Sustainable Estuarine Shoreline Stabilization: Research, Education and Public Policy in North Carolina

A Final Report Submitted to

The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET)

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1. EXPANDED EXECUTIVE SUMMARY AND KEY FINDINGS

What is the coastal resource issue the project sought to address? Coastal salt marshes have declined in area over the last 200 years, and currently are being lost at a higher rate than any other wetland category (Dahl 2011). Coastal development and shoreline stabilization practices can contribute to the rate of loss (Mattheus et al. 2010). Loss of marsh is especially problematic as marsh habitats are among the most productive and provide many important ecosystem services. In North Carolina, bulkheads are the most commonly used shoreline stabilization strategy. Yet, relatively little work has been done to understand the impact bulkheads have on the functioning of the marsh systems in which they are being built. There are several key features of bulkheads that could cause them to have deleterious impacts to marsh habitats. These include: they cut off the upland from the intertidal/subtidal region; they block coastal marshes from being able to transgress upland; they reflect wave energy potentially causing increased erosion and sediment scour; and they transform a gently sloped shoreline into one with a steep transition. Because of the widespread use of bulkheads, it is critical that coastal managers understand any potential adverse impacts of bulkheads. It is also critical that the waterfront property owners and marine contractors understand these issues as well as they are often the ones deciding what type of stabilization structure is to be utilized. This project was designed to quantify the ecological impact of bulkheading and translate those results through education and outreach to key stakeholders (e.g., coastal policy managers, marine contractors, and estuarine property owners).

Describe the technology: Our project utilized a three part approach to answer the coastal management issue described above: 1) Conduct field based research designed to quantify the impacts bulkheads have on the ecosystem services provided by the coastal marshes in which the bulkheads were built; 2) Construction of a demonstration project utilizing a living shoreline design (alternative to a bulkhead) to stabilize an eroding shoreline; 3) Dissemination of project results to the general public (coastal landowners, marine contractors, students and teachers) and natural resource managers. All aspects of the project were coordinated and overseen by an advisory panel made up of the stakeholders that the project was designed to reach.

How does it address the problem? The research portion of our project provided new data on the potential impacts of bulkheads on the structure and function of fringing marshes in which they are built. These data are needed to support efforts of resource agencies to develop best management policies to protect shoreline habitats, and to help property owners and the general public understand the potential impacts of bulkheading. Agencies and water front property owners are hesitant to require or use, respectively, alternative stabilization approaches if they are not confident in them. We targeted this issue with our outreach activities. We first conducted a needs assessment to quantify what our key stakeholders knew about estuarine stabilization. We used that knowledge to create outreach materials designed to inform key stakeholders regarding how the decisions they make regarding shoreline stabilization can impact the larger estuarine system beyond an individual property. That effort also provides a proven method to transfer the research results as they have become available. The installation of the demonstration project provides both new data and a visual example of how shoreline stabilization can be obtained while preserving natural habitats and the ecosystem services they provide.

What is the geographic reach of the technology? The project was conducted in three regions of the North Carolina coast, the northern (NoCo), central (CeCo), and southern (SoCo). The tide range of North Carolina's estuarine systems changes dramatically moving north to south. In the NoCo, astronomical tides are greatly muted because the nearest oceanic inlet is far removed. As a result, water levels are regulated mainly by wind direction and speed. Salinity in these estuaries is also reduced leading to altered marsh communities as compared to the CeCo and SoCo regions. In the CeCo region the tides are diurnal and typically range near 1m. In the SoCo region the tides are also diurnal, but much larger than in the CeCo region, ranging from 1.5-2m. The demonstration project was constructed in the CeCo region.

Is it transferable to other locations? Yes, as bulkheads are a universally utilized form of shoreline stabilization. Thus, potentially, the results from this work could be applied anywhere bulkheads are found. However, our work is most transferable to areas of the United States coastline that have passive continental margins consisting of sedimentary strata in a micro to meso tidal range, with marsh vegetation and oysters. This area includes most of the U.S. East and Gulf Coasts, with the exception of subtropical Florida which has mangrove ecosystems.

How is it an improvement over existing technologies? There is very little data available to detail the impact bulkheads have on marsh ecosystem services, and what does exist was not based on work done in North Carolina. This project addresses bulkhead impacts and does so using locations within North Carolina. This facilitates the use of project results in support of any potential policy revisions the State may consider; as local information is often considered more beneficial than results based on work conducted outside the state. Current shoreline stabilization efforts, including those described as 'living shorelines', often incorporate a hardened structure in the design. The demonstration project we installed utilizes loose oyster shell. This approach is in place of bagged oyster shell, granite, wooden breakwaters or coir logs, which have previously been used in conjunction with salt marsh. Our approach is completely constructed using native materials and designed to most closely mimic a natural oyster reef. The *Weighing Your Options* booklet developed as part of this project is an expansion of an 8 page pamphlet previously used by the N.C. Division of Coastal Management to convey stabilization options. This previous document provided much less information and did not account for the impacts to ecosystem services of various shoreline stabilization options.

What is the current stage of development? The research results are currently in the "roll out" stage. They are scheduled to be presented to state regulatory agencies (starting in November 2012), and are currently being translated into manuscripts for communication with other scientists. Our demonstration project is currently fully installed and operational. Our outreach materials are also in full operational mode, being circulated at appropriate meetings and available for download from our websites.

Describe any technical and/or non-technical barriers to application: The greatest barrier to full implementation of our results is the lack of understanding by the public and policy makers in regard to potential adverse impacts of bulkheads, existing policy frameworks, and public sentiment. Bulkheads are well-liked by coastal property owners and their potential impacts are not well understood. Prior to this study, little local data was available regarding bulkhead impacts. In North Carolina, bulkhead permits can be rapidly obtained, and the projects can be installed quickly as their design criteria are well-known. Alternatives to bulkheads typically require a longer permitting process, are not always available from marine contractors, and therefore require more effort to utilize. This framework has created a large amount of inertia that needs to be overcome before change can be realized. Education activities must be utilized to show the public why an alternative to a bulkhead may be advantageous even if it takes a little more effort up front to install in order to overcome this inertia.

Describe/name the intended users of the technology. We expect the results of this project to be utilized by the following groups/organizations. This list was compiled based on known users, users that have expressed a desire to use our results, and users whose goals/missions seem to mesh well with our project objectives.

- N.C. Division of Marine Fisheries
- N.C. Coastal Federation
- N.C. Division of Coastal Management
- Estuarine property owners
- Marine Contractors
- Public school teachers/students
- The University of North Carolina Chapel Hill – Institute of Marine Sciences
- The University of North Carolina Wilmington – Center for Marine Science
- The National Estuarine Research Reserve System
- NOAA's National Centers for Coastal Ocean Science
- U.S. Army Corp of Engineers
- N.C. Wildlife Resources Commission

Key Findings: The key findings can be summed up in the following statements.

- Bulkhead sites with no fringing marsh were at least 0.5 m lower in elevation than sites with marsh.
- Fringing marshes in front of bulkheads provided effective wave attenuation during storm events, whereas wave energy at unvegetated bulkheads is equal to or higher than incident wave energy.
- Denitrification (N removal via microbial activity) scales with marsh area, so that wider marshes provide greater N removal.
- Infauna distribution patterns were extremely variable by site, year, and region; but wider marshes had taxa more characteristic of well-established, interior marshes and narrow marshes and unvegetated sites were characterized by opportunistic species.
- Bulkheaded sites, with and without marsh, supported a lower abundance of birds compared to natural marshes. Bulkheads without marsh had much lower bird diversity and numbers.
- Marsh nekton abundance increases with increasing marsh width.
- Small narrow marshes in front of bulkheads provided a higher level of ecosystem services than expected, per unit area.
- Both waterfront property owners and marine contractors desired outreach materials be available online.
- Based on monitoring to date, shoreline stabilization using oyster reef with marsh plantings is a viable, cost-effective alternative to vertical bulkheads.
- Longer-term evaluation of elevation and vegetation is needed to determine the impact of bulkheads on fringing marsh sustainability.

2. PROJECT DEVELOPMENT

Abstract: Bulkheads are the predominant shoreline stabilization method used in North Carolina along estuarine shorelines. However, bulkheads have the potential to cause deleterious impacts to coastal marshes. This is especially problematic as coastal marshes provide many useful ecosystem services. Alternatives to bulkheads are available that provide similar levels of erosion protection while minimizing the impacts to coastal marshes and the ecosystem services that they provide. Yet, in North Carolina these alternatives are largely being ignored by estuarine property owners and marine contractors. This project was designed to address this problem using three approaches: 1) conduct new research to quantify the ecological impacts bulkheads have on fringing marshes and the ecosystem services that they provide; 2) construct an alternative stabilization structure demonstration project on a highly visible eroding estuarine shoreline; and 3) conduct education and outreach to disseminate the results from approaches 1 and 2 to key stakeholders and resource managers.

The research aspect examined a suite of metrics simultaneously at natural marshes and marshes associated with bulkheads. Work was conducted in three regions (northern, central, and southern) of North Carolina's coast to ensure results were inclusive of the full range of tidal and salinity conditions found in the state. Quantified metrics included: marsh vegetation and elevation, nutrient flux and denitrification, nekton and bird use, infauna communities, and wave dynamics. The demonstration project was constructed in the CeCo region on the Rachel Carson component of the North Carolina National Estuarine Research Reserve. The demonstration project utilized all natural materials (oyster shell and marsh plantings) and benefits from visitation as part of routine educational field trips conducted by the Reserve. The education and outreach aspect utilized a needs assessment to determine the perspectives and knowledge of key stakeholders regarding estuarine stabilization. Project results have been disseminated through printed materials, online downloadable materials, and face to face presentations.

Project results showed that: bulkhead sites with no fringing marsh were at least 0.5 m lower in elevation than sites with marsh; fringing marshes in front of bulkheads provided effective wave attenuation during storm events, whereas wave energy at unvegetated bulkheads is equal to or higher than incident wave energy; denitrification (N removal via microbial activity) scales with marsh area, so that wider marshes provide greater N removal; infauna distribution patterns were extremely variable by site, year, and region; but wider marshes had taxa more characteristic of well-established, interior marshes and narrow marshes and unvegetated sites were characterized by opportunistic species; bulkheaded sites, with and without marsh, supported a lower abundance of birds compared to natural marshes. Bulkheads without marsh had much lower bird diversity and numbers; marsh nekton abundance increases with increasing marsh width; small narrow marshes in front of bulkheads provided a higher level of ecosystem services than expected, per unit area; both waterfront property owners and marine contractors desired outreach materials be available online; based on monitoring to date, shoreline stabilization using oyster reef with marsh plantings is a viable, cost-effective alternative to vertical bulkheads; longer-term evaluation of elevation and vegetation is needed to determine the impact of bulkheads on fringing marsh sustainability.

The management implications for this work are impressive. Bulkheads are a universally utilized form of shoreline stabilization, thus our work is readily transferred. In North Carolina much work is currently occurring to reexamine the coastal policy that deals with shoreline stabilization, with a special emphasis on encouraging living shoreline approaches. Project personnel are engaged in this process providing a direct link for the use of our project results.

Introduction:

North Carolina has over 12,000 miles of estuarine shoreline or sheltered coast (NC DCM, 2012), distinct from ocean-facing beaches. Most North Carolina (N.C.) estuarine shorelines are experiencing significant erosion, with average rates of over 6 m per year in some areas (Riggs 2003). Compounding the challenges facing the N.C. estuarine coast is the amount of low-lying land adjacent to NC shorelines. Titus and Wang (2007) estimate that there are over 550 km^2 of dry land within 1.5 m of the Spring High Water mark in N.C., more than twice that found in any other mid-Atlantic state (New York to North Carolina). Coastal marshes have declined in area over the last 200 years, and currently are being lost at a higher rate than any other wetland category (Dahl 2011). The main loss is conversion of marsh to open water, as a consequence of sea level rise and storm events (Dahl 2011). Loss of estuarine habitats is especially problematic as they represent some of the most biologically productive and ecologically valuable habitats in the coastal region, including tidal marshes, seagrass beds, oyster reefs, and mudflats and sandflats (Levin et al. 2001, Peterson et al. 2007). In addition, fringing marsh habitats provide many important ecosystem services (e.g., wave attenuation, nutrient removal, nursery habitat) (Currin et al. 2010). Thus as marsh is lost, these additional benefits are also lost.

In North Carolina, bulkheads are the most commonly used shoreline stabilization strategy. N.C. Division of Coastal Management (DCM) permit data show that 79% of the permitted shoreline stabilization activity since 1980 was for bulkheads. There are several key features of bulkheads that could cause them to have deleterious impacts to marsh habitats. These include: they cut off the upland from the intertidal/subtidal region; they block coastal marshes from being able to transgress upland; they reflect wave energy potentially causing increased erosion and sediment scour; they transform a gently sloped shoreline into a steep transition to the subtidal by eliminating the intertidal (Currin et al. 2010 and references within). Thus, the most used stabilization structure in N.C. has the potential to cause detrimental effects to one of the most vulnerable and valuable habitats. Yet despite this heavy utilization, relatively little work has been done to understand the impact bulkheads have on the functioning of the marsh systems in which they are being built and the ecosystem services provided by those marshes.

This project was designed to fill this knowledge gap by quantifying the ecological impacts of bulkheads and translating those results through education and outreach to key stakeholders including coastal policy managers, marine contractors, and estuarine property owners. Because of the widespread use of bulkheads, it is critical that coastal managers understand any adverse impacts of bulkheads so they can best manage coastal resources. It is also critical that the waterfront property owners and marine contractors understand these issues as well as they are often the ones deciding what type of stabilization structure is to be utilized.

Objectives:

This project was originally designed to be six years in length, broken down into three phases each two years in length. Soon after project initiation, the project team was informed that only phase I would be funded because CICEET's funding at the federal level was not renewed. Due to this change in total project length, many of the original goals had to be revised. To preserve as many of the original project goals as possible, a place for time approach was utilized. This place for time approach is based on the assumption that marshes in front of bulkheads will become thinner with time. This may result from the presence of a vertical bulkhead behind a salt marsh inhibiting transgression of the marsh up-slope as sea level rises, and / or as a result of wave energy enhancing the rate of marsh loss by excavation and lowering the marsh surface

(NRC 2006). Consequently, as sea level continues to rise, one would expect a sequential loss over time of the shallow estuarine habitats, beginning with salt marsh. As such, a bulkhead with a narrow marsh in front of it can be representative of a bulkhead that has been in place a long time. A bulkhead with a wide marsh in front of it can be representative of a recently installed bulkhead. This overarching assumption was not tested as part of this work (that is what was planned in the original 6 year project). However, by carefully choosing the field sites (see Figure 2 below), data was collected to serve as a proxy for what would have been collected over the original 6 year project time frame. The phase I goals and objectives were:

- **Objective 1: Conduct research to quantify ecosystem trade-offs as a consequence of habitat alteration.**
  - Initiate research on effects of bulkhead design and physical setting on ecosystem services (nitrogen cycling, sediment elevation and properties, wave attenuation, marsh primary producer composition and biomass, infaunal community composition and biomass, fish utilization).
  - Complete complementary research on vegetated shorelines with and without natural or transplanted fringing oyster reefs (nitrogen cycling, sediment accretion rates, wave attenuation, marsh composition and production, infaunal community composition).
  - Complete complementary research on vegetated shorelines with and without offshore stone sills (nitrogen cycling, sediment accretion rates, wave attenuation, marsh composition and production, infaunal community composition).

- **Objective 2: Design and install a demonstration project utilizing alternative shoreline stabilization approaches for research and education purposes.**
  - Work with entire project team to identify priorities in design of demonstration projects and monitoring/research plan.
  - Obtain pre-installation data on shoreline habitats and ecosystem services of demo site**.**
  - Install demo project within boundaries of Rachel Carson component of the N.C. National Estuarine Research Reserve (NCNERR).

- **Objective 3: Develop and refine approach for evaluating ecological and socioeconomic costs and benefits of shoreline erosion & protection alternatives**
  - Finalize proposed ecosystem model with Advisory Panel and project team input
  - Develop approach for evaluating economic and noneconomic costs and benefits of shoreline erosion and various stabilization scenarios with input from Advisory Panel, project team, economists and human dimension specialist.

- **Objective 4: Develop effective communication methods for exchanging information between scientists, regulatory agencies, business community, politicians and general public in regard to costs-benefits of various short-term and long-term shoreline stabilization plans.**
  - Publish brochures illustrating shoreline erosion issues and stabilization options.
  - Conduct media campaign to publicize brochure and workshops.
  - Conduct workshops on shoreline stabilization for regulatory officials and stakeholders.

- Develop curriculum for use in K-12 classrooms.
- Develop and initiate citizen monitoring program at demo sites.

The following goals and objectives were outlined for phases II and III but were completed early as part of the funded portion of this project.

- Survey stakeholder knowledge, attitudes, perceptions & update education products.
- Package cost-benefit analysis into a easily distributed tool for coastal managers.

Methods:

Technical methods:

Objective 1: Conduct research to quantify ecosystem trade-offs as a consequence of habitat alteration.

Site Selection: The project was conducted in three regions of the N.C. coast, the northern coast (NoCo), the central coast (CeCo), and the southern coast (SoCo) (Figure 1). The tide range of N.C.'s estuarine systems changes dramatically moving north to south. In the north, the estuaries are microtidal because the nearest oceanic inlet is far removed. As a result, astronomical tides are greatly muted and water levels are regulated mainly by wind direction and speed. The salinity of the waters in these estuaries is also greatly reduced, and the marsh community composition very different from the CeCo and SoCo regions. In the central region the tides are diurnal and typically range near 1m. In the southern region the tides are also diurnal, but much larger than in the central region, ranging from 1.5-2m. To account for this dynamic tidal range and make our results more transferable we decided it was advantageous to do work in each of these distinct regions. Six sampling sites were chosen in the NoCo, CeCo, and SoCo (Figure 1, Table 1) for a total of 18 sites. Each region included the following: Bulkhead site with no marsh in front, Bulkhead site with a narrow marsh (< 5m) in front of it, two bulkhead sites with a medium marsh (5 - 15m) in front of them, bulkhead site with a wide marsh (> 20m) in front of it, and a natural fringing marsh site with no bulkhead. All six sites in each region were located in similar environmental conditions to try and control for other physical factors such as tide and fetch. In the NoCo the sampling sites were located along Kitty Hawk Bay near the town of Kitty Hawk, N.C. in Dare County. In the CeCo the sites were located in Carteret County along the back side of Bogue Banks in the Pine Knoll Shores, N.C. area. In the SoCo the sampling sites were split between two areas all along the Atlantic Intracoastal Waterway. Three sites were located in Brunswick County in the Saint James Plantation, N.C. area, and three were located in New Hanover County in the Wilmington, N.C. area. The goal of the sampling site locations was to provide the place for time comparison mentioned above running the full continuum of natural marsh no bulkhead, to bulkhead with no marsh (Figure 2). Table 1 summarizes the 18 sampling sites.

The demonstration project was constructed in the CeCo region to facilitate PI access and utilize existing outreach activities at the Rachel Carson component of NCNERR (Figure 1). Originally, additional demonstration sites were planned for the NoCo and SoCo regions as part of phase II and III. These were not completed by this project, but have been undertaken by other groups working in the state.

Table 1: Sampling site descriptions (marsh widths in meters, slope, lat x lon) in Northern Coast (NoCo), Central Coast (CeCo) and Southern Coast (SoCo) regions.

