A RAPID ASSESSMENT METHOD EXAMINING THE ECOLOGICAL HEALTH OF TIDAL MARINE WETLANDS IN GALVESTON BAY, TEXAS

A Thesis

by

LINDSEY ANN STASZAK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF MARINE RESOURCES MANAGEMENT

August 2010

Major Subject: Marine Resources Management

A Rapid Assessment Method Examining the Ecological Health of Tidal Marine Wetlands in Galveston Bay, Texas

A RAPID ASSESSMENT METHOD EXAMINING THE ECOLOGICAL HEALTH OF TIDAL MARINE WETLANDS IN GALVESTON BAY, TEXAS

A Thesis

by

LINDSEY ANN STASZAK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF MARINE RESOURCES MANAGEMENT

Approved by:

Chair of Committee,	Anna R. Armitage
Committee Members,	Thomas L. Linton
	Georgianne W. Moore
Head of Department,	Ernest Estes

August 2010

Major Subject: Marine Resources Management

ABSTRACT

A Rapid Assessment Method Examining the Ecological Health of Tidal Marine
Wetlands in Galveston Bay, Texas. (August 2010)
Lindsey Ann Staszak, B.S., University of North Carolina Wilmington
Chair of Advisory Committee: Dr. Anna R. Armitage

Wetlands are one of the most productive ecosystems in the world, housing diverse biota and serving important functions as nursery habitat and feeding grounds. However, nearly 70% of coastal wetlands, including 21% of the salt marshes in Texas, have been lost since 1950, due primarily to coastal development and declines in water quality. Restoration of wetlands is essential to reestablish lost functions, but there is no standard method to assess the ecological health of restored salt marshes in Texas. Numerous recent salt marsh restoration projects in Galveston Bay have made it an ideal model system to develop and implement an ecosystem health assessment, known as a rapid assessment method (RAM). In this study, I modified an established RAM, the Mid-Atlantic Tidal Fringe Assessment, to compare the ecological health of representative reference salt marshes to restored marshes around Galveston Bay.

I measured 14 biotic and abiotic characteristics at 12 restored and 6 reference sites around Galveston Bay, and then grouped those measurements into four functional groups: landscape/site characteristics, hydrology, wildlife habitat, and soil characteristics. I then developed a scoring system (minimum 0, maximum 100) to summarize the overall health of each site.

Most of the restored salt marshes in this study scored lower than reference marshes. The average reference site score was 81.8 and the average restored site score was 69.7. Functional group values for landscape/site characteristics, soil, and wildlife habitat were significantly lower in restored than in reference sites. In particular, restored sites had more hydrological modifications, more fill material, and fewer macrobenthos than reference wetlands.

The Galv-RAM effectively and efficiently identified restoration successes and weaknesses. With this information, management agencies can address restoration shortcomings by adapting management goals. The Galv-RAM will streamline monitoring protocols and facilitate long-term examination of restored wetland health. As a result, management decisions can be modified based on the scores received in different categories or variables to improve and or meet the goals of the project.

DEDICATION

To my dad, whose unending strength, guidance, and
support taught me all there is to love about science and about life.

ACKNOWLEDGEMENTS

Dr. Armitage, I am deeply grateful to you as my committee chair for your encouraging attitude and personal guidance throughout this research. Dr. Linton and Dr. Moore, my committee members, thank you for your guidance, contribution, and support.

Thank you to Lalise and Greg Mason (Scenic Galveston), Jeff DallaRosa (Galveston Bay Estuary Program), Ashley Estep, Jamie Schubert, Cheri O'Brien, and Andy Sipocz (Texas Parks and Wildlife Department), Tracey Prothro and John Mason (Baytown Wetland Center), and Jerry Judy (Texas City Prairie Preserve) for their extraordinary help in site access, logistics, and sharing their local wetland knowledge.

Also I am appreciative to Roger Zimmerman, Lawrence Rozas, Thomas Minello (NOAA), Kenny Jaynes (USACE), Wade Abbott, Jen Stevenot (Perennial Environmental Services), Philip Smith (Galveston Bay Foundation), and Jim Webb for facilitating the discussions and participating in my survey on weighting wetland variables.

I extend an exceptionally special thanks to the Coastal and Wetland Ecology lab for their on-going patience and never-ending help during my project. Thank you Mithriel MacKay, Sarah Norman, Laurissa Noack, Katie St. Clair, and Dr. B.J. Bench for taking the time to understand and experience my field work. Lastly, thank you Amanda Thronson for always being available to bounce ideas and thoughts off of, even when you preferred not to! Without any of you I would not have been able to complete this project.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Importance of wetlands

The EPA Clean Water Act defines wetlands as “areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions including swamps, marshes, bogs, and similar areas” (USACE 2008). Environmental conditions in wetlands lead to high productivity. Wetlands are one of the most productive ecosystems in the world, providing vital nursery grounds, habitat, and foraging grounds to a wide range of vertebrate and invertebrate species. It is estimated that up to 43% of federally threatened and endangered species rely directly or indirectly on wetlands for their survival (Moulton et al. 1997). Wetlands also perform a number of vital chemical and physical functions, serving as sites of chemical contaminant retention and transformation organic carbon production and export, groundwater recharge, sediment entrapment, shoreline erosion mitigation, and flood attenuation (Kennish 2001).

Wetland loss: magnitude and causes

The United States Fish and Wildlife Service (USFWS) estimates that over half of salt marshes that existed in the lower 48 states at the time of European settlement have

---

This thesis follows the style of Restoration Ecology.

been lost and an additional 290,000 acres continue to be lost per year (Dahl and Johnson 1991). The USFWS and Texas Parks and Wildlife Department (TPWD) reported that Texas salt marshes declined by nearly 70% between 1950 and 1990 (Moulton et al. 1997). In Galveston Bay, TX, USA, over 21% of salt marshes have been lost since 1950 (White et al. 2006).

Much of the wetland loss in Galveston Bay is attributable to physical alterations to the ecosystem. Many salt marshes have been converted to open water and mudflats due to natural and anthropogenic subsidence (lowering of the land surface due to withdrawal of water and petroleum products from below the surface) (White et al. 2006). Other marshes have been filled in for agricultural or urban development (Port of Houston Authority 2009). Dredging for navigation, flood control, mineral extraction, and filling or draining for dredge disposal have also contributed to salt marsh loss (EPA 1994). Hydrological alterations, including levee and dam construction, can accelerate erosion by large ship wakes, wind-driven waves, or isolation of small marshes from each other (EPA 1994). The construction of bulkheads and seawalls creates abrupt shorelines that limit the ability of wetlands to adapt to changes in sea level (Port of Houston Authority 2009).

Mitigation of wetland loss

Wetland protection policies have been in place since the early 1970s. The current United States Army Corps of Engineers (USACE) permitting policy complies with the federal regulation of “no net loss” under Section 404 of the Clean Water Act. This act mandates the restoration and maintenance of the chemical, physical, and biological integrity of the nation's surface waters including adjacent wetlands. The term *adjacent* means bordering, contiguous, or neighboring. Wetlands separated from other waters of the United States by structures like man-made dikes or barriers, natural river berms, or dunes are also considered to be "adjacent wetlands" (USACE 2008).

There are many different ways to define restoration based on the design (desired species composition and/or density) or on the monitoring plan (setting milestones and success criteria for restoration projects). The design and monitoring plan of each project impact restoration outcomes, and thus present new challenges and opportunities for further research. Primary goals of wetland creation and restoration should be to establish ecosystems that are similar in structure and community composition and perform functions like the natural system that they were designed to replace (Broome 1989; Zedler 1993). For this project, restored wetlands were defined by the National Research Council (National Research Council 1992) as "returning a system to a close approximation of its condition prior to disturbance, with both the structure and function of the system recreated." Knowledge of the pre-disturbance condition is rarely available and thus presents additional challenges for measuring restoration success. Therefore, reference wetlands that may or may not be representative are typically used as a standard of ecological health.

Reference wetlands are, by definition, in a comparatively natural state because they have experienced relatively few human impacts and still provide many ecological functions. They also function as natural guidelines to help land managers make more standardized and informed restoration decisions. Naturally occurring wetlands are complex, dynamic systems with many interacting natural processes (Coultas and Hsieh 1997). The complexities of these natural ecosystems (i.e. nutrient cycling, food webs) are challenging to restore and are frequently overlooked in the assessment of restoration success.

The Port of Houston Authority, Galveston Bay Estuary Program (GBEP), and USACE are among the active agencies combating salt marsh loss in Galveston Bay. For example, the Port of Houston Authority and the US Army Corps of Engineers created 4,250 acres of marsh as part of the Navigation Channel Project in and around Galveston Bay (Port of Houston Authority 2009). GBEP and its partners created, enhanced, and restored approximately 4,500 additional acres of wetlands and associated habitats between 2001 and 2005. These agencies are restoring acreage, but long-term, ecosystem-level assessments of the ecological success of these restoration projects are rarely performed.

Defining restoration success

According to the USACE definition, a wetland is defined by the presence of wetland hydrology, hydric soils, and wetland vegetation. When permits to develop on wetlands are distributed by the USACE, it is the responsibility of the permit holder to complete and successfully acquire all compensatory mitigation requirements (Lewis 1990). The Council on Environmental Quality defines mitigation (40 CFR 1508.20) as actions that avoid, minimize, reduce, rectify, or compensate for the adverse impacts of development. In the case of the unavoidable impact, mitigation is required to replace the loss of wetland and aquatic functions. However, mitigation permit requirements are rarely habitat-specific, and usually focus on structural (e.g., plant cover) features rather than functional (e.g., nursery support) aspects. As a consequence, newly constructed wetlands may be separated spatially from the existing wetland matrix or be of a different wetland type, often resulting in lower biodiversity reduced ecosystem functions (Kennish 2001).

The existing USACE ecological performance standard attempts to describe compensatory mitigation projects in ecological terms that can be measured (e.g., the project has established an appropriate hydrologic regime or has an appropriate number of acres of specific types of plant communities at specified levels of development, including particular species) (USACE 2008). However, the metrics used to quantify mitigation success vary among permits – some permits require the assessment of functional criteria and others can be assessed based on physical characteristics (i.e. plant dominance) of the mitigation project as outlined in the Corps of Engineers Wetland Delineation Manual (Pacific Estuarine Research Laboratory 1990). Furthermore, some mitigation requirements judged successful by some agencies are considered failures by others (Hackney 2000). Consequently, restoration "success" is usually quantified with basic, simple data such as the presence of plants and/or animals and percent vegetation cover. The presence of certain species of plants is used as an indicator of proper hydrology and soil properties (Seybold et al. 1998). Unstable hydrology and a lack of invertebrate habitats can also have negative impacts on the animals present and thus are used as an indicator of success. Invertebrates found in wetlands integrate the entire spectrum of available aquatic wetland habitats and conditions, yet unnaturally high levels of nutrients (i.e. phosphorus) and chemicals (i.e. chloride) have been shown to have negative impacts on the invertebrate community (Blinn et al. 2004). Assessing success is then based on comparing these easily measured variables with a relative simple set of criteria that were stipulated in the original permit (Mitsch and Wilson 1996).

Success in the context of wetland restoration and creation is a relative term and it depends, in part, on the goals of each restoration project (Whigham 1999). For example, creating habitat for migratory waterfowl usually focuses on minimizing fragmentation and providing more interior wetland space because many nest predators cannot access deep water habitats within wetlands (Picman et al. 1993). However, creating macroinvertebrate habitat requires more marsh/water interface, which is usually achieved by increasing tidal creek area (Minello et al. 1994).

Short term monitoring typically focuses on transplanted vegetation and pioneer organisms, but long-term functional success is rarely dependent on these initial conditions (Mitsch and Wilson 1996). Konisky et al. (2006) found following restoration that physical factors (i.e. salinity) rebounded rapidly after about one year yet, avian indicators were indistinguishable among reference, impacted, and restored areas. Other biological responses (i.e. nekton) were less definitive and occurred over longer time frames. Therefore, a multitude of indicators encompassing many functions and structures of the wetland should be assessed for success. Short term monitoring may impede the measurement of success by focusing on immediate responses, rather than incorporating long term changes in the physical, chemical, and biological properties of the system.

Measuring restoration success

The extent and the rate at which restored coastal wetlands can provide equivalent functions as in natural sites has not been assessed and remains uncertain (Gutrich and Hitzhusen 2004). Restoration successes and failures should help managers improve protocols and facilitate the production of healthy, largely self-sustaining systems that resemble reference areas (Hackney 2000). Thus, consistent annual or biannual monitoring programs like rapid assessment methods (RAMs) will help habitat managers evaluate the progress of restoration efforts (Zedler and Lindig-Cisneros 2002).

RAMs provide a standardized evaluation of the ecological health of wetlands at the ecosystem level. RAMs provide quantitative information on the status of the wetland resource with a relatively small investment of time and effort (Fennessy et al. 2004). Various states (New Jersey, Ohio, Florida, and California) and regions (Mid-Atlantic) are developing and implementing RAMs into their monitoring programs. The California Rapid Assessment method (CRAM) exemplifies the typical RAM approach, where scores were compiled for numerous sites within the state and analyzed for spatial patterns or trends. The CRAM uses a set of variable metrics (i.e. landscape connectivity, water source) to defined the potential range of conditions that can then be used as a frame of reference for subsequent project assessments (2009). However, no comparable RAM exists for the Galveston Bay region. Developing a RAM for Galveston Bay salt marshes will facilitate wetland monitoring programs and guide policy development and decision-making.

In this assessment of Galveston Bay, I will utilize a previously established field method called the Mid-Atlantic Tidal Fringe Wetland Assessment This method was created in part by the U.S. Environmental Protection Agency (U.S. EPA) and developed for salt marshes along the Atlantic coast. It is feasible to adapt this method for the Galveston Bay area because of similar vegetation and fauna between the two regions. Furthermore, this method focuses on variables such as hydrological modifications and belowground biomass that are important contributors to the function and ecological health of tidal marine wetlands but are rarely incorporated into restoration monitoring programs. These variables encompass important qualities of habitat structures, hydrological components, landscape and site characteristics, and soil properties that contribute to wetland health and sustainability.

Objectives

1. Use an established Rapid Assessment Method to quantify and compare the ecological health of reference and restored salt marshes in Galveston Bay, Texas.
2. Produce a customized Rapid Assessment Method for the Galveston Bay region (Galv-RAM) that can be integrated into local restoration efforts.

METHODS

Site selection

Data were collected from 12 restored and six reference salt marshes throughout a single growing season (early July – early September 2009) in Galveston Bay, Texas (Fig.1). Seven of the 12 restored sites were five to nine years old; the remaining five sites were between 10 and 15 years old (Table 1). Four criteria were used to select the study sites:

1. **Type of wetland**: all sites were classified as tidal fringe wetlands, as defined by the U.S Army Corps of Engineer Regional Guide book (Shafer et al. 2002). Tidal fringe wetlands occur along coasts and estuaries and experience tidal inundation by marine waters.
2. **Size**: all sites had minimum diameters of 50 meters.
3. **Availability of restoration history**: all sites had documentation available from various federal, state, and private agencies about the construction date and protection and/or management history.
4. **Site access**: all sites were accessible by foot or boat.

Table 1. Site descriptions, including wetland type, location, and age. Reference sites were not given an age.

