructed channels. Multivariate analyses showed fish assemblage composition was related to channel habitat characteristics, suggesting a channel's physical properties were more important in determining fish use than its restoration status. This relationship highlights the importance of designing restoration projects with natural hydrologic features and choosing proper assessment criteria in order to avoid misleading interpretations of constructed channel success. We recommend that future projects be designed to mimic natural marsh hydrogeomorphology and diversity more closely, the assessment process utilize better estimates of fish habitat function (e.g., individual and community-based species trends, residence time, feeding, growth) and reference site choice, and experimental research be further incorporated into the restoration process.

Yozzo, D. J. and D. E. Smith. 1998. Composition and abundance of resident marsh-surface nekton: comparison between tidal freshwater and salt marshes in Virginia, USA. *Hydrobiologia* 362:9-19.

Author Abstract. Previous research on intertidal nekton communities has identified important determinants of community structure and distribution; however, few studies have compared nekton utilization of disparate marsh habitats. In this study, abundance and distribution patterns of resident nekton were compared between tidal freshwater marsh and salt marsh surfaces varying in flooding depth and duration. Nekton were collected in pit traps installed along elevational transects at four marshes in coastal Virginia (two freshwater, two saline) from April through November 1992–1993. The dominant fish collected at all sites was the mummichog (*Fundulus heteroclitus)*. The daggerblade grass shrimp (*Palaemonetes pugio)* was the dominant nekton species collected at salt marsh sites, and was seasonally abundant on tidal freshwater marshes. A positive correlation between flooding depth and nekton abundance was observed on salt marshes; an opposite pattern was observed on tidal freshwater marshes. Tidal flooding regime influences the abundance of resident nekton, however, the effect may be confounded by other environmental variables, including variation in surface topography and seasonal presence or absence of submerged aquatic vegetation (SAV) in adjacent subtidal areas. In mid-Atlantic tidal freshwater wetlands, SAV provides a predation refuge and forage site for early life stages of marsh-dependent nekton, and several species utilize this environment extensively. Salt marshes in this region generally lack dense SAV in adjacent subtidal creeks. Consequently, between-site differences in species and size-specific marsh surface utilization by resident nekton were observed. Larvae and juveniles represented 79% and 59% of total fish collected at tidal freshwater and salt marsh sites, respectively. The resident nekton communities of tidal freshwater and salt marsh surfaces are characterized by a few ubiquitous species with broad environmental tolerances.

Yozzo, D. J. and R. J. Diaz. 1999. Tidal freshwater wetlands: invertebrate diversity, ecology, and functional significance, pp. 889-918. In Batzer, D. P., R. B. Rader and S. A. Wissinger (eds.), Invertebrates in Freshwater Wetlands of North America: Ecology and Management. John Wiley and Sons, Inc., New York.

Author Abstract. Tidal freshwater wetlands are vegetated intertidal habitats characterized by measurable tidal fluctuation and, on occasion, measurable salinity (usually <0.5 practical salinity units). They are unique endpoint habitats created by a combination of terrestrial-riverine and oceanic-estuarine influences. Vascular floral composition is species-rich, among the highest of any wetland type. In contrast, the invertebrate faunal composition of tidal freshwater wetlands is species-poor relative to nontidal rivers, lakes, or estuaries. Tidal freshwater wetlands are characterized by high primary and secondary production and provide critical nursery habitat for many freshwater and estuarine fishery species. Major habitat types found in tidal freshwater wetlands include submerged and floating aquatic macrophyte beds, intertidal emergent marshes, unvegetated intertidal mudflats, and tidal creeks. Macroinvertebrate communities of tidal freshwater wetlands are dominated by annelids (Tubificidae, Naididae, Enchytraidae) and insect larvae (Chironomidae). Meiofaunal communities are dominated by nematodes, microcrustaceans (Ostracoda, Copepoda), naidid oligochaetes, and tardigrades. Despite the potential ecological importance in tidal freshwater wetland invertebrate communities, we know relatively little about how they function in comparison to those of nontidal freshwater and/or estuarine wetlands and how they may respond to both natural and man-induced disturbance.

Zedler, J. B. 2001. Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, FL.

This handbook provides a collection of case studies and principle guidelines to guide tidal restoration management. In this handbook Zedler describes the conceptual planning for coastal wetlands restoration, strategies for management of hydrology and soils, the restoration of vegetation and assemblages of fishes and invertebrates, and the process of evaluating, monitoring, and sustaining restored wetlands. Zedler also highlights parameters that should be monitored and techniques that can be used during restoration. Such parameters that are addressed include: hydrology and topography, water quality, soils, substrate qualities, nutrient dynamics, elevation, species abundance and diversity (vegetation, invertebrates and fishes). Techniques that used to monitor certain parameters include: Global Positioning Systems (GPS) and Geographic Information Systems (GIS). Additional information on parameters monitored and techniques used are described in this handbook.

Zedler, J. B. 1996. Tidal Wetland Restoration: A Scientific Perspective and Southern California Focus, 129 pp. California Sea Grant College System, University of California, La Jolla, California. Report No. T-038.

Structural attributes are measured during monitoring as surrogates for functional processes. This is mainly due to the fact that basic ecosystem functioning is still being discovered, and monitoring structural criteria is cheaper than extensive functional assessments. Each monitoring program should have performance criteria that are tailored to that site. With respect to southern California tidal salt marshes, frequency of monitoring is as follows: water quality is biweekly or monthly; vegetation in September; salinity of marsh soil in April and September; fishes and invertebrates on a quarterly basis; and special interest species during reproductive periods.

Three indicators of ecosystem functioning were selected as simple criteria. These included ability to support biodiversity, canopy architecture, and other indicators. Monitoring should be designed to track populations of sensitive and endangered species in order to support biodiversity. Canopy architecture needs to be monitored such that the vegetation can support endangered birds. Other indicators such as water quality can be used to assess potential support of fishes and invertebrates. Once these indicators have been selected, they must be reviewed and accepted by scientific peers. Agencies that manage endangered species must then test the cause-effect relationship between the indicator and the ecosystem function it represents.

Zedler, J. B. 1995. Salt marsh restoration: lessons from California. In Cairns, J. Jr. (ed.) Rehabilitating Damaged Ecosystems, 2nd edition, CRC Press, Incorporated. Boca Raton, FL.

In order to evaluate success, goals and objectives need to be established before performing restoration efforts. Such goals should include the need for regional coordination, and maintaining native species communities that are uncommon in the region as well as maintaining natural variation in communities instead of increasing diversity. Additional goals for hydrological planning are discussed further in this publication.

Experimentation is the most efficient way to refine the science of salt marsh restoration. Practitioners must understand and learn from failures and successes through controlled, replicated field experiments, performed in conjunction with restoration will be extremely valuable. Restoration success should be assessed for two reasons. The first is the need for resource agencies to keep track of how much regional wetland is being restored. The second is to determine whether mitigation has met contractual requirements. Two general criteria of success are whether the restoration project has met the present objectives and what the restoration provided in comparison to the region's needs. Assessment must be performed over the long-term, from at least one to five years up to beyond twenty years. Detailed and frequent sampling is required to detect changes due to restoration as opposed to natural variation.

Zhang, M., S. L. Ustin and E. W. Sanderson. 1996. Monitoring Pacific coast salt marshes using remote sensing. *Ecological Applications* 7:1039-1053.

A study was conducted using field sampling and remote sensing approaches to understand salt marsh ecosystem functions and species distribution. This paper discusses the implications for salt marsh monitoring using remote sensing. Three sites were selected for study along the Petaluma River near the entrance into San Pablo Bay, California. The standing biomass was assessed by field sampling and estimated canopy reflectance. During this study, a positive relationship was found between salinity and biomass up to a threshold of 42kg, after which the biomass declined with increasing salinity for *Salicornia*. No strong relationships were found between the biomass and nitrate nitrogen.

The soil's ammonium nitrogen however had a positive relation to biomass. The soil's redox and salinity increased with elevation and distance from the shoreline, while the soil's moisture and H_2S decreased. Vegetation Index (VI) and Atmospherically Resistant Vegetation Index (ARVI) were measured by handheld field spectrometers and used for estimating green biomass for high cover of *Salicornia*. Soil Adjusted Vegetation Index (SAVI) and Soil Adjusted and Atmospherically Resistant Vegetation Index (SARVI) were used to estimate *Spartina* while the Global Environment Monitoring Index (GEMI) was used to give the best results for *Scirpus*. The relationships between the vegetation indices and biomass were established from the field spectra. The VI estimated spatial patterns of biomass across the salt marsh from Landsat satellite Thematic Mapper ™. The TM displayed spatial patterns equivalent to species zones and biomass abundance. The author indicates that a narrow band reflectance features measured with a handheld spectrometer can be used to predict canopy plant water content. Interpolated estimates of water content from field measured canopy reflectance shown relations to variation in salinity and soil moisture. The Airborne Advance Visible Infrared Imaging Spectrometer data was used to estimate plant water content, displayed similar spatial patterns at the site. The results indicate that biomass production and canopy water content can be determined from remotely sensed spectral measures. The differences in species-specific characteristics may be used for monitoring the species distribution and abundance from airborne or satellite images. Further details of techniques used in this study can be located in the article.

Zheng, L., R. J. Stevenson and C. Craft. 2004. Changes in benthic algal attributes during salt marsh restoration. *Wetlands* 24:309-323.

Author Abstract. To assess attributes of algal assemblages as indicators of salt marsh restoration, we chose eight pairs of salt marshes in North Carolina, USA, each pair with one restored marsh (from 1 to 28 years old) and a nearby existing salt marsh. Algae on both *Spartina alterniflora* and sediments (sediment algae) were collected in each marsh during spring and summer 1998 for assaying algal biomass (dry mass (DM), ash free dry mass (AFDM), chl *a* content, algal biovolume), algal species composition and diversity, and gross primary production. An attribute restoration ratio was calculated by dividing attribute values from each restored marsh by values from a paired reference marsh. Controlling for regional variation in reference marshes substantially increased precision in relations between attributes and the increase in age of restored marshes. The organic matter restoration ratio of sediments increased with age of restored marshes in both spring and summer. The algal biomass restoration ratios of epiphytes, calculated with algal biovolume and chl *a,* increased with restored marsh age in summer but not during spring. Biomass of sediment algae was not related to marsh age. The species diversity of sediment algae in summer showed an asymptotic relationship with sediment nutrient concentration. The similarity of diatom species composition between paired restored and reference sites increased with age of restored marshes during spring and summer. Primary production by epiphytic and sediment algae in summer showed site-specific changes and did not change consistently with marsh age. Algal biomass, algal diversity, and diatom species composition during summer were positively correlated with sediment nitrogen and phosphorus concentration. We concluded that other structural and functional development of restored wetlands, especially nutrient storage in sediments, regulates algal species composition and algal biomass accumulation, which can be used to evaluate salt marsh restoration.

APPENDIX II: COASTAL MARSHES
REVIEW OF TECHNICAL METHODS MANUALS

This Review of Technical Methods Manuals includes a variety of sampling manuals, Quality Assurance/Quality Control (QA/QC) documents, standardized protocols, or other technical resources that may provide practitioners with the level of detail needed when developing a monitoring plan for a coastal restoration project. Examples from both peer reviewed and grey literature are presented. Entries were selected through extensive literature and Internet searches as well as input from reviewers. As with the Annotated Bibliographys, these entries are not, however, a complete list. Entries are arranged alphabetically by author. Wherever possible, web addresses or other contact information are included in the reference to assist readers in more easily obtaining the original resource. Summaries preceded by the terms '*Author Abstract*' or '*Publisher Introduction*' or similar descriptors were taken directly from their original source. Summaries without such descriptors were written by the authors of the associated chapters.

Adamus, P. R., L. T. Stockwell, E. J. Clairain, Jr., M. E. Morrow, L. P. Rozas and R. D. Smith. 1991. Wetland evaluation technique. United States Army Corps of Engineers, Waterways Experiment Station. Technical report WRP-DE-2.

The Wetland Evaluation Technique (WET) provides information on predictors of wetland functions. The manual is divided into two volumes. Information presented in volume one includes: conceptual fundamentals for WET, wetland functions in relation to their processes and interactions with other functions, a review of technical literature on each function, the predictors used for determining the probability ratings for wetland functions, and discussion of the concept of wetland social significance as it is used in WET. Volume two of the manual outlines steps required to put into practice the WET method, discusses its application and limitations in detail, and provides documentation for a computer program designed to assist data analysis in WET. Detailed information on methods and procedures described here can be obtained from the manual.

Adamus, P. and K. Brandt. 2003. Impacts on quality of inland wetlands of the United States: a survey of indicators, techniques, and applications of community level biomonitoring data. U.S. Environmental Protection Agency. http://www.epa.gov/owow/wetlands/wqual/introweb.html

This on-line resource is based on the now out of print Report #EPA/600/3-90/073 prepared for the U.S. EPA Wetland Research Program. It is currently being updated. Although it is intended for inland wetlands, many of the resources cited and information provided is applicable to coastal freshwater wetlands. The report describes in detail many of the interactions and possible effects of eutrophication, organic loading, contaminant toxicity, acidification, salinization, sedimentation, turbidity/shade, vegetation removal, thermal alteration, dehydration, inundation, and fragmentation of habitat on wetland biological communities. The effect of these stressors on microbes, algae, vascular plants, invertebrates, fish, amphibians, reptiles, birds, mammals, and selected biological processes is presented wherever information is available. Extensive lists of literature cited could be used to supplement presented information if desired.

This resource was originally designed for use in developing biological criteria for use in wetland assessment, protection, and management as well as to help identify degraded sites for potential restoration. The information presented can also be used to develop parameters to monitor the progress of restoration efforts, before and after implementation. By linking many of the structural components that help make up wetland habitats with functional components (in this case biota) the information presented can be used to help restoration practitioners select the appropriate structural and functional parameters to monitor as they relate to project goals.