Site type	NoCo site # Lat x Lon	NoCo sites marsh width (m), slope	CeCo site # Lat x Lon	CeCo sites marsh width (m), slope	SoCo site # Lat x Lon	SoCo sites marsh width (m), slope
Bulkhead no marsh	2 36° 03.264 x -75° 41.638	0, -0.02	1 34° 42.188 x -76°48.812	0, 0.01	4 34° 12.513 x -77° 48.005	0, 0.11
Bulkhead narrow marsh	1 36° 03.486 x -75° 41.784	5, 0.06	3 34° 42.210 x -76°47.064	2, 0.15	3 33° 55.547 x -78° 08.699	4, 0.04
Bulkhead medium marsh	5 36° 02.723 x -75° 41.436	12, 0.05	4 34° 42.218 x -76°46.766	11, 0.05	1 33° 55.534 x -78° 07.901	14, 0.07
Bulkhead medium marsh	4 36° 02.795 x -75° 41.446	14, 0.05	2 34° 42.219 x -76°48.284	12, 0.06	2 33° 55.559 x -78° 08.095	16, 0.07
Bulkhead wide marsh	3 36° 02.987 x -75° 41.491	21, 0.02	6 34° 42.152 x -76°46.443	23, 0.04	6 34° 07.730 x -77° 52.101	19, 0.05
Natural marsh	6 36° 02.553 x -75° 41.355	20, 0.04	5 34° 42.190 x -76°46.667	24, 0.03	5 34° 08.506 x -77° 51.732	15, 0.09

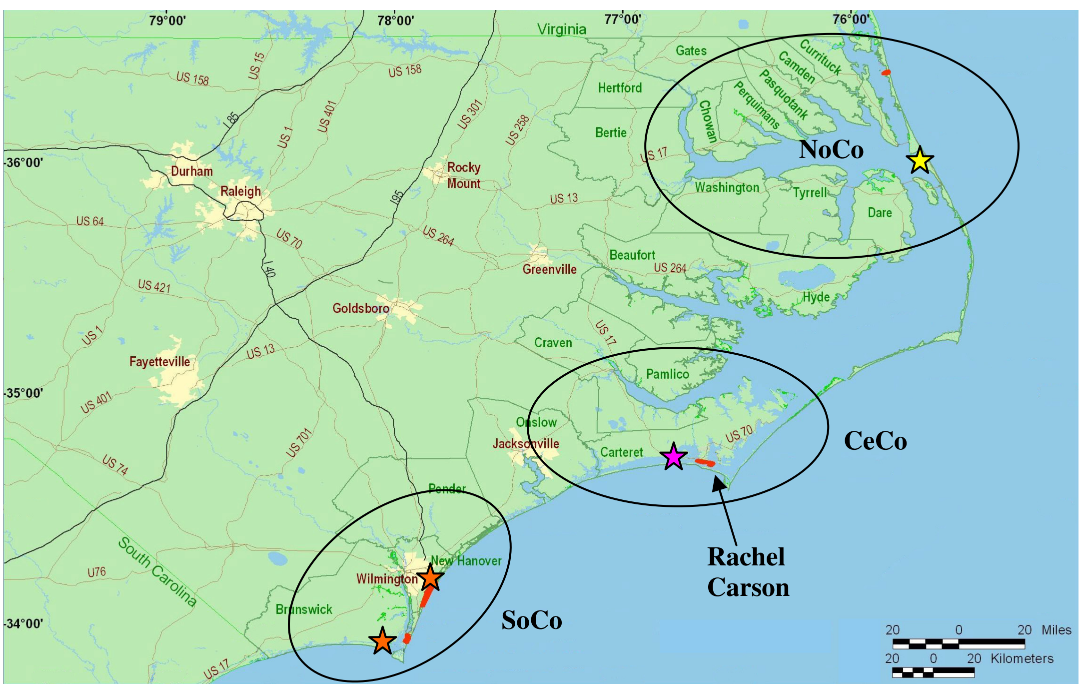

Figure 1: N.C. coastal map with NoCo, CeCo, and SoCo areas labeled. Red areas are the four components of the NCNERR (Rachel Carson component indicated by the arrow). Stars indicate location of actual sample sites within each region (yellow in NoCo, Pink in CeCo, and Orange in SoCo. For the SoCo region two sampling areas were needed to obtain the 6 sample sites.

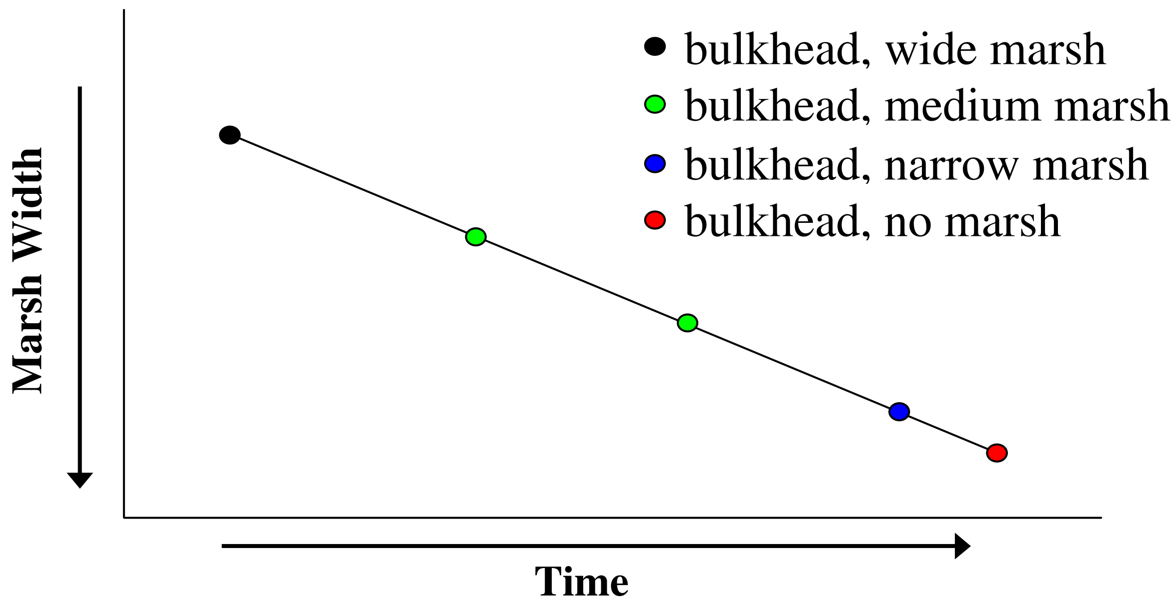

Figure 2: Conceptual model for site selection place based on decreasing marsh width over time after bulkhead installation.

Transects were installed at each sampling location to be utilized by all project team members. For smaller sites (< 30m), three transects were installed. For larger sites (> 30m) four transects were utilized. Transects ran perpendicular to the shore from the bulkhead (or upland transition for the natural site) to the marsh/water interface. The locations of the transects within each site were randomly selected and separated by at least 10m. Transects were marked at the upper and lower extent by PVC pole and a global positioning system (GPS) point taken to ensure they could be reacquired.

Sediment elevation: Surface elevation relative to mean sea level (MSL) at study sites was obtained using a Real Time Kinematic (RTK) GPS unit (Trimble 5800) and laser leveling. Temporary benchmarks were established as primary control points and were occupied by static campaigns with the RTK unit. NOAA Online Positioning User System post-processing was used to produce high resolution xyz coordinates. Elevations obtained with both methods were used to create a Digital Elevation Model (DEM) of the study sites using ArcGIS 9.2. At a minimum all the quadrats used for the vegetation surveys were sampled for elevation. In most instances, the entire marsh surface at the site was sampled at 2 second intervals using an RTK rover mounted on a wheeled vehicle (bicycle) to obtain elevation points at roughly 1 m wide intervals. A DEM was created for the demonstration site both pre and post construction (see Objective 2 results section below). This DEM will be used as the baseline to monitor how this site changes as it matures over the next few years. Elevations of vegetation plots were collected at least twice at each site, and data points to construct a site DEM were obtained in 2010 at each site. Elevation data were used to calculate marsh width and slope for each site, in support of analysis of factors affecting nekton use and vegetation.

Marsh vegetation composition and density: One m^2 vegetation monitoring quadrats were established along the transects based on the following guidelines. For the no marsh sites the entire site was walked and visually inspected for plants. For the narrow marsh sites, quadrats were place along the transects at meter intervals. For all other sampling locations quadrats were placed on the transects at 5 meter intervals with the exception of the marsh/water interface where two quadrats were obtained at meter intervals to capture this important transition. Within each quadrat the following parameters were recorded: vegetation percent cover by species using visual methods (Peet et al. 1998), stem counts for the dominant species present, and mean stem height for the dominant species present in the quadrat. Vegetation metrics were obtained once annually during the period of peak biomass (July – September). Vegetation data was digitized and provided to other team members for incorporation into analyses.

Wave dynamics associated with shoreline sites: We utilized a Nortek Vector to measure directional wave and current data, and deployed it away from the shoreline to measure the incident wavefield. RBR pressure sensors (RBR, Ltd., Kanata, Ontario) were deployed at three locations; 1) at the base of a bulkhead with no marsh vegetation, 2) within 3 m of the lower marsh edge and 3) at the base of a bulkhead with marsh vegetation fronting it. A typical schematic is shown in Figure 3. Sensors were deployed for 2-3 week periods, to capture both spring and neap tides. Wave sensors were set to collect bursts of 2048 samples at 2Hz every 30 min. In 2009, the instruments were initially tested at site adjacent to the NOAA lab, and then deployed at CeCo sites. In 2010, two deployments were made at NoCo site 1 (March 15- April 6 and June 16-30, 2010), while the physical structure of marshes at the southern sites required simultaneous deployments at two sites (SoCo 2 and 3, deployment dates April 27-May 11 and July 9-23, 2010). In an attempt to capture the potential for boat wakes to contribute to the wave energy experienced at study sites, a Memorial Day deployment (May 27-June 10, 2010) was made at CeCo site 3. In September 2010, we deployed RBR sensors at CeCo Site 3 during the passage of Hurricane Earl.

Figure 3: Wave sensor deployment at CeCo site. Directional wave information is provided by the Nortek Vector (blue dot). RBR pressure sensors measured wave energy in the marsh, at the foot of the seawall, and at the foot of the seawall in the marsh.

Sediment characteristics: Sediment grain size analysis was conducted on the top 5cm of sediment from each field site in the SoCo and NoCo regions. Grain size was determined by drying sediment samples and sorting using standard sieves. In the CeCo region, grain size was determined using a CILAS particle-size analyzer (CILAS, Orleans, France) at paired bulkheaded sites, with and without marsh. Sediment total carbon and nitrogen content was obtained from all sites in all regions. Sediment pellets were dried and ground and then analyzed on a Perkin Elmer C/N analyzer (PerkinElmer, Waltham, Massachusetts). Sediment organic matter content was obtained by measuring dried sediment before and after ignition at 500 °C for 5 hrs. (Ball 1964).

Core collection and denitrification rates: Cores were collected in triplicate from each site at all locations. At each site, cores were collected mid-marsh (both parallel and perpendicular to shore). Protocols for core collection and incubation were adapted from Piehler and Smyth, (2011). Sediment cores were 6.4 cm in diameter, 17 cm deep, and collected by hand in clear polycarbonate tubes. They were covered with sample water and returned to the Institute of Marine Science (IMS), Morehead City, NC and incubated in an environmental chamber (Bally Inc.) at in-situ temperatures (measured with a Yellow Science Instrument, YSI). Cores were capped with plexiglass tops equipped with two O-rings to attain air and water tight seals (Scott et al, 2008). Ports in each cap allowed a continuous flow of water collected from the field. Water column volume was maintained at approximately 400ml. Inflow water from the reservoir was passed over cores at a flow rate of 1ml per minute. Cores were pre-incubated for 18-24 hours prior to sampling to allow the sediment cores to reach steady-state (Erye et al. 2002; Scott et al., 2008). Membrane inlet mass spectrometry (MIMS) samples (5ml) were collected from the inflow and outflow in ground glass stoppered test tubes. MIMS was used to measure N_2(aq) and O_2(aq) in relation to Ar(aq). Benthic flux rates were calculated using equation 1.

Equation 1: Benthic Flux = $(C_{out} - C_{in})\ F/A$

where C represents the concentration of an analyte, C_{in} and C_{out} are the inflow and outflow concentrations, respectively, F is the peristaltic pump flow rate (litres hr^{-1}), and A is the surface area of the core (m^2; Miller-Way and Twilley, 1996). The C_{in} was measured from reservoir water pumped through the flow-through system in a bypass (i.e., does not make contact with any sediment from cores) directly into sample vials to account for any changes in water chemistry through tubing and pump effects (Piehler and Smyth, 2011). In addition, a water blank was used to account for any effects of the core tube and water column processes. The MIMS was standardized using DI water at 16°C and gas constants for the calculation of dissolved gases at incubation temperature and salinity. MIMS methodology was used to measure net DEN defined as the combined rates of traditional DEN (conversion of NO_3^- to N_2) and ANAMMOX (conversion of NH_4^+ to N_2) minus the rate of N fixation (N_2 to organic NH_3). Ratios of N_2 to Ar were used to calculate denitrification rates. Ratios of O_2 to Ar were used to calculate sediment oxygen demand (SOD).

Nutrient fluxes: During each denitrification experiment, 50ml of water were collected from the by-pass and core outflows for nutrient analysis. Samples were filtered using Whatman GF/F filters with a pore size of 0.7 µm. Nutrient samples were analyzed with a Lachat Quick-Chem 8000 automated ion analyzer (Hach Company, Loveland, CO) for NO_3^-, NH_4^+, PO_4^{3-}, total nitrogen (TN), and organic nitrogen (ON, by difference). Nutrient fluxes were calculated using equation (1). DEN efficiency is the total percentage of inorganic nitrogen that is released as N_2 from the sediment. It was calculated using equation 2.

Equation 2: DEN % = $[DEN/(DEN + NO_3^- + NH_2)] * 100$

where DEN % is DEN efficiency, DEN is the flux rate of N, NO_3^- is nitrate flux, and NH_3 is ammonia flux (Owens, 2009). All flux units are μmol m^{-2} hr^{-1}. Sediment samples for SOM content were collected from the surface sediment of each core at the end of MIMS experiments. Methods for loss-on-ignition (LOI) were adapted from Ball, (1964).

Infauna community composition: Benthic infauna were sampled in the lower intertidal immediately seaward of the vegetated area (or equivalent tidal level for non-vegetated or sparsely vegetated sites). Three replicate cores, 10cm diameter x 12 cm deep, were taken in spring and again in late summer to encompass seasons of varying infaunal community composition and abundance (reflecting spring and late summer recruitment periods as well as increased predation pressure in late spring to early fall; Posey et al. 2002, 2006). SoCo sites were sampled during 2009 and 2010 to provide information on interannual variability in infaunal patterns. CeCo and NoCo sites were each sampled only one year, CeCo in 2009 and NoCo in 2010. Each core was fixed in 10% formalin with rose Bengal dye. Preserved samples were sieved through a 0.5 mm screen and all retained macrofauna were preserved in 70% ethanol for later sorting and identification. Macrofauna were separated from remaining sediment and debris under a dissecting microscope. Taxa were identified to the genera or species level where possible. If species identification could not be reliably completed, organisms were identified to lowest possible taxonomic level.

Nekton sampling. Nekton using the flooded marsh surface were caught using fyke nets set at high tide and retrieved 6 hr later at low tide. Fyke nets had a mouth opening of 0.9 x 0.9m, a 3-m long catch bag, and attached wings 0.9 m tall x 5.1 m wide. The nets were placed at the marsh edge with the mouth opening landward. Potentially larger nekton in the shallow subtidal zone just below the marsh platform were caught using gill nets deployed 10 m below the bottom edge of marsh for 3 hr during a falling tide and beginning at dead high tide. The gill nets were 20 m long with panels in a range of sizes from 2.5 to 15 cm mesh openings, set parallel to the shoreline. The purpose of using both net types was to capture smaller nekton of the intertidal marsh as well as presumably larger species in permanently flooded areas that are connected to the marsh habitat by feeding on the smaller organisms flushed from the marsh platform with the receding tide. Each of the 6 marsh treatment sites was sampled for 2 replicate nights and 2 replicate days in a design that insured that any given site was being sampled by only one gear type at a time. Catches were retrieved and each individual was identified, counted, and measured (total length). A subset of each species was returned to the IMS for gut contents analysis, results of which were used in combination with literature information to assign an average trophic level to each species. Nekton sampling was conducted during both 2009 and 2010.

Bird sampling. Bird utilization of the marsh was measured by sets of 10-min field observations beginning at the first light of day for 6 successive days to encompass the full suite of tidal elevations. Birds were identified and counted and their behaviors were recorded to note what type of activity was observed (e.g., fishing, perching, etc.) and their position relative to the marsh (in the marsh, on the mudflat just below the marsh, flying, floating offshore, perched on a dock). Analyses of abundance and trophic guild composition used only the birds seen in the marsh or on mudflats below the marsh edge.

Statistical Analyses: Whenever possible (i.e. all necessary assumptions met), an analysis of variance (ANOVA) was used to compare rates of denitrification both seasonally and between sampling locations for each site. However, if the data did not meet all the assumptions necessary for an ANOVA, a Kruskall-Wallis was used. Linear regressions were used to assess the relationships between SOD, SOM, DEN, and DEN efficiency. All statistical analyses were completed in R with an alpha level of 0.05 unless otherwise noted.

Infauna differences among shoreline types and among sites were determined through ANOVA for specific taxa, sample total abundance and sample diversity. Analysis of Similarity, using the ANOSIM procedure of the PRIMER statistical package, was used to elucidate major infauna community groupings. Initial analysis indicated little variation among seasons, so infauna samples were combined within a year to allow greater power in identifying spatial trends. Abundances were log (10) transformed before Analysis of Variance to achieve homogeneity of variance. Infauna diversity was calculated using the Shannon Diversity Index. Descriptions of dominant infauna species were based on all taxa comprising at least 5% of the total faunal sampled within a region/year. For Analysis of Similarity and Multidimensional Scaling graphical analysis, infauna abundances were log transformed before analysis.

Linear regressions were calculated to determine if the average nekton abundance changes as a function of marsh width and excluded data from the natural marsh sites.

Technical methods:

Objective 2: Design and install a demonstration project utilizing alternative shoreline stabilization approaches for research and education purposes.

The primary goal of this demonstration project was to stabilize an estuarine shoreline experiencing erosion using only natural materials (marsh, oyster) in an accessible location for education and outreach. Prior to reef construction (April, 2012), we used a Trimble RTK GPS, high resolution mapping system to survey the existing site bathymetry and intertidal areas. In addition to generating baseline data for the 2012 shoreline location, we used this elevation map to identify sites immediately adjacent to the existing unvegetated shoreline (larger sill reefs) and *Spartina*–dominated marsh (small patch reefs) for reef construction. Oyster cultch shell for reef construction was purchased from Green Oyster Co. (Southport, NC) and delivered to the IMS in late April, 2012. Reef construction occurred in May 2012.

Twenty small patch reefs across 5 unique landscapes were constructed. Four 60-bushel reefs were built immediately adjacent to marsh scarps, while another six 60-bushel reefs were built on marsh ramp shorelines. Additionally, we identified features termed “blowouts” along the ramp shoreline, defined as concave bays in which rapid erosion of marsh (1-2 m of landward retreat) had occurred at scales of 10-15 m along the shore. We constructed two 60-bushel reefs in these “blowouts”. Within the network of marsh creeks, we also constructed eight more 60-bushel reefs: four reefs at the entrances of secondary tributaries, and four reefs along the banks of the primary creek (and at least 20 m from a secondary creek). For ongoing monitoring work, we also established non-restored reference sites that will be used as experimental controls for the effects of reefs on shoreline geomorphology and ecology.

Figure 4: Demonstration project construction activities.