Site #	Wetland Type	Latitude	Longitude	Age
1	Restored	24 19.41	94 55.53	8
2	Restored	29 18.89	94 54.89	10
3	Restored	29 19.09	94 55.00	7
4	Restored	29 19.09	94 55.82	9
5	Reference	29 02.90	95 09.85	N/A
6	Reference	29 02.65	95 10.17	N/A
7	Reference	29 32.95	94 29.94	N/A
8	Restored	29 26.04	94 56.87	15
9	Restored	29 26.00	94 56.54	15
10	Restored	29 11.92	94 59.48	9
11	Restored	29 11.75	94 59.32	9
12	Restored	29 13.62	94 56.52	10
13	Restored	29 13.97	94 56.48	7
14	Restored	29 45.24	95 02.83	15
15	Restored	29 45.04	95 04.65	5
16	Reference	29 27.27	94 41.57	N/A
17	Reference	29 28.61	94 39.69	N/A
18	Reference	29 15.33	94 55.05	N/A

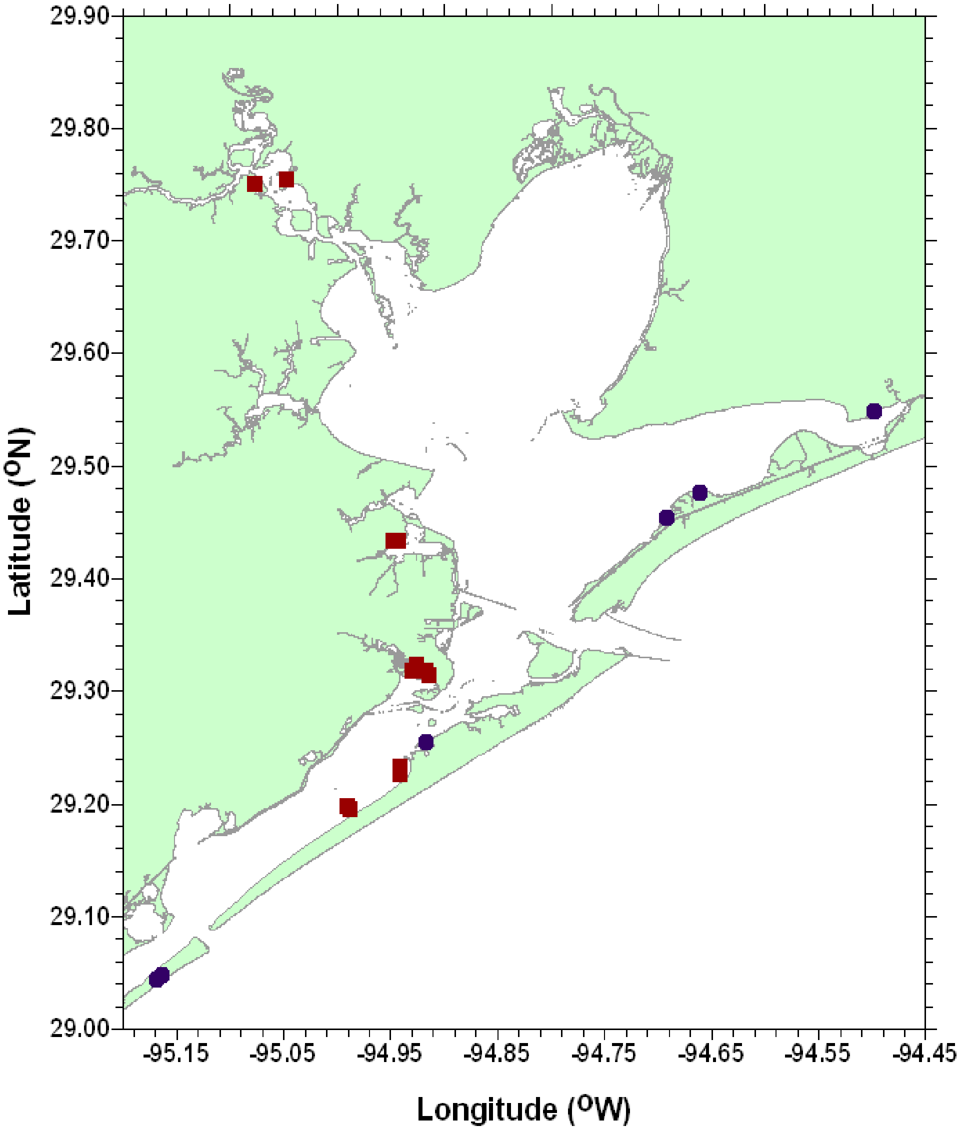

Figure 1. Sampling sites around Galveston Bay. Red rectangles (🟥) are restored sites, n=12. Blue circles (●) are reference sites, n=6.

Independent variable selection

Based on a literature review of other RAMs and exploratory field expeditions, fourteen independent variables from the Mid-Atlantic Tidal Fringe Wetland Assessment were determined to be particularly informative about Galveston Bay wetlands health and were measured within each AA (Table 2). MATFWA variables that were excluded from the protocol include those with high variability between sites (e.g., dissolved oxygen) and subjective variables (e.g., best possible judgment marsh assessment variable).

Table 2. Fourteen variables used to determine wetland ecological health.

Independent Variables
1. Barriers to Landward Migration
2. Percentage of Fill Volume
3. Man-made Structures
4. Tidal Restrictions
5. Hydrological Modifications
6. Vegetation Cover
7. Macrobenthos
8. Vegetation Diversity
9. Invasive Species
10. Soil stability
11. 2-4 cm Plant Fragments
12. 25-27 cm Plant Fragment
13. Pore Water Salinity
14. Pore pH

Barriers to landward migration are important because structures such as roads and railroad crossings may have enormous impacts on salt marshes by preventing migration inland as sea level increases, accelerating the loss of floristically-rich upper marshes during the landward retreat of tidal marshes (French 1993).

Fill was included in the score criteria because soils in restored wetlands have a smaller quantity of organic matter than soils in similar natural wetlands (Kentula 2002) and often contain other solids such as rock, wood, pieces of metal, glass, and other debris. Organic matter in reference marsh soils store nutrients critical to plant growth (Pacific Estuarine Research Laboratory 1990). The smaller amounts of organic matter in soils of restored wetlands can limit plant growth (Langis et al. 1991). Furthermore, fill material is often contaminated with heavy metals, chlorinated hydrocarbons, oil, and other pollutants originating from dredge spoils, sewage, industrial and municipal discharge (Kennish 1997).

The presence of man-made structures was included because construction of structures like docks and boardwalks can disrupt water flow, shade out plants, and add toxins to the water through the erosion of metal hardware (Weis and Weis 1998). In addition, species diversity of wintering shorebirds, an important wildlife component in wetland systems, can be lower in marshes with more man-made structures (Armitage et al. 2007).

Tidal restrictions were analyzed because structures such as impoundment dikes, water-control embankments, levees, and canals often interfere with normal tidal flooding and drainage, decreasing sediment supply to the marsh surface, and arresting vertical accretion (Kennish 2001).

Hydrological modifications were analyzed because wetland loss has been linked to human modification of marsh topography and hydrology (Mendelssohn and Morris 2002). In particular, structures such as channels and geotubes that are common in restored marshes contribute to a large amount of heterogeneity in marsh topography and may account for much of the wetland's perceived overall "quality" (Mack 2000).

Percent plant cover was included in the score criteria because plants fill vital ecosystem functions such as facilitating the settlement of sediments, providing habitat structure, and up taking pollutants and heavy metal accumulations from waste waters (Cole 2002).

Macrobenthos form the base of the consumer food chain supporting consumers such as crabs, fish, and birds (Posey et al. 1997). Benthic invertebrates (e.g. *Uca* species) are often sensitive indicators of pollution and may provide information on the health of potentially impacted salt marsh sites because of their association to sediment (Pennings et al. 2009).

Vegetation diversity index was analyzed because of the unpredictable weather-driven tidal regime on the Texas Gulf Coast. Marshes may experience high salinity due to evaporation during extended low tides, low salinity following heavy rains, and water logging during extended high tides (Kunza and Pennings 2008). Kunza and Pennings (2008) suggest that this variable tidal regime does not consistently favor any single species and that higher diversity is characteristic of intact, functional reference marshes.

Percent cover of invasive species may be higher where disturbances such as alteration of marsh elevation, soil type, hydrologic patterns, vegetative communities, and wildlife communities facilitate the colonization of invasive species (Bart and Hartman 2009). Restored wetlands are highly modified, which may make them vulnerable to species invasions (Zedler and Callaway 2000). Wetland invasive species can alter habitat structure, lower biodiversity, change nutrient cycling and productivity, and modify food webs (Zedler and Kercher 2004).

Soil stability has been shown to vary in restored and natural salt marsh, primarily due to differences in soil texture and elevation (Fearnley 2009).

Belowground biomass is an indicator of plant health in salt marshes (Turner et al. 2004). Reduced below-ground organic matter may precede above-ground changes in the plant community and indicate signs of ecological stress (O'Brien et al. 2007). Jackson et al. (1996) reported that the greatest proportion of root biomass occurs in the top 30 cm of the soil surface and thus samples were taken within this range.

Pore water salinity can limit species abundance within salt marsh habitat. Salinity variations within an estuary can be the result of impoundments and other structures that limit the normal tidal flushing. Alteration of the salinity regime in portions of a channel can result in ecological changes in vegetation, resulting in increased marsh salinities and degradation of the marsh ecosystem (Gedan et al. 2009).

Pore water pH was assessed because plant growth is often sensitive to pH levels. A range of 6 to 7 is generally most favorable for plant growth because most plant nutrients are attainable in this range and therefore are readily available to aid in growth. A pH of 6.6 to 7.3 is the most favorable environment for microbial activities that increase the availability of nitrogen, sulfur, and phosphorus in soils (USDA 1998).

Field protocol

Locating assessment area

Most of the RAM measurements were conducted within a 50 meter (m) diameter assessment area (AA). The MATFWA method utilized a 100-m diameter AA, but Galveston Bay salt marshes are often narrow, so I reduced the diameter to 50 m in order to capture a more consistent representation of these marshes. The center point of the AA was located by qualitatively identifying the center of the low marsh elevation zone dominated by smooth cordgrass *Spartina alterniflora* or saltgrass *Distichlis spicata*; detailed measurements were taken at predetermined distances from that center point as described below. In two of the restored sites, the low elevation zone was too small to contain a 50-m diameter study area; in these sites, the AA encompassed some high marsh as well. After the global positioning system (GPS) coordinates of the center point were recorded, transect tapes (50 m) were crossed perpendicularly at the center point (Fig. 2).

Photos were taken from the center point, facing each cardinal direction, and were archived in a database for future site visit comparisons. All data were recorded on modified data sheets from the Mid-Atlantic Tidal Fringe Wetland Assessment (Appendix A).

Wetland features

Visual inspection of the AA quantified the total number of barriers such as roads that limit the wetland from a landward progression. Tidal restrictions were reported as the number of features such as a berm or culvert that limited tidal flow entering and exiting the wetland. Man-made structures were identified as the number of docks boardwalks that limited expected wetland growth. Each structures identified was accounted for only once during the assessment to limit possible score bias.

Hydrological alterations

Hydrological modifications were assessed as the percentage of disruption to the surface water flow, such as the presence of channelization or “geo tubes”, which are sediment-filled sleeves of geotextile fabric used for temporary erosion control and storm surge protection. Alterations to the landscape were noted by acquiring the percentage of fill volume material (total historical sediment volume) used or added to the site. “Fill” (dredge) was defined as any historical/restoration soil, debris, garbage, or excavated material placed in the AA for the purpose of enhancing or building terraces or other marsh structures.

Site sketch

A sketch of the site recorded structures, variation in vegetation communities, or any other large alterations in the immediate area of the AA. The drawing included major channels, land area, and adjacent structures (i.e. roads). These sketches and all other site notes were archived at Texas A&M University at Galveston for comparisons to future site visits.

Vegetation plots for plant measurements

Detailed quantification of vegetation types and canopy coverage took place in subplots within the AA. Eight 1.0 m^2 quadrats were placed every ten meters on two 50–m transect tapes that bisected the AA (Fig. 2). Plot one was the northernmost point and plot four was the southernmost point. Plot five through eight fell west to east along the transect tape (Fig. 2). Visual estimates of live and dead plant cover (in 5% intervals) were recorded for each species in each plot (Goldsmith et al. 1986).

All invasive exotics in the quadrats were identified. A thorough examination of the entire AA was conducted to determine if any additional invasive species were present. Any native but rare species identified outside the quadrats were also noted.

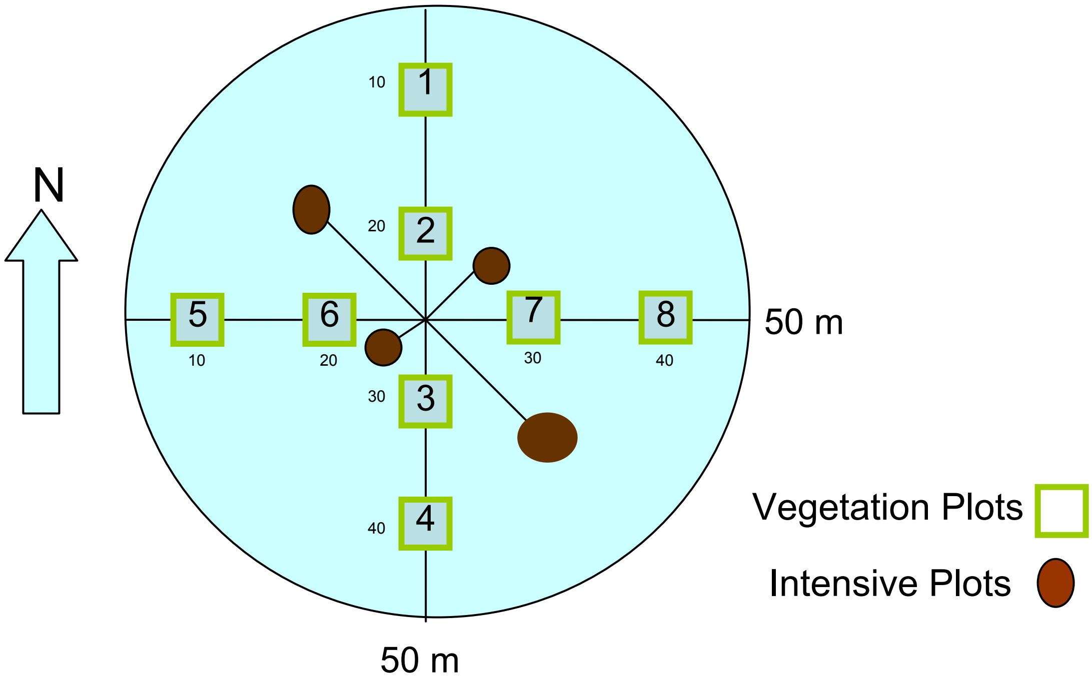

Figure 2. Diagram of the assessment area (AA). Diagram depicts vegetation plots for plant measurements and intensive plots for fauna, belowground biomass, water characteristics, and macrobenthos measurements.

Intensive plots

A random number table was used to determine the distance (up to 19 m) for four 10-cm diameter plots from the center of the AA outward, at 45 degree angles to the transect tapes (Fig. 2). Macrobenthos species (i.e. *Littorina littorea,* common periwinkle and *Uca* sp.*,* fiddler crab) density was recorded for each species; burrow density was also noted. Soil stability (expressed in pounds per square inch (psi)) was determined with a pocket penetrometer with a 1” adapter to estimate compressive strength of in situ soils (Carlisle et al. 2004).

Root volume was measured to estimate belowground plant biomass in the two plots that qualitatively appeared to be the most representative of the wetland as a whole, and at the closest bank (at the vegetation-tidal flat interface) to the AA center point. In each of these three locations, a core (5 cm diameter, 27 cm deep) was extracted and 2 cm subsamples were removed from depths of 2-4 cm and 25-27 cm below the surface. The subsamples were cut into fragments and put into separate large-mouth water bottles containing approximately 250 mL of seawater. Each sample was washed (shaken) in the bottle and decanted through a 2 mm sieve. The plant fragments from the sieve were placed into a 60 cc syringe and the water was expelled. The root volume (mL) was recorded and averaged for all three locations within the AA.

Water characteristics were obtained from water filling the extraction hole where the core sample was obtained. The pore water pH was measured with a Mettler Toledo SevenGo pH meter SG2 and a Mettler Toledo InLab 413 SG probe. Salinity was measured with an Orion 131S meter with a 01301A conductivity cell. Each of these meters also recorded temperature, so temperature was recorded as the average from the two meters.

Each site assessment took approximately one day to complete the full rapid assessment protocol, including field, administrative, and statistical time.

Variable scoring

To facilitated direct comparisons among variables, all data were converted onto a standardized scale from 0 (worst performance) to 4 (best performance).

Barriers to landward migration

The number of barriers observed was converted into a standardized scale, where the highest rating was given to sites with no barriers present (Table 3).

Table 3. Score conversion for the number of barriers to landward migration.

Number of barriers observed	Score
0	4
1	3
2	2
3	1
≥ 4	0

Fill

The amount of fill in the site was converted into a standardized scale by giving the highest rating to sites with no fill added or used in the AA (Table 4).

Table 4. Score conversion for the amount of fill volume present.

Historical Information	Score
No fill in assessment area	4
1 - 24 % of fill added to AA	3
25% - 49% of fill added to AA	2
50% - 74% of fill added to AA	1
≥ 75% of fill added to AA	0

Presence of man-made structures

The number of structures observed was converted into a standardized scale, where the highest rating was given to sites with no structures present (Table 5).

Table 5. Score conversion for the number of man-made structures.

Number of structures observed	Score
0	4
1	3
2	2
3	1
≥ 4	0

Tidal restrictions

The number of restrictions observed was converted into a standardized scale, where the highest rating was given to sites with no restrictions present (Table 6).

Table 6. Score conversion for the number of tidal restrictions.

Number of restrictions observed	Score
0	4
1	3
2	2
3	1
$\geq$ 4	0

Hydrological modifications

The percent of surface water flow that is disrupted, via hydrological modifications, in the site was converted into a standardized scale by giving the highest rating to sites with modifications (Table 7).

Table 7. Score conversion for the percent of hydrological modifications.

Percent of hydrological impact	Score
0% not impacted	4
1 - 25% impacted	3
26-50% impacted	2
51 - 75% impacted	1
76 - 100% impacted	0

Percent plant cover

A standardized scale was constructed by defining the largest mean percent cover (61.3%) value among all reference sites as the lower limit of the top score (Table 8). That value was then divided by four to determine the range of each subsequent score category.

Table 8. Score conversion for percent plant cover.