American Public Health Association. 1999. Standard Methods for Examination of Water & Wastewater. 20 ed. American Public Health Association, Washington, D.C.

Standard Methods for Examination of Water and Wastewater is an essential resource for any laboratory performing analyses on water samples for chemical or biological components. Procedures for the sampling of zooplankton, phytoplankton, periphyton, macrophytes, benthic macroinvertebrates, and fish are also included as well as general identification keys to these organisms. Each procedure is explained in step-by-step detail with information on the strengths and weaknesses of various measurement methods. To a general practitioner, this resource would be useful to explain the chemical and biological components they are sampling, what the analysis entails, and the meaning of the final value obtained from each analysis. Various editions should be available at most any laboratory, or scientific or university library.

American Society of Mammalogists. 1998. Guidelines for the capture, handling, and care of mammals, 47 pp. American Society of Mammalogists. http://www.unh.edu/osr/compliance/98acucguidelines.PDF

Partial Author Introduction. The objective of the Society's 1987 guidelines for acceptable field methods in mammalogy was to identify field methods in mammalogy that would meet standards of the American Society of Mammalogists. The guidelines were formulated with consideration for both the welfare of subject animals and the research needs of field investigators for whom guidelines for laboratory animal care generally do not apply. These published guidelines have served ASM members and non-members well during the past decade; however, the passage of time has seen advances in technology (e.g., passive integrated transponders - PIT tags - for marking animals) that need to be addressed. In addition, the past decade has produced increased recognition of the potential risks to field investigators from handling live and dead mammals, as well as heightened concern within and outside the scientific community regarding the humane treatment of mammals collected and used in scientific research.

Baker, J. M. and W. J. Wolff. 1987. Biological Surveys of Estuaries and Coasts. 449 pp. Cambridge University Press, Cambridge, England.

Baker and Wolff have compiled an indispensable resource for anyone planning a coastal monitoring effort. Various authors have contributed chapters detailing the planning and sampling of salt marsh, soft bottom, and rock bottom habitats. While one chapter focuses on remote sensing techniques, the bulk of the book is devoted to field survey equipment and techniques to sample a variety of biological components including: bacteria, fungi, plankton, fish, birds, and plants. A chapter listing identification manuals for each type of organism likely to be encountered in sampling coastal habitats is also provided. Each type of sampling gear and method is briefly described with readers directed to the original sources for more detail as needed.

Batzer, D. P., A. S. Shurtleff and R. B. Rader. 2001. Sampling invertebrates in wetlands, pp. 339-354. In Rader, R. B., D. P Batzer and S. A. Wissinger (eds.) Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. Difficulties in sampling have long hindered research on wetland macroinvertebrates. With the increasing interest in using macroinvertebrate populations to monitor the environmental health of wetlands, sampling of these organisms has become an important research focus. For this chapter we summarized sorting and subsampling procedures and queried many of the prominent researchers who study freshwater wetland macroinvertebrates about their preferences in samplers. For each device we provide a synopsis of their comments, both pro and con, and provide direction on how to use each sampler. Based on the results of this survey as well as published studies that contrast sampler efficacies, we conclude that the sweep net should probably become the sampler of choice for most bioassessment efforts that use wetland macroinvertebrates. We also recommend that most programs sort in the laboratory using either a selective or random technique (depending on the level of taxonomic expertise) and a fixed count of 100 to 300 individuals.

Carlisle, B. K., A. M. Donovan, A. L. Hicks, V. S. Kooken, J. P. Smith and A. R. Wilbur. 2002. A Volunteer's Handbook for Monitoring New England Salt Marshes, 164 pp. Massachusett's Office of Coastal Zone Management, Boston, MA.

This manual was designed to help volunteer groups collect and record data on salt marsh health in a consistent approach. Protocols discussed in this manual are a collaboration of information by the authors, other wetland scientists in the Northeast and federal and state agencies. Authors focused on bioassessment techniques, used to measure wetland health by examining resident plants, animals, and their habitat. In 1995 the authors began to develop scientific monitoring protocols in a series of pilot projects that allowed them to test, evaluate, and revise the sampling and analysis techniques for different biological, physical, and chemical parameters of the wetland condition. The manual highlights methods and parameters used when monitoring salinity, tidal hydrology, invertebrates, plants, fish and birds in salt marshes. Examples of methods used to monitor a few of the parameters previously mentioned include: sound surveys for monitoring birds; sampling fish using bag seines and then identifying the species; and sampling invertebrates using a ponar grab and then identifying taxa. The manual also discusses cost estimates and the time expected to be applied when monitoring each parameter. Additional information on methods used for monitoring salt marsh conditions are described in this document.

Cook Inlet Keeper. 1998. Volunteer training manual: citizens environmental monitoring program. U.S. Environmental Protection Agency. Homer, AK. http://www.inletkeeper.org/training.htm

This manual provides Cook Inlet Keeper volunteers with information needed to monitor water quality in the Cook Inlet watershed. It also provides guidelines for monitoring procedures that are currently included in the Keeper's Citizens' Environmental Monitoring Program (CEMP). Outlined in this document are safety and access issues; a monitoring overview that discusses water quality test methods, test parameters and a proposed sampling schedule; monitoring procedures including: a field procedure checklist, field observations, steps for collecting the samples, detailed testing procedures, sample custody guidelines, and instructions for completing data sheets; equipment care and waste disposal; data management and reporting; and quality control. Additional information for methods and procedures used can be obtained from this manual.

Davies, J., J. Baxter, M. Bradley, D. Connor, J. Khan, E. Murray, W. Sanderson, C. Turnbull and M. Vincent. 2001. Marine Monitoring Handbook. UK Marine Science Project, and Scottish Association of Marine Science. Joint Nature Conservation Committee, English Nature, Scottish Natural Heritage, Environment and Heritage Services. http://www.jncc.gov.uk/marine/mmh/Contents.htm

The UK Marine Science Project developed this handbook to provide guidelines for recording, monitoring and reporting characteristics and conditions of marine habitats. However, based on location and other environmental conditions, methodologies will have to be modified to suit the structural characteristics of the habitat. This manual addresses the fundamentals and procedures for monitoring different parameters in marine habitats, management tools, and benefits and costs for developing a monitoring project. Topics presented in this document include establishing marine monitoring programs highlighting what needs to be measured and methods to use; provides guidance when developing a monitoring program; selecting proper monitoring techniques to attain precision and accuracy; and procedural guidelines for monitoring a specific marine habitat. Detailed information on the tools needed for monitoring marine habitats are described within the marine monitoring handbook.

Dobson, J. E., E. A. Bright, R. L. Ferguson, D. W. Field, L. L. Wood, K. D. Haddad, H. Iredale III, J. R. Jensen, V. V. Klemas, R. J. Orth, and J. P. Thomas. 1995. NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation, 92 pp. NOAA Technical Report NMFS 123.

The coastal change analysis program (C-CAP) is part of the Estuarine Habitat Program of NOAA's Coastal Ocean Program. C-CAP inventories benthic habitats, wetland habitats, and adjacent uplands to learn more about the linkages between coastal and upland habitats, as well as impacts on living marine resources. Through remote sensing technology, C-CAP monitors changes in the habitats on a 1-5 year cycle. Satellite imagery, aerial photography, and field data are meshed in a geographic information for spatial analysis. Ongoing C-CAP research will continue to develop remote sensing techniques to measure biomass, productivity, and functional status of wetlands and other coastal habitats. Land-cover maps will be produced on both local and regional scales for distribution. This technique provides a better understanding of how the wetlands and organisms living there interact and which influence this whole ecosystem. This allows for a better restoration design to be created. Details for techniques used for monitoring vegetation cover and habitat change are described in this paper.

Erwin, R. M., C. J. Conway and S. W. Hadden. 2002. Species occurrence of marsh birds at Cape Cod National Seashore, Massachusetts. *Northeastern Naturalist* 9:1-12.

Author Abstract. We initiated an inventory and a field test of a protocol that could be used for monitoring marsh birds at the Cape Cod National Seashore in eastern Massachusetts during 1999 and 2000, as part of a more comprehensive national effort. Using cassette tapes during call broadcast surveys, we visited a total of 78 survey points at freshwater, brackish, and salt marsh sites three times on the ground or in canoes during the breeding season (May-June), fall migration (September to November), and twice during winter (December-January). Observer bias on our marsh bird surveys appeared negligible. Although both auditory and visual detection of most species was low (mean < 0.3 birds per replicate-survey point), we confirmed the presence of seven marsh species, including American Bittern (*Botaurus lentiginosus*), Least Bittern (*Ixobrychus exilis*), American Coot (*Fulica americana*), King Rail (*Rallus elegans*), Pied-billed Grebe (*Podilymbus podiceps*), Sora (*Porzana carolina*), and Virginia Rail (*Rallus limicola*). We suspected breeding of Least Bitterns and Soras at Great Pond in Provincetown, and for Virginia Rails at Hatches Harbor, Provincetown. The most frequently detected species were Soras, Pied-billed Grebes, and Virginia Rails. We recommend using call broadcast surveys for these cryptic species to enhance their probabilities of detection.

Firehock, K., J. V. Middleton, K. D. Starinchak, C. Williams and L. Geoff. 1998. Handbook for Wetlands Conservation and Sustainability. 2nd ed. Izaak Walton League of America. http://www.iwla.org/sos/handbook/

This 288-page handbook explains wetland ecology, functions, and values. It provides tips for organizing your community to monitor, conserve, and restore local wetlands. It also includes monitoring instructions, wetland project ideas, regulatory avenues for wetland protection, case studies, and an extensive resource section. Some sections of the book are available free on-line at the link above.

Gertz, S. M. 1984. Biostatistical aspects of macrophyton sampling, pp. 28-35. ASTM Special Technical Publication 1984. ASTM, Philadelphia.

Author Abstract. Problems of sampling macrophytes are related to the types of communities under consideration and the goals of a particular study. The communities may range from completely submersed beds of large algae, mosses, pteridophytes, or angiosperms to rooted plants with floating leaves or floating plants with emergent leaves to wetland areas. The goals of a study may be community description or impact analysis. Because of this community goal diversity a quantitative investigation often requires a rigorous statistical design to determine the best sampling design. Of the various sampling designs available there are two general techniques; plot or quadrat methods and plotless methods. Plot or quadrat methods are area methods of sampling communities where the plot may be rectangular, square, or circular, and all individuals in the plot are sampled. Plotless methods usually involve a more random approach of sampling; for example, a compass line is laid out through the community and samples are taken according to some fixed rule. It is the purpose of this paper to review these various sampling methodologies and to evaluate their efficacy, in a statistical sense, in view of the goals of a specific study.

Hayes, D. F., T. J. Olin, J. C. Fischenich and M. R. Palermo. 2000. Wetlands engineering handbook. 14 pp. ERDC/EL TR-WRP-RE-21, U. S. Army Engineer Research and Development Center, Vicksburg, MS. http://www.wes.army.mil/el/wetlands/pdfs/wrpre21/wrpre21.pdf

The *Wetlands Engineering Handbook* presents methods for monitoring and evaluating success of wetland restoration/creation efforts. Authors emphasize that local expertise and databases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter 8 of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, detailed information on how to assess wetland structure and function regarding hydrology, soils, vegetation, and fauna (e.g. macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring and evaluating success are described within this report.

Holst, L., R. Rozsa, L. Benoit, S. Jacobson and C. Rilling. 2003. Long Island Sound habitat restoration initiative: technical support for coastal habitat restoration. EPA Long Island Sound Office, Stamford, CT. http://www.longislandsoundstudy.net/habitat/

Partial Introduction. This document contains a series of reports produced through the Habitat Restoration Work Group of the Long Island Sound Study (LISS). It is designed to provide basic technical information about the subject habitat and its restoration for persons interested in planning and pursuing a restoration project. Topics covered include ecological descriptions of the plant and animal communities associated with the habitat, the natural history and effects of human influence on the habitat, and the state of the science in restoring the habitat. Included at the end of each section is a list of the literature cited. The reader is strongly urged to investigate these source materials further to achieve a fuller understanding of the ecology and issues related to the subject habitat. The reader is also encouraged to contact the state and federal agency representatives of the Habitat Restoration Work Group for technical advice.

The habitats covered to date include: tidal wetlands, freshwater wetlands, submerged aquatic vegetation, coastal grasslands, coastal barriers, beaches, and dunes.

Matthews, G. A., and T. J. Minnello. 1994. Technology and success in restoration, creation, and enhancement of *Spartina alterniflora* marshes in the United States. Vol. 2 Inventory and human resources directory. NOAA Coastal Ocean Program Office, Decision Analysis Series No.2. NOAA Coastal Ocean Office, Silver Spring, Maryland. Executive Summary available at: http://www.cop.noaa.gov/pubs/das/das2.html

Author Abstract. This document describes a project that was conducted to provide resource managers, habitat researchers, coastal planners and the general public with an assessment of the technology and success in restoration, enhancement, and creation of salt marshes in the United States. The objective was to be accomplished through the development of three products: 1) an annotated bibliography of the pertinent literature, 2) an inventory of restored, enhanced, or created *Spartina alterniflora* marshes, and 3) a directory of people working in salt marsh creation and restoration. This executive summary describes these products and provides an overall assessment of our understanding regarding restoration, enhancement, and creation of salt marsh habitats. In particular, we have stressed *Spartina alterniflora* marshes and habitat functions related to the support of fishes, crustaceans, and other aquatic life.

McCauley, V. J. E. 1975. Two new quantitative samplers for aquatic phytomacrofauna. *Hydrobiologia* 47:81-89.