In addition, we constructed three long sills (2 shorter, 1 longer) that extend across ~230 m of shoreline (interrupted by ~ 30 m gaps among the three sills). Shell for the sills was transported to the site on a rented barge, and then distributed using small skiffs. Based on the volume capacity of the basket used to load cultch shell from the barge to the skiffs (Figure 4), we estimate that the two smaller (t western) reef sills were each constructed with 1050 bushels of cultch shell, while the larger (eastern) reef sill was built from 3750 bushels of shell. We were able to deploy shell within narrow (2 m), PVC-marked alleys that ran parallel to shore. Immediately after deployment, IMS personnel shaped the sills to standardized mounds with a base of 2-2.5 m (seaward-landward axis) and a mean height of 0.8 m. As with the small reefs, the large sill reefs were marked with identifying floats and posts.

Sill relief and surrounding substrate elevations were measured again in mid August, 2012, to provide a baseline against which reef growth versus deterioration and shoreline change will be determined going forward. Following sill construction, ~3000 young *Spartina alterniflora* plants purchased from Native Roots Inc. (Clinton, NC), were planted during the last week of May, 2012 (with some replacement planting occurring throughout the next month). Planting following standard methods as proscribed by L. Weaver of the North Carolina Coastal Federation.

We manipulated patch size by planting *Spartina alterniflora* seedlings (culms) and *Spartina alterniflora* mimics in different sized, circular patches (radius = 0.5 m and 1 m respectively) (Figure 5). In each small patch, we planted either 24 *Spartina alterniflora* stems (supported with dowels) or 24 mimic stems. For each large patch (1 m radius), we planted 96 *Spartina alterniflora* stems or 96 mimic stems. To manipulate patch connectivity, we planted both large and small patches at different elevations (0 m, -0.1 m and -0.2 m NAVD88) resulting in three different periods of tidal inundation (~45%, 55% and ~65% inundated, respectively). Saltmarsh mimics were deployed to control for structure across vertical treatments (as plants could grow at different rates among treatments with subsequent effects on faunal recruitment) and as an experimental insurance policy in case all live seedlings died. Each mimic consisted of a 96 cm, 0.5 cm diameter dowel rod (the stem) with 5 green plastic cut straws (the leaves) alternating along the length of the dowel rod.

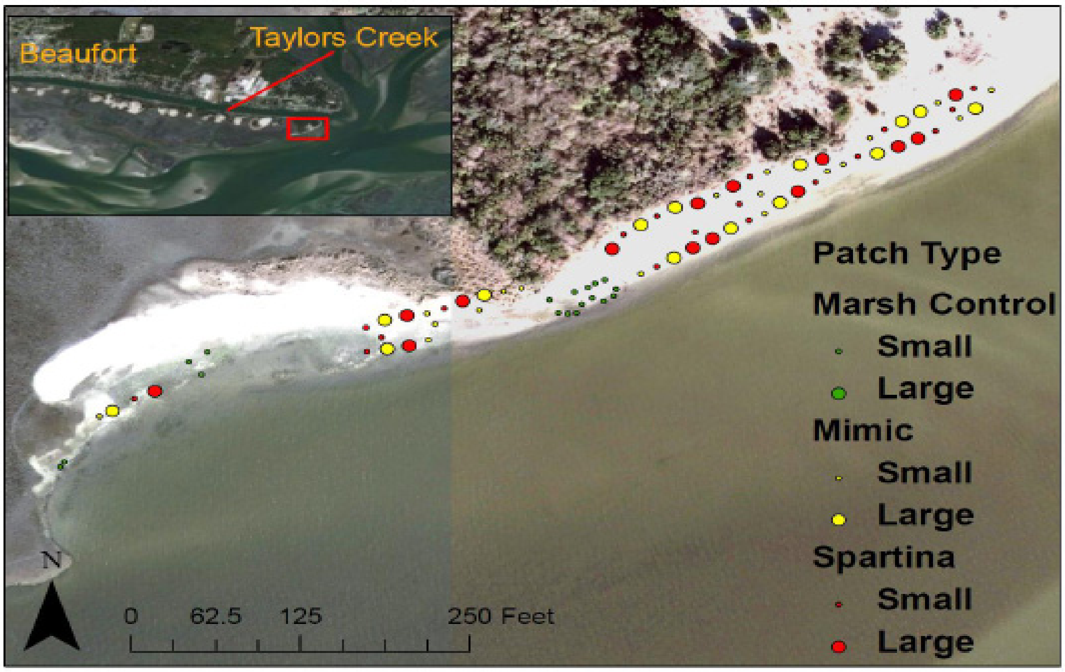

Figure 5: Map of experimental *Spartina alterniflora* plantings at the demonstration site.

Technical methods:

Objective 3: Develop and refine approach for evaluating ecological and socioeconomic costs and benefits of shoreline erosion & protection alternatives.

One of the original goals of this objective were to lay the groundwork for the economic analysis to be done in Phases II and III. When it became clear that phases II and III were not going to occur, the project team wanted to focus this objective on an effort that would have more immediate results. Advisory panelist Peter Wiley suggested to the project team that a new economist recently hired (2009) at the Duke University Marine Laboratory, Linwood Pendleton, as a good local contact to assist with this aspect of our project. Dr. Pendleton was approached by PI Currin and Co-PI Piniak in January 2010. Dr. Pendleton was willing to assist, but due to his time-constraints, suggested that one of his colleagues, Katherine McGlade, conduct the economic assessment scoping project. Mrs. McGlade had prior experience in the real estate business, a MS. in Marine Policy, and been involved in shoreline stabilization issues in the northern part of the state. It was decided that in order to meet the original spirit of this objective, McGlade would develop a booklet aimed at estuarine property owners describing and quantifying both the economic and ecological benefits of natural habitats on estuarine shorelines, and how different stabilization options impact these benefits.

McGlade's consulting company (Seachange) developed the booklet in close collaboration with PIs Fear and Currin. Seachange conducted focus group meetings and interviews with stakeholders to ensure the booklet presented information in a way that was understandable and was usable by the target audience. One focus group meeting included advisory panel members representing the following stakeholder groups: real estate broker, coastal developer, and local property owners. A second included five coastal contractors from all regions of the North Carolina coast. Interviews were conducted with the following stakeholders: DCM permit official, landscaper, nursery owner, a land management group, insurance agents/brokers, real estate agent, , town/county planners, a commercial developer, and representatives from the Federal Emergency Management Agency, N.C. Division of Marine Fisheries, N.C. Coastal Federation representative (local non-governmental organization) that does restoration work, N.C. Sea Grant (coastal engineering), United States Fish and Wildlife Service, N.C. Division of Soil and Water (relative to the incentive offered by that organization for marsh sills), N.C. Ecosystem Enhancement Program, and the N.C. Clean Water Management Trust Fund,

The booklet entitled, "*Weighing your options, How to protect your property from shoreline erosion*" was presented to the advisory panel for comment at the February 2011 meeting. The booklet was revised based on advisory panel comments and finalized by Aug 2011. 500 copies were printed and a PDF version was placed on the project website. The booklet has been distributed at many of the workshops described in the dissemination section below.

Technical methods:

Objective 4: Develop effective communication methods for exchanging information between scientists, regulatory agencies, business community, politicians and general public in regard to costs-benefits of various short-term and long-term shoreline stabilization plans.

Many different types of education and outreach methods have been utilized in completion of this project. For our project, this section is redundant with the "knowledge dissemination methods" below, and we have included objective 4 methods there.

Evaluation methods:

The project was primarily evaluated by documenting the completion of objectives according to the timeline. Additional evaluation was provided by the feedback from the advisory panel. On several occasions their input required a change in direction (see results section). The agreement of the advisory panel that their input was utilized was a criterion for success. The advisory panel meeting evaluations were also used to measure success. As most of the comments were positive, we feel our collaboration methods were successful. The number of research products also serves as a testament to the success of the project (see next section).

Collaboration method:

Collaboration was achieved using two approaches. The first was to maintain an open collaborative relationship between the project PIs and co-PIs. This was accomplished by holding semi-annual team meetings where PIs and Co-PIs reported on progress and impediments. Project impediments were discussed by the entire PI/Co-PI team and solutions found. The second was the formation of an advisory panel for the project. The advisory panel was made up of a diverse group of stakeholders to provide feedback to the project PIs and co-PIs regarding project performance and usefulness. A neutral facilitator was used to foster unbiased and equal communication between the stakeholders and project team. The advisory panel met semi-annually initially and then annually as the project progressed. The advisory panel meetings followed the format of updates by the PIs/Co-PIs and then two way discussions between the panel and the project team on current issues and the next steps for the project. At the end of each advisory panel meeting, participants filled out a survey that was used to modify future meetings to be more effective. In between the formal meetings, email was used to keep the panel up to speed on the project progress.

Knowledge dissemination methods:

Early on a needs assessment was conducted that surveyed both marine contractors and estuarine property owners. These surveys were utilized to help the project team target these key audiences with appropriate material and present them in the most desirable format. One of the most overwhelming responses from both of these surveys is that these groups wanted access to information via online resources. As such, many of the education and outreach methods have targeted this medium. Four 2-page fact sheets were developed to convey key information regarding this project and its expected results. A project webpage was also developed as an outreach method, and all project documents that have been developed are available for download as PDF files. Most recently, Facebook, Twitter, and other social media methods have been utilized to disseminate project results, milestones and upcoming events. Scientific manuscripts developed as part of this project will also be distributed electronically.

Printed hard copy outreach methods were also utilized. These were useful to handout to interested parties at conferences and meetings. The *Weighing Your Options* booklet (Appendix 2) is also available in printed format to provide to homeowners during permitting consultation visits by DCM field staff. Other printed outreach materials include the K-12 activity booklet, *Our Living Estuaries*, and the 2 page fact sheets.

Finally, oral communication has been successfully utilized to disseminate project results. Many presentations have been given at scientific conferences, key state committee meetings, workshops, and at civic group meetings. These face to face interactions have often been the most useful because they allowed a back and forth dialogue to occur. This back and forth dialogue allowed stakeholders to ask questions in real time and immediately receive answers. Similarly, at these encounters project team members were able to directly hear from the stakeholders regarding what information was useful and if there were any informational gaps.

Results discussion:

Objective 1: Conduct research to quantify ecosystem trade-offs as a consequence of habitat alteration.

Surface Elevation:

Study site slopes calculated from plot elevations are given in Table 1. With a few exceptions, slopes are less than 0.10 and characteristic of a ramped, rather than scarped, marsh edge. The only negative slope was associated with the No Marsh bulkheaded NoCo site. Surface elevation at the base of bulkheaded sites with fringing marsh was at least 0.5 m higher than at bulkheads with no marsh (Figure 6), and generally increased with marsh width. There was little difference in the bulkhead base elevation at sites with medium or wide marshes and the surface elevation at the landward edge of natural marshes.

The surface elevation data of wide and natural marshes demonstrates the ability of marshes to attenuate waves and trap sediments to maintain surface elevation, which protects the upland edge. Lowered surface elevation associated with unvegetated and narrow marsh bulkheads is consistent with wave scour effects at the base of bulkheads. Site DEMs provide a detailed map of site surface elevations which can be used in the future to detect changes in surface elevation, as well as shoreline position (Figure 7).

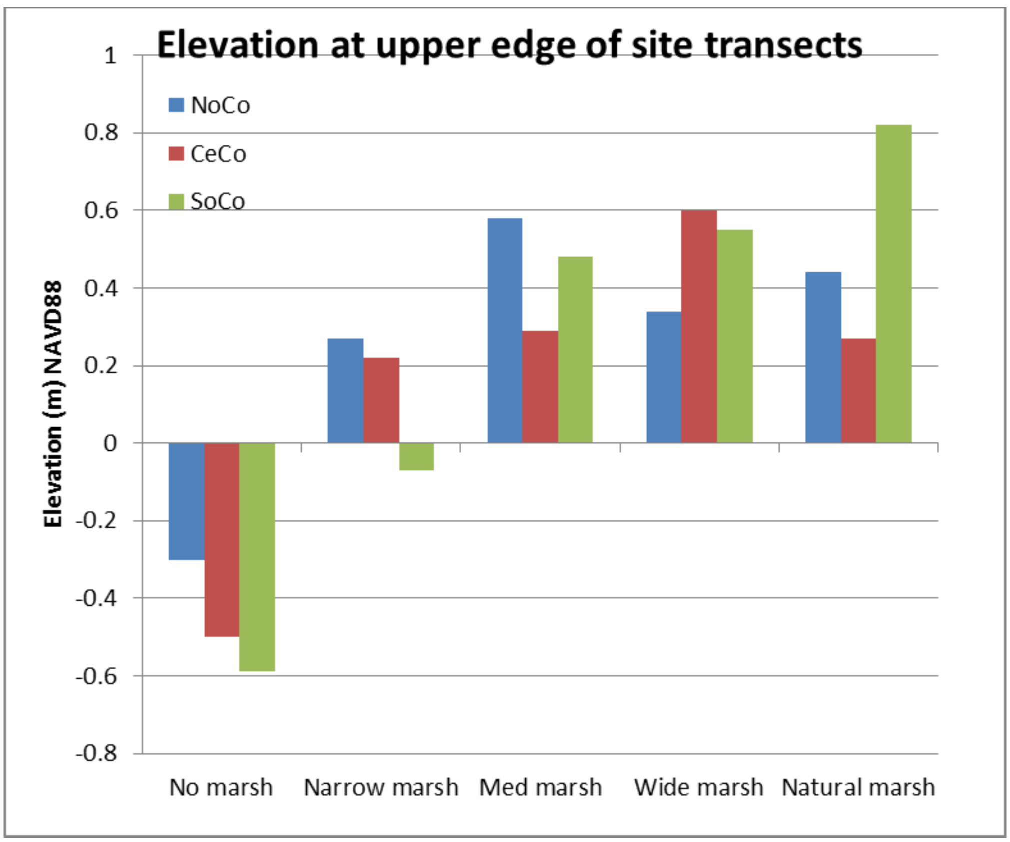

Figure 6: Surface elevation associated with the base of bulkheads in each region, and at the upper edge of natural marsh transects.

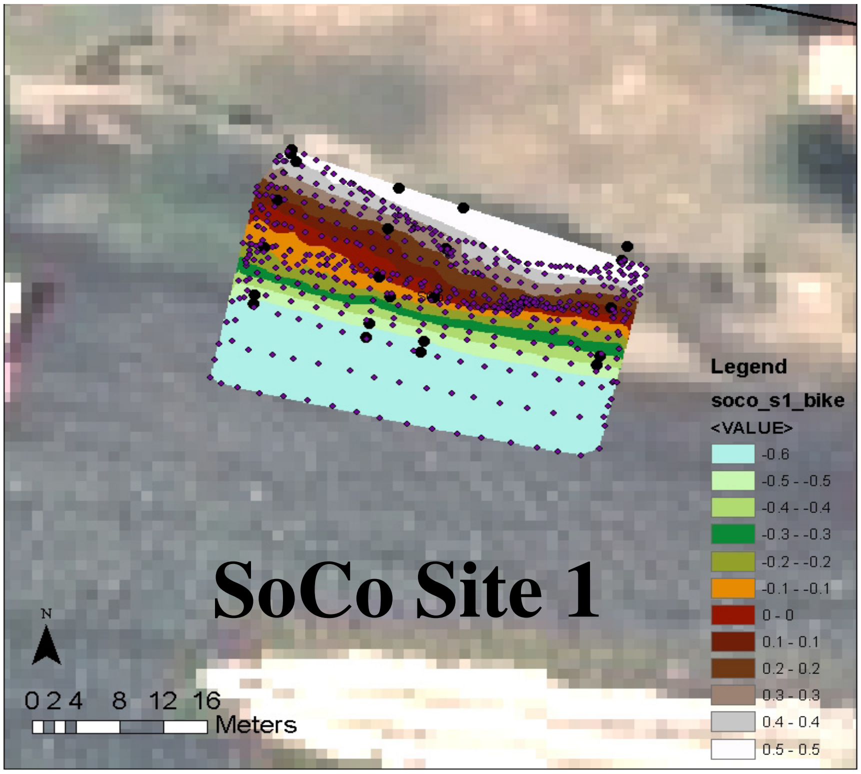

Figure 7: Map of SoCo site 1 illustrating location of vegetation plots (black dots), elevation points used for construction of digital elevation model (purple squares), and elevation contours. All elevations given in m NAVD88.

Vegetation results:

The vegetation community composition differed between the three sampling regions. In the NoCo, 11 species were documented. The NoCo marshes were dominated by *Spartina cynosuroides* (33%) and *Juncus roemerianus* (19%). In the CeCo region 7 species were documented. The CeCo marshes were dominated by *Spartina alterniflora* (89%) with *Salicornia sp*. the next most abundant (4%). In the SoCo region 7 species were documented. The SoCo marshes were dominated by *Spartina alterniflora* (85%) with *Phragmites australis* (6%) as the next most abundant. (Table 2).

Table 2: Observed marsh species in descending order of abundance by region.

NoCo Species	CeCo Species	SoCo Species
Spartina cynosuroides	*Spartina alterniflora*	*Spartina alterniflora*
Juncus roemerianus	*Salicornia spp*	*Phragmites australis*
Phragmites australis	*Spartina patens*	*Spartina patens*
Scirpus pungens	*Distichlis spicata*	*Distichlis spicata*
Spartina alterniflora	*Borrichia frutescens*	*Borrichia frutescens*
Sagittaria lancifolia	*Juncus roemerianus*	*Limonium carolinium*
Hydrocotyle sp.	*Limonium carolinium*	*Salicornia spp*
Spartina patens		
Typha sp.		
Scirpus validus		
Limonium carolinium		

The marshes in the NoCo region were much taller than those from the CeCo or SoCo region (Figure 8). This difference can be explained by the differing dominant plants (Table 2), as *Spartina cynosuroides* grows much taller than *Spartina alterniflora*. The average stem counts for the three regions did not differ dramatically (Figure 9) and had high variability. This is not unexpected as only two years of data were obtained and marsh productivity is known to vary annually in response to climatic factors (precipitation, drought, water level, etc.) (Dionne and Peter, 2012).

The sampling sites were chosen based on the amount of marsh that they had in front of them. As such, we knew a priori that there were differences in the total vegetation among the sample sites. However, the individual metrics of stem density and plant height were not known a priori. Figures 10 and 11 show the average stem density and plant height by sampling site type with the data from all three regions combined. The stem density drops as the marsh width in front of the bulkhead decreases. Compared to the natural marshes, all bulkhead sites except the wide marsh had lower stem density. There is no apparent change in the height of the marsh as marsh width decreases in front of a bulkhead. There also was no difference in marsh height comparing marshes associated with bulkheads to the natural marsh references.

Because this study was observational in nature we can not say what is causing the decreased stem density pattern shown in Figure 10. However, this pattern is consistent with the conceptual model we used in choosing our sampling sites (Figure 2). Decreased stem density may be a result of stress associated with bulkhead effects. As stem density decreases, the ability of the marsh to provide wave buffering, nursery shelter, etc. decreases. Given enough time, this process would cause the marsh to become more susceptible to erosion and eventual decreased width.