% cover	Score
≥ 61.3 %	4
46.0 - 61.2%	3
30.7 - 46.0%	2
15.4 - 30.7%	1
0 - 15.3 %	0

Macrobenthos

The number of macrobenthos was converted into a standardized scale by defining the largest mean (2.5) value among all reference sites as the lower limit of the top score (Table 9). That value was then divided by four to determine the range of each subsequent score.

Table 9. Score conversion for number of macrobenthos.

Average number of macrobenthos	Score
≥ 2.5	4
1.9 - 2.4	3
1.3-1.8	2
0.63 - 1.3	1
0 - 0.62	0

Vegetation diversity index

Indices of diversity were calculated using the Simpson Index of Diversity:

$$D = \sum_{i=1}^{S} p_i^2.$$

where *p* = the percentage of individuals in a species and S = number of species. Diversity is expressed as 1-D, where higher numbers represent more diversity. Vegetation diversity was converted into a standardized scale by defining the largest mean diversity index (0.11) value among all reference sites as the lower limit of the top score (Table 10). That value was then divided by four to determine the range of each subsequent score.

Table 10. Score conversion for vegetation diversity index.

Vegetation diversity index	Score
≥ 0.11	4
0.08 - 0.10	3
0.05 - 0.07	2
0.03 - 0.04	1
0 - 0.02	0

Percent plant cover of invasive species

The percent cover of invasive species in the site was converted into a standardized scale by giving the highest rating to sites with no invasive species present (Table 11).

Table 11. Score conversion for percent cover of invasive species.

% Cover of Invasive species	Score
0%	4
1-25%	3
26-50%	2
51-75%	1
76-100%	0

Soil stability

A standardized scale was created by defining the lowest mean soil stability (0.05) value among all reference sites as the lower limit of the top score (Table 12). That value was then divided by four to determine the range of each subsequent score.

Table 12. Score conversion for soil stability.

Soil stability (psi)	Score
$\leq$ 0.05	4
0.051 - 0.06	3
0.061 – 0.07	2
0.071 - 0.08	1
$\geq$ 0.081	0

Belowground

Shallow belowground root volume (2-4 cm) and deep belowground root volume (25-27 cm) were converted into a standardized scale by defining the largest mean belowground root volume (shallow root volume 22.0 mL, deep root volume 15.2) value among all reference sites as the lower limit of the top score (Tables 13 and 14). That value was then divided by four to determine the range of each subsequent score.

Table 13. Score conversion for shallow belowground biomass, as estimated by root volume.

Shallow (2-4 cm) belowground root volume (mL)	Score
≥ 22.0	4
16.5- 21.9	3
11.0 - 16.4	2
5.5 - 10.9	1
0.0 – 5.4	0

Table 14. Score conversion for deep belowground biomass, as estimated by root volume.

Deep (25-27 cm) belowground root volume (mL)	Score
≥ 15.2	4
11.4 - 15.1	3
7.6 - 11.3	2
3.8 - 7.5	1
0 - 3.7	0

Pore water salinity

Pore water salinity was converted into a standardized scale by defining the largest mean pore water salinity (27.4) value among all reference sites. This value plus and minus the standard error defined the range for the top score (Table 15). That value was then divided by four to determine the upper and lower range of each subsequent score.

Table 15. Score conversion for pore water salinity.

Pore water salinity (ppt)	Score
≥ 48.5	0
42.0 - 48.4	1
35.4 - 41.9	2
29.1 - 35.5	3
25.8 - 29.0	4
19.3 - 25.7	3
12.9 - 19.2	2
6.4 - 12.8	1
0 - 6.3	0

Pore water pH

Pore water pH cover was converted into a standardized scale by defining the largest mean pore water pH (7.0) value among all reference sites. This value, plus and minus the standard error, defined the range for the top score (Table 16). That value was then divided by four to determine the upper and lower range of each subsequent score.

Table 16. Score conversion for pore water pH.

Pore water pH	Score
≥ 12.6	0
11.0 - 12.5	1
9.5 - 10.9	2
7.9 - 9.4	3
6.2 - 7.8	4
4.7 - 6.1	3
3.1 - 4.6	2
1.6 - 3.0	1
0 - 1.5	0

Composite score calculations

Composite health scores were calculated in three different ways; all methods yielded a final score between 0 and 100, where 0 was the lowest and 100 was the highest level of ecological health.

Method 1, *independent variables score*, was the summation of all 14 independent variables scores divided by the maximum number possible (56 points) and multiplied by 100 (Fig. 3).

Method 2, *grouped variables score,* classified each variable into one of four categories: landscape/site characteristics (Lv), hydrology (Hv), wildlife habitat (Wv), and soils (Sv) (Table 17). Within each category, scores were summed and then divided by the number of independent variables that composed that variable to yield a maximum possible score of four for each category (Fig. 3). The overall ecosystem score was calculated by summing all category scores, dividing by the maximum possible score (16) and multiplying by 100 (Fig. 3).

Table 17. Description of independent variables and categories used to generate index scores.

Independent Variables	Categories
L1. Barriers to Landward Migration	Lv: Landscape/Site Characteristics
L2. Fill	
L3. Man-made Structures	
H1. Tidal Restrictions	Hv: Hydrology
H2. Hydrological Modifications	
W1. Vegetation Cover	Wv: Wildlife Habitat
W2. Macrobenthos	
W3. Vegetation Diversity	
W4. Invasive Species	
S1. Soil Stability	Sv: Soil
S2. 2-4 cm Plant Fragments	
S3. 25-27 cm Plant Fragment	
S4. Pore Water Salinity	
S5. Pore pH	

Method three, *weighted grouped variables score,* applied different weights to each variable category (landscape/site characteristics, hydrology, wildlife habitat, and soils). Weighting factors were formulated by consulting a panel of eleven wetland scientists throughout the Galveston Bay region. These wetland scientists worked directly with the Bay in a variety of professions, including wetland restoration scientists, Method 1. Calculation of *independent variable scores*:

Variables (range 0-4)
Landscape/Site Characteristics
= (Barriers to landward migration + Fill + Man-made structures)
Hydrology
= (Tidal restrictions + Hydrological modifications)
Wildlife Habitat
= (Percent Plant Cover + Macrobenthos + Vegetation diversity + Invasive)
Soil
= (Soil stability + 2-4cm BGB + 25-27 cm BGB + salinity+ pH)

$$\textbf{Score} = \frac{\text{Sum of independent variable scores (I)}}{\text{Sum of max. independent variable scores } (I_{max}=56)} = [\sum (I / 56) \text{ x } 100]$$

Method 2. Calculation of *grouped variables scores*:

Categories (range 0-4)
Lv: Landscape/Site Characteristics = (*Barriers to landward migration + Fill + Man-made structures)/3*
Hv: Hydrology = (*Tidal restrictions + Hydrological modifications)/2*
Wv: Wildlife Habitat = (*Percent Plant Cover + Macrobenthos + Vegetation diversity + Invasive)/4*
Sv: Soil = (*Soil stability + 2-4cm BGB + 25-27 cm BGB + salinity+ pH)/5*

$$Lv + Hv + Wv + Sv = G$$

$$\textbf{Score} = \frac{\text{Sum of grouped variables (G)}}{\text{Sum of max. grouped variable scores } (G_{max}=16)} = [\sum (G/ 16) \text{ x } 100]$$

Method 3. Calculation of *weighted grouped variables scores*:

Wetland Category	Weighting Factor (WF)	Max G_w
Lv: Landscape/Site Characteristics	1.4	5.6
Hv: Hydrology	2.5	10
Wv: Wildlife Habitat	1.9	7.6
Sv: Soil	1.6	6.4

Category x Weighting factor (WF) = Weighted Value (G_w)

$$\textbf{Score} = \frac{\text{Sum of weighted values } (G_w)}{\text{Sum of weighting factor (29.6)}} = [\sum ((G_w / 29.6) \text{ x } 100]$$

Figure 3. Calculations of wetland scores (Balzano et al. 2002).

fisheries ecologists, and non-profit agencies. They were asked to rank the four categories in order of importance (four being the most important, and one being the least important to wetland restoration) (Appendix C). The purpose of this panel was to provide a comprehensive perspective about factors relevant to wetland health from professionals with a wide range of expertise and interests. The results of the surveys were averaged and the mean value was used as the "weighting factor" (WF) for each category. Categories ranked the highest were determined to be the most important to the "ecosystem health" of the wetlands and those with the lowest ranking were determined to be less influential and received a smaller "weighting factor" (Balzano et al. 2002). The most important factor was hydrology, followed by wildlife habitat, soils, and landscape/site characteristics (Fig. 3). Category scores were calculated as described for Method 2 and then were adjusted to weighted values by multiplying the category score by the WF. The summation of all weighted values was then divided by the total sum possible of the WFs (29.6) and multiplied by 100 (Fig. 3).

Differences between reference and restored site scores were determined for each of the three scoring methods with an unpaired 2-sample *t*-test. Differences between the three composite score calculations were analyzed with a one-way analysis of variance (ANOVA), where the independent factor was scoring method.

Studies show that restored sites in other areas of the country gradually evolve overtime (Zedler and Callaway 1999). To evaluate if ecological health scores improved in older restored wetlands, I used a linear regression to compare *grouped variable scores* from restored site scores (dependent variable) to site age (independent variable). Since each scoring method yielded similar composite health scores (see Results), I only used the *grouped variable scores* for this analysis.

A principal component analysis (PCA) was used to identify differences between reference and restored sites using the 14 independent variables. Prior to this analysis, I assigned the 18 sampling sites into three groups: reference sites (6 sites), restored sites less than 10 years old (7 sites), and restored sites greater than and equal to 10 years old (5 sites). Two reference sites (site 5 and 6) were excluded from this analysis because logistical constraints prevented measurements of all 14 variables. Extremely low variance for invasive species values violated the assumptions of PCA; therefore, invasive species were excluded from this analysis.

RESULTS

Comparison of independent variables scores

When independent variables scores were considered separately, reference site scores were significantly higher than restored site scores (t-test, $p < 0.005$; Fig. 4). Restored sites scores had greater variance (21.4) relative to reference wetlands (4.2).

Comparison of grouped variables scores

When grouped variables unweighted scores were classified into four categories (landscape/site characteristics, hydrology, wildlife habitat, and soils) and were given equal weight in the total site score, reference site scores were significantly higher than restored site scores (t-test, $p < 0.001$; Fig. 5). Restoration sites scores had greater variance (23.3) relative to reference wetland sites (6.9).

Reference site scores were significantly higher in three of the four variable categories: landscape and site characteristics ($p < 0.001$), wildlife habitat ($p = 0.024$), and soils ($p < 0.001$) (Fig. 6). The landscape/site category had the highest reference score. Hydrology had the greatest variability (2.0) of all the categories in both the reference and restored site wetland groups but did not significantly differ between reference and restored sites.

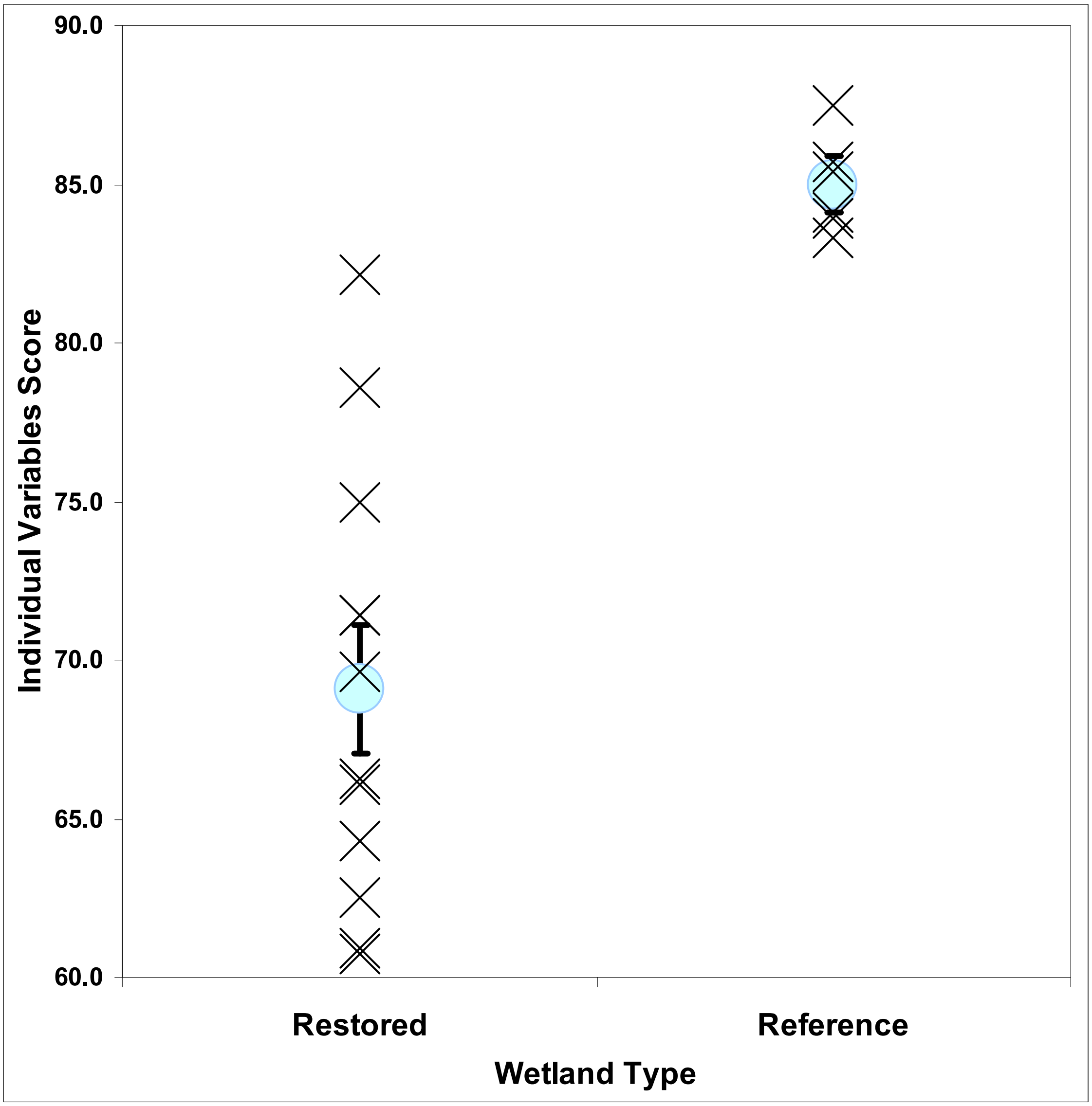

Figure 4. Comparison of individual variables scores for restored and reference wetlands. Crosses (X) indicate individual site scores for each wetland. Circles (O) are mean scores for each wetland type and error bars indicate one standard error of the mean. Scores can range from 0 to a maximum 100 points. For restored wetlands, n=12 and for reference wetlands, n=6.

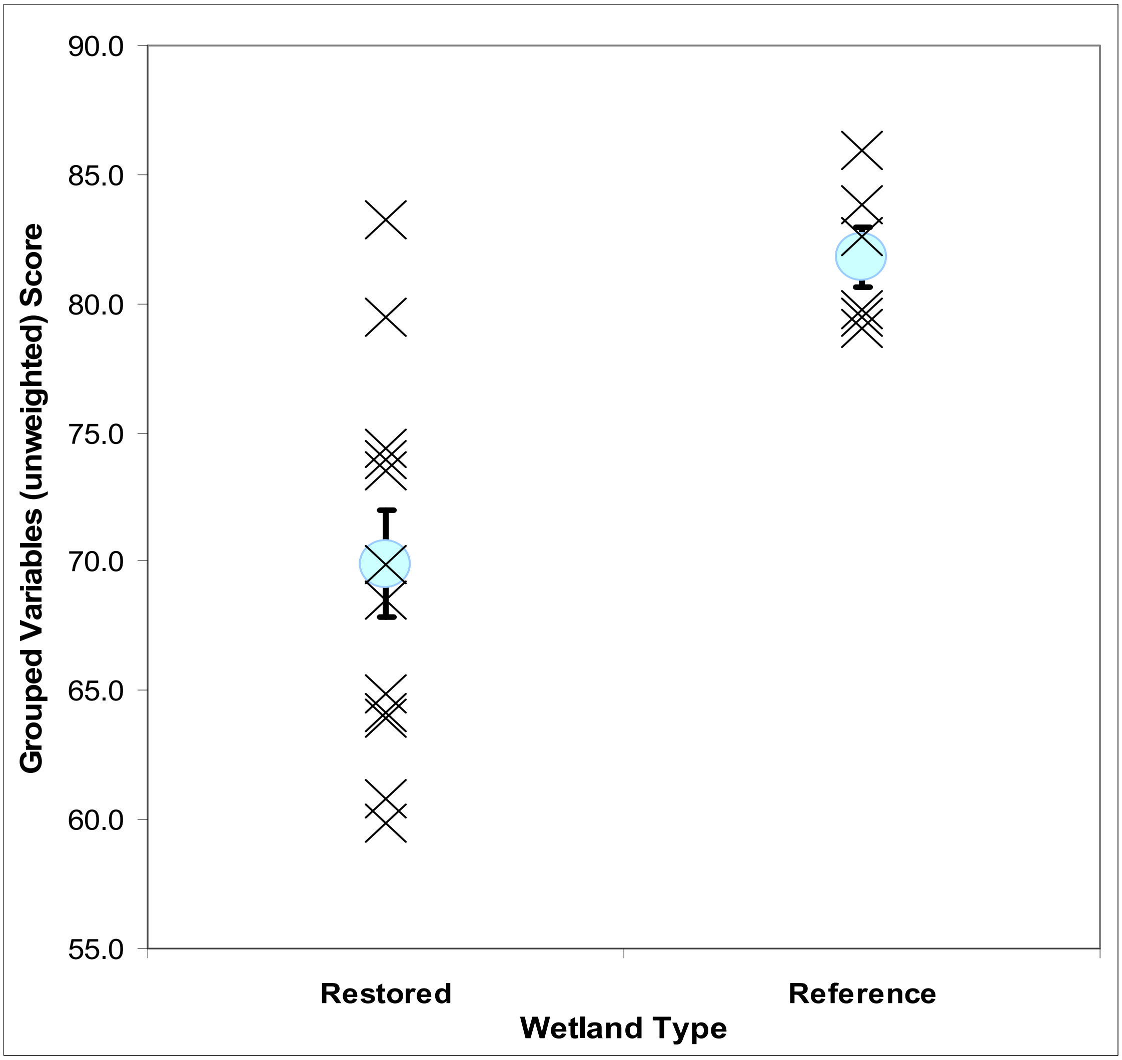

Figure 5. Comparison of grouped variables scores for restored and reference wetlands. Crosses (X) indicate individual site scores for each wetland. Circles (O) are mean scores for each wetland type and error bars indicate one standard error of the mean. Scores can range from 0 to a maximum of 100. For restored wetlands, n=12 and for reference wetlands, n=6.