Author Abstract. A description and drawings are given for 2 new samplers for quantitative studies on invertebrates associated with aquatic macrophytes. One was designed for sampling rushes and bullrushes, and the other for submerged and/or floating vegetation.

McCobb, T. D. and P. K. Weiskel. 2002. Long-term hydrologic monitoring protocol for coastal ecosystems, 93 pp. Protocol, USGS

Patuxent Wildlife Research Center, Coastal Research Field Station, University of Rhode Island, Narragnasett, RI. http://science.nature.nps.gov/im/monitor/protocols/caco_hydrologic.pdf

Author Abstract. Long-term monitoring of hydrologic change using a standard data-collection protocol is essential for the effective management of terrestrial, aquatic, and estuarine ecosystems in the coastal park environment. This study develops a consistent protocol for monitoring changes in ground-water levels, pond levels, and stream discharge using methods and techniques established by the U.S. Geological Survey for use in the Long-term Coastal Monitoring Program at the Cape Cod National Seashore. The protocol establishes a hydrologic sampling network in the four ground-water-flow cells in the Seashore area, and provides justification for the measurement methods selected and for the spatial and temporal sampling frequency. Data collected during the first year of monitoring are included in this report; common hydrologic analyses such as hydrographs for ground-water and pond levels, and rating curves between stream stage and discharge for streamflow, are presented for selected sites. Long-term hydrologic monitoring at the Seashore will aid in interpretation of the findings of other monitoring programs. Developing and initiating long-term hydrologic monitoring programs will provide a better understanding of effects of natural and human-induced change at both the local and global scales on coastal water resources in park units.

Merritt, R. W. and K. W. Cummins, (eds.). 1996. An Introduction to the Aquatic Insects of North America. Third edition ed. Kendall/Hunt Publishing Company, Dubuque, IA, USA.

While the bulk of this book is on identification of aquatic insects of North America, Merritt and Cummins include several chapters useful in project planning as well. Various experts in the field of aquatic insect collection and identification have submitted chapters on: the general morphology of aquatic insects, designing studies, collection equipment and techniques, aquatic insect respiration, habitat and life history, and the ecology and distribution of aquatic insects. The rest of the manual is devoted to identification keys for each family of aquatic insect found in North America with many detailed and useful pictures of identifying characteristics.

Since this book is continental in scope, it is suggested that practitioners first look for identification keys prepared for their local or regional waterways. This will reduce much confusion in the identification process by eliminating species that are not found locally. Any local aquatics expert or science librarian should be able to locate these materials. If local materials are not available, then Merritt and Cummins will be useful, however, be sure to check the distribution of species identified whenever possible as a way to check accuracy.

Molano-Flores, B. 2002. Critical trends assessment program: monitoring protocols, 39 pp. Illinois Natural History Survey, Office of the Chief Technical Report 2002-2, Champaign, IL. http://ctap.inhs.uiuc.edu/mp/pdf/mp.htm

The Critical Trends Assessment Program (CTAP) monitors the conditions of forests, grasslands, wetlands and streams throughout Illinois. CTAP also assesses current and future trends in ecological conditions for state, regional and site-specific basis. The CTAP document presents standardized monitoring protocols for the habitat types previously mentioned. Wetland habitat criteria as well as wetland sampling protocols are discussed in this document. Highlighted in this section are methods used to monitor ecological changes occurring in wetlands. These methods include establishing study plots, GPS data, general site characteristics, slope and aspects, ground cover and woody vegetation measurements, big plot and collection of voucher specimens. Each method used and parameters measured provide data on the structural and functional characteristic of the habitat as well as the habitat's overall condition.

Murphy, B. R. and D. W. Willis, (eds.). 1996. Fisheries Techniques: Second edition. American Fisheries Society, Bethesda, MD.

Murphy and Willis have edited the industry standard for fisheries sampling techniques. A variety of experts in the field have written chapters that cover all aspects of how to sample and measure fish. Topics include: planning for sampling, data management and statistical techniques, safety, habitat measurements, care and handling of samples, passive and active capture techniques, collection and identification of eggs and larvae, sampling with toxics, invertebrates, tagging and marking, acoustic assessment, field examination and measurements, age and growth rate determination, diet, underwater observation, creel sampling, commercial surveys, and socioeconomic measurements.

Muscha, M. J., K. D. Zimmer, M. G. Butler and M. A. Hanson. 2001. A comparison of horizontally and vertically deployed aquatic invertebrate activity traps. *Wetlands* 21:301-307.

Author Abstract. Activity traps are commonly used to develop abundance indices of aquatic invertebrates and may be deployed with either the funnel parallel to the water surface (horizontal position) or facing down (vertical position). We compared the relative performance of these two positions in terms of numbers of invertebrates captured, species richness of samples, detection rates of specific taxa, and community-level characterizations. Estimates of zooplankton abundance were also compared to quantitative estimates obtained using a water-column sampler. We used a matched pairs design where 10 pairs of traps (one horizontal, one vertical) were deployed in each of 4 prairie wetlands on 5 dates in 1999. Vertical traps had higher detection rates and captured greater numbers of adult and larval Coleoptera, Hemiptera, Chaoboridae, hydracarina, cladocera, and Copepoda and also produced samples with greater species richness. Horizontal traps captured greater numbers of Amphipoda and Ostracoda and had higher detection rates for these taxa. Estimates of zooplankton abundance with vertical traps also correlated better with quantitative estimates and indicated greater differences between wetlands than horizontal traps. Both traps showed similar relationships among wetlands and changes through time at the community level, but vertical traps were more sensitive to temporal change. Our results indicate that vertical traps outperform horizontal traps and are preferable for obtaining indices of invertebrate abundance.

National Park Service Inventory and Monitoring. Guidance for designing an integrated monitoring program. http://science.nature.nps.gov/im/monitor/vsmTG.htm#Introduction

The goal of the National Park Service (NPS) program is to monitor the status and trend of the park's habitat structure and function as well as its condition. Monitoring tracks management and restoration efforts, detects early warning signs of threats to the habitat and provides fundamentals needed to understand and identify changes occurring in the habitat. NPS provides information on developing a scientifically sound monitoring program. Information needed to develop a monitoring plan include: the establishment of clearly stated project goals and objectives; creation of effective, realistic, specific, unambiguous, and measurable monitoring objectives; development of conceptual models of relevant ecosystems processes; selection and prioritization of indicators to be monitored; consideration of sampling designs; development of protocols; and management and analysis of data. Additional information on guidelines for developing monitoring protocols is described in this report.

Neckles, H. A., M. Dionne, D. M. Burdick, C. T. Roman, R. Buchsbaum and E. Hutchins. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. Restoration Ecology 10:556-570.

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

Niedowski, N. L. 2000. New York state salt marsh restoration and monitoring guidelines, 141 pp. New York Department of State, Albany, N.Y. and the New York Department of Environmental Conservation, East Setauket, New York. http://www.csc.noaa.gov/lcr/rhodeisland/html/resource/nymarsh.pdf

This monitoring protocol is designed to assess the progress towards, success or failures of salt marsh restoration. The author discusses in this document parameters and methods to be used to monitor a salt marsh restoration project. Depending on restoration goals and details of the project, modifications of the suggested protocol may be needed. Guidelines followed when planning and locating restoration project transects, 1.0m^2 quadrats, and fixed-point photo stations are presented in the document. Monitoring parameters and activities should also be clearly expressed and documented.

The author suggested that monitoring be conducted at the restoration site and at an appropriate reference site. The reference site should consist of a minimum of three control transects and three quadrats, and located adjacent with or nearby the restoration project site. It should also be similar in morphology and vegetation. Techniques used when monitoring salt marsh restoration such as transects, quadrats, permanent fixed-photo stations, video monitoring, aerial infrared photography are discussed in detail within the document. The importance of pre-restoration monitoring activities and post-construction monitoring activities are described in the document with suggested timeline for each. Assessments performed for more than five years on vegetation development, benthic invertebrates, macrofauna and soil properties (salinity and organic matter) are described in the document. See document for additional information on guidelines and methods used.

Olin, T. J., J. C. Fischenich, M. R. Palermo and D. F. Hayes. 2000. Wetlands Engineering Handbook: Monitoring. U. S. Army Engineer Research and Development Center, Vicksburg, MS. Technical Report ERDC/EL TR-WRP-RE-21.

The wetlands engineering handbook presents methods for monitoring and evaluating success. Authors emphasize that local expertise and data bases for particular wetland types must be used together with the guide to ensure monitoring plans for a specific project are effectively developed. Chapter eight of this report provides a guide for developing evaluation criteria and monitoring projects for wetland restoration and creation. Also presented is guidance for monitoring and success evaluation on basic monitoring concepts, assessing wetland hydrology, evaluating soils and vegetation, and fauna usage. The authors also outline an approach to determining project goals and evaluation criteria, basic considerations related to monitoring, provide detailed information on how to assess wetland structure and function regarding hydrology, soils and vegetation, and fauna (e.g., macroinvertebrates, birds and fish). Additional information needed on assessment, monitoring and evaluating success are described within this report.

Ossinger, M. 1999. Success standards for wetland mitigation projects - a guideline, 31 pp. Washington State Department of Transportation, Environmental Affairs Office. http://pnw.sws.org/forum/success.PDF

This report offers guidance and examples on how to write specific success criteria for mitigation and restoration projects. Though it was designed to address mitigation projects in the Pacific Northwest, its information and approach make it useful throughout the United States. It outlines the steps necessary for planning the monitoring and management of a mitigation/restoration project. Guidance in writing the following program elements is provided: how to set project goals, how to select specific project objectives (i.e., what functions or values will the mitigation/restoration provide), how to select performance objectives (i.e., what structural characteristics need to be in place to provide desired functions), selection of success standards (measurable benchmarks used to determine success of performance objectives), monitoring method (how will the success standard be measured), contingency measure (what to do if the success standards are not met). Several examples are provided of each of these steps. These examples, while not all-inclusive, facilitate the application of this method to diverse areas and project types.

Ozesmi, S. L. and M. E. Bauer. 2002. Satellite remote sensing of wetlands. *Wetlands Ecology and Management* 10:381-402.

Author Abstract. To conserve and manage wetland resources, it is important to inventory and monitor wetlands and their adjacent uplands. Satellite remote sensing has several advantages for monitoring wetland resources, especially for large geographic areas. This review summarizes the literature on satellite remote sensing of wetlands, including what classification techniques were most successful in identifying wetlands and separating them from other land cover types. All types of wetlands have been studied with satellite remote sensing. Landsat MSS, Landsat TM, and SPOT are the major satellite systems that have been used to study wetlands; other systems are NOAA AVHRR, IRS-1B LISS-II and radar systems, including JERS-1, ERS-1 and RADARSAT. Early work with satellite imagery used visual interpretation for classification. The most commonly used computer classification method to map wetlands is unsupervised classification or clustering. Maximum likelihood is the most common supervised classification method. Wetland classification is difficult because of spectral confusion with other landcover classes and among different types of wetlands. However, multi-temporal data usually improves the classification of wetlands, as does ancillary data such as soil data, elevation or topography data. Classified satellite imagery and maps derived from aerial photography have been compared with the conclusion that they offer different but complimentary information. Change detection studies have taken advantage of the repeat coverage and archival data available with satellite remote sensing. Detailed wetland maps can be updated using satellite imagery. Given the spatial resolution of satellite remote sensing systems, fuzzy classification, subpixel classification, spectral mixture analysis, and mixtures estimation may provide more detailed information on wetlands. A layered, hybrid or rule-based approach may give better results than more traditional methods. The combination of radar and optical data provide the most promise for improving wetland classification.

Pacific Estuarine Research Laboratory. 1990. A manual for assessing restored and natural coastal wetlands with examples from Southern California. La Jolla, California. California Sea Grant Report -T-CSGCP-021. http://www.tijuanaestuary.com/nat_res.asp

This manual provides information for assessing the structure and functions of coastal wetlands. The main purpose of this document is to standardize methods of assessing restored, enhanced or constructed wetlands in order to maintain biodiversity. However, the function of this manual emphasizes use for salt marshes and tidal creeks. The document provides strategies for wetland construction, restoration and enhancement that include stating the rationale for functional assessment, objectives of assessment, criteria, and reference wetlands and reference data sets. Sampling methods and comparative data collected from natural wetlands include hydrologic functions, water quality, soil substrate quality and nutrient dynamics, vegetation composition and growth, and fauna presence and abundance. Additional information on methods used for coastal wetlands are described in this document.

Poppe, L. J., A. H. Eliason, J. J. Fredericks, R. R. Rendigs, D. Blackwood and C. F. Polloni. 2003. Grain-size analysis of marine sediments: methodology and data processing, 58 pp. In USGS East-coast Sediment Analysis: Procedures, Databases, and Georeferenced Displays. US Geological Survey Open-File Report 00-358. http://pubs.usgs.gov/of/of00-358/text/chapter1.htm

Partial Author Introduction. The purpose of this chapter is to describe some of the laboratory methods, equipment, computer hardware, and data-acquisition and data-processing software employed in the sedimentation laboratory at the Woods Hole Field Center of the Coastal and Marine Geology Program of the U.S. Geological Survey. The recommendations and laboratory procedures given below are detailed, but are by no means complete. Serious users are strongly encouraged to consult the original references and product manuals.

Purinton, T. A. and D. C. Mountain. 1997. Tidal crossing handbook: A volunteer guide to assessing tidal restrictions. Parker River Clean Water Association. http://www.parker-river.org/PRCWAbookstore/Publications/Guides/TidalHandbook/HB-Contents.htm

This online resource outlines methods for volunteers to monitor water level fluctuations in tidally-restricted areas. Methods are broken down into three phases. Phase I consists of locating crossings and performing a preliminary, visual assessment to determine which crossings are potentially restrictive and may require the collection of quantitative data. Phase II is based on an intensive, day-long monitoring effort to provide quantitative data on the impact on tidal range of the crossing. Phase III consists of analyzing the data obtained from Phase II and formulating recommendations for changes that can be made to improve tidal flow. Troubleshooting recommendations and sample data sheets are also included.