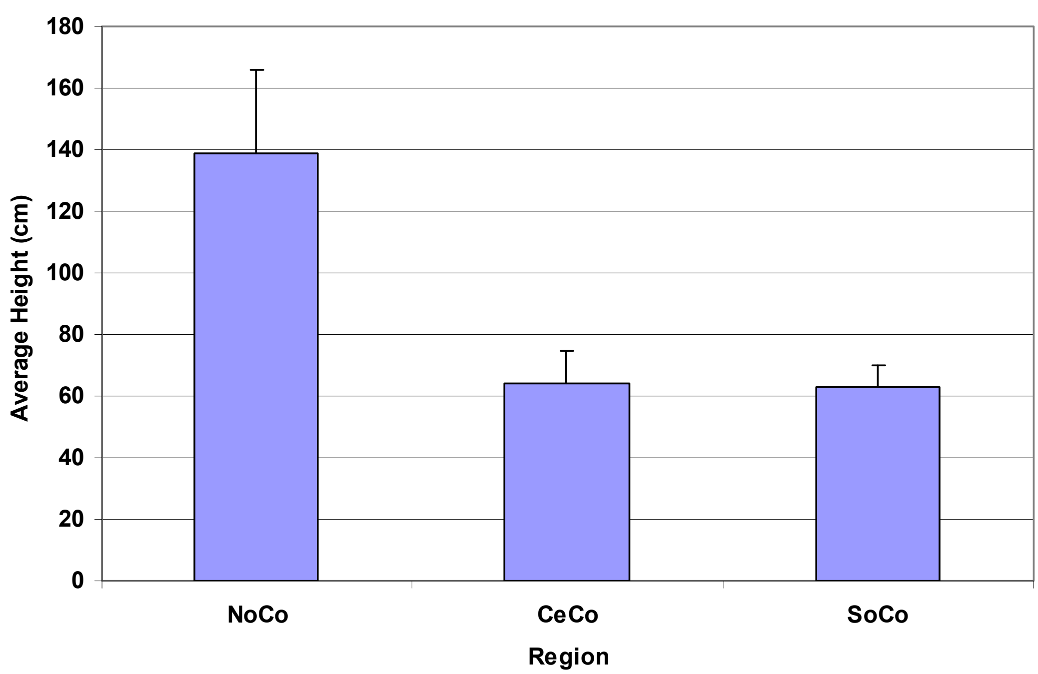

Figure 8: Average marsh stem height by region. Error bars represent one standard deviation.

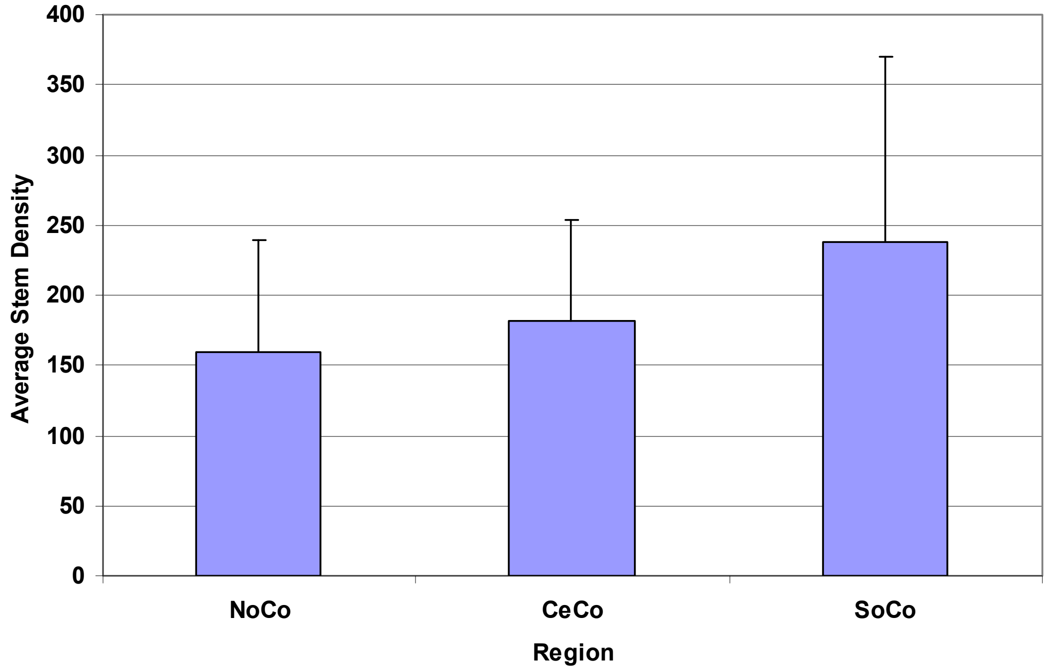

Figure 9: Average stem density by region. Error bars represent one standard deviation.

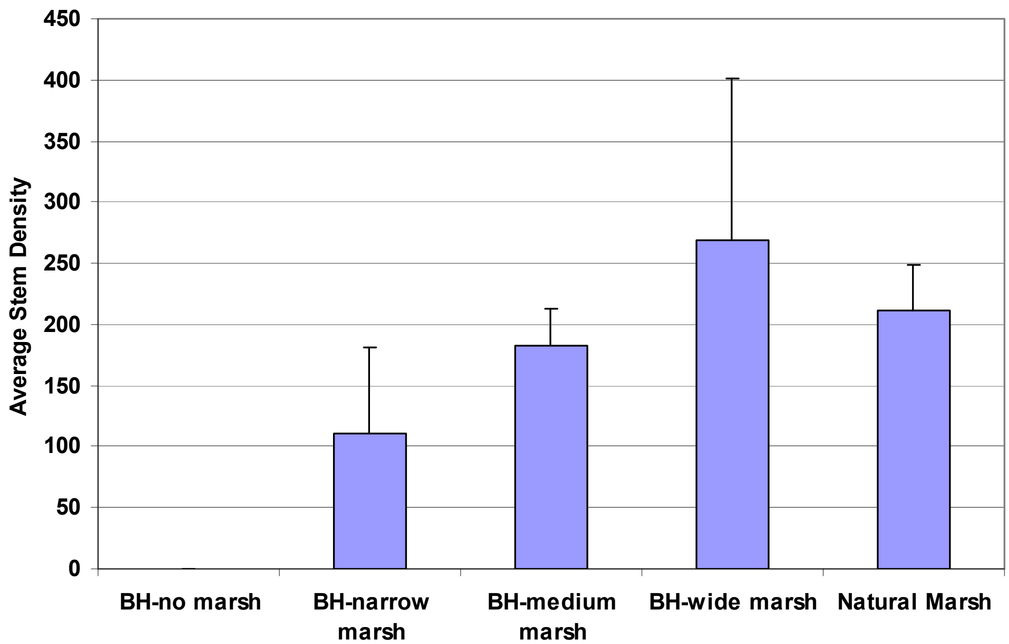

Figure 10: Average stem density by marsh type. Error bars represent one standard deviation.

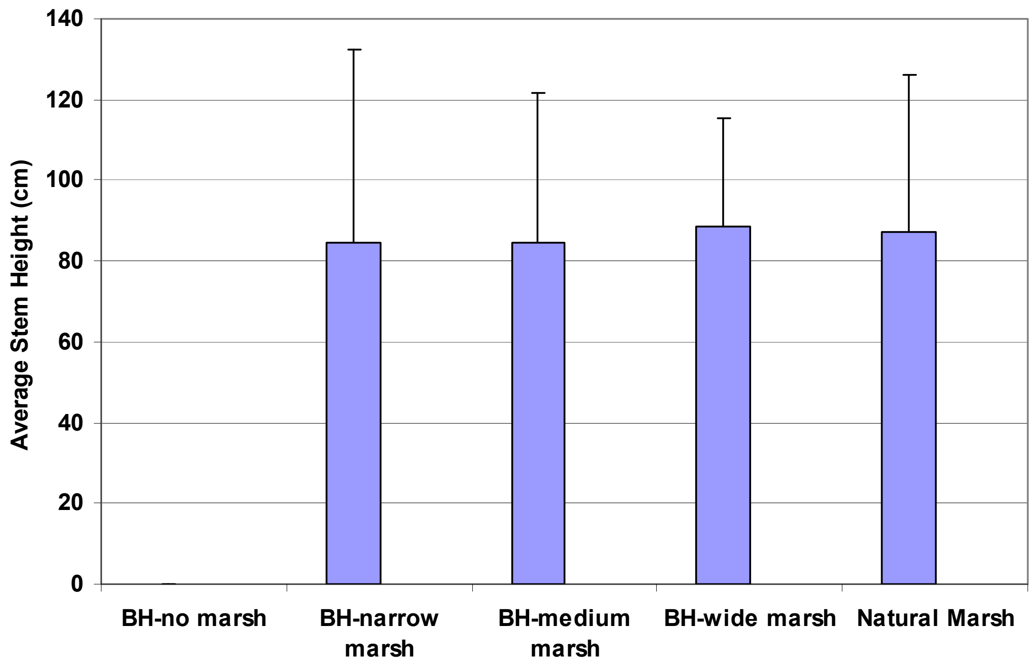

Figure 11: Average stem height by marsh type. Error bars represent one standard deviation.

Waves:

Results from sensors deployed as seen at the CeCo Site 3 on the north shore of Bogue Banks are shown in Figure 12. Although there is a neighborhood boat ramp at the site, the majority of the wave energy at this site is due to wind-driven waves across Bogue Sound. Relatively small waves were observed at this site during instrument deployments in October 2009 and November 2009 (Figure 12). Generally speaking, wave energy measured offshore by the Vector is highly correlated with wave energy at the seawall, but less correlated with wave energy in the marsh. The highest wave energy was observed during periods of sustained wind events (> 6 knot winds out of the north). Whether the marsh was effective in dissipating wave energy (Figure 12) was dependent on the stage of the tide. The first wind event (~Julian Day 325) was during high tide, and the marsh reduced significant wave energy by ~13% and maximum wave height by ~16% relative to the seawall. However, during wind events at lower tidal stages (~JD 327) there was no difference in wave energy in the marsh and at the seawall because the very shallow water depths prevented the formation of large waves. Lower wave energy at the bulkhead base behind the fringing marsh was a function both of wave attenuation by the marsh, and by the higher elevation of the sediment surface, so that the sensor was out of the water during substantial periods of the tide.

The NoCo site did not experience substantial wave energy during either deployment. In March the site only experienced significant wave heights (Hsig) of 5cm or greater when relatively high tides combined with sustained winds greater than 7 m/sec (e.g., Julian Day ~81.5 to ~82.875, shaded in gray on Figure 13.). Qualitatively the same type of wave patterns were observed in June 2010; NoCo1 had very low wave energy, with the biggest waves (Hsig 5 cm or greater) during high water levels combined with sustained winds (June 27-29; data not shown.). During both deployments, higher wave energy was usually recorded at the seawall base than at the lower marsh edge, but this was a difference of only a few cm and this effect was not as apparent during the period of highest inundation and wave energy (shaded area Figure 13). The sensor at the bulkhead base behind the marsh was at a higher elevation and therefore usually out of the water, so little data was obtained from that location.

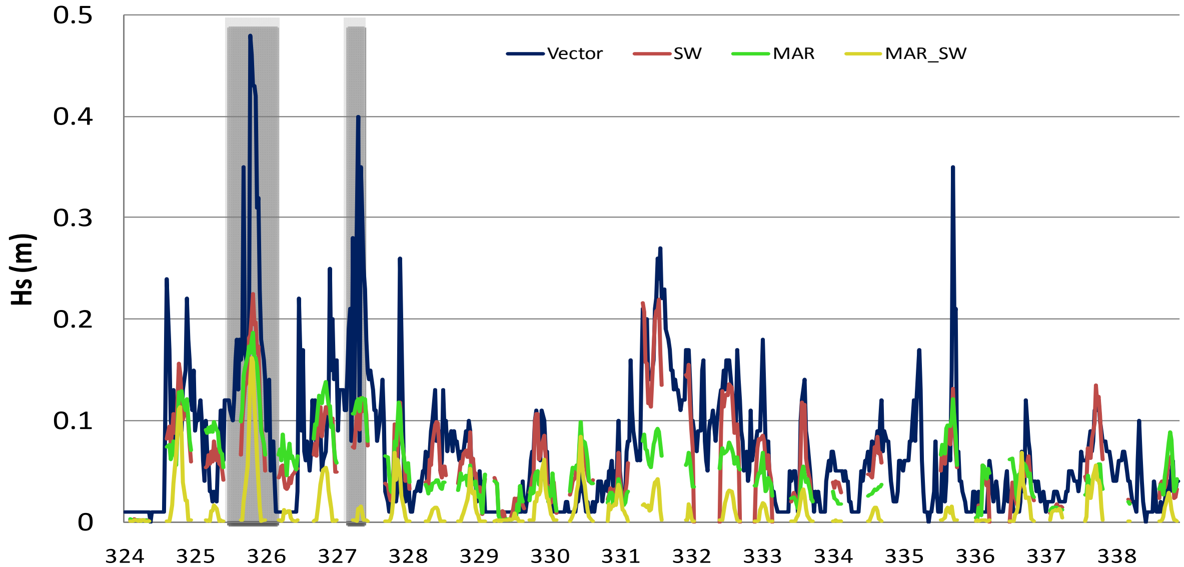

Figure 12: Significant wave height (Hs) at CeCo3 from November 19-December 4, 2009. Wave energy was highest during sustained wind events (gray bars).

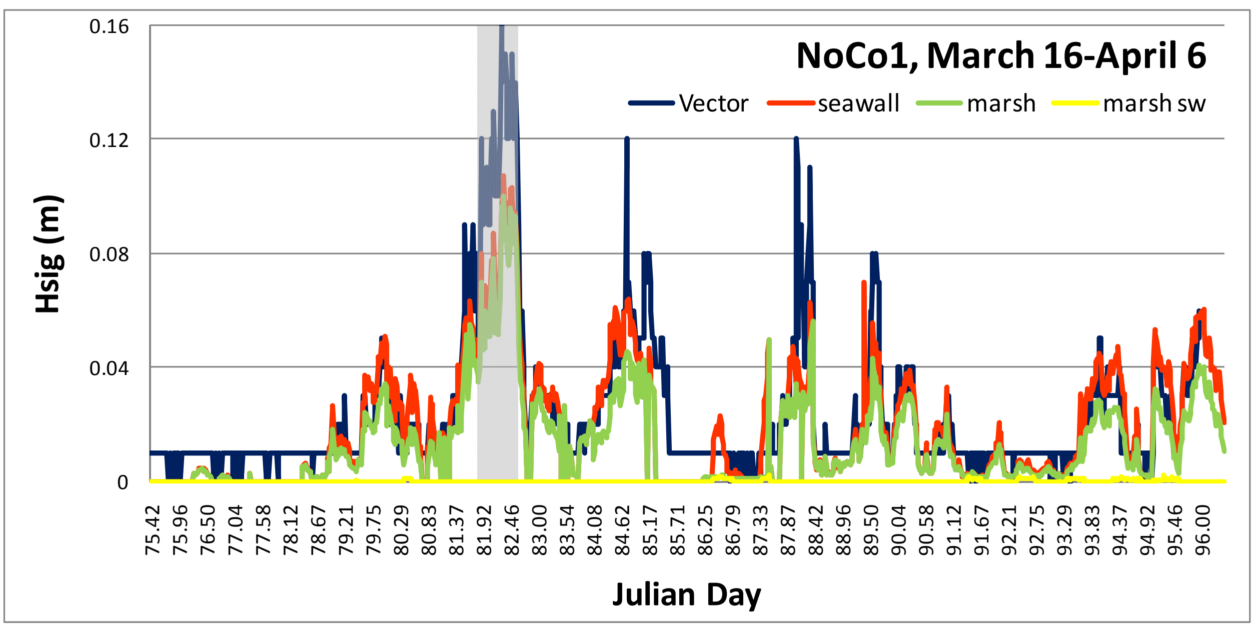

Figure 13: Significant wave height (Hsig) at Northern Coast site recorded March 16-April 6, 2010. The Vector data was collected approximately 35 m offshore, while the seawall and marsh sw (seawall) sensors were within 1 m of a bulkhead base. The marsh sensor was located approximatly 2.5 m inside the lower marsh edge, and 4 m from the bulkhead base.

The SoCo sites at St. James Plantation (sites 1 and 2) and Oak Island (site 3) both show significant wave heights about the same magnitude of those at CeCo (range 0 – 0.20 m). The steeper slope of these sites, combined with the distance between sites, precluded our ability to obtain clear evidence of the wave attenuation role of fringing marsh, as the signal could be obscured by the tide, and we could not accurately record the offshore signal at both sites with a single Vector. The SoCo sites are located along a portion of the Intracoastal Waterway which is less than 500 m wide. The sites therefore lack sufficient fetch for substantial wind-waves to develop—instead, boat wakes are the primary source of wave energy at these sites. The impacts from boat wakes become readily apparent when the maximum wave heights are plotted along with significant wave heights –maximum wave energy resulting from boat wakes is often about three times as high as the measured significant wave height (Figure 14). In contrast, at CeCo Site 3, boat wakes (as estimated by maximum wave height) were more typically only 1.5x the significant wave height (Figure 15). The CeCo deployment was made over the Memorial Day weekend, specifically to try and capture the effects of boat wakes. However, the SoCo sites have a deeper channel closer to the shoreline, allowing bigger boats to move at high speed and propagate bigger wakes into the marsh. The boat ramp at the CeCo sites is only accessible to smaller vessels with shallower drafts.

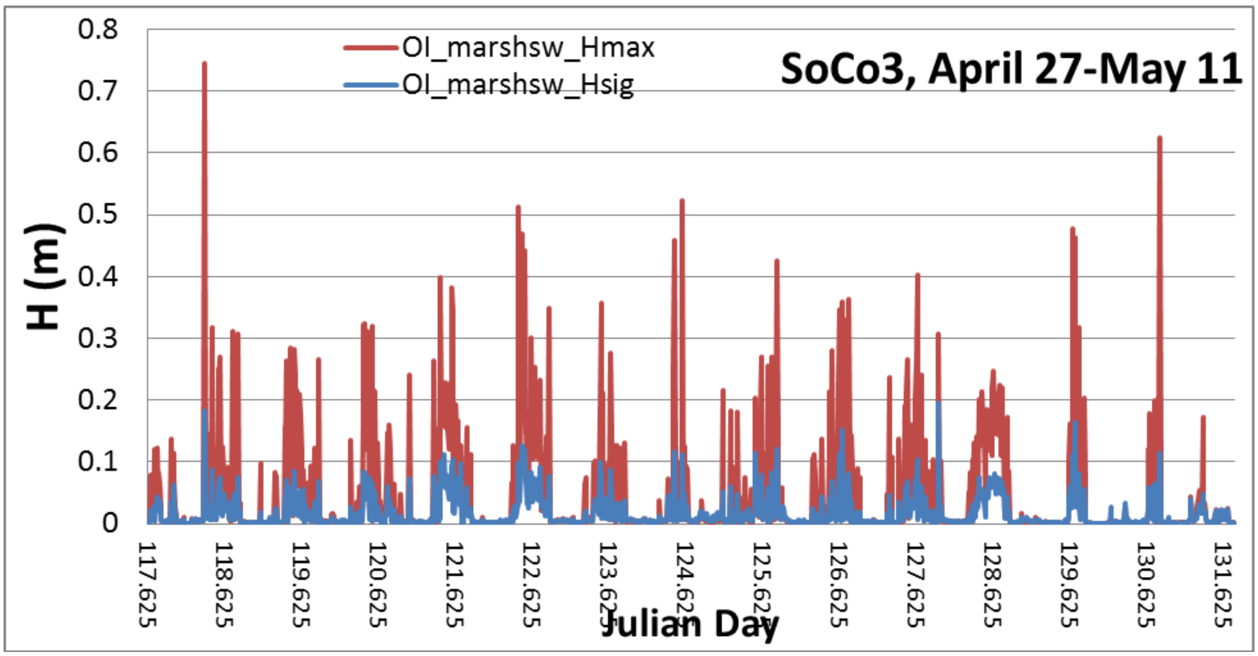

Figure 14: Wave heights recorded at the base of the bulkhead behind fringing salt marsh at SoCo Site 3. The red line illustrates maximum wave height and blue line represents significant wave height (average wave heights > 5 cm) during the sampling period.