Comparison of weighted grouped variables scores

When weighted grouped variables scores were considered separately, reference site scores were significantly higher than restored site scores (t-test, $p < 0.002$). Restored sites scores had greater variance (24.4) relative to reference wetlands (12.9).

Comparison among scoring methods

Reference and restored mean scores of the three scoring methods were not significantly different from each other (ANOVA, reference scores $p = 0.10$, restored scores $p = 0.89$) (Table 18), suggesting that all scoring methods produce similar outcomes. Method 2 *grouped variables (unweighted)* scores is (1) the most versatile, since variables can be analyzed independently or in categories, and (2) is the most quantitative, since the determination of the WF was somewhat subjective. Therefore, this method was chosen for the final scoring protocol for the Galv-RAM. All independent variable scores for all sites are listed in Appendix D.

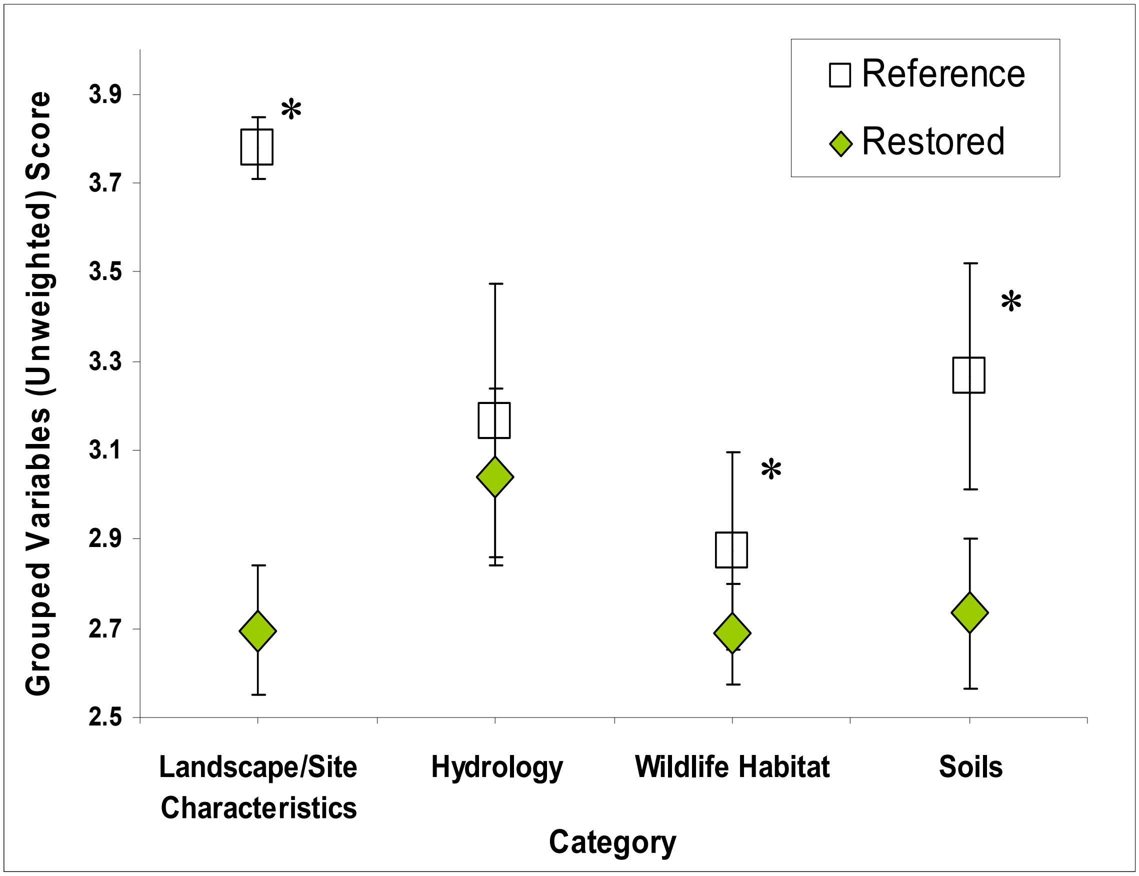

Figure 6. Comparison of categories within the grouped variables scores for reference and restored wetlands. Symbols represent the mean score of each category and the error bars to indicate one standard error of the mean. Stars (*) indicate significant differences ($p < 0.05$). Category scores range from 0.0 to a maximum of 4.0 points. For restored wetlands, n=12 and for reference wetlands, n=6.

Table 18. Mean scores of reference and restored sites using all scoring methods. Best possible ecological health score is 100.

	Individual Variables Score		Grouped Variables Unweighted Score		Grouped Variables Weighted Scores	
	Reference	Restored	Reference	Restored	Reference	Restored
Average	85.0	69.0	81.8	69.9	80.7	70.5
SE	0.63	2.01	1.14	2.08	1.98	2.22
Variance	4.2	21.4	6.9	23.3	12.9	24.4

Restored site development over time

Restored site grouped variables unweighted scores did not increase with site age (linear regression, $p = 0.24$, $r^2 = 0.14$, Fig. 7). Scores of older restored sites ($\geq$ 10 years old) were not significantly higher than younger (< 10 years old) restored sites (t-test, $p = 0.107$, Fig. 8).

Principal component analysis (PCA) revealed two significant functions (eigenvalues > 1); factor 1 accounted for 83.3% of the total variance and factor 2 accounted for 16.7% of the variance (Fig. 9). Reference and restored sites (regardless of age) separated out along function one, which was most strongly correlated (correlation between function and variable > 0.20) with the number of macrobenthos and percentage of fill volume. Young and old restored sites separated out along function 2, which was most strongly related to the plant diversity index, soil stability, and 2-4 cm belowground root volume.

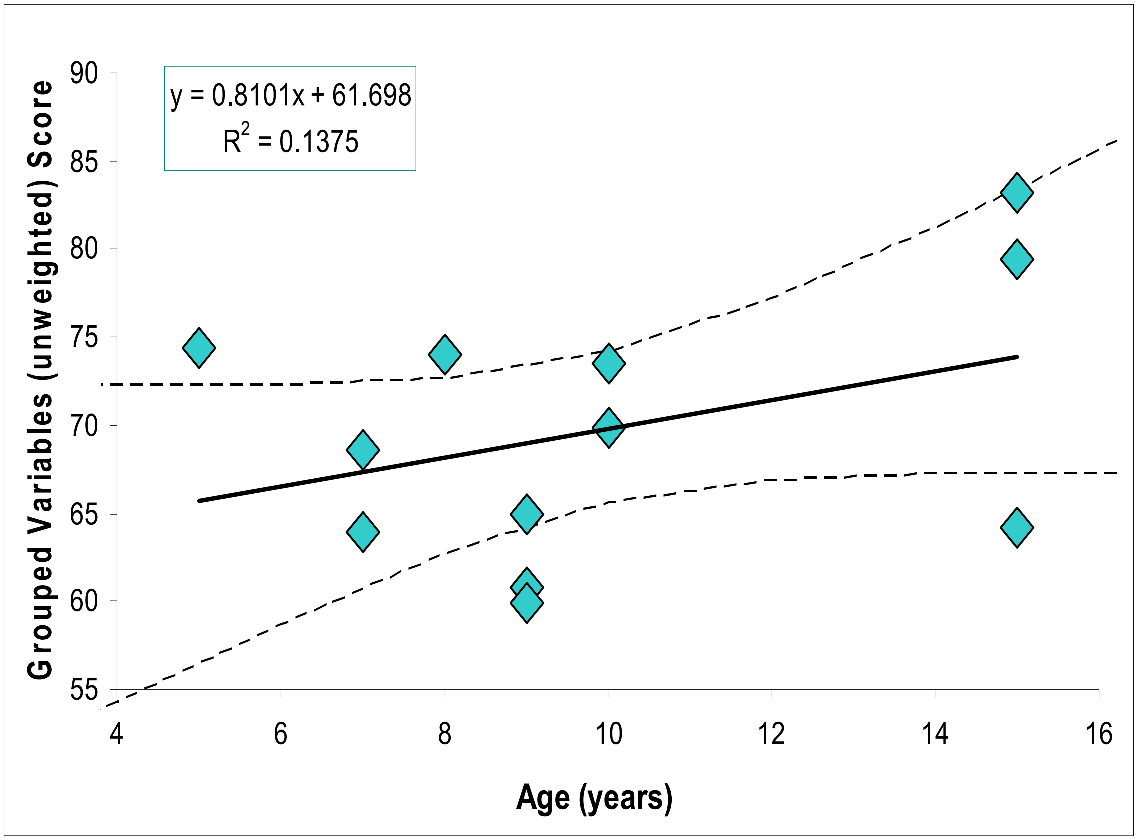

Figure 7. Relationship of restored grouped variables scores to marsh age. Scores can range from 0 to a maximum of 100 points. Dashed lines include the 95 percent confidence intervals. n=12.

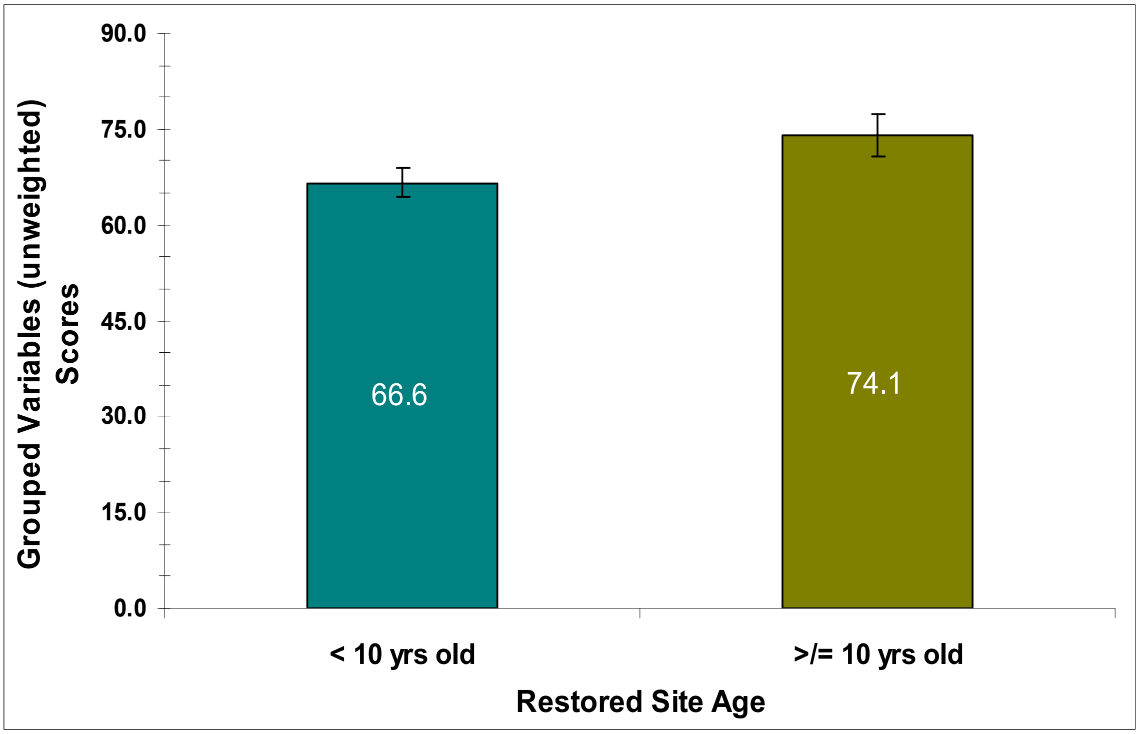

Figure 8. Grouped variables scores in younger and older restored marshes. Restored sites that are < 10 years old, n=5 and restored sites that are ≥ 10 years old, n=7.

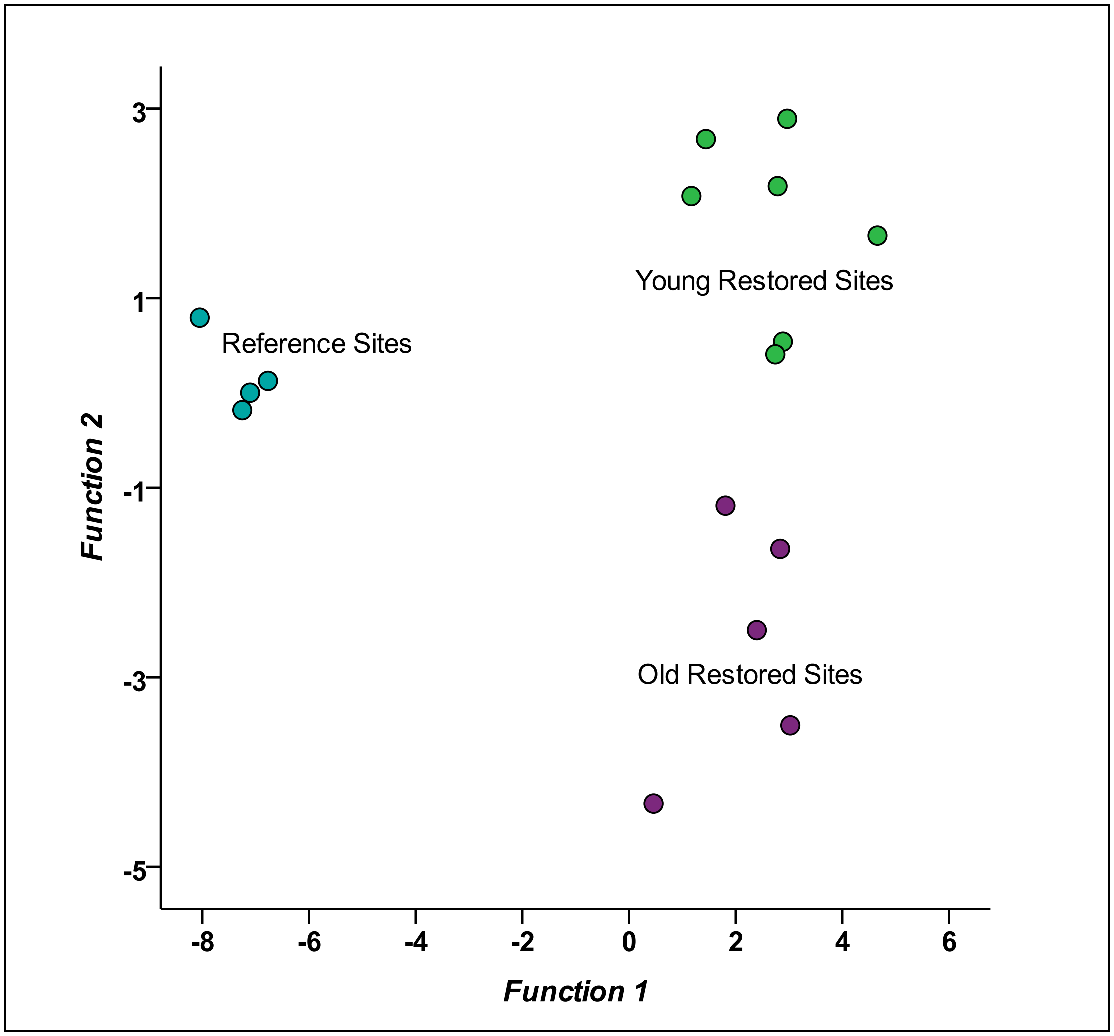

Figure 9. Principal component analysis revealing three wetland groups. Blue circles (●) represent reference wetland sites, n = 4. Green circles (●) represent young restored sites < 10 years old, n=5, and purple circles (●) represent old restored sites ≥ 10 years, n=6.