Raposa, K. B. and C. T. Roman. 2001. Monitoring nekton in shallow estuarine habitats, 39 pp. Protocol, Long-term Coastal Ecosystem Monitoring Program, Cape Cod National Seashore, Wellfleet, MA. http://science.nature.nps.gov/im/monitor/protocols/caco_nekton.pdf

Author Abstract. Long-term monitoring of estuarine nekton has many practical and ecological benefits but efforts are hampered by a lack of standardized sampling procedures. This study develops a protocol for monitoring nekton in shallow (<1 m) estuarine habitats for use in the Longterm Coastal Monitoring Program at Cape Cod National Seashore. Sampling in seagrass and salt marsh habitats is emphasized due to the susceptibility of each habitat to anthropogenic stress and to the abundant and rich nekton assemblages that each habitat supports. Extensive sampling with quantitative enclosure traps that estimate nekton density is suggested. These gears have a high capture efficiency in most habitats and are small enough (typically 1 m2) to permit sampling in specific microhabitats. Other aspects of nekton monitoring are discussed, including seasonal sampling considerations, sample allocation, station selection, sample size estimation, parameter selection, and associated environmental data sampling. Developing and initiating long-term nekton monitoring programs will help track natural and human-induced changes in estuarine nekton over time and advance our understanding of the interactions between nekton and the dynamic estuarine environment.

Rey, J. R., R. A. Crossman, T. R. Kain, F. E. Vose and M. S. Peterson. 1987. Sampling zooplankton in shallow marsh and estuarine habitats: gear description and field tests. *Estuaries* 10:61-67.

Author Abstract. Pump and net samplers for collecting zooplankton from very shallow marsh and estuarine habitats are described. Their use is illustrated with data obtained in salt marshes along the Indian River lagoon in east central Florida. In general, both pump and net samplers were found to be satisfactory for sampling zooplankton in these areas. Larger sample volumes were obtained with gear utilizing 202 μ mesh sizes than with gear using 63 μ mesh because the latter became clogged very quickly. Quantitative and qualitative similarity between samples collected with different gear was moderate to low. Comparison of the kinds and densities of taxa captured with the various gear indicate that a combination of techniques may be needed to ensure a proper description of the plankton communities of the area.

Ribic, C. A., T. R. Dixon and I. Vining. 1992. Marine debris survey manual, 92 pp. NOAA Technical Report NMFS 108, NOAA National Marine Fisheries Service, Seattle, Washington.

Author Introduction. Over the last several years, concern has increased about the amount of man-made materials lost or discarded at sea and the potential impacts to the environment. The scope of the problem depends on the amounts and types of debris. One problem in making a regional comparison is the lack of a standard methodology. The objective of this manual is to discuss designs and methodologies for assessment studies of marine debris.

This manual has been written for managers, researchers, and others who are just entering this area of study who seek guidance in designing marine debris surveys. Active researchers will be able to use this manual along with applicable references herein as a source for design improvement. To this end, the authors have synthesized their work and reviewed survey techniques that have been used in the past for assessing marine debris, such as sighting surveys, beach surveys, and trawl surveys, and have considered new methods (e.g., aerial photography). All techniques have been put into a general survey planning framework to assist in developing different marine debris surveys.

Richardson, C. J. and J. Vymazal. 2001. Sampling macrophytes in wetlands, pp. 297-336. In Rader, R. B., D. P Batzer and S. A. Wissinger (eds.), Bioassessment and Management of North American Freshwater Wetlands. John Wiley and Sons, New York.

Author Abstract. The use of macrophytes as biomonitors in wetland ecosystems are presented in terms of assessment of plant population and community responses to disturbance or anthropogenic inputs. The life forms of macrophytes are reviewed and the sampling procedures for estimating changes in population size as well as community structure are presented for herbaceous plants, shrubs, and trees. The methods and formulas for determining abundance and cover as well as frequency, density and dominance are given for plant biomass and productivity measurements. We also outline procedures for establishing macrophytes growth rates and nutrient status in wetland plants. Procedures for determining both above- and belowground biomass, nitrogen and phosphorous as well as ash-free dry matter are presented along with representative data for typical wetland species. In this chapter, we provide a comprehensive plan for sampling and monitoring of plant populations and communities in wetlands.

Roman, C. T., M. J. James-Pirri and J. F. Heltshe. 2001. Monitoring salt marsh vegetation. A protocol for the long-term coastal ecosystem monitoring program at Cape Cod National Seashore, 48 pp. Long-term Coastal Ecosystem Monitoring Program, Cape Cod National Seashore, Wellfleet, MA 02667. http://science.nature.nps.gov/im/monitor/protocols/caco_marshveg.pdf

Author Abstract. The protocol presented is a minimum for monitoring vegetation in salt marshes. Provided in this document are consistent methods for sampling programs in different geographical areas that allows comparisons to be made among datasets over time. The authors present methods used when monitoring salt marshes. Permanent plots using point intercept methods are suggested for sampling vegetation community composition and abundance. Before sampling species present within the plot should be recorded. Using the point intercept method, the number of “hits” per species is recorded for each of fifty points. The study areas should be defined and divided into marsh segments (e.g., tide-restricted, unrestricted, upstream, downstream, etc.). Permanent quadrats must be arranged in transects and spaced a minimum of 10-20 m. Transects should be randomly located within each marsh segment. Additional environmental parameters that can be recorded include: water table level, soil salinity, soil sulfide concentration, height of indicator species such as *Phragmites australis*, and elevation of the permanent plots.

Rozas, L. P. and T. Minello. 1997. Estimating densities of small fishes and decapod crustaceans in shallow estuarine habitats: a review of sampling design with focus on gear selection. *Estuaries* 20:199-213.

Author Abstract. Shallow estuarine habitats often support large populations of small nekton (fishes and decapod crustaceans), but unique characteristics of these habitats make sampling these nekton populations difficult. We discuss development of sampling designs and evaluate some commonly used devices for quantitatively sampling nekton populations. Important considerations of the sampling design include the size and number of samples, their distribution in time and space, and control of tide level. High, stable catch efficiency should be the most important gear characteristic considered when selecting a sampling device to quantify nekton densities. However, the most commonly used gears in studies of estuarine habitats (trawls and seines) have low, variable catch efficiency. Problems with consistently low catch efficiency can be corrected, but large unpredictable variations in this gear characteristically pose a much more difficult challenge. Study results may be biased if the variability in catch efficiency is related to the treatments or habitat characteristics being measured in the sampling design. Enclosure devices, such as throw traps and drop samplers, have fewer variables influencing catch efficiency than do towed nets (i.e., trawls and seines); and the catch efficiency of these enclosure samplers does not appear to vary substantially with habitat characteristics typical of shallow estuarine areas (e.g., presence of vegetation). The area enclosed by these samplers is often small, but increasing the sample number can generally compensate for this limitation. We recommend using enclosure samplers for estimating densities of small nekton in shallow estuarine habitats because these samplers provide the most reliable quantitative data, and the results of studies using these samplers should be comparable. Many kinds of enclosure samplers are now available, and specific requirements of a project will dictate which gear should be selected.

Shafer, D. J. and D. J. Yozzo. 1998. National guidebook for application of hydrogeomorphic assessment of tidal fringe wetlands, 69 pp. U.S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi. Technical Report WRP-DE-16. http://www.wes.army.mil/el/wetlands/pdfs/wrpde16.pdf

Authors described in the regional guidebook the HGM approach used for assessing tidal wetlands. The procedures used to assess wetland functions in relation to regulatory, planning or management programs are described (Smith et al. 1995). The Application Phase includes characterization, assessment analysis, and application components. Characterization describes the wetland ecosystem and the surrounding landscape, describes the planned project and potential impacts, and identifies wetland areas to be assessed. Assessment and analysis involves collecting field data that is needed to run the assessment models and calculating the functional indices for the wetland assessment areas under the existing conditions.

The Tidal Wetland HGM Approach Application Phase involves determining the wetland assessment area (WAA) and the indirect wetland assessment area (IWAA) and, determining wetland type. The boundaries of the area and the type of tidal wetland to be assessed are identified. The WAA is the wetland area impacted by a proposed project. The WAA defines specific boundaries where many of the model variables are ascertained and directly contributes to calculations for other variables (e.g., maximum aquatic and upland edge). Methods for determining WAA are discussed in detail in the procedural manual of the HGM approach (Smith et al. 1995). The IWAA is any adjacent portions of hydrologic unit that may not be affected by the project directly but indirectly affected through hydrologic flow alterations. Wetland types are determined by comparing the hydroperiod, salinity regime, and vegetation community structure with those described in the wetland type profiles for each region. Plant communities react to change in the environment (e.g., salinity and hydrologic alterations) so are considered good indicators of a wetland type. Descriptions of the vegetation present, salinity levels, and hydrological conditions for each wetland type are presented in each regional wetland type profile. To determine the salinity regime of an area, one can refer to available references on salinity and or wetland distribution. Data collected on average salinity or the range of salinity helps to sort each site into one of the four categories of the Cowardin system.

Shuman, C. S. and R. F. Ambrose. 2003. A comparison of remote sensing and ground-based methods for monitoring wetland restoration success. Restoration Ecology 11:325-333.

Author Abstract. Efficient and accurate vegetation sampling techniques are essential for the assessment of wetland restoration success. Remotely acquired data, used extensively in many locations, have not been widely used to monitor restored wetlands. We compared three different vegetation sampling techniques to determine the accuracy associated with each method when used to determine species composition and cover in restored Pacific coast wetlands dominated by Salicornia virginica (perennial pickleweed). Two ground-based techniques, using quadrat and line intercept sampling, and a remote sensing technique, using low altitude, high resolution, color and color infrared photographs, were applied to estimate cover in three small restoration sites. The remote technique provided an accurate and efficient means of sampling vegetation cover, but individual species could not be identified, precluding estimates of species density and distribution. Aerial photography was determined to be an effective tool for vegetation monitoring of simple (i.e., single-species) habitat types or when species identities are not important (e.g., when vegetation is developing on a new restoration site). The efficiency associated with these vegetation sampling techniques was dependent on the scale of the assessment, with aerial photography more efficient than ground-based sampling methods for assessing large areas. However, the inability of aerial photography to identify individual species, especially mixed-species stands common in southern California salt marshes, limits its usefulness for monitoring restoration success. A combination of aerial photography and ground-based methods may be the most effective means of monitoring the success of large wetland restoration projects.

Smart, R. M. and G. O. Dick. 1999. Propagation and establishment of aquatic plants: a handbook for ecosystem restoration projects. 37 pp. Technical Report A-99-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. http://www.wes.army.mil/el/elpubs/pdf/tra99-4.pdf

Smart and Dick have prepared an excellent document to help guide practitioners through the many steps necessary to grow and transplant aquatic plants for restoration or mitigation purposes. The first step in the process is the establishment of pioneer colonies on site. These are small groups of a variety of plant species, grown in wire cages to protect them from herbivores. Pioneer colonies should be scattered throughout the area to be restored. Through monitoring, it can be determined which plant species perform best under existing site conditions. These species then can be grown for the restoration project. The authors explain why it is advisable to grow one's own plants, what the physical and chemical requirements of different aquatic plants types are, and how to prepare and build off-site and in-place facilities. They include a chapter on how to implement the planting project containing information on proper site selection, planting depth, species selection, and timing of planting projects. The authors also include a variety of methods for protecting plantings from herbivores, a critical part of successful planting projects.

[1] Note: Growing one's own plants for restoration projects can be a cost effective means for supplying propagules for a restoration project. However, it requires that the hydrodynamics of the area in question are relatively predicable from one year to the next. Coastal wetlands of the Great Lakes for example are subject to water level fluctuations of the lakes that can drastically alter available habitat type. Unless water level fluctuations can be controlled or reliably predicted from year to year, the expense of growing your own plants may not be worthwhile.

Smith, R. D., R. C. Solomon and N. R. Sexton. 1994. Methods for evaluating wetland functions, 7 pp. WRP Technical Note WG-EV-2.2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

The purpose of this technical note is to review the major wetland evaluation methods currently in use among wetland professionals and to provide a comprehensive list of these methods for use by field biologists and managers. Method selection can be based on study objectives; amount of time, budget and personnel available; regional or local controversy; and degree of precision and accuracy required.

Steyer, G. D., R. C. Raynie, D. L. Steller, D. Fuller and E. Swenson. 1995. Quality management plan for Coastal Wetlands Planning, Protection, and Restoration Act monitoring program, 82 pp. Open-File Report 95-01, Louisiana Department of Natural Resources, Coastal Restoration Division, Baton Rouge, LA. http://www.lacoast.gov/cwppra/reports/MonitoringPlan/index.htm

This document is a Quality Assurance Project Plan (QAPP) used for all restoration projects conducted under the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) and similar legislation for coastal Louisiana. Though it does not explain how to develop a QAPP for new wetland restoration monitoring projects, it can be used as a template by which monitoring plans can be developed. Detailed explanations of how to data is to be collected, acceptable error rates, and methods to ensure high quality data is collected, recorded, and analyzed are included. Quality assurance guidelines are provided for field data collection, remote sensing and airphoto interpretation, computer systems to be used, data entry procedures, data review, laboratory procedures, and documentation and reporting. Any restoration practitioner attempting to develop a monitoring plan or preparing a QAPP for their project may find this document a valuable example to follow.

Thursby, G. B., M. M. Chintala, D. Stetson, C. Wigand and D. M. Champlin. 2002. A rapid, non-destructive method for estimating aboveground biomass of salt marsh grasses. *Wetlands* 22:626-630.