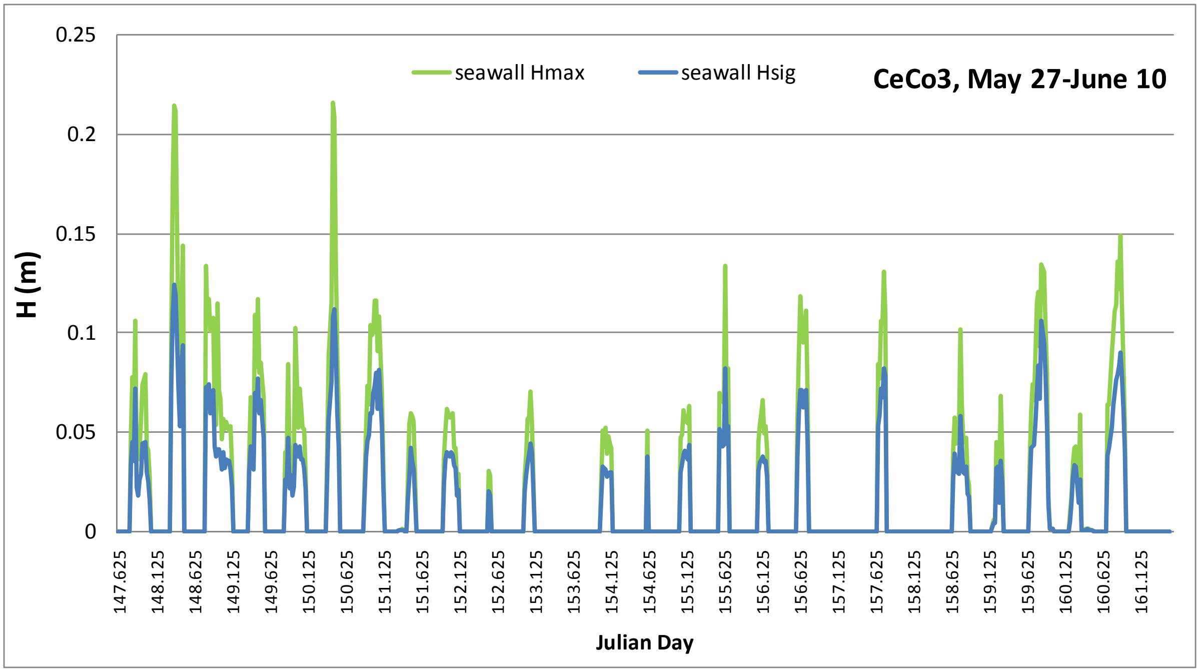

Figure 15: Wave heights recorded at the base of the bulkhead at Central site 3. The green line illustrates maximum wave height and blue line represents significant wave height (average wave heights > 5 cm) during the sampling period.

Hurricane Earl passed offshore of Beaufort in September 2010, providing an opportunity forsampling during a storm event. Local winds within Bogue Sound exceeded 20 mph for approximately 12 hr on September 2-3. In anticipation of this storm, wave sensors were installed at site CeCo3 on September 2 before 9am. Significant wave heights (Figure 16) and maximum wave heights (Figure 17) were on average approximately 3x greater against the seawall than within the marsh. The higher waves at the seawall were likely due to a combination of wave reflection off the hard structure and a lack of wave attenuation because there was no marsh in front of the bare seawall. The tide was lowest between 11pm on Sept. 2 and 1am on Sept. 3, creating the dip in the graph. However, the tide came back in during the peak winds of the storm (1am-3am Sept. 3), at which time wave energy also peaked.

Waves discussion:

The ability of fringing marshes to attenuate wave energy, and the quantity and source of wave energy, varied across the geographic range of the study sites. The NoCo sites, although exposed to a long fetch, experienced relatively little wave energy, perhaps in part due to the extensive seagrass bed and shallow bar located offshore. During both deployments there was little difference in wave energy between the bare seawall and the marsh, even during the one brief interval when a prolonged wind event occurred.. The wind event did generate a substantial amount of wrack and debris in both the marsh and at the seawall. During our deployments, the surface elevation of the base of the bulkhead behind the fringing marsh was high enough that it was rarely submerged, so that the wave sensor rarely recorded wave height. The buffering effect of the marsh might only be effective during a storm event bringing a significant storm surge.

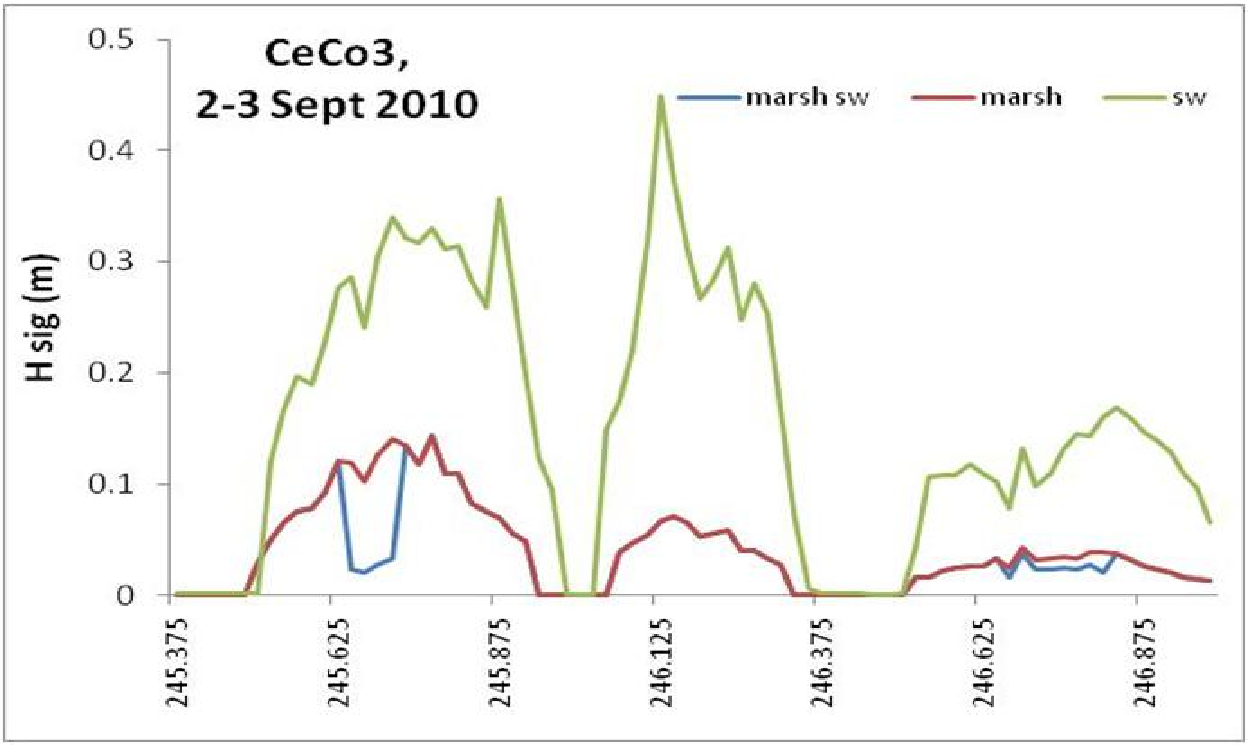

Figure 16: Significant wave heights at CeCo3 during Hurricane Earl. The x-axis is Julian Day.

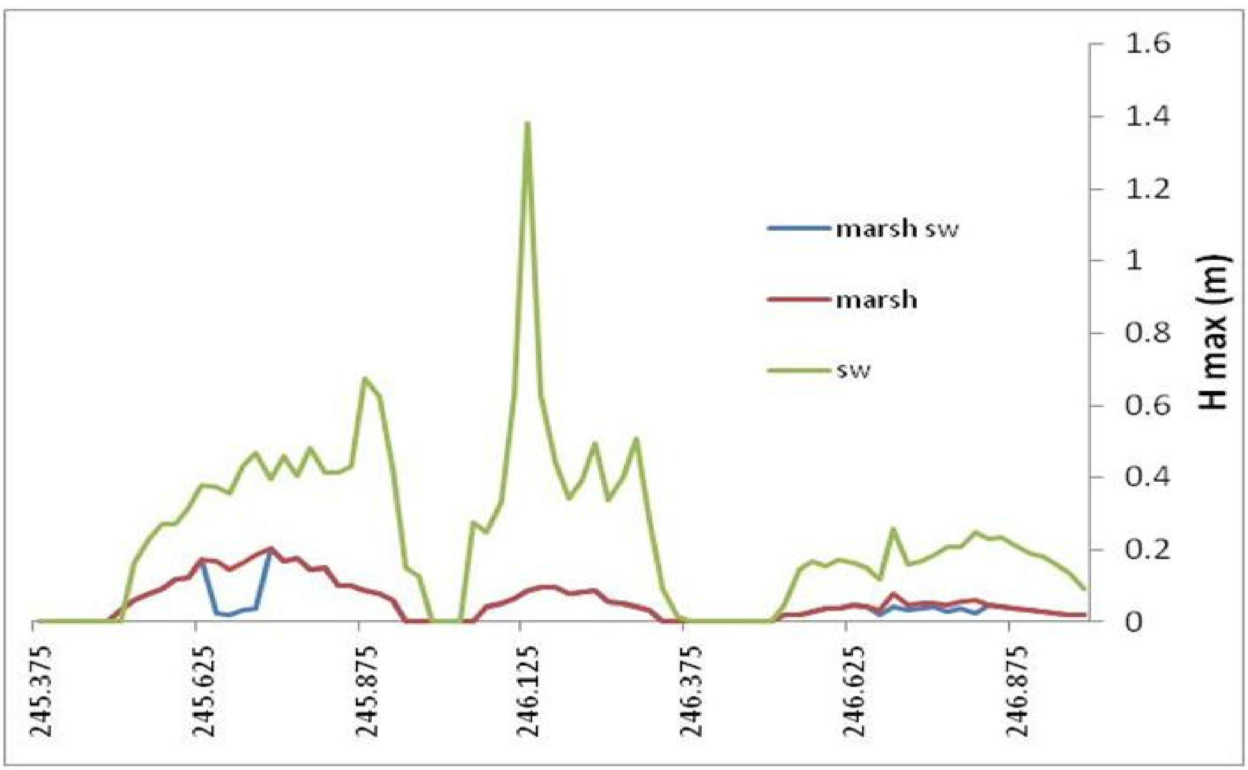

Figure 17: Maximum wave heights at CeCo3 during Hurricane Earl. The x-axis is Julian Day.

In the central part of the coast, the marsh slope is slightly steeper, and the vegetation is dominated by *Spartina alterniflora*. Significant wave heights at the CeCo site often exceed 5 cm, in contrast to the NoCo sites. Wave attenuation by the marsh fringe was evident during several deployments, and wave energy at the bulkhead base behind a fringing marsh was always much less than that experienced by a bulkhead with no marsh fringe. The ability of fringing marsh to attenuate wave energy was especially evident during a brief deployment which coincided with the passage of Hurricane Earl in September 2010, when the bulkhead sensor recorded wave heights 2-3x higher than the sensor located several m inside the fringing marsh, and the bulkhead base behind the marsh fringe had even greater reductions in wave energy.

In the southern part of the NC coast, tidal ranges are greater, marsh slopes are steeper, and study sites were located along a fairly narrow (> 500 m wide) portion of the Intracoastal Waterway. Our sampling scheme was somewhat complicated by the distance between sites, which precluded using a single offshore sensor as a control for all marsh and seawall sensors, and by the topography of the sites which often sometimes left the marsh and/or seawall sensors out of the water. However, the data clearly showed that boat wakes, rather than wind waves, dominated the wave energy at these sites. The ability of marsh to attenuate waves was not as apparent at these sites due to differences in sensor elevation and thus submergence. Marsh elevation, edge topography and vegetation density and height have all been shown to have an effect on wave attenuation (Moller and Spencer 2002, Moller 2006). Our results are consistent with previous reports that significant attenuation (50-90%) of wave energy can occur within 10 m of marsh vegetation (Knutson 1988, Moller and Spencer 2002).

Nekton abundance:

The results from sampling in 2009 at Pine Knoll Shores and in 2010 at Pine Knoll Shores, Kitty Hawk, and Wilmington reveal several patterns in nekton abundance as a function of sampling season and marsh width. There are two apparent differences between sampling gear type and season in nekton abundance. First, in the spring the fyke nets caught a greater abundance of nekton than gill nets regardless of marsh width (Figures. 18A, 19A, 20A, 21A). Second, in the fall the abundance of total nekton caught by fyke and gill nets was less than in the spring (Figures. 18B, 19B, 20B, 21B).

Results from fyke net sampling at the CeCo site at Pine Knoll Shores indicate a linear relationship between increasing marsh width and increasing nekton abundance in the spring of 2009 (Figure 18A) and spring of 2010 (Figure 19A). Nekton abundance from fyke net sampling also increased with marsh width at NoCo sites in Kitty Hawk (Figure 20A) and SoCo sites in Wilmington (Figure 21A), but showed greater variability in abundance and seasonal differences in the strength of the effect of marsh width. Across all sites, fyke net samples taken in the spring reflected increasing nekton abundance as a response to increasing marsh width (Figures 18A, 19A, 20A, 21A). Results from sampling conducted in the fall of 2009 at Pine Knoll Shores and in the fall of 2010 at Pine Knoll Shores, Kitty Hawk, and Wilmington did not reveal clear patterns in nekton abundance across marsh treatments (Figures 18B, 19B, 20B, 21B).

In each region the natural marsh and bulkheaded wide marsh were of similar widths. Despite this similarity there is an apparent seasonal effect of a bulkhead on nekton abundance at two sites. In other words, the magnitude and direction that the bulkhead depresses nekton abundance depends upon sampling season and region. Comparisons of wide marshes with bulkheads and natural marshes without bulkheads indicate that in the spring a higher abundance of nekton was caught in fyke nets at the natural marsh than at the wide marsh with a bulkhead at

Kitty Hawk (Figure 20A) and Wilmington (Figure 21A) but not at Pine Knoll Shores (Figures 18A, 19A). A similar pattern appears in the fall at Kitty Hawk when a higher abundance of nekton was caught in fyke nets at the natural marsh sites than at the wide marsh with a bulkhead (Figure 20B). In contrast, the number of nekton caught by fyke net sampling at the wide marsh with a bulkhead was greater than at the natural marsh in the fall at Wilmington (Figure 21B).

During neither season did gill net sampling conducted 10 m below the lower marsh edge at each site reveal indication of a relationship between marsh width and nekton abundance at any site (Figures 18-21). Additionally, the abundance of nekton caught below the natural marsh site did not differ from the abundance caught below the similarly wide marsh with a bulkhead.

We combined data from all three geographical regions and seasons to analyze changes in total nekton abundance (summing the catches of 4 replicate net sets, 2 during day and 2 at night) as function of marsh width for marshes with bulkheads. Figures were created for each gear type separately (Figure 22). Regression analyses of the total abundances of nekton caught in fyke nets and gill nets across marshes with bulkheads show a significant relationship between nekton abundance and marsh width for fyke net catches ($p=0.02$) but fail to show a significant relationship for gill net catches ($p=0.28$) (Figure 22A vs. 22B). The statistical power of these tests is limited by error variance introduced by regional differences and by limited numbers of data points. Nevertheless, it seems clear that no relationship exists between marsh width and gill net catch, whereas the fyke net catch does suggest a repeatable and real pattern of increase in nekton use with marsh width. The presence or absence of a bulkhead does not appear to influence nekton found on the marsh or seaward of the lower marsh margin

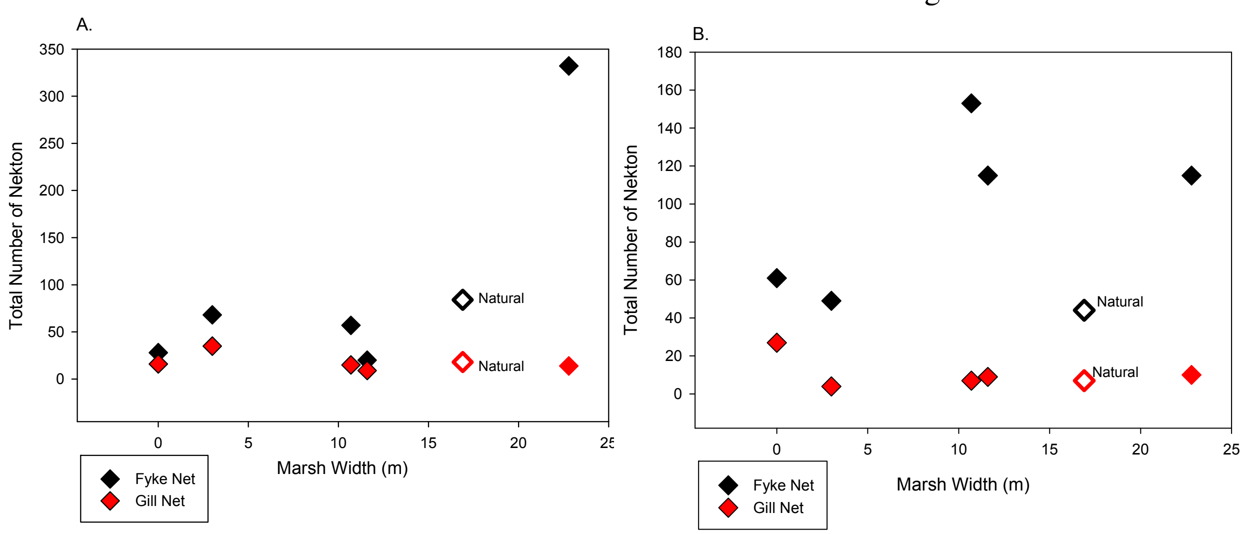

Figure 18: The total number of nekton as function of marsh width (m) presented by sampling net type at CeCo sites. Each point represents the sum of four net sets, two day sets and two night sets, for fyke and gill nets. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. Gill nets were deployed at high tide for three hours at a position 10 m seaward of the lower marsh margin. A. Spring of 2009. B. Fall of 2009.

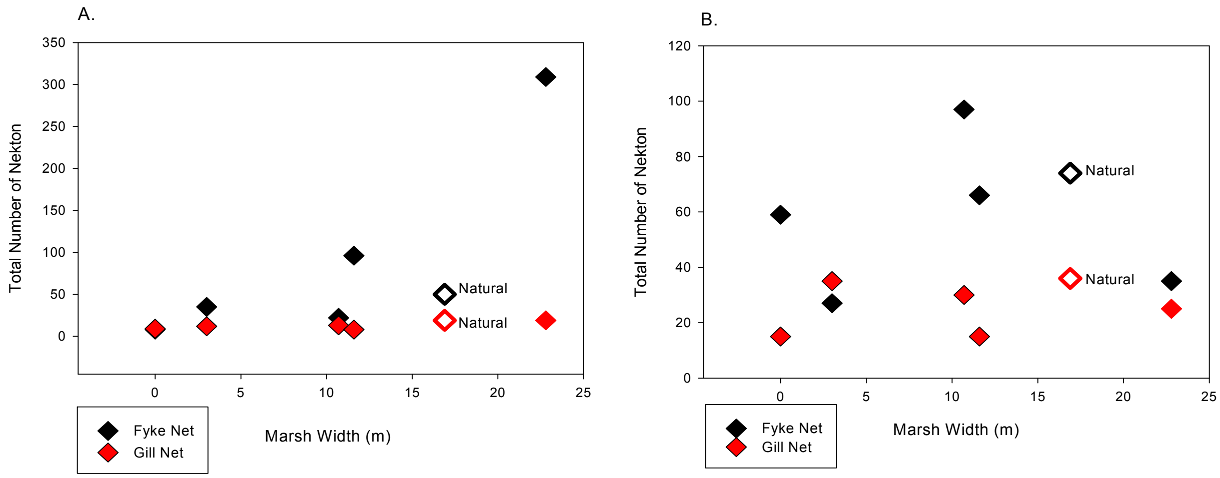

Figure 19: The total number of nekton as function of marsh width (m) presented by sampling net type at CeCo sites. Each point represents the sum of four net sets, two day sets and two night sets, for fyke and gill nets. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. Gill nets were deployed at high tide for three hours at a position 10 m seaward of the lower marsh margin. A. Spring of 2010. B. Fall of 2010 .