To further investigate the individual variables that were most influential for the PCA, I conducted a 1-way ANOVA where selected variables (number of invertebrates and percentage of fill volume for function 1, plant diversity, soil stability, and 2-4 cm belowground root volume for function 2) were the response variables and site type (reference, young restored, old restored) was the independent variable.

For function 1, both number of macrobenthos and percent fill were significantly different among habitat types, (ANOVA, number of macrobenthos $p < 0.001$, percent fill $p < 0.001$) (Figs. 10 and 11). Turkey HSD post-hoc tests revealed that reference sites had significantly more macrobenthos and less fill than both young and old restored sites.

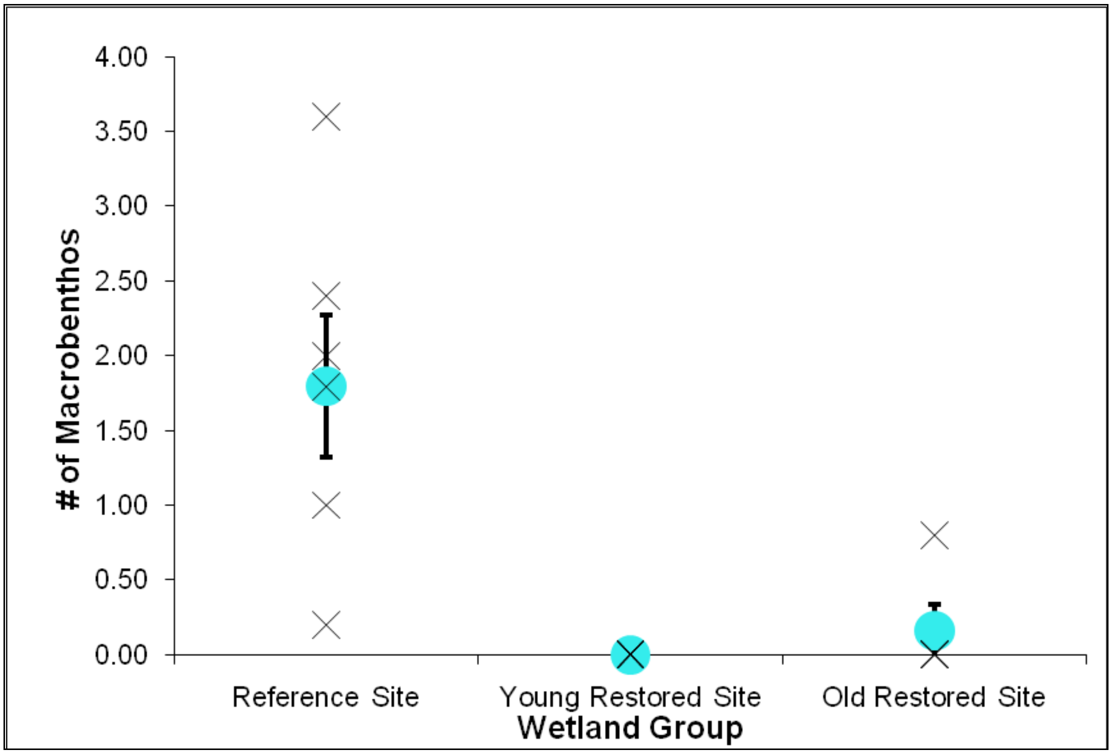

Figure 10. Comparison of number of macrobenthos values for reference and restored wetlands. Crosses (X) indicate individual values for each wetland. Circles (**O**) are mean values for each wetland group and error bars indicate one standard error of the mean for each wetland group. For reference wetlands, n=6, for young restored wetlands, n=7, for old restored wetlands, n=5.

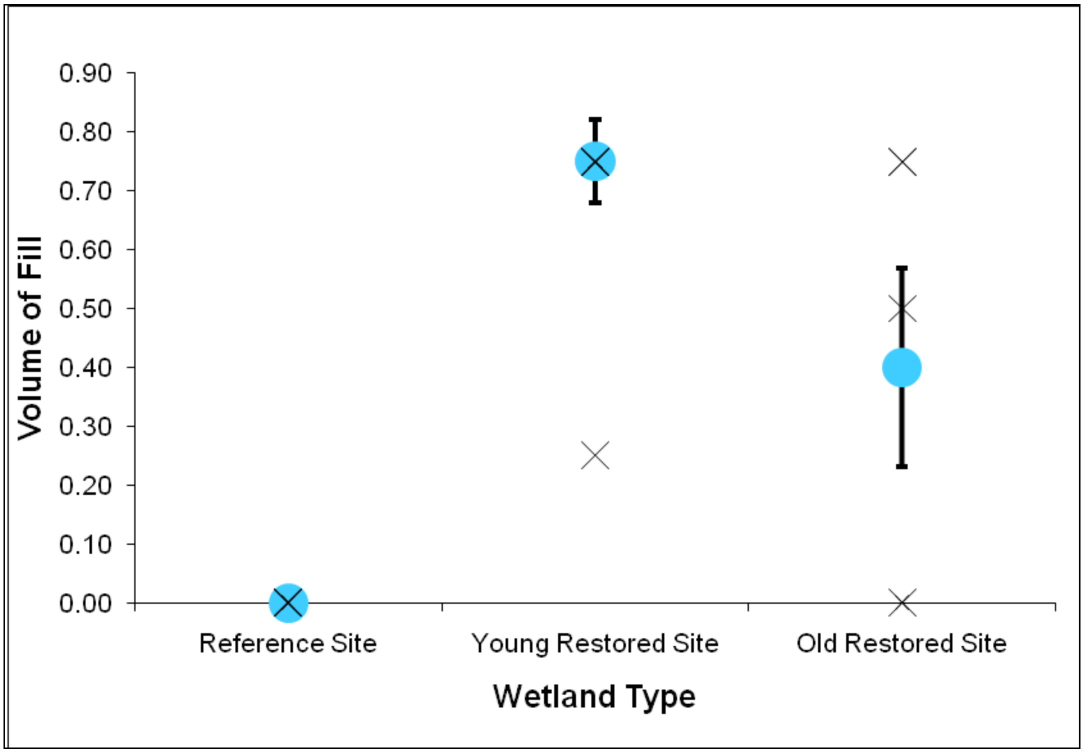

Figure 11. Comparison of percentage of fill volume values for reference and restored wetlands. Crosses (X) indicate individual values for each wetland. Circles (O) are mean values for each wetland group and error bars indicate one standard error of the mean for each wetland group. For reference wetlands, n=6, for young restored wetlands, n=7, for old restored wetlands, n=5.

For function 2, species diversity was significantly different among habitat types (ANOVA, p = 0.03) (Fig. 12). Turkey HSD post-hoc tests showed that older restored sites had significantly higher plant species diversity than young restored sites and reference sites. Neither soil stability nor shallow belowground root volume were significantly different among habitat types (ANOVA, soil stability p = 0.10, shallow belowground root volume p = 0.25) (Figs. 13 and 14).

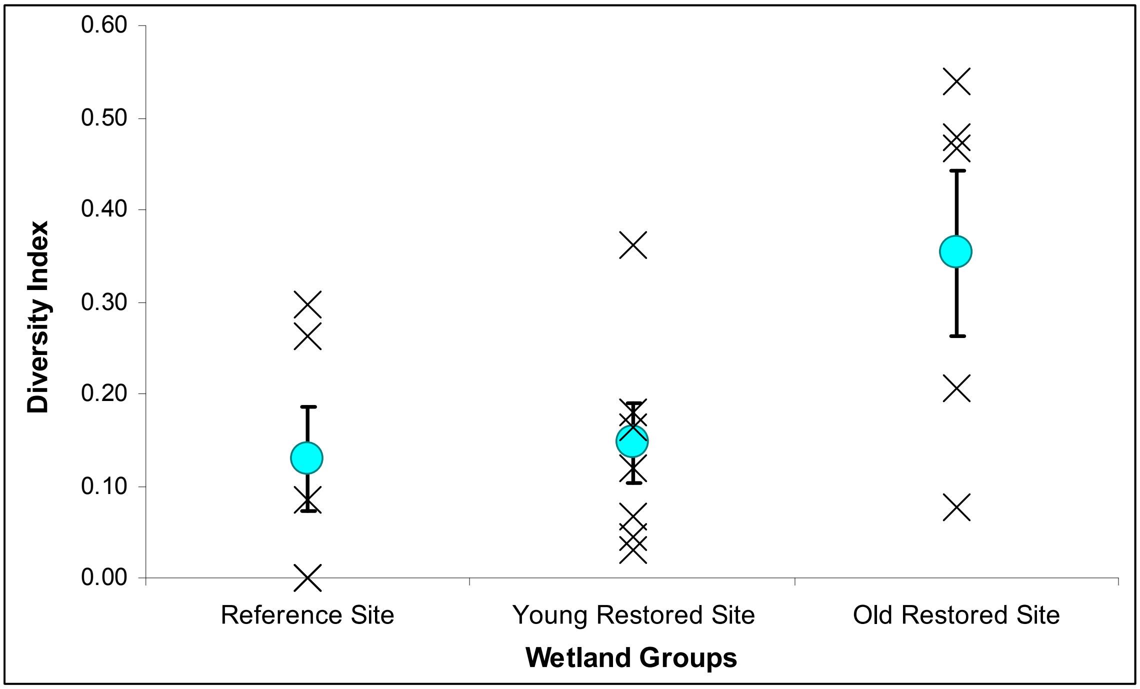

Figure 12. Comparison of plant diversity index values for reference and restored wetlands. Crosses (X) indicate individual values for each wetland. Circles (O) are mean values for each wetland group and error bars indicate one standard error of the mean for each wetland group. For reference wetlands, n=6, for young restored wetlands, n=7, for old restored wetlands, n=5.

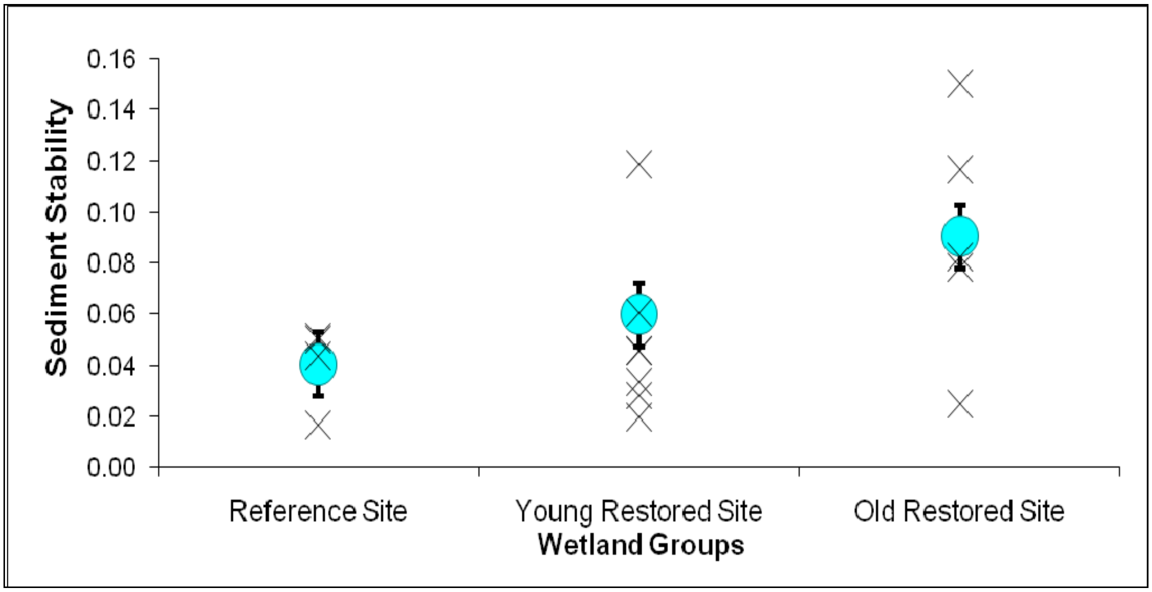

Figure 13. Comparison of soil stability values for reference and restored wetlands. Crosses (X) indicate individual site values for each wetland. Circles (O) are mean values for each wetland group and error bars indicate one standard error of the mean for each wetland group. For reference wetlands, n=6, for young restored wetlands, n=7, for old restored wetlands, n=5.

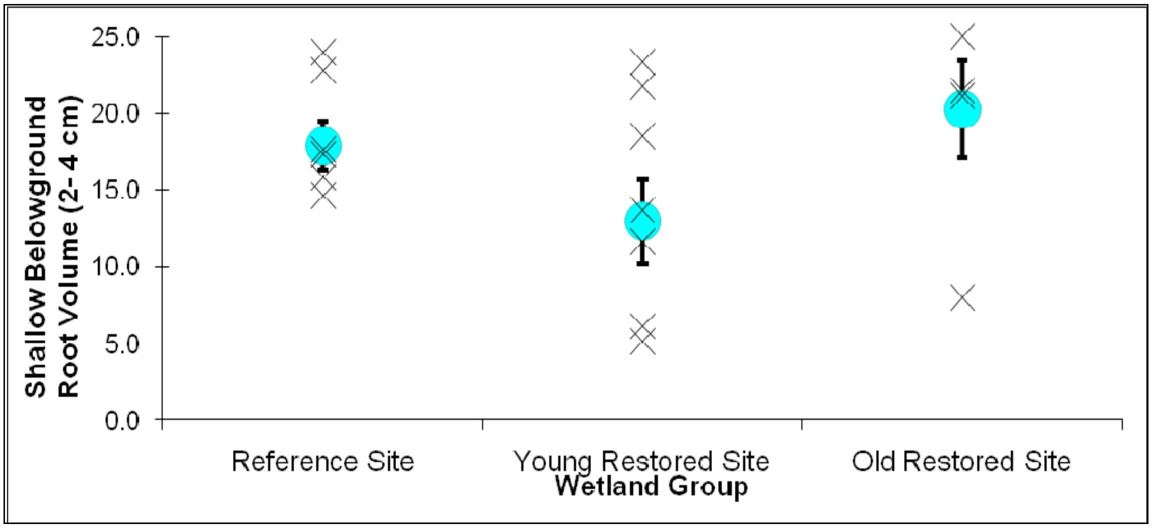

Figure 14. Comparison of shallow belowground root volume values for reference and restored wetlands. Crosses (X) indicate individual site values for each wetland. Circles (O) are mean values for each wetland group and error bars indicate one standard error of the mean for each wetland group. For reference wetlands, n=6, for young restored wetlands, n=7, for old restored wetlands, n=5.

The conclusion of this study resulted in the creation of the Galveston Bay Rapid Assessment Method, Galv-RAM (Appendix E). The Galv-RAM uses the 14 variables and scoring method 2 to provide an overall assessment of salt marsh ecological health as compared to reference marshes. This protocol can be utilized by various entities creating and restoring salt marshes around Galveston Bay for the purpose of ensuring the highest potential of ecological health and function.

DISCUSSION AND CONCLUSION

Score comparisons

This rapid assessment study determined that restored salt marshes in Galveston Bay had lower ecological health relative to reference salt marshes. Reference sites scored 18.8, 14.6, and 12.6 percent higher in the independent variables scores, grouped variables scores, and weighted grouped variables scores, respectively. Similar results were seen in California where health scores in reference wetlands were about 20% higher than in restored wetlands (2009).

Comparison of weighted grouped variables scores to unweighted grouped variables scores produced statistically similar outcomes, suggesting that the weighting factors were not a necessary component of the analysis; therefore, the weighted scores were not included in the final Galv-RAM protocol. The unweighted grouped variables scores integrated a multitude of variables and, similar to other RAM protocols (Collins et al. 2008), facilitated comparisons from different projects or from the same project over time. Therefore, the unweighted grouped variable score was the primary score evaluated in this discussion.

Scores were more variable in restored than in reference wetlands. The range of scores may reflect variations in ecological health and habitat conditions. The greater range may also be a reflection of differences in restoration goals, design and creation, and successional path. Because restored sites gradually change over time (Shafer and Streever 2000), incorporating restored sites of various ages could integrate a large amount of temporal heterogeneity into the restored site characterization. However, the regression and PCA analyses did not suggest that there was a strong effect of site age. Rather, the larger variance in restored sites might have resulted from spatial heterogeneity within the tidal marsh ecosystem in this region. Sacco et al. (1994) and Moy and Levin (1991) discussed how increased proximity of restored salt marsh sites to natural marsh areas accelerated community development. For this study many of the restoration sites were not in close proximity to a natural marsh area.