Author Abstract. Understanding the primary productivity of salt marshes requires accurate estimates of biomass. Unfortunately, these estimates vary enough within and among salt marshes or require large numbers of replicates if the averages are to be statistically meaningful. Large numbers of replicates are rarely taken, however, because they involve too much labor. Here, we present data on a fast, non-destructive method for measuring aboveground biomass of *Spartina alterniflora* and *Phragmites australis* that uses only the average height of the five tallest shoots and the total density of shoots over 10 cm tall. Collecting the data takes only a few minutes per replicate, and calculated values for biomass compare favorably with destructive measurements on harvested samples.

Tiner, R. W. 1987. A Field Guide to Coastal Wetland Plants of the Northeastern United States. University of Massachusetts Press, Amherst, MA.

Tiner has compiled a simple to use guide designed help nonspecialists identify common vascular wetland plants from the northeastern coast of the United States. He has included an overview of the ecology of northeastern coastal systems along with maps showing their general distribution. The types of coastal systems covered includes rocky shores, tidal flats, salt marshes, brackish marshes, tidal fresh marshes, tidal swamps, and coastal aquatic beds. Keys to identify about 280 different species are provided, with black and white drawing to aid in the identification of about 150. As with Tiner's *Field Guide to Coastal Wetland Plants of the Southeaster United States* this is only one of many resources available to help the beginner learn to identify wetland plant species. These introductory books should not be used as the final authority on plant identification if results from the monitoring effort are to be published. More thorough books that provide identification for ALL species present in an area should be consulted. Examples for the north and northeast regions include Maggee, Rorer, and Ahles' *Flora of the Northeast: A Manual of the Vascular Flora of New England and Adjacent New York*, Voss' three-volume *Michigan Flora*, Crow and Hellquist's *Aquatic and Wetland Plants of Northeastern North America: Pteridophytes, Gymnosperms and Angiosperms: Dicotyledons* and *Aquatic and Wetland Plants of Northeastern North America: Angiosperms: Monocotyledons (Volume II)*.

Tiner, R. W. 1993. Field Guide to Coastal Wetland Plants of the Southeastern United States. University of Massachusetts Press, Amherst, MA.

Tiner has compiled a simple to use guide designed help nonspecialists identify common vascular wetland plants from the southeastern and gulf coasts of the United States. He has included an overview of the ecology of southeastern coastal systems along with maps showing their general distribution. The types of coastal systems covered include mangrove swamps, salt marshes, salt barrens and flats, brackish marshes, tidal fresh marshes, tidal swamps, tidal flats, and coastal aquatic beds. Keys to identify about 450 different species are provided, with black and white drawing to aid in the identification of about 250. As with Tiner's *Field Guide to Coastal Wetland Plants of the Northeastern United States* this is only one of many resources available to help the beginner learn to identify wetland plant species. These introductory books should not be used as the final authority on plant identification if results from the monitoring effort are to be published. More thorough books that provide identification for ALL species present in an area should be consulted. Examples for the southeast region include Godfrey and Wooten's *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons* and *Aquatic and Wetland Plants of Southeastern United States: Dicotyledons*.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). 1994. Evaluation of restorable salt marsh in New Hampshire, 43 pp. Natural Resources Conservation Service. Durham, NH. http://www.nh.nrcs.usda.gov/technical/Ecosystem_Restoration/Ecosystem_Restoration.html

Researchers evaluated non-natural restrictions to tidal flow in the vegetated tidal marsh in New Hampshire and determined the potential restoration of the marshes that deteriorated ecologically due to past tidal restrictions. Methods used included field identification of sites that experienced tidal flow restrictions; and an engineering field survey was done of the structures and their relationship to the tide elevation. A modeling procedure was developed to analyze the level in which each opening and a preliminary cost estimate of remedial measures were arranged. A field evaluation of marsh health in segments was performed along with an analysis of economic and social impacts. Restriction locations and the evaluated marsh segments were digitized into a geographic information system (GIS) format and a database. By using this method, researchers were able to observe trends over time, such as how much wetland deterioration occurred due to tidal flows. In addition it also assisted in establishing a successful restoration method. Details of the methods used can be seen in the report.

U.S. EPA. 1992. Monitoring guidance for the National Estuary Program. United States Environmental Protection Agency, Office of Water, Office of Wetlands, Washington D.C. EPA Report 842-B-92-004.

This document provides guidance on the design, implementation, and evaluation of the required monitoring programs. It also identifies steps to be taken when developing and implementing estuarine monitoring programs and provides technical basis for discussions on the development of monitoring program objectives, the selection of monitoring program components, and the allocation of sampling effort. Some of the criteria listed for developing a monitoring program and described in this document include: monitoring program objectives, performance criteria, establish testable hypotheses, selection of statistical methods, alternative sampling designs, use of existing monitoring programs, and evaluate monitoring program performance. Additional information on guidelines for developing a monitoring program is described in this document.

U.S. EPA. 1993. Volunteer estuary monitoring: a methods manual, 383 pp. EPA 842-B-93-004, U.S. Environmental Protection Agency, Office of Water, Washington, D.C. http://www.epa.gov/owow/estuaries/monitor/.

This document presents information and methodologies specific to estuarine water quality. Information presented in the first eight chapters include understanding estuaries and what makes them unique, impacts to estuarine habitats and the human role in solving the problems; guidance on how to establish and maintain a volunteer monitoring program; guidance for working with volunteers and ensuring that they are well-positioned to collect water quality data safely and effectively; ensuring that the program consistently produces high quality data; and managing the data and making it readily available to data users. Also presented are water quality measures that determine the condition of the estuary including physical (e.g., substrate texture), chemical (e.g., dissolved oxygen), and biological parameters (e.g., plant and animal presence and abundance). The importance of each parameter and methods used to monitor the conditions are described in a gradual process. Proper quality assurance and quality control techniques must also be described in detail to ensure that the data are beneficial to state agencies and other data users.

U.S. EPA. 1996. The volunteer monitor's guide to quality assurance project plans, 59 pp. EPA 841-B-96-003, U. S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/volunteer/qapp/vol_qapp.pdf

Author Abstract. The Quality Assurance Project Plan, or QAPP, is a written document that outlines the procedures a monitoring project will use to ensure that the samples that participants collect and analyze, the data they store and manage, and the reports they write are of high enough quality to meet project needs.

U.S. Environmental Protection Agency-funded monitoring programs must have an EPA-approved QAPP before sample collection begins. However, even programs that do not receive EPA money should consider developing a QAPP, especially if data might be used by state, federal, or local resource managers. A QAPP helps the data user and monitoring project leaders ensure that the collected data meet their needs and that the quality control steps needed to verify this are built into the project from the beginning.

Volunteer monitoring programs have long recognized the importance of well-designed monitoring projects; written field, lab, and data management protocols; trained volunteers; and effective presentation of results. Relatively few programs, however, have tackled the task of preparing a comprehensive QAPP that documents these important elements. This document is designed to help volunteer program coordinators develop such a QAPP.

U.S. EPA. 2002. Assessing and monitoring floatable debris, 49 pp. EPA-842-B-02-002, Oceans and Coastal Protection Division, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/owow/oceans/debris/floatingdebris/pdf.html

This manual is designed to help states, tribes, and local units of government develop assessment and monitoring programs for floating debris (trash) in coastal waterways. The manual is broken into five parts with appendices. Part 1 introduces the impacts of floating debris on the aquatic environment and describes current legislation to address the issue. Part 2 discusses the types and origins of trash in coastal waters. Part 3 describes a variety of plans and programs that have been developed and implemented in various coastal areas to assess and monitor trash. Part 4 provides recommendations for developing assessment and monitoring programs that were originally presented in NOAA's *Marine Debris Survey Manual* and the EPA's *Volunteer Estuary Monitoring: A Methods Manual*. Part 5 provides methods to prevent and mitigate the problems associated with floating debris. The Appendices include information on international coastal cleanup efforts, a National Marine Debris Monitoring Program data card, storm drain stenciling cards, and surveys from the *Marine Debris Survey Manual*.

U.S. EPA. 2002. Guidance for quality assurance project plans, 130 pp. EPA QA/G-5, U. S. Environmental Protection Agency, Washington, D. C. http://www.epa.gov/swerust1/cat/epaqag5.pdf

Author Abstract. This document is designed to guide those involved with Quality Assurance Project Plan (QAPP) development for environmental monitoring and data analysis. It describes various issues to be addressed when preparing a QAPP, with an emphasis on systematic planning. The report is divided into three chapters. An introduction that describes the target audience and the importance of systematic sampling. A second chapter describes all of the pieces of a QAPP, focusing on environmental data collection and analysis. The third chapter describes methods for developing QAPPs for projects that use previously collected data.

The importance of having high quality, reliable data cannot be over estimated. Use of this document or the EPA's *Volunteer monitor's guide to quality assurance project plans*, will help restoration practitioners develop monitoring plans that will provide the high quality, reliable data necessary to monitor and manage restoration projects. The step-by-step approach of this document takes restoration practitioners through the entire planning, data collection, data analysis, and reporting process from start to finish. Ensuring that all aspects of the monitoring project are well thought out ahead of time and that contingency plans are in place.

U.S. EPA. 2002. Methods for evaluating wetland condition: introduction to wetland biological assessment, 42 pp. Office of Water, U.S. Environmental Protection Agency, Washington, D.C. EPA-822-R-02-014. http://www.epa.gov/ost/standards or http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. In 1999, the U.S. Environmental Protection Agency (EPA) began work on this series of reports entitled *Methods for Evaluating Wetland Condition*. The purpose of these reports is to help States and Tribes develop methods to evaluate (1) the overall ecological condition of wetlands using biological assessments and (2) nutrient enrichment of wetlands, which is one of the primary stressors damaging wetlands in many parts of the country. This information is intended to serve as a starting point for States and Tribes to eventually establish biological and nutrient water quality criteria specifically refined for wetland waterbodies. This purpose was to be accomplished by providing a series of "state of the science" modules concerning wetland bioassessment as well as the nutrient enrichment of wetlands. The individual module format was used instead of one large publication to facilitate the addition of other reports as wetland science progresses and wetlands are further incorporated into water quality programs. Also, this modular approach allows EPA to revise reports without having to reprint them all. A list of the inaugural set of 20 modules can be found at the end of this section.

More information about biological and nutrient criteria is available at the following EPA website: http://www.epa.gov/ost/standards

More information about wetland biological assessments is available at the following EPA websites: http://www.epa.gov/owow/wetlands/bawwg and http://www.epa.gov/waterscience/criteria/wetlands/

U.S. EPA. 2002. Methods for evaluating wetland condition: study design for monitoring wetlands. 21 pp. EPA-822-R-02-015, Office of Water, U.S. Environmental Protection Agency, Washington, D.C. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. State and Tribal monitoring programs should be designed to assess wetland condition with statistical rigor while maximizing available management resources. The three study designs described in this module—stratified random sampling, targeted/tiered approach, and before/after, control/impact (BACI)—allow for collection of a significant amount of information for statistical analyses with relatively minimal effort. The sampling design selected for a monitoring program will depend on the management question being asked. Sampling efforts should be designed to collect information that will answer management questions in a way that will allow robust statistical analysis. In addition, site selection, characterization of reference sites or systems, and identification of appropriate index periods are all of particular concern when selecting an appropriate sampling design. Careful selection of sampling design will allow the best use of financial resources and will result in the collection of high quality data for evaluation of the wetland resources of a State or Tribe. Examples of different sampling designs currently in use for State and Tribal wetland monitoring are described in the Case Study (Bioassessment) module and on http://www.epa.gov/owow/wetlands/bawwg/case.html.

U.S. EPA. 2002. Methods for evaluating wetland condition: developing an **invertebrate** index of biological integrity for wetlands, 45 pp. EPA-822-R-02-019, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. The invertebrate module gives guidance for developing an aquatic invertebrate Index of Biological Integrity (IBI) for assessing the condition of wetlands. In the module, details on each phase of developing the IBI are given. First, in the planning stage, invertebrate attributes are selected, the wetland study sites are chosen, and decisions are made about which stratum of the wetland to sample and what is the optimal sampling period or periods. Then, field sampling methods are chosen. The module describes field methods used in several States, and gives recommendations. Laboratory sampling procedures are reviewed and discussed, such as whether and how to subsample, and what taxonomic level to choose for identifications of the invertebrates. Specific categories of attributes, such as taxa richness, tolerance, feeding function, and individual health are discussed, with examples. Appendices to the invertebrate module give details about the advantages and disadvantages of using invertebrates, of the different attributes, of various field sampling methods, and of lab processing procedures as used by several State and Federal agencies. The module and appendices give a detailed example of one State's process for developing an invertebrate IBI, with a table of metrics with scoring ranges, and a table of scores of individual metrics for 27 wetlands. A glossary of terms is provided as well as sampling methods.

U.S. EPA. 2002. Methods for evaluating wetland condition: using vegetation to assess environmental conditions in wetlands, 46 pp. EPA-822-R-02-020, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. Vegetation has been shown to be a sensitive measure of anthropogenic impacts to wetland ecosystems. As such it can serve as a means to evaluate best management practices, assess restoration and mitigation projects, prioritize wetland related resource management decisions, and establish aquatic life use standards for wetlands. The basic steps necessary for developing a vegetation-based wetland biological assessment and monitoring program are relatively straightforward, but their simplicity belies their effectiveness. By building upon such monitoring tools, we will be able to more fully incorporate wetlands into water quality assessment programs.

Some methods for sampling vegetation in coastal marshes are presented.