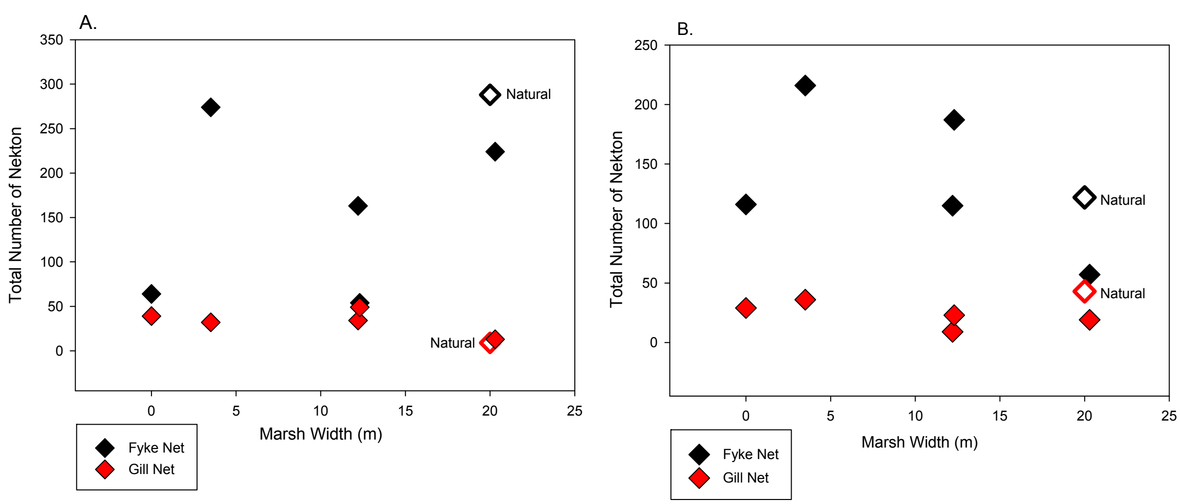

Figure 20: The total number of nekton as function of marsh width (m) presented by sampling net type at NoCo sites. Each point represents the sum of four net sets, two day sets and two night sets, for fyke and gill nets. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. Gill nets were deployed at high tide for three hours at a position 10 m seaward of the lower marsh margin. A. Spring of 2010. B. Fall of 2010.

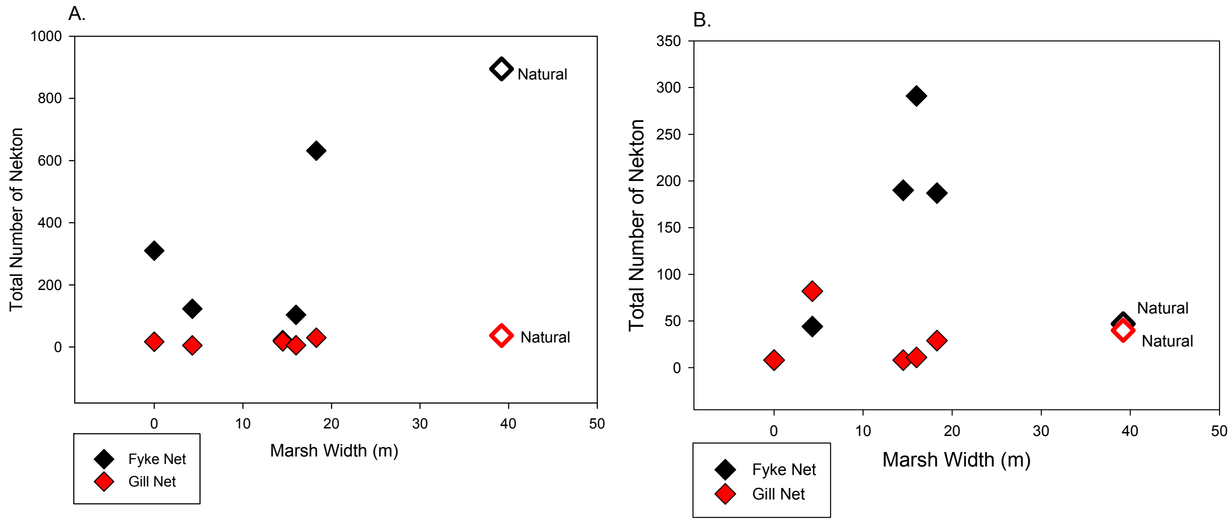

Figure 21: The total number of nekton as function of marsh width (m) presented by sampling net type at SoCo sites. Each point represents the sum of four net sets, two day sets and two night sets, for fyke and gill nets. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. Gill nets were deployed at high tide for three hours at a position 10 m seaward of the lower marsh margin. A. Spring of 2010. B. Fall of 2010.

Nekton density:

One advantage of using fyke nets to sample water draining from a marsh as the tide ebbs is the ability to relate the organisms captured to the area of marsh that was drained. We calculated the density of nekton per m^2 of marsh using the average abundance of individuals caught by fyke nets (averaged over 4 replicate net sets, 2 during day and 2 at night) and the marsh area of each treatment site. Area was determined as the product of the width of marsh and the opening size of the fyke net (10 m).

In Pine Knoll Shores the average density of nekton computed from fyke net samples was highest at the shortest marsh width for both spring 2009 and spring 2010 (Figure 23AB). The density declined steeply as marsh width increased at the treatment sites with bulkheads. Fyke net sampling in Pine Knoll Shores during fall of 2009 and 2010 also revealed a pattern of declining nekton density with increasing marsh width (Figure 23AB). At Kitty Hawk, sampling in spring and fall produced sharply declining nekton density with increasing marsh width similar to Pine Knoll Shores (Figure 23C). In contrast to the other two sites, Wilmington produced data showing no evident pattern of changing density of nekton with marsh (Figure 23D). Unlike at Pine Knoll Shores and Kitty Hawk, density of nekton in fyke net catches from the natural marsh was far higher in spring than in fall (Figure 23D).

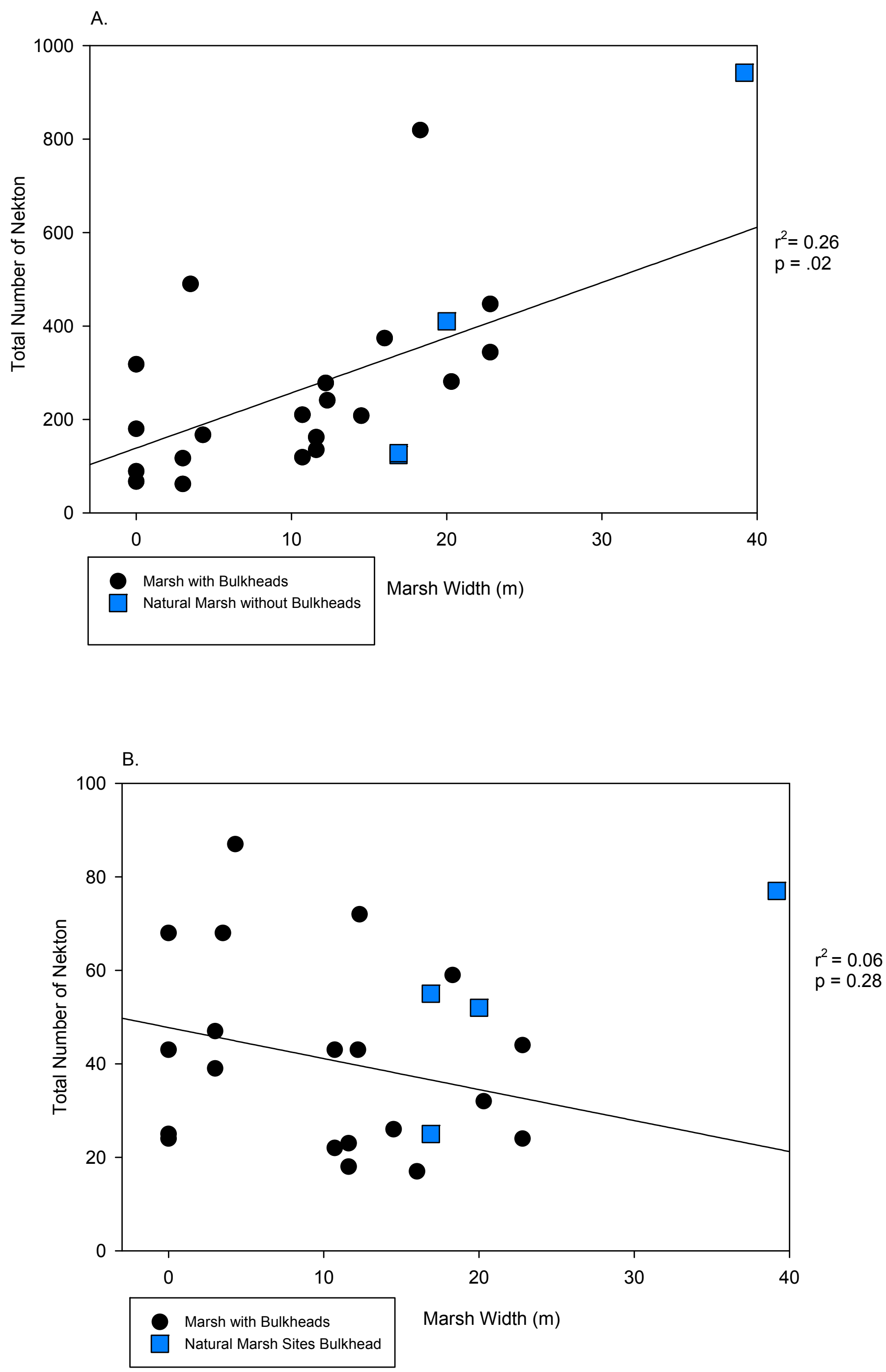

Figure 22: The total number of nekton as function of marsh width (m). Graphs are result of combining the data from all geographical regions and seasons in 2009 and 2010. Black points represent nets set at marshes with bulkheads and blue points represent the nets set at natural marshes. Each net set is the sum of four net sets, two day sets and two night sets. The regression lines represent the average nekton abundance caught at marshes with bulkheads. The p-values are from nonlinear regression analyses excluding data from the natural marshes. A. Fyke nets. B. Gill nets.

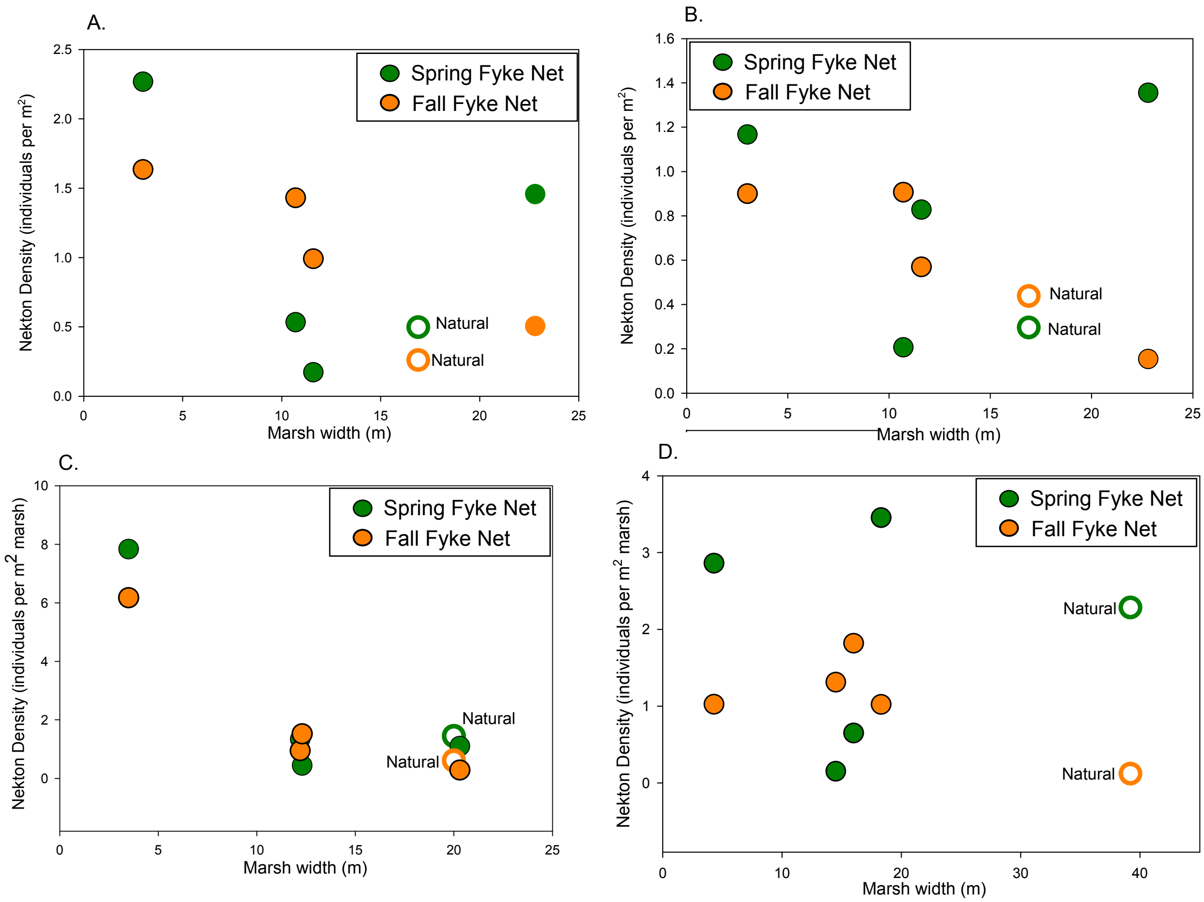

Figure 23: The nekton density as function of marsh width (m) presented by season for fyke net samples from each region across the years 2009-2010. Each point represents the sum of four net sets, two day sets and two night sets. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. A. Pine Knoll Shores sampled in 2009. B. Pine Knoll Shores sampled in 2010. C. Kitty Hawk sampled in 2010. D. Wilmington sampled in 2010.

Nekton trophic levels:

The mean trophic level of nekton using the marsh itself as determined from fyke net catches or occupying the shallow subtidal 10 m below the lower marsh edge level as determined from gill nets was determined by calculating the average trophic level for each species based on literature information on diet, multiplying this average trophic level by the numbers of individuals of this species in the catch, summing this product over all species in the catch, and dividing by the total number of all nekton caught. This calculation results in an average trophic level weighted by differing relative abundance of each species.

During spring and fall, mean tropic level of nekton was greater in gill net catches than in fyke net catches, consistent with our assumptions about differences between those species occupying the marsh service and those in permanently flooded areas below the marsh (Figure 24). Mann-Whitney Rank Sum tests revealed statistical significance of both of these differences ($p = 0.001$ in spring and $p = 0.001$ in fall).

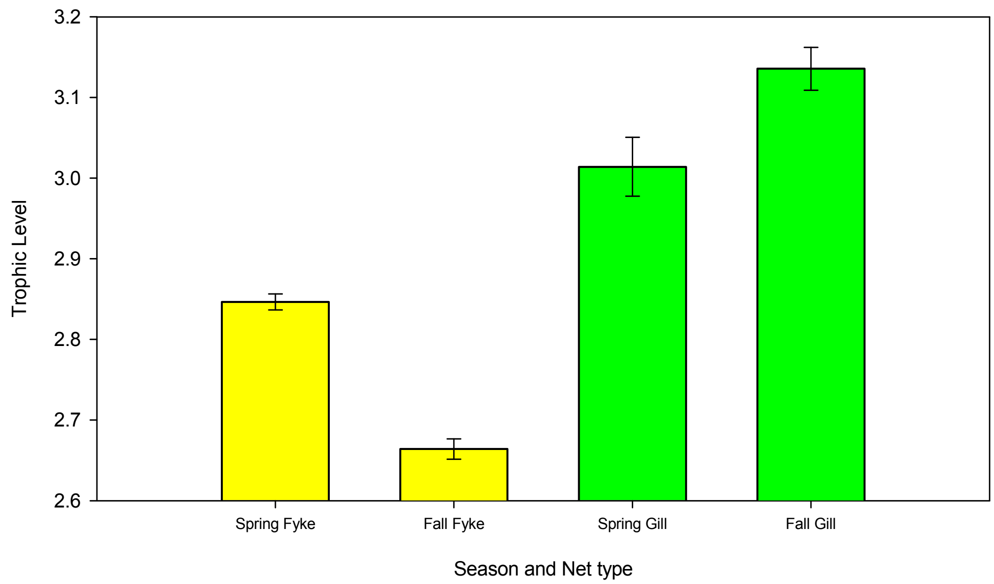

Figure 24: The average trophic level of nekton caught by fyke and gill nets. Each column represents the seasonal catch with site and region combined. Fyke nets were deployed at high tide for six hours to catch the falling tide and nekton draining from the marsh. Gill nets were set at high tide for three hours at a position 10 m seaward of the lower marsh margin. Trophic levels were assigned to each species of nekton ranging from 2 (purely herbivorous) upwards, using literature reviews and gut content analysis.

Bird abundance:

The total abundance of birds observed in the marsh or in the shallow subtidal fringe below the marsh edge was computed by adding observations made on each of the six successive days of counting for each season and then also summing totals over the two seasons for each site. The resulting distribution of points did not reveal any compelling effect of marsh width on bird abundance in any region (Figure 25). In all three geographical regions, the bulkheaded shorelines lacking marsh habitat had relatively low counts of birds, and had the fewest of any shoreline treatment at CeCo (Pine Knoll Shores) and SoCo (Wilmington) (Figure 25).

Bird trophic guilds:

Birds observed in the marsh (including the shallow subtidal fringe just below) were categorized into trophic guilds based upon their feeding behaviors. We summed all bird counts by trophic guild for each marsh width, combining all three geographic areas (Figure 26). At the bulkheaded shorelines that lacked marsh, the only guild represented was shorebirds were observed and their numbers were low. In marshes with widths of 3-4 m, total counts were substantially higher and shorebirds comprised the most abundant guild (Figure 26). Wading birds (herons and egrets) exhibited generally increasing abundances with increasing marsh widths, comprising over half the bird counts on the natural, unbulkheaded marsh of 20-40 m in width.

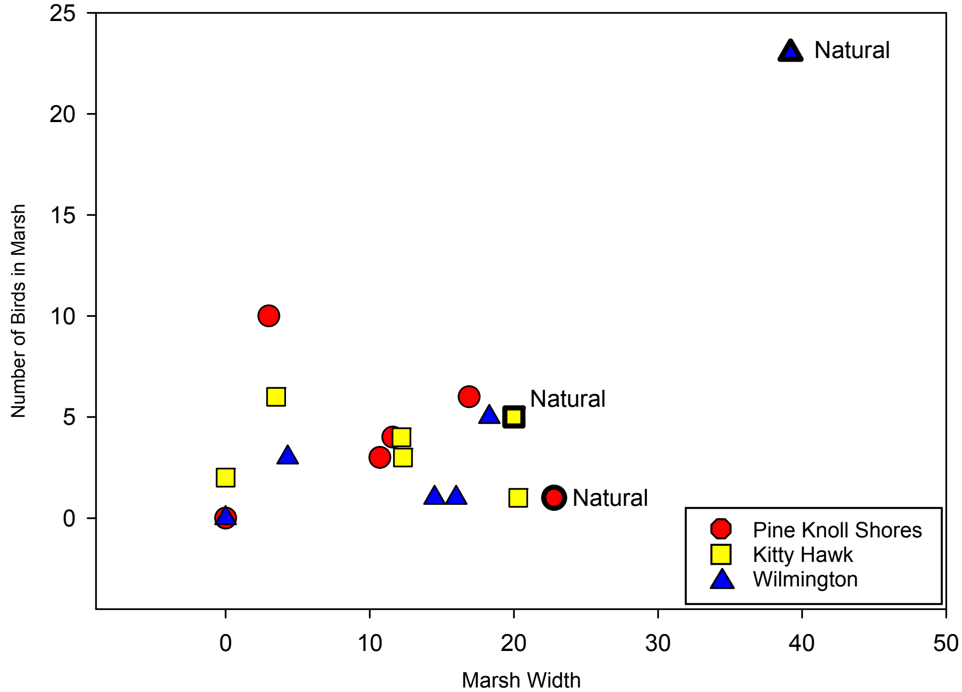

Figure 25: The number of birds observed in the marsh for each region sampled. Abundance includes the only birds observed in the marsh or in the shallow subtidal fringe below the marsh edge.