It is important to note that none of the reference sites achieved a perfect ecological health score. Reference sites are not necessarily unaffected, however they have not been directly altered (by restoration techniques) in recent history, therefore they were classified as relatively intact reference sites. Nonetheless, the relatively high scores observed for reference wetlands suggest that most reference wetlands have fairly high levels of ecological health.

The score criterion for this assessment was based on data collected over a single growing season. Wetland characteristics fluctuate from year to year based on weather and hydrological conditions. Thus, future use of the Galv-RAM protocol should occur during the growing season (June-August) for every application of the assessment.

The Galv-RAM scores were also calibrated based on results from the low marsh elevation. Although the methods can be repeated at other elevations, the reference site scores may be very different in high verses low elevations within reference marshes. So, expanding this to other elevations will require some additional calibration of the reference state.

Comparisons over time

As restored marshes age, they generally approach reference marsh conditions (Shafer and Streever 2000). However, restored wetland scores in this evaluation showed little increase with marsh age. The oldest restored sites I examined were 15 years old, but complete restoration of certain coastal salt marshes may take up to 50 years (Frenkel and Morlan 1991). It cannot be expected for newly restored marshes to quickly replicate all functions and values of natural sites rapidly (Haltiner et al. 1996). Furthermore, structural and functional processes can develop over different time scales, suggesting that restoration may require setting sequential, multi-step goals and long-term monitoring (Palmer et al. 1997). Implementation of the Galv-RAM on an annual basis will facilitate long-term monitoring by providing a standardized protocol that can be easily replicated by various investigators. Long-term monitoring will also aid in defining the progress of wetland restoration towards reference wetland conditions.

Categorical comparisons

Each of the four variable categories in the Galv-RAM scoring method provides unique insights into overall wetland health. By understanding the composition of the categorical scores within the grouped variables score, managers can modify and re-direct management plans to ensure they reach their specific goals for each of the categories necessary to maximize ecological health.

Landscape/site characteristic scores were significantly higher in reference than in restored sites, primarily due to the amount of fill added. Ten of the 12 restored wetlands received high inputs of fill during restoration, while all six of the reference sites had no fill added.

Wildlife habitat scores were significantly higher in reference than in restored sites, primarily due to the number of macrobenthos. Wetlands are well known for their ability to function as a wildlife habitat (Kentula 2002), but if restoration efforts address fauna, they generally focus on a few commercially important or charismatic species, but food webs remained disjointed, suggesting that functions within the two marsh types were not equivalent (NOAA 2000). It is often assumed that the biological communities will reestablish following restoration of plant communities, though this assumption is largely unverified in the field (MacArthur 1965; Palmer et al. 1997). My data do not support this assumption, as wildlife habitat scores were lower in restored sites.

Soil scores were significantly higher in reference than in restored sites, primarily due to shallow and deep belowground root volume. If belowground biomass is low, then a marsh with high aboveground biomass might quickly become open water when the plants senesce in the winter (Mendelssohn et al. 1981). Stauffer and Brooks (1997) demonstrated that the addition of organic material to created wetland soils assisted the development of vegetation and thus increased accumulation of belowground biomass. This assumption promotes the development of increased organic matter at depth.

Hydrology was the only category where differences between reference and restored site scores were not significant. The hydrology category assessed the water movements within the marsh as well as tidal movements in and out of the marsh. Although the similar scores suggest that restoration was more or less successful, many of the reference sites had low hydrology scores due to the presence of riprap or geotubes that influenced tidal flow. Due to the highly developed nature of Galveston Bay, I was unable to locate reference wetlands with unmodified hydrology for comparison to restored sites.

Variable influences on wetland types

Differences between the reference and restored sites (regardless of age) were most strongly related to the number of macrobenthos and the amount of fill. Macrobenthos were observed in five of the six reference sites, but only in one of the 12 restored sites. Spatial distribution of benthic invertebrates is heterogeneous, so high variability was expected even within various habitat types. However, it is likely that dispersal limitations and lower habitat suitability have restricted invertebrate colonization of the restored sites (Armitage and Fong 2004).

Fill was another characteristic that distinguished reference and restored sites. Ten of the 12 restored sites had some fill, whereas none of the reference sites had added fill material. Fill typically has less organic matter than soils in reference wetlands (Langis et al. 1991). Inadequate amounts of organic matter in soils can limit nutrient storage, subsequently lowering plant growth rates (Pacific Estuarine Research Laboratory 1990). Furthermore, placement of fill may harm flora and fauna by releasing contaminants into the water column (Johnston 1981).

Differences between young and old restored sites were most strongly related to plant diversity, soil stability, and shallow (2-4 cm) belowground biomass. Within the low marsh where the study was conducted, vegetation diversity was low because most marshes were planted with a single species, *S. alterniflora.* Higher diversity indices were seen in the older restored marshes, where more time had elapsed for the recruitment of new species.

Older restored marshes tended to have harder soil than both younger restored sites and reference marshes, though the differences between marsh types were not significant. A study done in restored marshes in Texas showed similar results in restored marshes that used dredge material with high clay-silt fractions. When this material is continually exposed to drying, it will compact for years following material placement (Shafer and Streever 2000).

Although soil stability is an important variable to measure, using the pocket penetrometer may not have been the proper tool. The outcome of values and score ranges from the penetrometer were minute and therefore may not have been sensitive enough to subtle changes in the various sites.

Older restored sites also had more shallow (2-4 cm) belowground biomass than at newer sites, though the differences between marsh types were not significant. Some studies have shown that belowground biomass requires 3–5 years to reach natural marsh quantities (Broome et al. 2000), but my study suggests that it may take even longer (more than 10 years) for restored sites to reach comparable reference values.

Although soil stability and shallow belowground biomass contributed to the separation between old and young restored marshes in the PCA analysis, these variables did not significantly vary among habitat types. This suggests that differences between older and younger restored sites cannot be attributed to single characteristics alone – they must be considered together. The Galv-RAM facilitates the identification of suites of characteristics that act in concert as restored marshes develop.

Comparison of mean percent vegetation cover values for each wetland groups were not significant and was not strongly related to either function in the PCA, concluding that all sites are similar at any age of this variable. This suggests that permit requirements that regularly monitor only plant cover as an indicator of health may not detect critical differences.

Importance

Long-term goals and evaluations are rarely integrated into wetland mitigation. Generally, restoration monitoring only lasts a few years (Mitsch and Wilson 1996). However, the Galv-RAM will streamline monitoring protocols and facilitate long-term examination of restored wetland health. Based on plant cover data, all restoration sites were successful, given that permits usually only require the establishment of plant cover. However, the Galv-RAM protocol revealed important differences between reference and restored sites, including number of macrobenthos, percentage of fill volume and plant diversity. Therefore, the Galv-RAM is a better assessment of restored wetland health than a simple percent cover assessment. As a result, it would be better for permits to stipulate a RAM score for permit compliance rather than just a plant cover score.

Furthermore, the Galv-RAM can promote public understanding of these critical habitats by converting complex ecosystem features into an easily understood “grade” on a scale of 0-100. The “grade” will allow restoration managers to educate the public on the health of these ecosystems, leading to an increase in interest, awareness, and participation by the local community and benefiting long-term restoration and management efforts.

Adaptive management allows restoration managers to make ongoing alterations to management decisions resulting in increased ecological health. RAM assessments will facilitate realistic re-evaluations of what can be accomplished at the restored site (Hackney 2000). Conducting annual RAM evaluations will provide updated measurements of ecosystem development and allow managers to evaluate the progress towards restoration goals or targets (Steyer and Llewellyn 2000).

Creation of the Galveston Bay Rapid Assessment Method (Galv-RAM) (Appendix E) provides a standardized protocol for assessing local salt marsh restoration success. Although many restored tidal marine wetlands in this region do not meet reference marsh conditions, the Galv-RAM is an effective, timely, and useful management tool that will enable management agencies to identify and address restoration shortcomings. Since the Galv-RAM takes minimal field time requires little taxonomic expertise, and provides an extensive overview of many marsh functions, this efficient protocol can lead to significant cost savings and increase the number of marshes agencies can assess (Fennessy et al. 2009). Furthermore, the Galv-RAM is quantitative, strengthening management decisions intended to improve ecosystem health (Redmond 2000), which should be the ultimate goal for all restoration managers. Goals of coastal ecological restoration should center around a future where coastal wetland systems, formed as a patchwork of preserved, natural, created, and restored wetlands will function as an integrated healthy whole (Redmond 2000).

LITERATURE CITED

Armitage, A. R. and P. Fong. 2004. Gastropod colonization of a created coastal wetland: potential influences of habitat suitability and dispersal ability. Restoration Ecology **12**(3):391-400.

Armitage, A. R., S. M. Jensen, J. E. Yoon and R. F. Ambrose. 2007. Wintering shorebird assemblages and behavior in restored tidal wetlands in southern California. Restoration Ecology **15**(1):139-148.

Balzano, S., A. Ertman, L. Brancheau and B. Smejkal. 2002. Creating an indicator of wetland status (quantity and quality): freshwater wetland mitigation in New Jersey. New Jersey Department of Environmental Protection, Trenton, NJ.

Bart, D. and J. M. Hartman. 2009. Environmental constraints on early establishment of *Phragmites australis* in salt marshes. Wetlands **22**(2):201-213.

Blinn, D., S. Halse, A. Pinder and R. Shiel. 2004. Diatom and micro-invertebrate communities and environmental determinants in the western Australian wheatbelt: a response to salinization. Hydrobiologia **528**(1):229-248.

Broome, S., C. Craft and W. Toomey. 2000. Soil organic matter (SOM) effects on infaunal community structure in restored and created tidal marshes. Pages 737-747 in M. P. Weinstein and D. A. Kreeger, editors. Soil organic matter (SOM) effects on infaunal community structure in restored and created tidal marshes. Springer, New York.

Broome, S. W. 1989. Creation and restoration of tidal wetlands in the southeastern United States. Pages 37-72 in J. A. Kusler and M. E. Kentula, editors. Wetland creation and restoration: The status of the science. Vol.1: Regional overview. EPA/600/3-89/038. USEPA, Washington DC.

California Wetlands Monitoring Group. 2009. Using CRAM (California Rapid Assessment Method) to assess wetland projects as an element of regulatory and management programs**:**46 pgs.

Carlisle, B., C. Wigand, M. Carullo, D. Fillis, R. McKinney, et al. 2004. DRAFT: Rapid assessment method for characterizing the condition of New England salt marshes (Version 1). Massachusetts Office of Coastal Zone Management and US Environmental Protection Agency Atlantic Ecology Division, Boston, MA.

Cole, C. A. 2002. The assessment of herbaceous plant cover in wetlands as an indicator of function. Ecological Indicators **2**(3):287-293.

Collins, J. N., E. D. Stein, M. Sutula, R. Clark, A. E. Fetscher, et al. California Wetlands Monitoring Workgroup 2008. California Rapid Assessment Method (CRAM) for wetlands and riparian areas (website). www.cramwetlands.org. Retrieved January 2, 2010.

Coultas, C. L. and Y. Hsieh, Eds. 1997. Ecology and management of tidal marshes: a model from the Gulf of Mexico. St. Lucie Press, Delray Beach, FL.

Dahl, T. E. and C. E. Johnson. 1991. Status and trends of wetlands in conterminous United States, mid-1970's to mid-1980's. USFWS, Washington, DC.

EPA. 1994. Coastal and shoreline erosion action agenda for the Gulf of Mexico. 800-B-94-003. USEPA, Stennis Space Center, MS.

Fearnley, S. 2009. The soil physical and chemical properties of restored and natural back-barrier salt marsh on Isles Dernieres, Louisiana. Journal of Coastal Research **24**(1):84-94.

Fennessy, M. S., A. D. Jacobs and M. E. Kentula. 2004. Review of rapid methods for assessing wetland condition EPA/620/R-04/009. USEPA, Washington, DC.

Fennessy, M. S., A. D. Jacobs and M. E. Kentula. 2009. An evaluation of rapid methods for assessing the ecological condition of wetlands. Wetlands **27**(3):543-560.

French, J. R. 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, U.K. Earth Surface Processes and Landforms **18**(1):63-81.

Frenkel, R. E. and J. C. Morlan. 1991. Can we restore our salt marshes? Lessons from the Salmon River, Oregon. Northwest Environmental Journal **7**:119-135.

Gedan, K. B., B. R. Silliman and M. D. Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science **1**(1):117-141.

Goldsmith, F. B., C. M. Harrison and A. J. Morton. 1986. Description and analysis of vegetation. Pages 437-524 in P. D. Moore and S. B. Chapman, editors. Description and analysis of vegetation. Blackwell Scientific Publications, Boston, MA.

Gutrich, J. J. and F. J. Hitzhusen. 2004. Assessing the substitutability of mitigation wetlands for natural sites: estimating restoration lag costs of wetland mitigation. Ecological Economics **48**(4):409-424.

Hackney, C. T. 2000. Restoration of coastal habitats: expectation and reality. Ecological Engineering **15**(3-4):165-170.

Haltiner, J., J. Zedler, K. Boyer, G. Williams and J. Callaway. 1996. Influence of physical processes on the design, functioning and evolution of restored tidal wetlands in California (USA). Wetlands Ecology and Management **4**(2):73-91.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, et al. 1996. A global analysis of root distributions for terrestrial biomes. Oecologia **108**(3):389-411.

Johnston, S. A. 1981. Estuarine dredge and fill activities: a review of impacts. Environmental Management **5**(5):427-440.

Kennish, M. J., Ed. 1997. Practical handbook of estuarine and marine pollution. CRC Marine Science Series. CRC Press, Boca Raton, FL.

Kennish, M. J. 2001. Coastal salt marsh systems in the U.S: a review of anthropogenic impacts. Journal of Coastal Research **17**(3):731-748.

Kentula, M. E. 2002. Restoration, creation, and recovery of wetlands: wetland restoration and creation. Water Supply Paper 2425. United States Geological Survey, USEPA, Corvallis, OR.

Konisky, R. A., D. M. Burdick, M. Dionne and H. A. Neckles. 2006. A regional assessment of salt marsh restoration and monitoring in the Gulf of Maine. Restoration Ecology **14**(4):516-525.

Kunza, A. and S. Pennings. 2008. Patterns of plant diversity in Georgia and Texas salt marshes. Estuaries and Coasts **31**(4):673-681.

Langis, R., M. Zalejko and J. B. Zedler. 1991. Nitrogen assessments in a constructed and a natural salt marsh of San Diego Bay. Ecological Applications **1**(1):40-51.

Lewis, R. R., Jr. 1990. Wetlands restoration/creation/enhancement terminology: Suggestions for standardization. Pages 417-423 in J. A. Kusler and M. A. Kentula, editors. Wetlands restoration/creation/enhancement terminology: Suggestions for standardization. Island Press, Washington, DC.

MacArthur, R. H. 1965. Patterns of species diversity. Biology Review **40**:510-533.

Mack, J. J. 2000. ORAM version 5.0 Quantitaive score calibration. State of Ohio, Environmental Protection Agency, Columbus, OH.

Mendelssohn, I. A., K. L. McKee and W. H. Patrick, JR. 1981. Oxygen deficiency in *Spartina alterniflora* roots: metabolic adaptation to anoxia. Science **214**(4519):439-441.

Mendelssohn, I. A. and J. T. Morris. 2002. Eco-physiological controls on the productivity of *Spartina alterniflora* Loisel. Pages 59-80 in M. P. Weinstein and D. A. Kreeger, editors. Eco-physiological controls on the productivity of *Spartina alterniflora* Loisel. Kluwer Academic Publishers, New York.

Minello, T., R. Zimmerman and R. Medina. 1994. The importance of edge for natant macrofauna in a created salt marsh. Wetlands **14**(3):184-198.

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**(1):77-83.

Moulton, D. W., T. E. Dahl and D. M. Dall. 1997. Texas coastal wetlands: status and trends, mid-1950s to early 1990s. USFWS, Albuquerque, NM.

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

National Research Council. 1992. Restoration of aquatic ecosystems: science, technology, and the public. National Research Council. National Academy Press, Washington, D.C.

NOAA. 2000. Trophic linkages in created and natural salt marshes in southern California http://www.nmfs.noaa.gov/habitat/restoration/projects_programs/research/funded_projects/4.html. Retrieved May 17, 2010.

O'Brien, D. L., A. Jacobs, M. R. Berman, T. Rudnicky, E. McLaughlin, et al. 2007. Refinement and validations of a multi-level assessment method for Mid-Atlantic tidal wetlands. USEPA, Philadelphia.

Pacific Estuarine Research Laboratory. 1990. A manual for assessing restored and natural coastal wetlands with examples from southern California: LaJolla, California. Report Number T-CSGCP-021. California Sea Grant, 105 p.

Palmer, M. A., R. F. Ambrose and N. L. Poff. 1997. Ecological theory and community restoration ecology. Restoration Ecology **5**:291-300.

Pennings, S. C., V. D. Wall, D. J. Moore, M. Pattanayek, T. L. Buck, et al. 2009. Assessing salt marsh health: a test of the utility of five potential indicators. Wetlands **22**(2):406-414.