U.S. EPA. 2002. Methods for evaluating wetland condition: biological assessment methods for **birds**, 22 pp. EPA-822-R-02-023, Office of Water, U.S. Environmental Protection Agency, Washington, DC. http://www.epa.gov/waterscience/criteria/wetlands/

Author Abstract. Birds potentially detect aspects of wetland landscape condition that are not detected by the other groups commonly used as indicators. Moreover, birds are of high interest to a broad sector of the public. When using birds as indicators, one must pay particular attention to issues of spatial scale. This requires an understanding of home range sizes of the bird species being surveyed. The development of wetland and riparian bird indices of biological integrity is still in its infancy, but holds considerable promise.

Methodologies for sampling birds in coastal habitats are also presented.

Vasey, M., J. Callaway and V. T. Parker. 2002. Data collection protocol, tidal wetland vegetation. San Francisco Estuary Wetlands Regional Monitoring Program Plan, San Francisco CA. http://www.wrmp.org/documents.html.

The goal of the data collection protocol is to encourage wetland scientists to monitor all tidal wetlands in the San Francisco Bay Estuary with a consistent theoretical approach and standard methods to produce tidal wetland vegetation. This protocol is designed to evaluate three important plant community parameters in tidal marshes: 1) plant species diversity, 2) community physical structure, and 3) the invasion of non-native species. Methods used include: a stratified-random sampling approach to characterize the plant community along major gradients of environmental factors expected to influence community structure including heterogeneity. The sampling takes place along these gradients within self-evident drainage basins within the sampling sites. In tidal marshes, tidal hydroperiod, environmental moisture, aqueous salinity, invasion by NIS plants, and edaphic chemical factors vary with intertidal elevation and distance from tidal source are primarily taken into consideration.

Any reference site or wetland project, a permanent transect should be established and extends from the starting point from foreshore to backshore to evaluate vegetation changes over time. Data on percent cover and maximum height per species are collected every 1 meter for the first 30 meters. Sampling should take place at low tide to allow access to sample sites; taken yearly so that annual variation in vegetation can be traced and correlated with other physical and wildlife patterns. Each stratum is analyzed for frequency of occurrence of each species, average cover per occurrence of each species, and maximum plant height per species. Data collected can then be used to assess dominant, common, and rare species in these different habitats. This allows plants to be classified and show the effect of stressors and habitat heterogeneity on biodiversity within and among marshes.

Wells National Estuarine Research Reserve. 1999. Regional standards to identify and evaluate tidal wetland restoration in the Gulf of Maine, pp. 6-18. In Neckles, H. and M. Dionne (eds.), Global Program of Action Coalition for the Gulf of Maine (GPAC Report). http://www.pwrc.usgs.gov/resshow/neckles/Gpac.pdf

A monitoring protocol was designed for tidal wetlands based core variables that are in general categories of wetland structural and functional responses to restoration. The natural marsh and restoration site are monitored before and after restoration is complete. The natural marsh serves as a reference site for determining whether restoration reached the set goals made during the planning process. The natural marsh and restoration site must be in a similar physical environment. The core variables include: hydrology, soils and sediments, vegetation, fish, and birds. Hydrology was measured using automatic water level recorders which were operated simultaneously for a minimum of two weeks. Five stations were used to establish the soil's salinity by using wells for sampling. Soil water was collected 5-20 cm deep. A 19 mm diameter CPVC plastic pipe with seven pairs of 4 mm holes at sediment depths of 5-20 cm was used to determine salinity. Vegetation was sampled using 1m^2 quadrats. Visual animation was used to estimate percentage cover for each species. The tallest three individuals of each species in each plot were measured and the average recorded. Fish samples were measured using throw traps for sampling on open water of creeks and channels and fyke net were used on the vegetated marsh surface. Birds were evaluated by simple observations only in the morning. Details for techniques used can be seen in this report.

Wenner, E. L. and M. Geist. 2001. The National Estuarine Research Reserve's program to monitor and preserve estuarine waters. *Coastal Management* 29:1-17.

The National Estuarine Research Reserve (NERR) sites in 1992 coordinated a program that would attempt to identify and track short-term variability and long-term changes in representative estuarine ecosystems and coastal watersheds. Water quality parameters monitored include: pH, conductivity, temperature, dissolved oxygen, turbidity, and water level. Standardized protocols are also used at each site so that sampling, processing, and data management techniques are consistent among sites. Statistical techniques are being used to identify periodicity in water quality variables. Periodic regression analysis indicated that diel periodicity in dissolved oxygen is a larger source of variation than tidal periodicity at sites with less tidal amplitude. Authors of this document stress how understanding the functions of estuaries and how they change over time will help predict how these systems respond to changes in climate and anthropogenic sources.

APPENDIX III: LIST OF COASTAL MARSH EXPERTS

The experts listed below have provided their contact information so practitioners may contact them with questions pertaining to the restoration or restoration monitoring of this habitat. Contact information is up-to-date as of the printing of this volume. The list below includes only those experts who were 1) contacted by the authors and 2) agreed to submit their contact information. Some of those listed also reviewed the associated habitat chapter. In addition to these resources, practitioners are encouraged to seek out the advice of local experts as well faculty members and researchers at colleges and universities. Engineering, planning, and landscape architecture firms also have experts on staff or contract out the services of botanists, biologists, ecologists, and other experts whose skills are needed in restoration monitoring. These people are in the business of providing assistance in restoration and restoration monitoring and are often extremely knowledgeable in local habitats and how to implement projects on the ground. Finally local, state, and Federal environmental agencies also house many experts who monitor and manage coastal habitats. In addition to the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA), the Army Corps of Engineers (ACE), Fish and Wildlife Service (FWS), and the United States Geologic Survey (USGS) are important Federal agencies to contact for assistance in designing restoration and monitoring projects as well as potential sources of funding and permits to conduct work in coastal waterways.

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GLOSSARY

Abiotic - non-living

Adaptive management - a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. Its most effective form–"active" adaptive management–employs management programs that are designed to experimentally compare selected policies or practices, by evaluating alternative hypotheses about the system being managed.

Aerobic - (of an organism or tissue) requiring air for life; pertaining to or caused by the presence of oxygen

Algae - simple plants that are very small and live in water through photosynthesis, algae are the main producers of food and oxygen in water environments

Allochthanous - carbon that is formed outside of a particular area as opposed to an autochthanous carbon that is produced within a given area

Alluvial plain - the floodplain of a river, where the soils are alluvial deposits carried in by overflowing river

Alluvium - any sediment deposited by flowing water, as in a riverbed, floodplain, or delta

Alternate hypothesis - a statement about the values of one or more parameters usually describing a potential change

Anaerobic - living in the absence of air or free oxygen; pertaining to or caused by the absence of oxygen

Anoxic - without oxygen

Anthropogenic - caused by humans; often used when referring to human induced environmental degradation

Apical - the tips of the plants

Aquatic - living or growing in or on water

Asset mapping - a community assessment research method that provide a graphical representation of a community's capacities and assets

Assigned values - the relative importance or worth of something, usually in economic terms. Natural resource examples include the value of water for irrigation or hydropower, land for development, or forests for timber supply (see held values).

Attitude - an individual's consistent tendency to respond favorably or unfavorably toward a given attitude object. Attitudes can be canvassed through survey research and are often defined utilizing scales ranging from positive to negative evaluations.

Backwater - a body of water in which the flow is slowed or turned back by an obstruction such as a bridge or dam, an opposing current, or the movement of the tide

Baseline measurements - a set of measurements taken to assess the current or pre-restoration condition of a community or ecosystem

Basin morphology - the shape of the earth in the area a coastal habitat is found

Benefit-cost analysis - a comparison of economic benefits and costs to society of a policy, program, or action

Benthic - on the bottom or near the bottom of streams, lakes, or oceans

Bequest value - the value that people place on knowing that future generations will have the option to enjoy something

Biogenic - produced by living organisms

Biomass - the amount of living matter, in the form of organisms, present in a particular habitat, usually expressed as weight- per-unit area

Blackwater streams - streams that do not carry sediment, are tannic in nature and flow through peat-based areas

Brackish - water with a salinity intermediate between seawater and freshwater (containing from 1,000 to 10,000 milligrams per liter of dissolved solids)

Calcareous - sediment/soil formed of calcium carbonate or magnesium carbonate due to biological deposition or inorganic precipitation

Canopy formers - plants that form a diverse vertical habitat structure

Carnivores - organisms that feed on animals

Catchment - the land area drained by a river or stream; also known as "watershed" or "drainage basin"; the area is determined by topography that divides drainages between watersheds

Causality - or causation, refers to the relationship between causes and effects: i.e., to what extent does event 'A' (the cause) bring about effect 'B'

Coastal habitat restoration - the process of reestablishing a self-sustaining habitat in coastal areas that in time can come to closely resemble a natural condition in terms of structure and function

Coastal habitat restoration monitoring - the systematic collection and analysis of data that provides information useful for measuring coastal habitat restoration project performance

Cognitive mapping - a community assessment research method used to collect qualitative data and gain insight into how community members perceive their community and surrounding natural environment

Cohort studies - longitudinal research aimed at studying changing in a particular subpopulation or cohort (e.g., age group) over time (see longitudinal studies)

Community - all the groups of organisms living together in the same area, usually interacting or depending on each other for existence; all the living organisms present in an ecosystem

Community (human) - a group of people who interact socially, have common historical or other ties, meet each other's needs, share similar values, and often share physical space; A sense of "place" shaped by either natural boundaries (e.g., watershed), political or administrative boundaries (e.g., city, neighborhood), or physical infrastructure

Computer-assisted telephone interviewing (CATI) - a system for conducting telephone survey interviews that allows interviewers to enter data directly into a computer database. Some CATI systems also generate phone numbers and dial them automatically.

Concept mapping - community assessment research method that collects data about how community members perceive the causes or related factors of particular issues, topics, and problems

Content validity - in social science research content validity refers to the extent to which a measurement (i.e., performance standard) reflects the specific intended domain of content (i.e., stated goal or objective). That is, how well does the performance standard measure whether or not a particular project goal has been met?

Contingent choice method - estimates economic values for an ecosystem or environmental service. Based on individual's tradeoffs among sets of ecosystems, environmental services or characteristics. Does not directly ask for willingness to pay; inferred from tradeoffs that include cost as an attribute.

Contingent valuation method (CVM) - used when trying to determine an individual or individuals' monetary valuation of a resource. The CVM can be used to determine changes in resource value as related to an increase or decrease in resource quantity or quality. Used to measure non-use attributes such as existence and bequest values; market data is not used.

Coral reefs - highly diverse ecosystems, found in warm, clear, shallow waters of tropical oceans worldwide. They are composed of marine polyps that secrete a hard calcium carbonate skeleton, which serves as a base or substrate for the colony.

Coralline algae - algae that contains a coral-like, calcareous outer covering

Cost estimate - estimates on costs of planning and carrying out a project. Examples of items that may be included in a cost estimate for a monitoring plan may be personnel, authority to provide easements and rights-of-way, maintenance, labor, and equipment.

Coulter counter - a device that measures the amount of particles in water

Coverage error - a type of survey error that can occur when the list – or frame – from which a sample is drawn does not include all elements of the population that researchers wish to study

Cross-sectional studies - studies that investigate some phenomenon by taking a cross section (i.e., snapshot) of it at one time and analyzing that cross section carefully (see longitudinal studies)

Crowding - in outdoor recreation, crowding is a form of conflict (see outdoor recreation conflict) that is based on an individual's judgment of what is appropriate in a particular recreation activity and setting. Use level is not interpreted negatively as crowding until it is perceived to interfere with one's objectives or values. Besides use level, factors that can influence perceptions of crowding include participant's motivations, expectations, and experience related to the activity, and characteristics of those encountered such as group size, behavior, and mode of travel.

Cryptofauna - tiny invertebrates that hide in crevices

Cultch - empty oyster shells and other materials that are on the ground and used as a place of attachment

Culture - a system of learned behaviors, values, ideologies, and social arrangements. These features, in addition to tools and expressive elements such as graphic arts, help humans interpret their universe as well as deal with features of their environments, natural and social.

Cyanobacteria - blue-green pigmented bacteria; formerly called blue-green algae

Dataloggers - an electronic device that continually records data over time

Deepwater swamps - forested wetlands that develop along edges of lakes, alluvial river swamps, in slow-flowing strands, and in large, coastal-wetland complexes. They can be found along the Atlantic and Gulf Coasts and throughout the Mississippi River valley. They are distinguished from other forested habitats by the tolerance of the dominant vegetation to prolonged flooding.

Demersal - bottom-feeding or bottom-dwelling fish, crustaceans, and other free moving organisms

Detritivorous - the practice of eating primarily detritus

Detritus - fine particles of decaying organic and inorganic matter fomed by excrement and by plant and animal remains; maybe suspended in water or accumulated on the bottom of a water body

Diatoms - any of a class (Bacillariophyceae) of minute planktonic unicellular or colonial algae with silicified skeletons that form shells.

Direct impacts - the changes in economic activity during the first round of spending. For tourism this involves the impacts on the tourism industries (businesses selling directly to tourists) themselves (see Secondary Effects)

Dissolved oxygen - oxygen dissolved in water and available to aquatic organisms; one of the most important indicators of the condition of a water body; concentrations below 5 mg/l are stressful and may be lethal to many fish and other species

Dominant species - a plant species that exerts a controlling influence on or defines the character of a community

Downwelling - the process of build-up and sinking of surface waters along coastlines

Driving forces - the base drivers that play a large role in people's decision making processes and influence human behavior. Societal forces such as population, economy, technology, ideology, politics and social organizations are all drivers of environmental change.

Duration - a span or interval of time

Ebb - a period of fading away, low tide

Echinoderms - any of a phylum (Echinodermata) of radially symmetrical coelomate marine animals including the starfishes, sea urchins, and related forms

Economic impact analysis - used to estimate how changes in the flow of goods and services can affect an economy. Measure of the impact of dollars from outside a defined region/area on that region's economy. This method is often used in estimating the value of resource conservation.