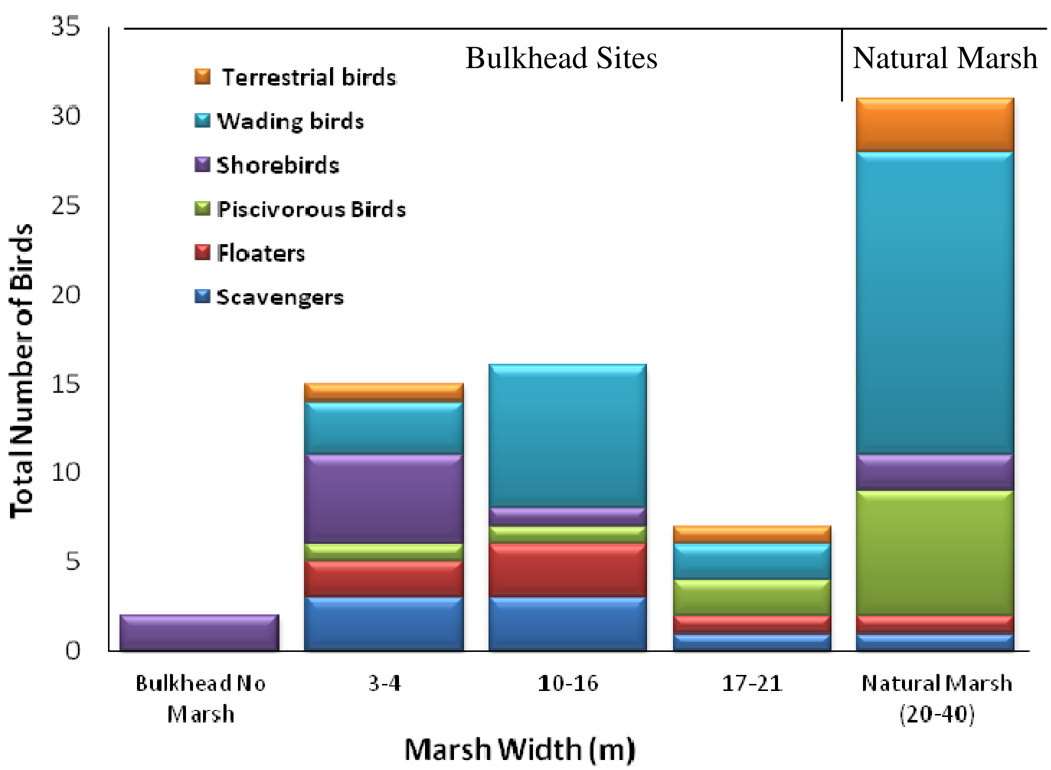

Figure 26: Distribution of bird group guilds by marsh width. Data combined from all three regions.

Nekton discussion:

Our study of the use of coastal marshes by upper trophic levels confirms the accepted wisdom that *Spartina* marshes are used by an abundance of fish, crabs, shrimps, and birds. High levels of nekton use were similar at all three regions sampled. More importantly, our study of how use varies quantitatively with marsh width on bulkheaded shores as a means of projecting future scenarios under conditions of a higher sea-level stand and widespread bulkhead implementation reveals clear indications that the ecosystem service of marshes as habitat for nekton and some valued birds will diminish as marsh area shrinks. Our sampling of nekton reveals clear and largely consistent patterns of lower total abundance of nekton using the marsh surface habitat as marsh width declines. This implies less production of forage fish and crustaceans for higher-level predators, which include several species of commercially and recreationally important fish as well as sea birds and marine mammals. In other words, the vital base of the estuarine and coastal marine food web is challenged by the joint effects of widespread use of bulkheads as a shoreline protection device and the impacts of rising sea levels.

Our assessment of the larger nekton inhabiting the shallow subtidal zone at 10 m below the lower margin of the Spartina marshes did not exhibit declining abundances of nekton as a function of marsh width immediately shoreward of the sampling sites. We demonstrated that this set of nekton occupies a trophic position higher on average than that of those organisms than utilize the marsh surface and move on and off of the marsh as the tide floods and ebbs. These nektonic species tend also to be larger on average and probably more mobile. That mobility combined with their feeding at higher trophic levels tends to disconnect them from a small-scale relationship with the nearby (10 m) coastal marsh habitat. Because many of these species prey upon the nekton that actually use the marsh surface, nekton abundance and production on the marsh is almost certainly important to the production of this more mobile suite of larger nektonic species, but our small spatial scale of sampling did not detect any indication of a difference with width of marsh immediately landward because of the high mobility of this suite of fish and crustaceans.

Calculation and analysis of the density of nekton per unit area of *Spartina* marsh habitat allowed use to evaluate the quantitative value of marsh of different widths in producing this ecosystem service of promoting production of fish and mobile crustaceans. First, we showed that even a narrow fringe of *Spartina alterniflora* marsh is effectively and abundantly used by the nekton in every geographic region. Second, we demonstrated that the density of nekton using the marsh is typically dramatically higher for thin marshes than for marshes of greater width. This phenomenon is best explained by a strong preference among nekton for occupying and foraging in the marsh edge near to permanent estuarine waters, such that as we sample ever wider marshes the average density of nekton falls because the marsh area further from the edge does not experience nearly as intense use by the nekton. By using pop-up nets that can target sampling at different locations within the salt marsh, Peterson and Turner (1994), Waley and Minello (2002) and Minello and Rozas (2002) have previously demonstrated this preference for occupying marsh edge, leading us to our interpretation of why nekton density typically is far greater for the thin marshes than the wider ones. The underlying causes of more intense use of marsh edges include the greater accessibility of edge habitat as the tide rises because the source of the fish and mobile crustaceans is the shallow subtidal zone. In addition, water levels will on average be higher near the marsh edge than higher up on the marsh platform, enabling swimming organisms to occupy the habitat and move freely within it. Furthermore, the duration of water coverage will be greater for the marsh edge, providing more time for nekton numbers to build up and more time of marsh habitat occupation. Sampling of the benthos on the marshes in our study revealed differences in those organisms that provide prey resources for the nekton, which can also influence the density of nekton. The lower edge of *Spartina* marshes in North Carolina is the zone where oysters (*Crassostrea virginica*) and marsh mussels (*Geukensia demissa*) are found in relatively high levels of biomass. These organisms provide prey for blue crabs, one component of the marsh nekton that we found in our samples, and also produce biodeposits, rich in organic matter and nutrients that can fuel primary production and support higher trophic levels that consume microphytobenthos that benefit from this biodeposition.

While our bird censuses failed to detect any difference on numbers of marsh and shallow subtidal birds as a function of marsh width, we did detect interesting information on how bird guilds changed with loss of marsh habitat. The shorebird guild was virtually the only one present in our censuses of the bulkheaded sites that lacked coastal marsh habitat. Shorebirds also comprised the majority of birds when marsh was present, but a more diverse suite of guilds was also represented including waders. Because of the secrecy of rails, the iconic bird of the salt marsh, our counts were inadequate to detect patterns of use of this species, Similarly, use by seaside sparrows and marsh wrens was not well determined by our limited sampling scope. Bird abundance was lower on shores lacking marsh entirely. Wading birds generally increased in abundance with increasing marsh width.

This study of higher trophic levels associated with *Spartina* marsh of varying widths revealed much of significance to coastal management. We showed clearly the value of even thin fringing marsh, implying that such thin strips of shoreline marsh habitat provide a valuable ecosystem service to higher trophic levels, justifying their aggressive protection. In fact, we discovered that the nekton density per unit area of marsh habitat was far greater in the thin marsh strips than in wider marshes even though total fish and crustacean use increased with rising marsh width. This pattern is best explained by recognizing the higher habitat value of the marsh edge. Our demonstration that nekton abundance declines as marsh width thins implies that the erosive action of sea-level rise in the presence of bulkheads promises serious loss of the marsh habitat services to higher trophic levels (MEA 2005). Bulkheads prevent transgression of the marsh up-slope and squeeze existing marsh habitat between a fixed wall and the rising waters of the estuary. Alternative means of shoreline stabilization, such as marsh sills, are urgently needed to protect the ecosystem services of coastal marsh and create climate-ready estuaries. This represents one of the most critically needed management adaptations to climate change.

Nutrient transformations:

At our study sites, DEN rates were not significantly different between marshes of different widths. However, there was a significant difference between sites with and without marsh (Figure 27). This trend holds true for both the CeCo and SoCo, but not NoCo. We can attribute this lack of trend in NoCo to overall low DEN rates due to differences in water chemistry. NoCo is fresher and has significantly lower concentrations of sediment organic matter (SOM, Figure 28). NoCo sites, regardless of marsh presence, have SOM contents comparable to unvegetated sites in CeCO and SoCo.

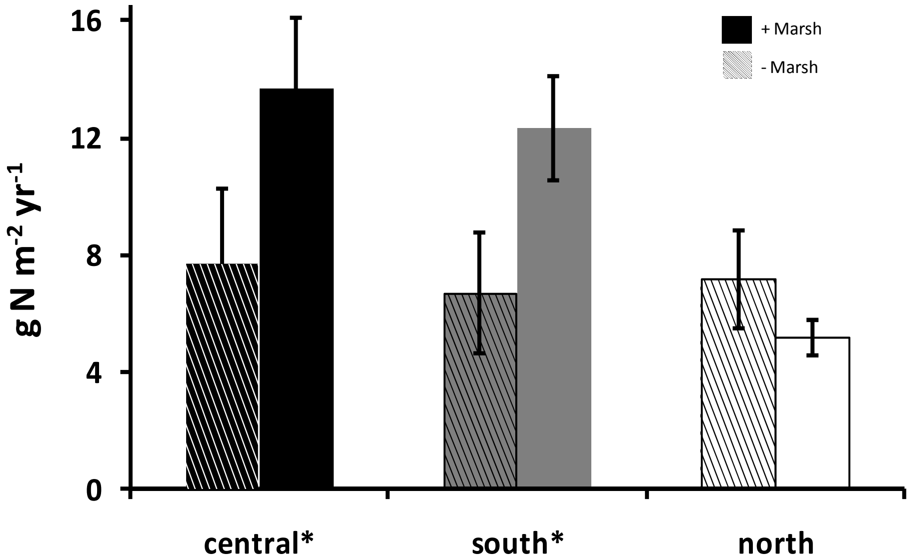

Figure 27: Comparison of marsh to no marsh DEN. + Marsh refers to sampling locations with any marsh vegetation. – Marsh refers to sampling locations without any marsh vegetation present.

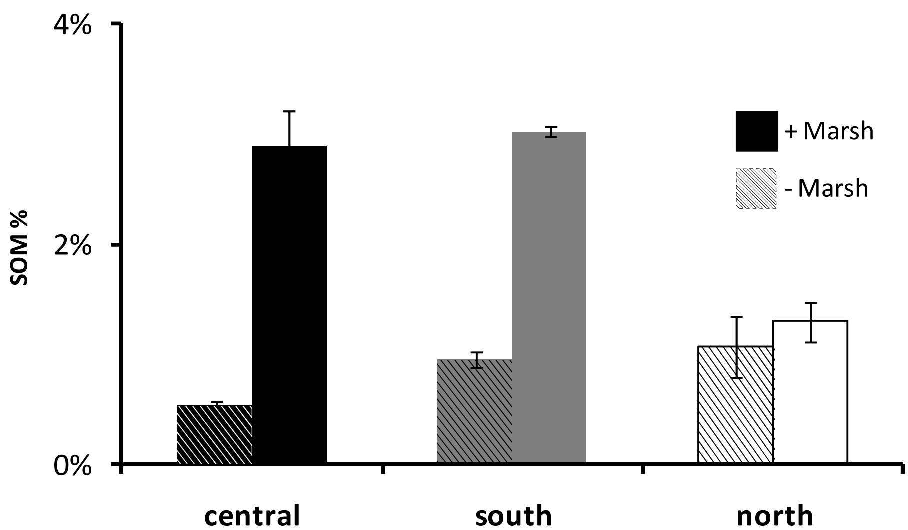

Figure 28: SOM content of each site for vegetated (+ Marsh) and unvegetated (-Marsh) sites.

Site width does play a vital role in the total quantity of N which can be removed from the ecosystem. DEN rates are normally standardized to area. When the rate is extrapolated to the entire width of the marsh, larger marshes provide more surface area for processing nitrogen. Therefore, as marsh width increases, the amount of nitrogen processed also increases (Figure 29).

DEN and sediment oxygen demand (SOD) were positively related (Figure 30). It has been shown that SOD is an indicator of organic matter (OM) quality (positively correlated). Therefore, we would expect DEN rate to increase as SOD increases. In addition, a positive linear relationship between SOD and DEN indicates coupled nitrification/denitrification. Points which do not lie on the line of best fit can most likely be attributed to DEN alone and not a coupled reaction.

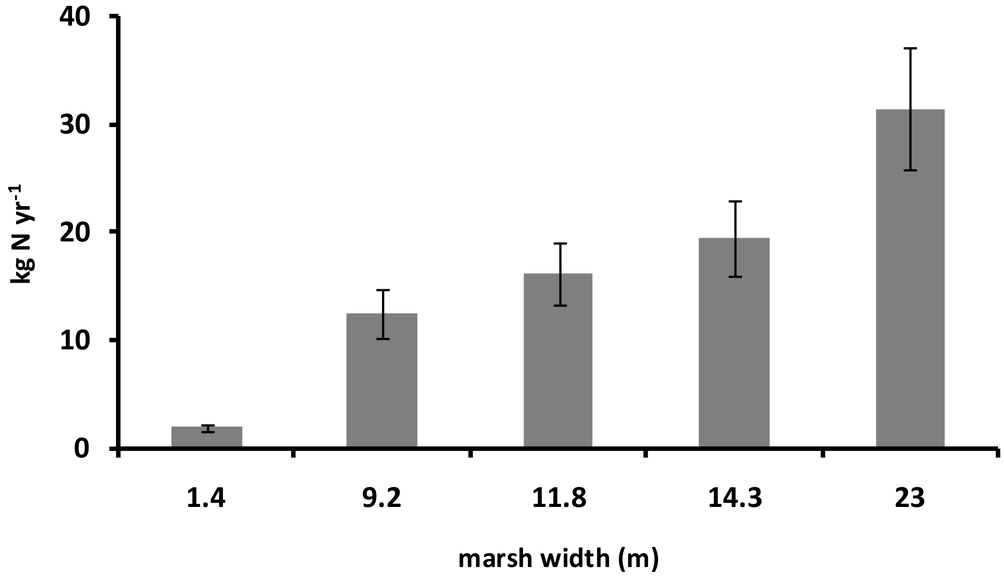

Figure 29: Kilograms of N removed by marshes in the central site per year. Each removal rate was calculated based on the "some marsh" (Figure 32) yearly summation.

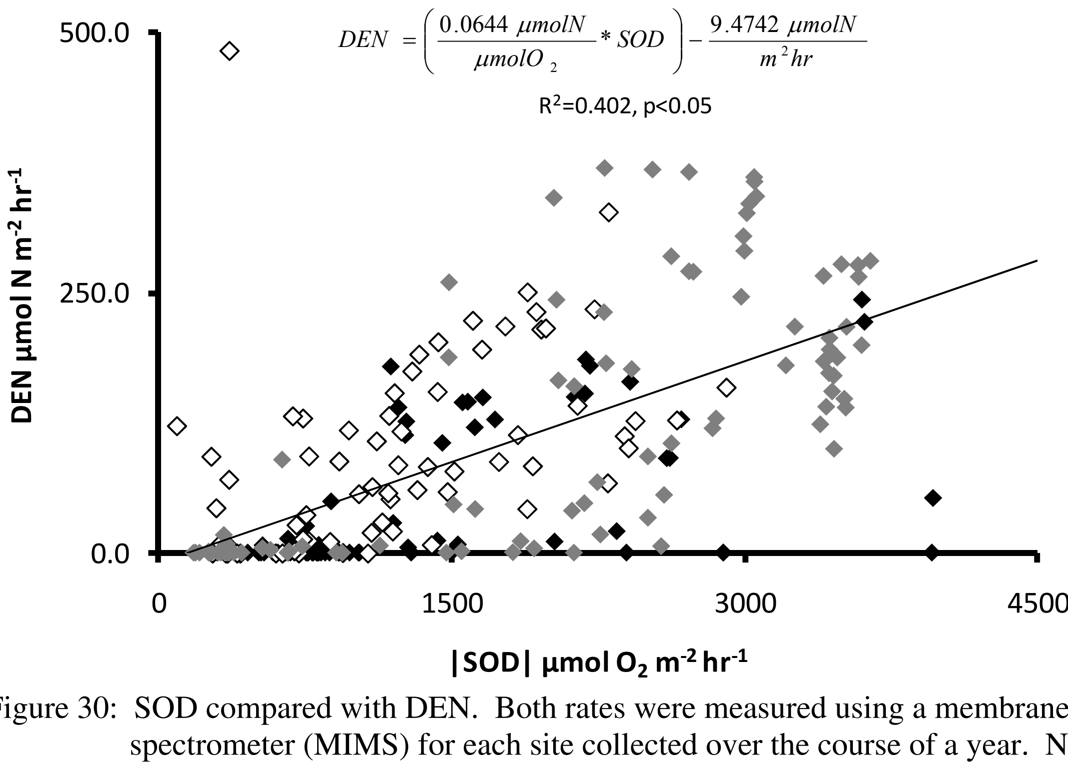

Figure 30: SOD compared with DEN. Both rates were measured using a membrane inlet mass spectrometer (MIMS) for each site collected over the course of a year. Note that the SOD reported is an absolute value because it is a demand.

Nutrient fluxes trended differently by season and region. In the north, fluxes were highest in the summer and lowest in the fall. In the southern and central sites, fluxes were generally lowest in the winter and highest in the summer. There were no observed trends between marsh width and nutrient fluxes. Relationships between DEN, SOD, and nutrient fluxes was highly dependent on region (Table 3).

Table 3: Summary of flux regressions. * indicates statistical significance.

Region	**Fluxes**	**NO_x**	**NH_3**	**PO_4^{3-}**
North	DEN	R^2=0.025, p=0.098	**R^2=0.594, p<0.05***	R^2=0.002, p=0.747
	SOD	R^2=0.004, p=0.582	**R^2=0.373, p<0.05***	R^2<0.001, p=0.897
Central	DEN	R^2=0.003, p=0.592	**R^2=0.099, p<0.05***	**R^2=0.123, p<0.05***
	SOD	**R^2=0.095, p<0.05***	**R^2=0.113, p<0.05***	**R^2=0.254, p<0.05***
South	DEN	**R^2=0.103, p<0.05***	**R^2=0.105, p<0.05***	**R^2=0.208, p<0.05***
	SOD	**R^2=0.152, p<0.05***	**R^2=0.079, p<0.05***	**R^2=0.090, p<0.05***

Data from CeCo showed there was a significant difference in nutrient concentrations between natural and bulkheaded sites as well as at sites with and without marsh (Figure 31). NO_{3-} concentrations were higher in the presence of bulkheads at sites with and without marsh. NH_{4+} concentrations were higher at bulkhead sites without marsh than natural sites. However, in the presence of marsh vegetation, there appeared to be no significant difference. All sites showed trends between ammonium flux and DEN and SOD. DEN and SOD were trended with phosphate flux in SoCo and CeCo. SOD was trended with NOx flux in CeCo and SoCo. However, only the DEN in SoCo trended with NOx flux. When measuring DEN, we include anaerobic denitrification and ANNAMOX or anaerobic ammonium oxidation. Because DEN and SOD are positively correlated with the efflux of NH3 from the sediment, this indicates that measured DEN is primarily anaerobic denitrification and not ANNAMOX. If ANNAMOX was significant in our cores, it would be indicated by a net flux of NH3 into the sediment.