Picman, J., M. L. Milks and M. Leptich. 1993. Patterns of predation on passerine nests in marshes: effects of water depth and distance from edge. Auk **110**(1):89-94.

Port of Houston Authority. 2009. Wetlands of the Galveston Bay System. http://www.betterbay.org/html/newspubs_galbay.html. Retrieved August 22, 2009.

Posey, M., T. Alphin and C. Powell. 1997. Plant and infaunal communities associated with a created marsh. Estuaries and Coasts **20**(1):42-47.

Redmond, A. M. 2000. Dredge and fill regulatory constraints in meeting the ecological goals of restoration projects. Ecological Engineering **15**(3-4):181-189.

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

Seybold, C. A., M. J. Mausbach, D. L. Karlen and H. H. Rogers. 1998. Quantification of soil quality. Editors R. Lal, J. M. Kimble, R. F. Follett and B. A. Stewart. CRC Press, Boca Raton, FL. 387-404.

Shafer, D. J., B. Herczeg, D. W. Moulton, A. Sipocz, K. Jaynes, et al. 2002. Regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of northwest Gulf of Mexico tidal fringe wetlands. ERDC/EL TR-02-5. USACE, Washington, DC.

Shafer, D. J. and W. J. Streever. 2000. A comparison of 28 natural and dredged material salt marshes in Texas with an emphasis on geomorphological variables. Wetlands Ecology and Management **8**(5):353-366.

Stauffer, A. and R. Brooks. 1997. Plant and soil responses to salvaged marsh surface and organic matter amendments at a created wetland in central Pennsylvania. Wetlands **17**(1):90-105.

Steyer, G. D. and D. W. Llewellyn. 2000. Coastal Wetlands Planning, Protection, and Restoration Act: a programmatic application of adaptive management. Ecological Engineering **15**(3-4):385-395.

Turner, R. E., E. M. Swenson, C. S. Milan, J. M. Lee and T. A. Oswald. 2004. Below-ground biomass in healthy and impaired salt marshes. Ecological Research **19**(1):29-35.

USACE. 2008. Compensatory mitigation for losses of aquatic resources. 33 CFR Parts 325 and 332. April 10, 2008. EPA, Washington, DC.

USDA. 1998. Soil quality indicators: pH. Natural Resources Conservation Service, Washington, DC.

Weis, J. S. and P. Weis. 1998. Effects of CCA wood docks and resulting boats on bioaccumulations of contaminants in shellfish resources: final report to DEP. New Jersey Department of Environmental Protection, Trenton, NJ.

Whigham, D. F. 1999. Ecological issues related to wetland preservation, restoration, creation and assessment. Science of the Total Environment **240**(1-3):31-40.

White, W. A., T. A. Trembly, R. L. Waldinger and T. R. Calnan. 2006. Status and trends of wetland and aquatic habitats on Texas barrier islands coastal bend. GLO Contract No. 05-041. University of Texas at Austin.

Zedler, J. and S. Kercher. 2004. Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Critical Reviews in Plant Sciences **23**(5):431-452.

Zedler, J. B. 1993. Canopy architecture of natural and planted cordgrass marshes: selecting habitat evaluation criteria. Ecological Applications **3**(1):123-138.

Zedler, J. B. and J. C. Callaway. 1999. Tracking wetland restoration: do mitigation sites follow desired trajectories. Restoration Ecology **7**(1):69-73.

Zedler, J. B. and J. C. Callaway. 2000. Evaluating the progress of engineered tidal wetlands. Ecological Engineering **15**:211-225.

Zedler, J. B. and R. Lindig-Cisneros. 2002. Functional equivalency of restored and natural salt marshes. 565-582 in M. P. Weinstein and D. A. Kreeger, editors. Functional equivalency of restored and natural salt marshes. Springer, New York, NY.

APPENDIX A

DATASHEETS

Site Information Datasheet
Galveston Bay Rapid Assessment Method

Version 1.0 April 2010

Site # ________ **Site Name** ________________________ **Date** ____/___/_____
Field Crew____ **Crew Leader Initials** _
Wetland Type ___________________________ **Reference or Assessment Site (circle one)**
Watershed ______________________________ **Lat/Long** ______________________
Photos: __________________________ **Wetland Size (ha)**________________

Barriers to Landward Migration:

Man-made Structures:

Tidal Restrictions:

Fill (dumped soil, debris, garbage):

_____ No fill in assessment
_____ 1-25 % of AA covered in fill
_____ 26-50 % of AA covered in fill
_____ 51-75 % of AA covered in fill
_____ > 76 % of AA covered in fill

Hydrological modifications:

_____ 0 % not impacted
_____ 1-25 % of AA covered in fill
_____ 26-50 % of AA covered in fill
_____ 51-75 % of AA covered in fill
_____ > 76 % of AA covered in fill

Vegetation Plots Datasheets

Galv-RAM

Site # ________ Site Name ________________________ Date ____/___/_____

Vegetation Zone: ________________________

Cover Estimates in 8 vegetation plots (1x1 meter plots)										
			Plot Number							
C	**I**	**Identified Species**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

C=Collected, I = Identified

Invasive Species

Species Name	**% in Veg. Plot**

Macrobenthos Datasheets

Galv-RAM

Site #:	**Site Name:**	**Date:**
Field Crew:		**Vegetation Zone:**

			Plant Fragments		**Water Samples**		
Plot # and Location	**# of Macrobenthos**	**Soil stability**	**2-4 cm Belowground**	**25-27 cm Belowground**	**pH**	**Salinity**	**Temperature**

APPENDIX B

GALV-RAM SCORE CRITERIA

Version 1.0 April 2010

Number of barriers observed	Score
0	4
1	3
2	2
3	1
≥ 4	0

Historical Information	Score
No fill in assessment area	4
1 - 24 % of fill in AA	3
25% - 49% of fill in AA	2
50% - 74% of fill in AA	1
≥ 75% of AA of fill in AA	0

Number of structures observed	Score
0	4
1	3
2	2
3	1
≥ 4	0

Number of restrictions observed	Score
0	4
1	3
2	2
3	1
≥ 4	0

Percent of hydrological impact	Score
0% not impacted	4
1 - 25% impacted	3
26-50% impacted	2
51 - 75% impacted	1
76 - 100% impacted	0

Percent plant cover	Score
≥ 61.3 %	4
46.0 - 61.2%	3
30.7 - 46.0%	2
15.4 - 30.7%	1
0 - 15.3 %	0

Number of macrobenthos	Score
≥ 2.5	4
1.9 - 2.4	3
1.3-1.8	2
0.63 - 1.3	1
0 - 0.62	0

Vegetation diversity index	Score
≥ 0.11	4
0.08 - 0.10	3
0.05 - 0.07	2
0.03 - 0.04	1
0 - 0.02	0

% Cover of Invasive species	Score
0%	4
1-25%	3
26-50%	2
51-75%	1
76-100%	0

Soil stability (psi)	Score
< 0.05	4
0.051 - 0.06	3
0.061 – 0.07	2
0.071 - 0.08	1
> 0.081	0

Shallow (2-4 cm) belowground root volume (mL)	Score
> 22.0	4
16.5- 21.9	3
11.0 - 16.4	2
5.5 - 10.9	1
0.0 – 5.4	0

Deep (25-27 cm) belowground root volume (mL)	Score
> 15.2	4
11.4 - 15.1	3
7.6 - 11.3	2
3.8 - 7.5	1
0 - 3.7	0

Pore water salinity (ppt)	Score
> 48.5	0
42.0 - 48.4	1
35.4 - 41.9	2
29.1 - 35.5	3
25.8 - 29.0	4
19.3 - 25.7	3
12.9 - 19.2	2
6.4 - 12.8	1
0 - 6.3	0

Pore water pH	Score
> 12.6	0
11.0 - 12.5	1
9.5 - 10.9	2
7.9 - 9.4	3
6.2 - 7.8	4
4.7 - 6.1	3
3.1 - 4.6	2
1.6 - 3.0	1
0 - 1.5	0

Overall Score Criteria

Site Number: **Site Name:** **Date:**

Variables, Categories, and Metrics		**Scores**	**Comments:**
Landscape/Site Characteristics	**Raw #**		
L1. Barriers to Landward Migration			
L2. Fill			
L3. Man-made Structures			
(∑(L1, L2, L3)) = **Landscape Score**		Score	
Hydrology	**Raw #**		
H1. Tidal Restrictions			
H2. Hydrological Modifications			
(∑(H1, H2)) = **Hydrology Score**		Score	
Wildlife Habitat	**Raw #**		
W1. Percent Plant Cover			
W2. Macrobenthos			
W3. Vegetation Diversity			
W4. Percent Invasive			
(∑(W1, W2, W3, W4)) = **Wildlife Habitat Score**		Score	
Soil	**Raw #**		
S1. Soil stability			
S2. 2-4 cm Plant Fragments			
S3. 25-27 cm Plant Fragment			
S4. Pore Water Salinity			
S5. Pore pH		Score	
(∑(S1, S2, S3, S4, S5)) = **Soil Score**			

Method 1: Independent Variables score = $\frac{\sum(\text{Land} + \text{Hydrology} + \text{Wildlife} + \text{Soil})}{\sum(I_{max}) = 56} \times 100$

Method 2: Grouped Variables score = $\frac{\sum((L/3) + (H/2) + (W/4) + (S/5))}{\sum(G_{max}) = 16} \times 100$

Method 3: Weighted Grouped Variables score

$$= \frac{(\sum([(L/3)*2.5] + [(H/2)*1.4] + [(W/4)*1.9] + [(S/5)*1.6]) \quad /4)}{\sum(WF_{max}) = 7.4} \times 100$$

GALV-RAM FINAL SCORE = ______________________________

APPENDIX C

RANKING OF SALT MARSH RESTORATION CATEGORIES

The purpose of this ranking is to calibrate a rapid assessment method (RAM) for Galveston Bay and I am drawing on your expertise to weigh the factors. This RAM is a standardized, cost-effective field sampling technique for assessing the overall health of tidal wetlands. Please rank the following characteristics between 1 (least important) to 4 (most important) based on their importance to wetland restoration. Categories with higher weightings are determined to be more essential for a wetland to achieve natural wetland functioning than categories with a lower weighting factor.

1. **Hydrology**

    Hydrology is being characterized based on:

        Tidal Restrictions (i.e. riprap, geotubes)
        Hydrological Modifications (i.e. ditches, channels)

    ____

2. **Landscape/Site Characteristics**

    Landscape/Site Characteristics are being characterized based on:

        Barriers to landward migration (i.e. levees, roads)
        Fill percentage volume
        Presence of man-made structures

    ____

3. **Wildlife Habitat**

    Wildlife Habitat is being characterized based on:

        Vegetation cover
        Vegetation diversity
        Macrobenthos
        Invasive species present

    ____

4. **Soils**

    Soil is being characterized based on:

        Soil stability
        Belowground root volume (plant fragments at 2-4cm and 25-27cm belowground)
        Pore water (soil) salinity
        Pore water pH

    ____

APPENDIX D

SITE SCORES

	Reference Site #					
Independent Variables	5	6	7	16	17	18
1. Barriers to Landward Migration	3	4	4	3	3	3
2. Percent of Fill Volume	4	4	4	4	4	4
3. Man-made Structures	4	4	4	4	4	4
4. Tidal Restrictions	4	4	3	4	4	3
5. Hydrological Modifications	4	4	1	2	2	3
6. Vegetation Cover	4	4	4	3	3	3
7. Macrobenthos	3	0	1	2	4	3
8. Vegetation Diversity	4	3	4	0	0	0
9. Invasive Species	4	4	4	4	4	4
10. Soil Stability	-	-	4	4	4	4
11. 2-4 cm Plant Fragments	2	4	2	3	3	4
12. 25-27 cm Plant Fragment	1	0	4	4	4	2
13. Pore Water Salinity	-	-	3	4	4	4
14. Pore pH	4	4	4	4	4	4

	Restored Site #											
Independent Variables	1	2	3	4	8	9	10	11	12	13	14	15
1. Barriers to Landward Migration	3	3	3	3	3	3	3	3	4	4	3	4
2. Percent of Fill Volume	0	0	0	0	4	4	0	0	0	0	1	2
3. Man-made Structures	4	4	4	4	4	4	4	4	4	4	4	3
4. Tidal Restrictions	4	4	2	4	3	4	4	4	4	4	4	3
5. Hydrological Modifications	4	4	3	3	3	3	0	0	3	1	2	3
6. Vegetation Cover	2	1	4	3	4	4	4	4	4	4	4	4
7. Macrobenthos	0	0	0	0	1	0	0	0	0	0	0	0
8. Vegetation Diversity	4	4	4	4	4	3	1	1	4	4	4	2
9. Invasive Species	4	4	4	4	4	4	4	4	4	4	4	4
10. Soil Stability	4	1	3	0	0	4	4	4	1	4	0	4
11. 2-4 cm Plant Fragments	1	3	0	2	4	3	4	3	4	2	1	3
12. 25-27 cm Plant Fragment	4	4	3	1	2	2	2	1	0	0	0	2
13. Pore Water Salinity	2	2	2	2	4	4	3	3	4	4	3	4
14. Pore pH	4	3	4	4	4	4	4	4	4	4	4	4

APPENDIX E

GALVESTON BAY RAPID ASSESSMENT METHOD

Galv-RAM

May 2010 edition

Program Contacts:

Lindsey Staszak
Lindsey.staszak@gmail.com

TABLE OF CONTENTS

Page

METHOD DEVELOPMENT

This assessment was developed utilizing a previously established field method called the Mid-Atlantic Tidal Fringe Wetland Assessment (MATFWA). This method was chosen for its non-invasive field emphasis and evaluation of numerous ecosystem-level variables that are important to wetland health. I am thankful to the MATFWA, New England Rapid Assessment Method (NERAM), the California Rapid Assessment Method (CRAM) and the New Jersey Rapid Assessment Method from which I borrowed some of their metrics, variables, and indices of development.

This method provides an “on the spot” evaluation of salt marshes in Galveston Bay based on current environmental conditions and provides a standard protocol for comparing managed, natural, and restored marshes. This protocol will continue to evolve and develop with increased usage; it must be reviewed and updated as more information is discovered about the wetlands in our area. Rather than expecting newly restored marshes to quickly replicate the functions and values of natural sites (which evolve over several years), it is more important to assess whether or not the appropriate “template” exists to allow the restored sites to develop the desired characteristics over an appropriate time frame.

The development of a RAM for Galveston Bay tidal fringe wetlands will maximize the efficiency of wetland creation and restoration by providing indices of functional equivalency and biotic integrity relative to reference wetlands. Furthermore, monitoring programs using RAMs will help habitat managers evaluate the progress of restoration efforts.

This method explains how to measure four variables that have been shown through other RAMs to provide useful information about wetland health. The variables are: Landscape/Site Characteristics, Hydrology, Wildlife Habitat, and Soil. Each variable is given a score of 0 (least ecologically healthy) to 4 (most ecologically healthy). The four variable scores are summed and then divided by the potential maximum points (16) and multiplied by 100. The maximum composite “health” score is 100.

A. Time and Effort Involved

The time needed to sample each site, depends on the number of people in the field, their knowledge of wetlands and site conditions. An experienced crew can complete a normal site evaluation in approximately 3 hours.

B. Experience and Qualifications Needed

The Galv-RAM should be completed by individuals with field experience in wetlands and a working knowledge of the data collection methods. Knowledge should include the ability to identify common wetland fauna and flora and a familiarity with reference wetland conditions.

FIELD PREPARATION

A. Landowners Permission

Permission should be obtained before access to any private property. Often, if contact can be made with property owner, then access is readily granted.

B. Equipment List

-Global positing system (GPS)
-Map
-Datasheets
-Clipboard
-Pencils
-Field guide to tidal wetland flora and fauna
-Shovel
-60 cc syringe
-500 mL plastic bottle
-Corer (5 cm diameter, 30 cm long)
-Ruler
-2 mm sieve
-Large bucket
-Shears
-two 50 m transect tapes
-one 25 m transect tape
-1 m^2 quadrat
-Refractometer
- Dissolved oxygen meter
- pH meter
-Salinity meter
-Temperature meter
-10 cm diameter metal ring
-Penetrometer (with 1” adapter)
-Invasive species guide

CLASSIFYING APPROPRIATE TIDAL WETLANDS

Tidal wetlands are classified based on their influence by tidal cycles from Galveston Bay and classified as tidal fringe wetlands, as defined by the U.S Army Corps of Engineer Regional Guide book (Shafer et al. 2002). Tidal fringe wetlands occur along coasts and estuaries and experience tidal inundation by marine waters.

ESTABLISHING THE ASSESSMENT AREA

The majority of the measurements will be performed within a 50 meter (m) diameter assessment area (AA). Locate the center point of the AA by qualitatively identifying the center of the low marsh elevation zone dominated by smooth cordgrass *Spartina alterniflora* or saltgrass *Distichlis spicata*. The ecological scores are calibrated for the low marsh zone only therefore every effort should be made to maintain the AA within low marsh. Detailed measurements will be taken at predetermined distances from that center point as described below. Record the GPS coordinates of the center point. Cross two transect tapes (50 m) perpendicularly at the center point (Fig. 1). Take photos from the center point, facing each cardinal direction.