Ecosystem - a topographic unit, a volume of land and air plus organic contents extended aerially for a certain time

Ecosystem services - the full range of goods and services provided by natural ecological systems that cumulatively function as fundamental life-support for the planet. The life-support functions performed by ecosystem services can be divided into two groups: production functions (i.e., goods) and processing and regulation functions (i.e., services).

Emergent plants - water plants with roots and part of the stem submerged below water level, but the rest of the plant is above water; e.g., cattails and bulrushes

Environmental equity - the perceived fairness in the distribution of environmental quality across groups of people with different characteristics

Environmental justice - a social movement focused on the perceived fairness in the distribution of environmental quality among people of different racial, ethnic or socio-economic groups

Ephemeral - lasting a very short time

Epifaunal - plants living on the surface of the sediment or other substrate such as debris

Epiphytes - plants that grow on another plant or object upon with it depends for mechanical support but not as a source of nutrients

Estuary - a part of a river, stream, or other body of water that has at least a seasonal connection with the open sea or Great Lakes and where the seawater or Great Lakes water mixes with the surface or subsurface water flow, regardless of the presence of man-made structures or obstructions.

Eukaryotic - organisms whose cells have a nucleus

Eulittoral - refers to that part of the shoreline that is situated between the highest and lowest seasonal water levels

Eutrophic - designating a body of water in which the increase of mineral and organic nutrients has reduced the dissolved oxygen, producing an environment that favors plant over animal life

Eutrophication - a natural process, that can be accelerated by human activities, whereby the concentration of nutrients in rivers, estuaries, and other bodies of water increases; over time this can result in anaerobic (lack of oxygen) conditions in the water column; the increase of nutrients stimulates algae "blooms; " as the algae decays and dies, the availability of dissolved oxygen is reduced; as a result, creatures living in the water accustomed to aerobic conditions perish

Evapotranspiration - a term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration

Existence value - the value that people place on simply knowing that something exists, even if they will never see it or use it

Exotic species - plants or animals not native to the area

Fauna - animals collectively, especially the animals of a particular region or time

Fecal coliforms - any of several bacilli, especially of the genera *Escherichia*, found in the intestines of animals. Their presence in water suggests contamination with sewage of feces, which in turn could mean that disease-causing bacteria or viruses are present. Fecal coliform bacteria are used to indicate possible sewage contamination. Fecal coliform bacteria are not harmful themselves, but indicate the possible presence of disease-causing bacteria, viruses, and protozoans that live in human and animal digestive systems. In addition to the possible health risks associated with them, the bacteria can also cause cloudy water, unpleasant odors, and increased biochemical oxygen demand.

Fetch - the distance along open water or land over which the wind blows

Fishery dependent data - data on fish biology, ecology and population dynamics that is collected in connection with commercial, recreational or subsistence fisheries.

Flooding regime - pattern of flooding over time

Floodplain - a strip of relatively flat land bordering a stream channel that may be overflowed at times of high water; the amount of land inundated during a flood is relative to the severity of a flood event

Flora - plants collectively, especially the plants of a particular region or time

Fluvial - of, relating to, or living in a stream or river

Focus group - a small group of people (usually 8 to 12) that are brought together by a moderator to discuss their opinions on a list of predetermined issues. Focus groups are designed to collect very detailed information on a limited number of topics.

Food chain - interrelations of organisms that feed upon each other, transferring energy and nutrients; typically solar energy is processed by plants who are eaten by herbivores which in turn are eaten by carnivores: sun –> grass –> mouse –> owl

Food webs - the combined food chains of a community or ecosystem

Frequency - how often something happens

Fronds - leaf-like structures of kelp plants

Function - refers to how wetlands and riparian areas work – the physical, chemical, and biological processes that occur in these settings, which are a result of their physical and biological structure

Functional habitat characteristics - characteristics that describe what ecological service a habitat provides to the ecosystem

Gastropods - any of a large class (Gastropoda) of mollusks (as snails and slugs) usually with a univalve shell or none and a distinct head bearing sensory organs

Geomorphic - pertaining to the form of the Earth or of its surface features

Geomorphology - the science that treats the general configuration of the Earth's surface; the description of landforms

Habitat - the sum total of all the living and non-living factors that surround and potentially influence an organism; a particular organism's environment

Hard bottom - the floor of a water body composed of solid, consolidated substrate, including reefs and banks. The solid floor typically provides an attachment surface for sessile organisms as well as a rough three-dimensional surface that encourages water mixing and nutrient cycling.

Hedonic pricing method - estimates economic values for ecosystem or environmental services that directly affect market prices of some other good. Most commonly applied to variations in housing prices that reflect the value of local environmental attributes.

Held values - conceptual precepts and ideals held by an individual about something. Natural resource examples include the symbolic value of a bald eagle or the aesthetic value of enjoying a beautiful sunset (see assigned values).

Herbivory - the act of feeding on plants

Holdfasts - a part by which a plant clings to a flat surface

Human dimensions - an multidisciplinary/interdisciplinary area of investigation which attempts to describe, predict, understand, and affect human thought and action toward natural environments in an effort to improve natural resource and environmental stewardship. Disciplines within human dimensions research is conducted include (but are not limited to) sociology, psychology, resource economics, geography, anthropology, and political science.

Human dominant values - this end of the natural resource value continuum emphasizes the use of natural resources to meet basic human needs. These are often described as utilitarian, materialistic, consumptive or economic in nature.

Human mutual values - the polar opposite of human dominant values, this end of the natural resource value continuum emphasizes spiritual, aesthetic, and nonconsumptive values in nature

Hydric soil - a soil that is saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions that favor the growth and regeneration of hydrophytic vegetation; field indicators of hydric soils can include: a thick layer of decomposing plant material on the surface; the odor of rotten eggs; and colors of bluish–gray, gray, black, or sometimes gray with contrasting brighter spots of color

Hydrodynamics - the motion of water that generally corresponds to its capacity to do work such as transport sediments, erode soils, flush pore waters in sediments, fluctuate vertically, etc. Velocities can vary within each of three flow types: primarily vertical, primarily bidirectional and horizontal, and primarily unidirectional and horizontal. Vertical fluxes are driven by evapotranspiration and precipitation. Bidirectional flows are driven by astronomic tides and wind-driven seiches. Unidirectional flows are downslope movement that occurs from seepage slopes and floodplains.

Hydrogeomorphology - a branch of science (geology) that studies the movement of subsurface water through rocks, either as underground streams or percolating through porous rocks.

Hydrology - the study of the cycle of water movement on, over and through the earth's surface; the science dealing with the properties, distribution, and circulation of water

Hydroperiod - depth, duration, seasonality, and frequency of flooding

Hydrostatic pressure - the pressure water exerts at any given point when a body of water is in a still motion

Hypersaline - extremely saline, generally over 30 ppt salinity (average ocean water salinity)

Hypoxic - waters with dissolved oxygen less than 2 mg/L

IMPLAN - a micro-computer-based input-output (IO) modeling system (see Input-output model below). With IMPLAN, one can estimate 528 sector I-O models for any region consisting of one or more counties. IMPLAN includes procedures for generating multipliers and estimating impacts by applying final demand changes to the model.

Indirect impacts - the changes in sales, income or employment within the region in backward-linked industries supplying goods and services to tourism businesses. The increase in sales of linen supply firms that result from more motel sales is an indirect effect of visitor spending.

Induced impacts - the increased sales within the region from household spending of the income earned in tourism and supporting industries. Employees in tourism and supporting industries spend the income they earn from tourism on housing, utilities, groceries, and other consumer goods and services. This generates sales, income and employment throughout the region's economy.

Infauna - plants that live in the sediment

Informed consent - an ethical guideline for conducting social science research. Informed consent emphasizes the importance of both accurately informing research participants as to the nature of the research and obtaining their verbal or written consent to participate. The purpose, procedures, data collection methods and potential risks (both physical and psychological) should be clearly explained to participants without any deception.

Infralittoral - a sub-area of the sublittoral zone where upward-facing rocks are dominated by algae, mainly kelp

Input-output model (I-O) - an input-output model is a representation of the flows of economic activity between sectors within a region. The model captures what each business or sector must purchase from every other sector in order to produce a dollar's worth of goods or services. Using such a model, flows of economic activity associated with any change in spending may be traced either forwards (spending generating income which induces further spending) or backwards (visitor purchases of meals leads restaurants to purchase additional inputs -- groceries, utilities, etc.). Multipliers may be derived from an input-output models (see multipliers).

Instrumental values - the usefulness of something as a means to some desirable human end. Natural resource examples include economic and life support values associated with natural products and ecosystem functions (see non-instrumental values).

Intergenerational equity - the perceived fairness in the distribution of project costs and benefits across different generations, including future generations not born yet

Interstices - a space that intervenes between things; especially one between closely spaced things

Intertidal - alternately flooded and exposed by tides

Intrinsic values - values not assigned by humans but are inherent in the object or its relationship to other objects

Invasive species - a species that does not naturally occur in a specific area and whose introduction is likely to cause economic or environmental harm

Invertebrate - an animal with no backbone or spinal column; invertebrates include 95% of the animal kingdom

Irregularly exposed - refers to coastal wetlands with surface exposed by tides less often than daily

Lacunar - a small cavity, pit, or discontinuity

Lacustrine - pertaining to, produced by, or formed in a lake

Lagoons - a shallow stretch of seawater (or lake water) near or communicating with the sea (or lake) and partly or completely separated from it by a low, narrow, elongate strip of land

Large macroalgae - relatively shallow (less then 50 m deep) subtidal algal communities dominated by very large brown algae. Kelp and other large macroalgae grow on hard or consolidated substrates forming extensive three-dimensional structures that support numerous flora and fauna assemblages.

Large-scale commercial fishing - fishing fleets that are owned by corporations with large capital investments, and are highly mobile in their global pursuit of fish populations

Littoral - refers to the shallow water zone (less than 2 m deep) at the end of a marine water body, commonly seen in lakes or ponds

Longitudinal studies - social science research designed to permit observations over an extended period of time (see trend studies, cohort studies, and panel studies)

Macrofauna - animals that grow larger than 1 centimeter (e.g., animals exceeding 1 mm in length or sustained on a 1 mm or 0.5 mm sieve)

Macroinvertebrate - animals without backbones that can be seen with the naked eye (caught with a 1 mm^2 mesh net); includes insects, crayfish, snails, mussels, clams, fairy shrimp, etc

Macrophytes - plant species that are observed without the aid of an optical magnification e.g., vascular plants and algae

Mangroves - swamps dominated by shrubs that live between the sea and the land in areas that are inundated by tides. Mangroves thrive along protected shores with fine-grained sediments where the mean temperature during the coldest month is greater than 20º C, which limits their northern distribution.

Marine polyps - refer to the small living units of the coral that are responsible for secreting calcium carbonate maintaining coral reef shape

Market price method - estimates economic values for ecosystem products or services that are bought and sold in commercial markets

Marshes (marine and freshwater) - coastal marshes are transitional habitats between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water tidally or seasonally. Freshwater species are adapted to the short- and long-term water level fluctuations typical of freshwater ecosystems.

Mast - the nuts of forest trees accumulated on the ground

Measurement error - a type of survey error that occurs when a respondent's answer to a given question is inaccurate, imprecise, or cannot be compared to other respondent's answers

Meiofauna - diverse microorganisms that are approximately between .042 mm and 1 mm in size

Meristematic - the ability to form new cells that separate to form new tissues

Mesocosm - experimental tanks allowing studies to be performed on a smaller scale

Metadata - data that describes or provides background information on other data

Microfauna - animals that are very small and best identified with the use of a microscope, such organisms include protozoans and nematodes

Microinvertebrates - invertebrate animals that are so small they can only be observed with a microscope

Micro-topography - very slight changes in the configuration of a surface including its relief and the position of its natural and man-made features

Migratory - a creature that moves from one region to another when the seasons change

Morphology - the study of structure and form, either of biological organisms or features of the earth surface

Mottling - contrasting spots of bright colors in a soil; an indication of some oxidation or ground water level fluctuation

Mudflat - bare, flat bottoms of lakes, rivers and ponds, or coastal waters, largely filled with organic deposits, freshly exposed by a lowering of the water level; a broad expanse of muddy substrate commonly occurring in estuaries and bays

Multipliers - capture the size of the secondary effects in a given region, generally as a ratio of the total change in economic activity in the region relative to the direct change. Multipliers may be expressed as ratios of sales, income or employment, or as ratios of total income or employment changes relative to direct sales. Multipliers express the degree of interdependency between sectors in a region's economy and therefore vary considerably across regions and sectors

Nanoplankton - plankton of minute size, generally size range is from 2 to 20 micrometers

Native - an animal or plant that lives or grows naturally in a certain region

Nearshore - nearshore waters begin at the shoreline or the lakeward edge of the coastal wetlands and extend offshore to the deepest lakebed depth contour, where the thermocline typically intersects with the lake bed in late summer or early fall

Nekton - free-swimming aquatic animals (such as fish) essentially independent of wave and current action

Non-instrumental values - something that is valued for what it is; a good of its own; an end in itself. Natural resource examples include aesthetic and spiritual values found in nature (see instrumental values)

Non-market goods and services - goods and services for which no traditional market exists whereby suppliers and consumers come together and agree on a price. Many ecosystem services and environmental values fall under this category

Non-point source - a source (of any water–carried material) from a broad area, rather than from discrete points

Nonresponse error - a type of survey error that occurs when a significant proportion of the survey sample do not respond to the questionnaire and are different from those who do in a way that is important to the study

Non-use values - also called “passive use” values, or values that are not associated with actual use, or even the option to use a good or service

Norms - perceived standards of acceptable attitudes and behaviors held by a society (social norms) or by an individual (personal norms). Serve as guideposts for what is appropriate behavior in a specific situation.