A. Locating subplots within the AA

Subplots in the AA will be used to study vegetation types and canopy coverage. Place eight 1.0 m^2 quadrats every ten meters on the two 50–m transect tapes that bisect the AA (Fig. 1). Plot 1 will be the northernmost point and plot 4 will be the southernmost point. Plots five through eight will fall east to west along the transect tape (Fig. 1).

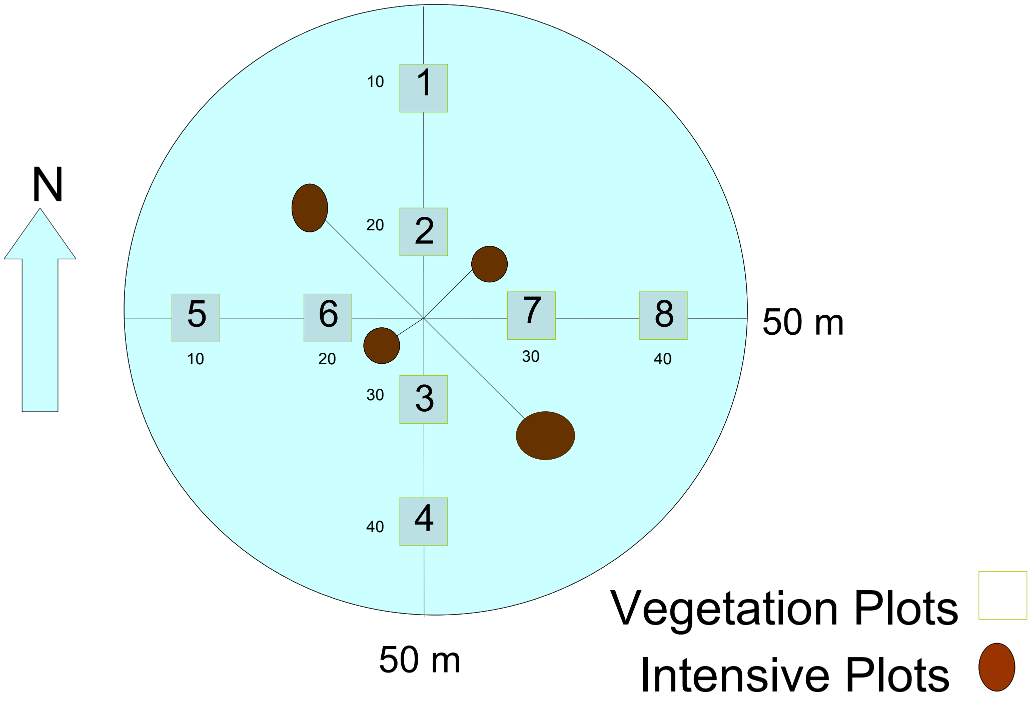

Figure 1. Diagram of assessment area (AA), including vegetation plots for plant measurements and intensive subplots for fauna, belowground biomass, and additional plant measurements.

B. Site Sketch

Sketch the site, noting structures, variation in vegetation communities, or other large alterations in the immediate area of the AA. A general drawing should entail major channels and land masses that compose the wetland, as well as any structure or inhibitor to the wetland itself (i.e. roads).

METRIC OVERVIEW

Category	***Variable***	***Description***
Landscape/Site Characteristics	Barriers to Landward Migration	The number of physical barriers that prevent migration inland
Landscape/Site Characteristics	Fill	The volume of fill added to or used in the wetland
Landscape/Site Characteristics	Presence of man-made structures	The number of docks and other structures
Hydrology	Tidal Restrictions	The presence of embankment or other restrictions
Hydrology	Hydrological Modifications	The percent of channels, ditches, and other modifications to the wetland's surface water
Wildlife Habitat	Vegetation Cover Total	The percent of total vegetation cover in AA
Wildlife Habitat	Macrobenthos	The average number of macrobenthos found in the AA
Wildlife Habitat	Vegetation Diversity Index	The index of vegetation diversity
Wildlife Habitat	Percent Invasive	The percent cover of invasive species in AA
Soils	Soil stability	Soil stability using a penetrometer
Soils	2-4 cm Belowground Root Volume	Root volume of plants in upper soil horizon
Soils	25-27 cm Belowground Root Volume	Root volume of plants in lower soil horizon
Soils	Pore Water Salinity	The salinity of soil water
Soils	Pore Water pH	The pH of soil water

DATA COLLECTIONS

Category 1: Landscape/Site Characteristics

L1. Landscape and Site Characteristics: Barriers to Landward Migration

Method: Visually inspect the AA to identify barriers such as roads and railroad crossings that may prevent migration inland with increased sea levels.

Scoring: L1. Barriers to Landward Migration

L1. Barriers to Landward Migration

Number of barriers	Rating (circle one)
0	4
1	3
2	2
3	1
≥ 4	0

L2. Landscape and Site Characteristics: Fill

Method: This is a qualitative variable that is based on the alterations to landscape and site characteristics. Using historical records from the site (e.g., inquire with the landowner or the local Army Corps of Engineers office), acquire the percentage of fill volume material (total historical sediment volume) used or added to the site for restoration or enhancement. “Fill” is defined as any soil, debris, garbage, or excavated material placed in the AA.

Scoring: L2. Fill

L2. Fill

Historical Information	Rating (circle one)
No fill in assessment area	4
1 - 24 % of fill added to AA	3
25% - 49% of fill added to AA	2
50% - 74% of fill added to AA	1
≥ 75% of fill added to AA	0

L3. Landscape and Site Characteristics: Man-made Structures

Method: Visually inspect the AA to identify the number of man-made structures. Include any structure that encroaches on the wetland site, such as viewing platforms, walking bridges, or boardwalks.

Scoring: L3. Man-made Structures

L3. Man-made Structures

Number of structures	Rating (circle one)
0	4
1	3
2	2
3	1
≥ 4	0

Category 2: Hydrology

H1. Hydrology: Tidal Restrictions

Method: Visually inspect the AA to quantify the number of tidal restrictions impacting the wetland. These restrictions are any feature such as a berm or culvert that limits tidal flow entering and exiting the wetland.

Scoring: H1. Tidal Restrictions

H1. Tidal Restrictions

Number of restrictions	Rating (circle one)
0	4
1	3
2	2
3	1
≥ 4	0

H2. Hydrology: Hydrological Modifications

Method: Visually assess hydrological modifications for any changes in surface water flow, such as the presence of geo-tubes or deep channelization.

Scoring: H2. Hydrological Modifications

H2. Hydrological Modifications

Percent of surface flow impacted	Rating (circle one)
0% not impacted	4
1 - 25% impacted	3
26-50% impacted	2
51 - 75% impacted	1
76 - 100% impacted	0

Category 3: Wildlife Habitat

W1. Wildlife Habitat: Percent Plant Cover

Method: Place eight 1.0 m^2 quadrats every ten meters on two 50–m transect tapes that bisect the AA (Fig. 1). Record species types (live and dead) and visual estimates of plant cover (in five percent intervals) for each species in each plot.

Scoring: W1. Vegetation Cover Total

W1. Vegetation Cover Total

Average % cover	Rating (circle one)
$\geq$ 61.3 %	4
46.0 - 61.2%	3
30.7 - 46.0%	2
15.4 - 30.7%	1
0 - 15.3 %	0

W2. Wildlife Habitat: Macrobenthos

Method: Place four 10-cm diameter metal rings at 45 degree angles to the transect tapes; use a random number table to determine the distance (up to 19 m) from the center of the AA for each plot (Fig. 1) and at the closest bank (at the vegetation-tidal flat interface) to the AA center point. In each of the plots, determine the most abundant plant species. Record macrobenthos species and abundance and burrow density within each plot.

Scoring: W2. Macrobenthos

W2. Macrobenthos

Average number of macrobenthos	Rating (circle one)
≥ 2.5	4
1.9 - 2.4	3
1.3-1.8	2
0.63 - 1.3	1
0 - 0.62	0

W3. Wildlife Habitat: Vegetation Diversity Index

Method: In each plot, calculate plant species diversity using Simpson's Index of Diversity:

$$D = \sum_{i=1}^{S} p_i^2 .$$

D = (Cover(sp1)/total cover for plot)^2 + (Cover(sp i)/total cover for plot)^2. Diversity is expressed as 1-D, where higher numbers are more diverse communities.

Scoring: W3. Vegetation Diversity Index

W3. Vegetation Diversity Index

Average Simpson's Index score	Rating (circle one)
≥ 0.11	4
0.08 - 0.10	3
0.05 - 0.07	2
0.03 - 0.04	1
0 - 0.2	0

W4. Wildlife Habitat: Percent Invasive Species

Method: Identify in the field (or collect for later identification) all invasive or unknown plant species found in the quadrats. Thoroughly examine the entire AA to determine if any additional invasive species are present. Record any native but rare species identified outside the quadrats.

Scoring: W4. Percent Invasive Species

W4. Percent Invasive Species:

Average percent cover	Rating (circle one)
0%	4
1-25%	3
26-50%	2
51-75%	1
76-100%	0

Category 4: Soils

S1. Soil: Soil Stability

Method: test soil stability using a pocket penetrometer with a 1” adapter within the four intensive sampling plots that were sampled for macrobenthos.

Scoring: S1. Soil stability

S1. Soil stability

Average penetrometer reading (psi)	Rating (circle one)
≤ 0.05	4
0.051 - 0.06	3
0.061 – 0.07	2
0.071 - 0.08	1
≥ 0.081	0

S2 & S3. Soils: 2-4cm & 25-27cm Belowground Root Volume

Method: Determine belowground plant biomass in the two intensive plots (where soil stability was measured) that are most representative of the wetland as a whole. In each of these plots, extract a core (5 cm diameter, 27 cm deep) and remove 2 cm subsamples from 2-4 cm and 25-27 cm below the surface. Place each subsample into separate large-mouth water bottles containing approximately 250 mL of seawater. Shake each bottle and decant the contents through a 2 mm sieve. Place the plant fragments from the sieve into a 60 cc syringe and expel all the water. Record the quantity (mL) of roots as an estimate of belowground plant biomass.

Scoring: S2. 2-4cm Belowground and S3. 25-27cm Belowground

S2. 2-4 cm Belowground Root Volume

Average root volume (mL)	Rating (circle one)
≥ 22.0	4
16.5- 21.9	3
11.0 - 16.4	2
5.5 - 10.9	1
0.0 – 5.4	0

S3. 25-27 cm Belowground Root Volume

Average root volume (mL)	Rating (circle one)
≥ 15.2	4
11.4 - 15.1	3
7.6 - 11.3	2
3.8 - 7.5	1
0 - 3.7	0

S4 & S5. Soils: Pore Water Salinity and pH

Method: Measure the characteristics of the water filling the extraction hole where the core sample was obtained. Record pore water salinity and pH using salinity and pH probes (e.g., Orion 131S meter with a 01301A conductivity cell, Mettler Toledo SevenGo pH meter SG2 and a Mettler Toledo InLab 413 SG probe).

Scoring: S4. Pore Water Salinity

S4. Pore Water Salinity

Average pore water salinity (ppt)	Rating (circle one)
≥ 48.5	0
42.0 - 48.4	1
35.4 - 41.9	2
29.1 - 35.5	3
25.8 - 29.0	4
19.3 - 25.7	3
12.9 - 19.2	2
6.4 - 12.8	1
0 - 6.3	0

Scoring: S5. Pore Water pH

S5. Pore Water pH

Average pore water pH	Rating (circle one)
≥ 12.6	0
11.0 - 12.5	1
9.5 - 10.9	2
7.9 - 9.4	3
6.2 - 7.8	4
4.7 - 6.1	3
3.1 - 4.6	2
1.6 - 3.0	1
0 - 1.5	0

SCORING

After determining the score of each of the 14 variables on a scale of zero to four, calculate the composite health score of each site. Classify each variable into one of four categories: landscape/site characteristics (Lv), hydrology (Hv), wildlife habitat (Wv), and soils (Sv) (Table 1). Within each category, sum the scores and then divide by the number of independent variables that composed that variable to yield a maximum possible score of four for each category (Fig. 2). Calculate the overall ecosystem score by summing all category scores, dividing by the maximum possible score (16) and multiplying by 100 (Fig. 3).

Table 1. Description of variables and categories used to generate final Galv- RAM scores

Variables	Categories
L1. Barriers to Landward Migration	Lv: Landscape/Site Characteristics
L2. Percentage of Fill Volume	
L3. Man-made Structures	
H1. Tidal Restrictions	Hv: Hydrology
H2. Hydrological Modifications	
W1. Vegetation Cover	Wv: Wildlife Habitat
W2. Macrobenthos	
W3. Vegetation Diversity	
W4. Invasive Species	
S1. Soil Stability	Sv: Soil
S2. 2-4 cm Belowground Root Volume	
S3. 25-27 cm Belowground Root Volume	
S4. Pore Water Salinity	
S5. Pore pH	

Site Number:	**Site Name:**	**Date:**	
Variables, Categories, and Metrics		**Scores**	**Comments:**
Landscape/Site Characteristics	**Raw #**		
L1. Barriers to Landward Migration			
L2. Percentage of Fill Volume			
L3. Man-made Structures			
(∑(L1, L2, L3)) = **Landscape Score**		Score	
Hydrology	**Raw #**		
H1. Tidal Restrictions			
H2. Hydrological Modifications			
(∑(H1, H2)) = **Hydrology Score**		Score	
Wildlife Habitat	**Raw #**		
W1. Percent Plant Cover			
W2. Macrobenthos			
W3. Vegetation Diversity			
W4. Percent Invasive Species			
(∑(W1, W2, W3, W4)) = **Wildlife Habitat Score**		Score	
Soil	**Raw #**		
S1. Soil Stability			
S2. 2-4 cm Root Volume			
S3. 25-27 cm Root Volume			
S4. Pore Water Salinity			
S5. Pore pH		Score	
(∑(S1, S2, S3, S4, S5)) = **Soil Score**			

$$\textbf{Galv-RAM score} = \frac{\sum((L/3)+(H/2)+(W/4)+(S/5))}{\sum(P_{max})=16} \quad \textbf{x100}$$

GALV-RAM FINAL SCORE =

____

Fig. 2 Overall score sheet for Galv-RAM.

A. Calculations of scores:

Categories (range 0-4)

Lv - Landscape/Site Characteristics
= (Barriers to landward migration + Fill + Man-made structures)/3

Hv - Hydrology
= (Tidal restrictions + Hydrological modifications)/2

Wv - Wildlife Habitat
= (Vegetation Cover + Macrobenthos + Vegetation diversity + Invasive)/4

Sv - Soil
= (Soil stability + 2-4cm root volume + 25-27 cm root volume + Soil salinity+ Soil pH)/5

$$(G) = Lv + Hv + Wv + Sv$$

Galv-Ram Score = $\dfrac{(G)}{\text{Maximum possible score } (G_{max})}$ x100

Fig. 3. Calculations of Galv-RAM scores.

DATASHEETS

Site Information Datasheet
Galveston Bay Rapid Assessment Method

Version 1.0 April 2010

Site # ________ **Site Name** ________________________ **Date** ____/___/_____
Field Crew____ **Crew Leader Initials** _
Wetland Type ___________________________ **Reference or Assessment Site (circle one)**
Watershed ______________________________ **Lat/Long** ______________________
Photos: __________________________

Barriers to Landward Migration:

Man-made Structures:

Tidal Restrictions:

Fill (dumped soil, debris, garbage):

_____ No fill in assessment
_____ 1-25 % of AA covered in fill
_____ 26-50 % of AA covered in fill
_____ 51-75 % of AA covered in fill
_____ > 76 % of AA covered in fill

Hydrological modifications:

_____ 0 % not impacted
_____ 1-25 % of AA covered in fill
_____ 26-50 % of AA covered in fill
_____ 51-75 % of AA covered in fill
_____ > 76 % of AA covered in fill

Vegetation Plots Datasheets
Galv-RAM

Site # ________ Site Name ________________________ Date ____/___/_____

Vegetation Zone: ________________________

Cover Estimates in 8 vegetation plots (1x1 meter plots)										
			Plot Number							
C	**I**	**Identified Species**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**

C=Collected, I = Identified

Invasive Species

Species Name	**% in Veg. Plot**

Macrobenthos Datasheets
Galv-RAM

Site #: **Site Name:** **Date:**

Field Crew: **Vegetation Zone:**

				Plant Fragments		Water Samples		
Plot # and Location	Belowground Bagged?	# of Inverts	Soil Stability	2-4 cm Belowground	25-27 cm Belowground	pH	Salinity	Temperature

VITA

Name: Lindsey Ann Staszak

Address: Texas A&M University Galveston
P.O. Box 1675
Galveston, Texas 77553

Email Address: Lindsey.Staszak@gmail.com

Education: M.M.R, Marine Resources Management, Texas A&M University at Galveston, 2010
B.S., Biology, University of North Carolina Wilmington, 2008