Nuisance species - undesirable plants and animals, commonly exotic species

Null hypothesis - a statement about the values of one or more parameters usually describing a condition of no change or difference

Nutria - a large South American semiaquatic rodent (*Myocastor coypus*) with webbed hind feet that has been introduced into parts of Europe, Asia, and North America

Nutrient - any inorganic or organic compound that provides the nourishment needed for the survival of an organism

Nutrient cycling - the transformation of nutrients from one chemical form to another by physical, chemical, and biological processes as they are transferred from one trophic level to another and returned to the abiotic environment

Octocorals - corals with eight tentacles on each polyp. There are many different forms that may be soft, leathery, or even those producing hard skeletons.

Oligohaline - an area of an estuary with salinities between 0.5 and 5.0 ppt

Oligotrophic - a water body that is poor in nutrients. This refers mainly to lakes and ponds

One-hundred year flood - refers to the floodwater levels that would occur once in 100 years, or as a 1.0 percent probability per year

Opportunity cost - the cost incurred when an economic decision is made. This cost is equal to the benefit of the most highly valued alternative that would have been gained if a different decision had been made. For example, if a consumer has $2.00 and decides to purchase a sandwich, the economic cost may be that consumer can no longer use that money to buy fruit.

Option value - the value associated with having the option or opportunity to benefit from some resource in the future

Organic - containing carbon, but possibly also containing hydrogen, oxygen, chlorine, nitrogen, and other elements

Organic material - anything that is living or was living; in soil it is usually made up of nuts, leaves, twigs, bark, etc.

Osmotic stress - water stresses due to differences in salinity between an organism and its aquatic environment

Outdoor recreation conflict - defined as behavior of an individual or group that is incompatible with the social, psychological or physical goals of another person or group

Oyster beds - dense, highly structured communities of individual oysters growing on the shells of dead oysters

Panel studies - longitudinal research that studies the same set of people through time in order to investigate changes in individuals over time (see longitudinal studies)

Pelagic - pertaining to, or living in open water column

Personal area network (PAN) - a computer network used for communicating between computer devices (including telephones and personal digital assistants) and a person

Petiole - the stalk of a leaf, attaching it to the stem

pH - a measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral

Phenology - refers to the life stages a plant/ algae experiences (e.g., shoot development in kelp)

Physiographic setting - the location in a landscape, such as stream headwater locations, valley bottom depression, and coastal position. Similar to geomorphic setting.

Physiography - a description of the surface features of the Earth, with an emphasis on the mode or origin

Phytoplanktivores - animals that eat planktonic small algae that flow in the water column

Phytoplankton - microscopic floating plants, mainly algae that are suspended in water bodies and are transported by wave currents because they cannot move by themselves swim effectively against a current.

Piscivorous - feeding on fish

Planktivorous - eating primarily plankton

Plankton - plant and animal organisms, generally microscopic, that float or drift in water

Pneumatocysts - known as gas bladders or floaters that help the plant stay afloat such as the bladders seen in the brown alga *Macrocystis*

Pneumatophores - specialized roots formed on several species of plants occurring frequently in inundated habitats; root is erect and protrudes above the soil surface

Polychaete - a group of chiefly marine annelid worms armed with setae, or bristles, extending from most body segments

Population - a collection of individuals of one species or mixed species making up the residents of a prescribed area

Population list - in social science survey research, this is the list from which the sample is drawn. This list should be as complete and accurate as possible and should closely reflect the target population.

ppt - parts per thousand. The salinity of ocean water is approximately 35 ppt

Precision - a statistical term that refers to the reproducibility of the result or measurement. Precision is measured by uncertainty and is usually expressed as the standard error or some confidence interval around the estimated mean.

Prop roots - long root structures that extend midway from the trunk and arch downward creating tangled branching roots above and below the water's surface, such as the mangrove *Rhizophora*

Propagules - a structure (cutting, seed, spore, rhizome, etc.) that causes the continuation or increase of a plant, by sexual or asexual reproduction

Protodeltaic - similar in form to the early stages of delta formation

Pseudofeces - material expelled by the oyster without having gone through the animal's digestive system

Quadrats - are rectangular, or square shaped instruments used to estimate density, cover and biomass of both plants and animals

Quality assurance/quality control plan - a detailed plan that describes the means of data collection, handling, formatting, storage, and public accessibility for a project

Random utility models - a non-market valuation technique that focuses on the choices or preferences of recreationists among alternative recreational sites. Particularly appropriate when substitutes are available to the individual so that the economist is measuring the value of the quality characteristics of one or more site alternatives (e.g., a fully restored coastal wetland and a degraded coastal wetland).

Receiving water bodies - lakes, estuaries, or other surface waters that have flowing water delivered to them

Recruitment - the process of adding new individuals to a population or subpopulation (as of breeding individuals) by growth, reproduction, immigration, and stocking; also a measure (as in numbers or biomass) of recruitment

Redox potential - oxidation-reduction potential; often used to quantify the degree of electrochemical reduction of wetland soils under anoxic conditions

Reference condition - set of selected measurements or conditions of minimally impaired waterbodies characteristic of a waterbody type in a region

Reference site - a minimally impaired site that is representative of the expected ecological conditions and integrity of other sites of the same type and region

Reflectance - The ratio of the light that radiates onto a surface to the amount that is reflected back

Regime - a regular pattern of occurrence or action

Reliability - the likelihood that a given measurement procedure or technique will yield the same result each time that measure is repeated (i.e., reproducibility of the result) (see Precision)

Remote sensing - the process of detecting and monitoring physical characteristics of an area by measuring its reflected and emitted radiation and without physically contacting the object

Restoration - the process of reestablishing a self-sustaining habitat that in time can come to closely resemble a natural condition in terms of structure and function

Restoration monitoring - the systematic collection and analysis of data that provides information useful for measuring restoration project performance at a variety of scales (locally, regionally, and nationally)

Rhizome - somewhat elongate usually horizontal subterranean plant stem that is often thickened by deposits of reserve food material, produces shoots above and roots below, and is distinguished from a true root in possessing buds, nodes, and usually scale-like leaves

Riparian - a form of wetland transition between permanently saturated wetlands and upland areas. These areas exhibit vegetation or physical characteristics reflective of permanent surface of subsurface water influence. Lands along, adjacent to, or contiguous with perennially and intermittently flowing rivers and streams, glacial potholes, and the shores of lakes and reservoirs with stable water levels are typically riparian areas. Excluded are such sites as ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil.

Riverine - of, or associated with rivers

Riverine forests - forests found along sluggish streams, drainage depressions, and in large alluvial floodplains. Although associated with deepwater swamps in the SE United States, riverine forests are found throughout the US and do not exhibit prolonged flooding.

Rocky shoreline - extensive hard bottom littoral habitats on wave-exposed coasts

RVD (recreational visitor day) - one RVD is defined as 12 hours of use in some recreational activity. This could be one person using an area for 12 hours, or 2 people using an area for 6 hours each, or any combination of people and time adding to 12 hours of use.

Salinity - the concentration of dissolved salts in a body of water; commonly expressed as parts per thousand

Salt pans - an undrained natural depression in which water gathers and leaves a deposit of salt on evaporation

Sample - in social science survey research, this is a set of respondents selected from a larger population for the purpose of a survey

Sampling designs - the procedure for selecting samples from a population and the subsequent statistical analysis

Sampling error - a potential source of survey error that can occur when researchers survey only a subset or sample of all people in the population instead of conducting a census. To minimize this error the sample should be as representative of the population as possible.

Satisfaction - in outdoor recreation, satisfaction is defined as the difference between desired and achieved goals. Can be measured through surveys of recreation participants.

SAV (submerged aquatic vegetation) - marine, brackish, and freshwater submerged aquatic vegetation that grows on soft sediments in sheltered shallow waters of estuaries, bays, lagoons, and lakes

Seasonality - the change in naturally cycles, such as lunar cycles and flooding cycles, from one season to the next

Secondary data - information that has already been assembled, having been collected for some other purpose. Sources include census reports, state and federal agency data, and university research.

Secondary effects - the changes in economic activity from subsequent rounds of re-spending of tourism dollars. There are two types of secondary effects: indirect effects and induced effects.

Sector - a grouping of industries that produce similar products or services. Most economic reporting and models in the U.S. are based on the Standard Industrial Classification system (SIC code). Tourism is more an activity or type of customer than an industrial sector. While hotels (SIC 70) are a relatively pure tourism sector, restaurants, retail establishments and amusements sell to both tourists and local customers. There is therefore no simple way to identify tourism sales in the existing economic reporting systems, which is why visitor surveys are required to estimate tourist spending.

Sediment porewater - water in the spaces between individual grains of sediment

Seiches - a sudden oscillation of the water in a moderate-size body of water, caused by wind

Seine - a net weighted at the bottom with floats at the top so it remains vertical in the water. A seine can be towed behind a boat or smaller versions, attached to poles, may be operated by hand.

Senescence - the growth phase in a plant or plant part (as a leaf) from full maturity to death, also applies to winter dormancy

Sessile - plants that are permanently attached or established; animals that do not freely move about

Simple random sampling (SRS) - in survey research, when each member of the target population has an equal change of being selected. If a population list exists, SRS can be achieved using a computer-generated random numbers.

Small-scale commercial fishing - fishing operations that have relatively small capital investment and levels of production, and are more limited in terms of mobility and resource options (compared to large-scale operations). Terms that are commonly used to describe small-scale fishermen include native, coastal, inshore, tribal, peasant, artisanal, and traditional.

Social capital - describes the internal social and cultural coherence of society, the norms and values that govern interactions among people and the institutions in which they are embedded

Social impact assessment (SIA) - analysis conducted to assess, in advance, the social consequences that are likely to follow from specific policy actions and alternatives. Social impacts in this context refers to the consequences to human populations that alter the ways in which people live, work, play, relate to one another, organize and generally cope as members of society.

Social network mapping - community assessment research method used to collect, analyze, and graphically represent data that describe patterns of communication and relationships within a community

Socioeconomic monitoring - tracking of key indicators that characterize the economic and social state of a community

Soft bottom - loose, unconsolidated substrate characterized by fine to coarse-grained sediment

Soft shoreline - sand beaches, dunes, and muddy shores. Sandy beaches are stretches of land covered by loose material (sand), exposed to and shaped by waves and wind.

Stakeholders - individuals, groups, or sectors that have a direct interest in and/or are impacted by the use and management of natural resources in a particular area, or that have responsibility for management of those resources

Statistical protocol - a method of a analyzing a collection of observed values to make an inference about one or more characteristic of a population or unit

Strands - a diffuse freshwater stream flowing through a shallow vegetated depression on a gentle slope

Structural habitat characteristics - characteristics that define the physical composition of a habitat

Subsistence - describes the customary and traditional uses of renewable resources (i.e., food, shelter, clothing, fuel) for direct personal/family consumption, sharing with other community members, or for barter. Subsistence communities are often held together by patterns of natural resource production, distribution, exchange, and consumption that helps maintain a complex web of social relations involving authority, respect, wealth, obligation, status, power and security.

Subtidal - continuously submerged; an area affected by ocean tides

Supralittoral region - is that area which is above the high tide mark receiving splashing from waves

Target population - the subset of people who are the focus of a survey research project

Taxa - a grouping of organisms given a formal taxonomic name such as species, genus, family, etc. (singular form is taxon)

Temporal - over time

Thermocline - the region in a thermally stratified body of water which separates warmer oxygen-rich surface water from cold oxygen-poor deep water and in which temperature decreases rapidly with depth

Tide - the rhythmic, alternate rise and fall of the surface (or water level) of the ocean, and connected bodies of water, occurring twice a day over most of the Earth, resulting from the gravitational attraction of the Moon, and to a lesser degree, the Sun

Topography - the general configuration of a land surface or any part of the Earth's surface, including its relief and the position of its natural and man–made features

Transect - two types of transects, point and line. Point intercept transect methods is performed by placing a point frame along a set of transect lines. Line transects are when a line is extended from one point to the next within the designated sample area

Transient - passing through or by a place with only a brief stay or sojourn

Transit - a surveying instrument for measuring horizontal and vertical angles; appropriate to help determine actual location of whale surfacing. It contains a small telescope that is placed on top of a tripod.

Travel cost method (TCM) - TCM is used to estimate monetary value of a geographical site in its current condition (i.e., environmental health, recreational use capacity, etc.) by site-users. Individuals or groups report travel-related expenditures made while on trips to single and multiple recreational sites. Market values are used.

Trend studies - longitudinal research that studies changes within some general population over time (see longitudinal studies)

Trophic - refers to food, nutrition, or growth state

Trophic level - a group of organisms united by obtaining their energy from the same part of the food web of a biological community

Turf - cover (the ground) with a surface layer of grass or grass roots

Unconsolidated - loosely arranged

Utilitarian value - valuing some object for its usefulness in meeting certain basic human needs (e.g., food, shelter, clothing). Also see human-dominant values

Validity - refers to how close to a true or accepted value a measurement lies

Vibracore - refers to a high frequency, low amplitude vibration, coring technique used for collecting sediment samples without disrobing the sample

Viviparous - producing living young instead of eggs from within the body in the manner of nearly all mammals, many reptiles, and a few fishes; germinating while still attached to the parent plant

Water column - a conceptual volume of water extending from the water surface down to, but not including the substrate. It is found in marine, estuarine, river, and lacustrine systems.

Watershed - surface drainage area that contributes water to a lake, river, or other body of water; the land area drained by a river or stream

Willingness-to-pay - the amount in goods, services, or dollars that a person is willing to give up to get a particular good or service

Zonation - a state or condition that is marked with bands of color, texture, or plant species

Zooplanktivorus - animals that feed upon zooplankton

Zooplankton - free-floating animals that drift in the water, range from microscopic organisms to larger animals such as jellyfish

References

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