We expect NO_{3-} flux into the sediment to increase as DEN rate increases. However, the only site which followed this anticipated pattern was SoCO. In CeCo, a general negative trend is observed, but more data may be required to determine a significant relationship. The NoCo had a slightly positive trend.

A significant relationship between PO_{4-} flux and DEN or SOD was found at CeCo and SoCo. Through a complicated set of processes, PO_{4-} can be rapidly released from both recently deposited sediments and oxidized surficial sediments as oxygen concentrations decrease. In addition, the presence of decaying plant debris and other particulates enhances the release of soluble reactive phosphorus (SRP) into the water column. Both of these mechanisms involve the depletion of oxygen, or the increase in SOD. Therefore, PO_{4-} flux, SOD, and DEN are intertwined, but there is no causal relationship.

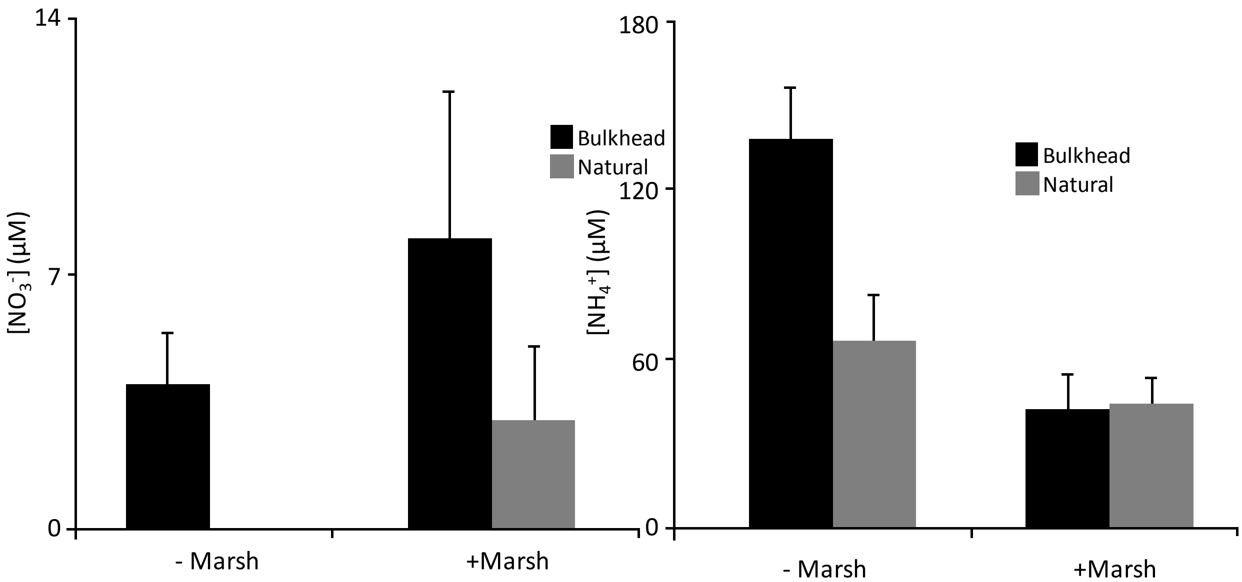

Figure 31: Summary of nutrient data from sites in the CeCo region.

Groundwater:

Wells were installed in Kitty Hawk to represent different sites with and without bulkheads. Groundwater data was difficult to collect. The primary issues were damage due to inclement weather and theft of In-Situ Inc. Level Troll sensors. We were able to collect data from two sites: narrow marsh with bulkhead and wide marsh with bulkhead. However, our data remains inconclusive due to lack of data from a reference site.

Nutrient transformation discussion:

DEN was not related to bulkhead presence, but there was a significant effect of marsh presence, SOD, and SOM. Overall, measured rates and correlations were similar in the southern and central sites, but differed from the northern sites. Some of the differences can be attributed to low SOM content (Figure 28) in the northern site providing less substrate for DEN, but a contributing factor may be salinity. Salinity can affect DEN by altering NH_3 concentrations, release of inorganic benthic N, and sulfate reduction (Giblin et al, 2010). These changes in water chemistry can affect not only the rate and efficiency of DEN, but also the seasonality of the process. The literature suggests a highly variable relationship between salinity and DEN along estuarine gradients. Rysgaard et al. (1999) and Giblin et al. (2010) found that salinity and DEN were negatively correlated. Conversely, Magalhaes et al. (2005) concluded that nitrification and DEN were both positively correlated with salinity. Finally, Fear et al. (2005) found that salinity had no significant effect on denitrification. Our study agrees with Magalhaes et al. (2005) in that rates of DEN were significantly lower at fresher sites (northern site) when compared to more saline sites (southern and central sites). Unlike salinity, the literature clearly supports a positive relationship between SOM and DEN (Francis and Mankin, 1976; Glass et al, 1997; Kim et al, 2002). As SOM increases, DEN rate increases due to the abundance of available substrate. While our measured relationship between SOM and DEN is weak, it is not out of the ordinary given that SOM is a gross measure and is not indicative of lability. SOD, however, is an indicator of lability. SOD and DEN were positively correlated (Figure 30) as expected.

Groundwater data was difficult to interpret due to loss of equipment. However, despite several confounding factors, we are still able to see a significant increase in DEN rate with the addition of some marsh vegetation. Therefore, using rate standardized to area, DEN is significantly higher in areas with marsh than areas without implying that a narrow fringing marsh is as functional as a wide fringing marsh in terms of DEN. Our data illustrates that even a narrow restored marsh will provide significant benefit to the estuary and should be considered as a valid means of mitigating nutrient loading to estuaries. It is also important to note that larger marshes will provide more surface area for DEN to occur, thereby increasing the overall amount of NO_{x-} ($NO_{2-}$and NO_{3-}) that can be removed from the biologically active pool of nitrogen. In summation, some marsh is good, more marsh is better.

Benthic infauna total abundance and diversity:

Abundances of each taxa collected are given in Appendix 3. Total faunal abundances varied by site, marsh type and year. For the SoCo sites, total faunal abundance in the natural marshes in 2009 was significantly greater than any of the bulkhead sites ($F=6.86$, $p<0.004$, SNK post hoc test $p<0.05$) (Figure 32). An analogous pattern was observed for the CeCo sites in 2009, with the natural marsh and the bulkhead with wide marsh seaward of the structure trending towards greater overall abundances than the narrower marsh sites, but this difference was not significant ($p>0.05$ SNK test). Total faunal abundance patterns did not show as consistent a pattern by marsh size for 2010. For the SoCo sites, highest abundances were observed in the medium and natural marsh ($F=3.60$, $p<0.005$; $p<0.05$ SNK test) (Figure 33), while higher abundances were observed in the narrow and wide marshes for the NoCo site. Examining the 2 years combined for the SoCo sites, the natural marsh had significantly higher total faunal abundances than the 5 sites with adjacent bulkheads and the site with no marsh had significantly lower total faunal abundances ($F=10.93$, $p<0.0001$; SNK test) (Figures 32-33).

Diversity showed a more mixed pattern with respect to marsh thickness than observed for total abundance. For 2009 SoCo sites, diversity differed among areas sampled ($F=9.22$, $p<0.001$) with the wide marsh site having significantly lower diversity than all sites except the no marsh area, and the no marsh area having lower diversity than one of the medium marsh sites (Figure 34). For the CeCo site, the medium marshes had higher diversity than other sites (SNK test). In 2010, the NoCo sites exhibited considerable variability in sample diversity and there was no significant difference among sites (Figure 35). SoCo sites did have a significant difference among marsh types ($F=7.95$, $p<0.0002$), with narrow marsh site having significantly higher diversity than the natural and wide marsh sites and the medium marsh sites differing from the natural marsh area as well (SNK test, $p<0.05$).

Infaunal composition:

Faunal composition varied by site, year and marsh type. For the SoCo sites, there were clear differences among marsh types. The wide and natural marshes in 2009 were dominated by Tubificidae oligochaetes and the polychaetes *Streblospio benedicti*, *Fabriciola* and *Capitella capitata* (Figure 36). The no marsh and narrow marsh sites were dominated by the polychaetes *Capitella, Heteromastis*, and *Laeonereis*. Medium marsh sites were dominated by a mix of these species. Tubificid oligochaetes and the polychaetes *Streblospio* and *Laeonereies* were common in all marsh types for the CeCo sites in 2009 (Figure 37), with *Capitella* also being common in the no marsh sites and the mud snail *Illyanasa* common among some of the medium marsh sites. Faunal dominance did differ somewhat at SoCo sites between years, with a greater variety of co-dominant species in 2010 (Figure 38). However, all but 2 of the dominant taxa in 2009 samples were also among the common taxa in 2010. All of the NoCo sites were dominated by oligochaetes, reflecting the lower salinity of this area (Figure 39), with chironomid insect larvae also being dominant in the natural marsh site. *Streblospio* was common at one of the medium marsh sites.

Analysis of Similarity indicates a significant difference in overall benthic community composition among sites, with a particularly strong difference noted for the NoCo sites relative to the CeCo and SoCo regions (Figure 40). The SoCo area in 2009 had strong separation among no marsh, narrow+medium marsh, and wide+natural marsh groupings (overall ANOSIM $p<0.01$) (Figure 41). Though differing somewhat, this pattern generally held for 2010 SoCo samples as well (Figure 42). In 2010 no marsh samples were still distinct from other samples, and natural marsh and wide marsh samples were not distinct from each other but were distinct from other marsh sizes. However, medium marshes showed greater separation from each other and from narrow marshes than observed in 2009.

Distinction among marsh types varied for the other regions. For the CeCo sites, the main faunal groupings were no marsh samples, one of the medium marshes, a small separation for narrow marshes, and then a grouping containing all other sites (Figure 43). For the NoCo sites, greatest differences were observed for the natural marsh and one of the medium marshes (Figure 44). Lesser difference was observed for the no marsh, wide marsh and medium marsh samples.

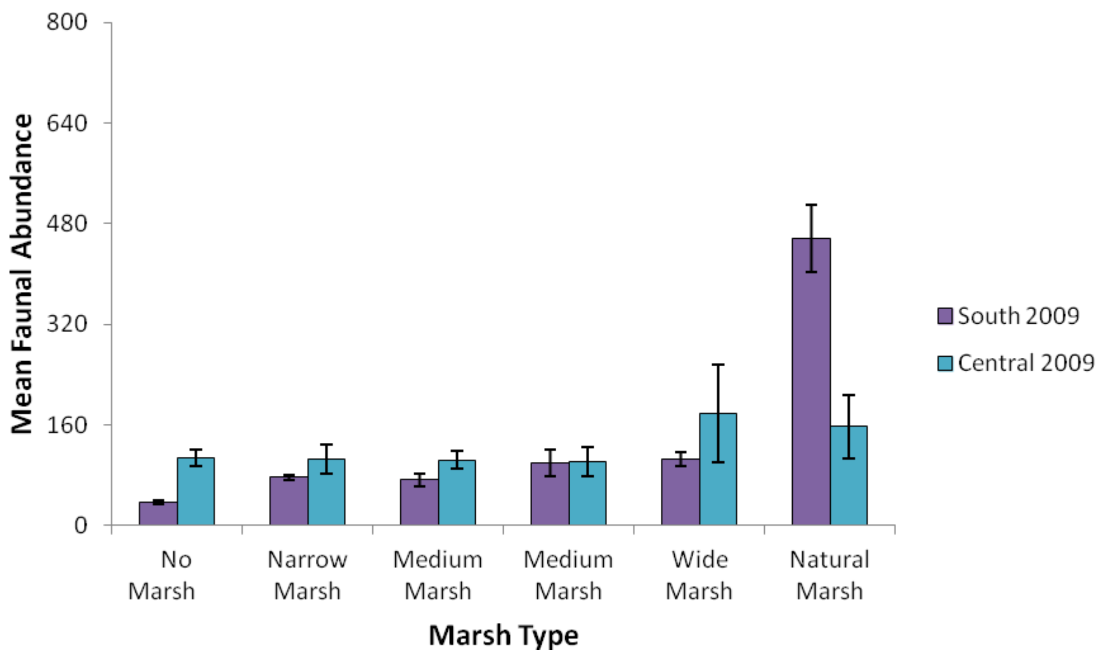

Figure 32: Total faunal abundance at SoCo and CeCo sites in 2009. Numbers are means per 0.01 m^2 +/- 1SE

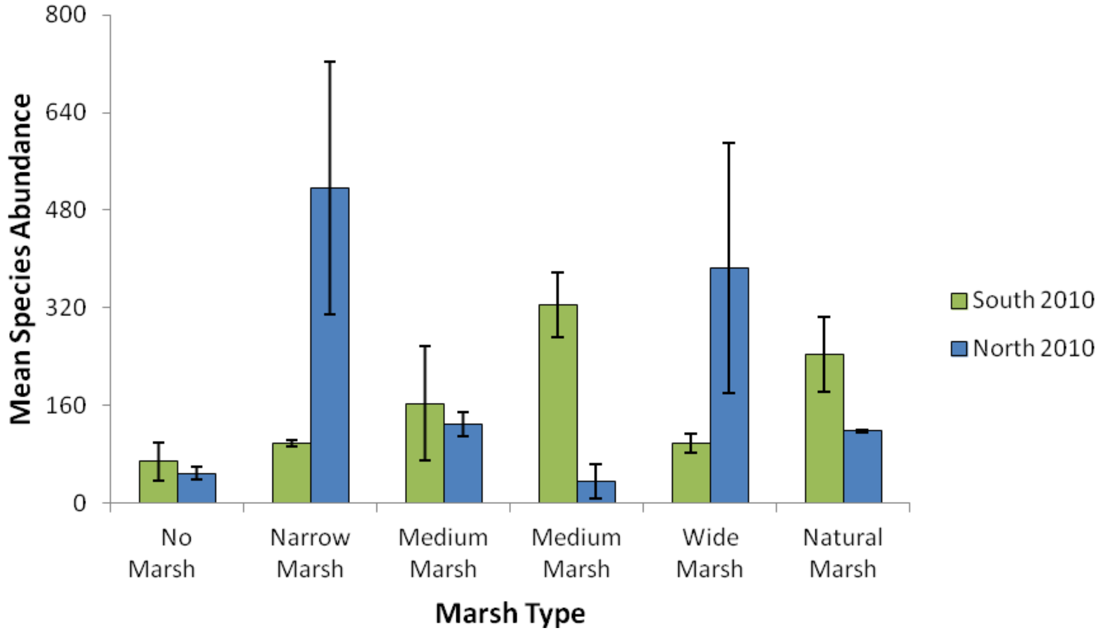

Figure 33: Total faunal abundance at SoCo and NoCo sites in 2010. Numbers are means per 0.01 m^2 +/- 1SE.

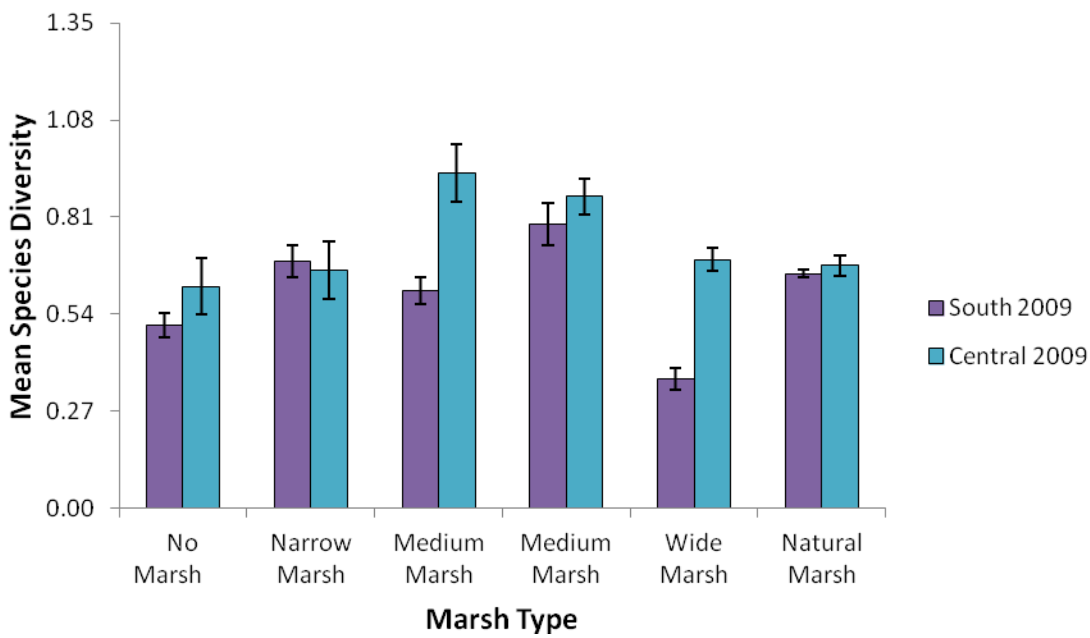

Figure 34: Mean sample diversity at SoCo and CeCo sites in 2009. Numbers are means per 0.01 m^2 cores +/- 1SE.

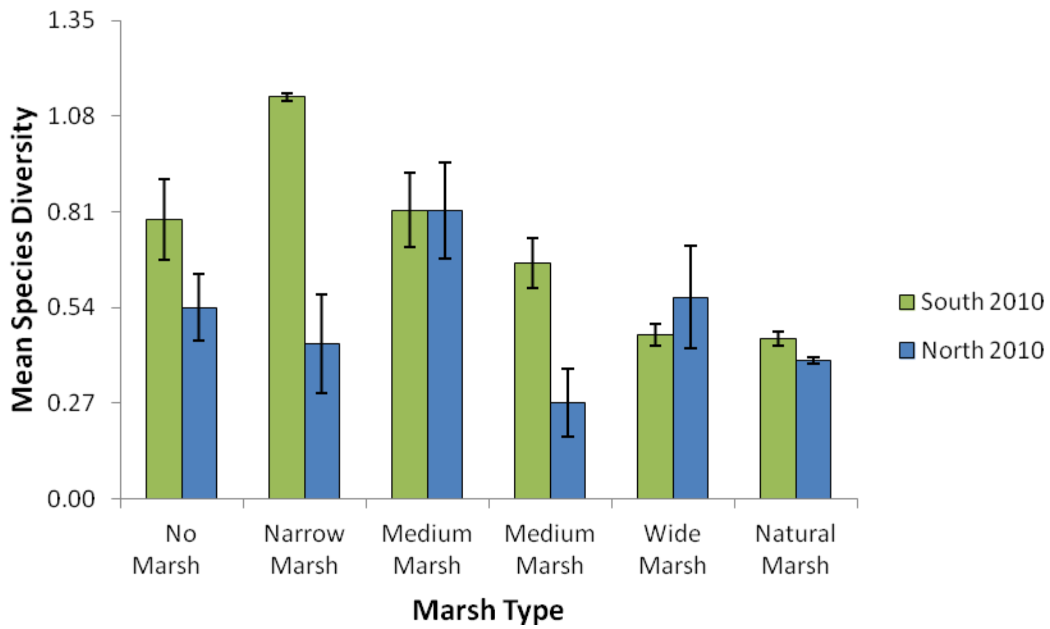

Figure 35: Mean sample diversity at SoCo and NoCo sites in 2010. Numbers are means per 0.01 m^2 cores +/- 1SE.

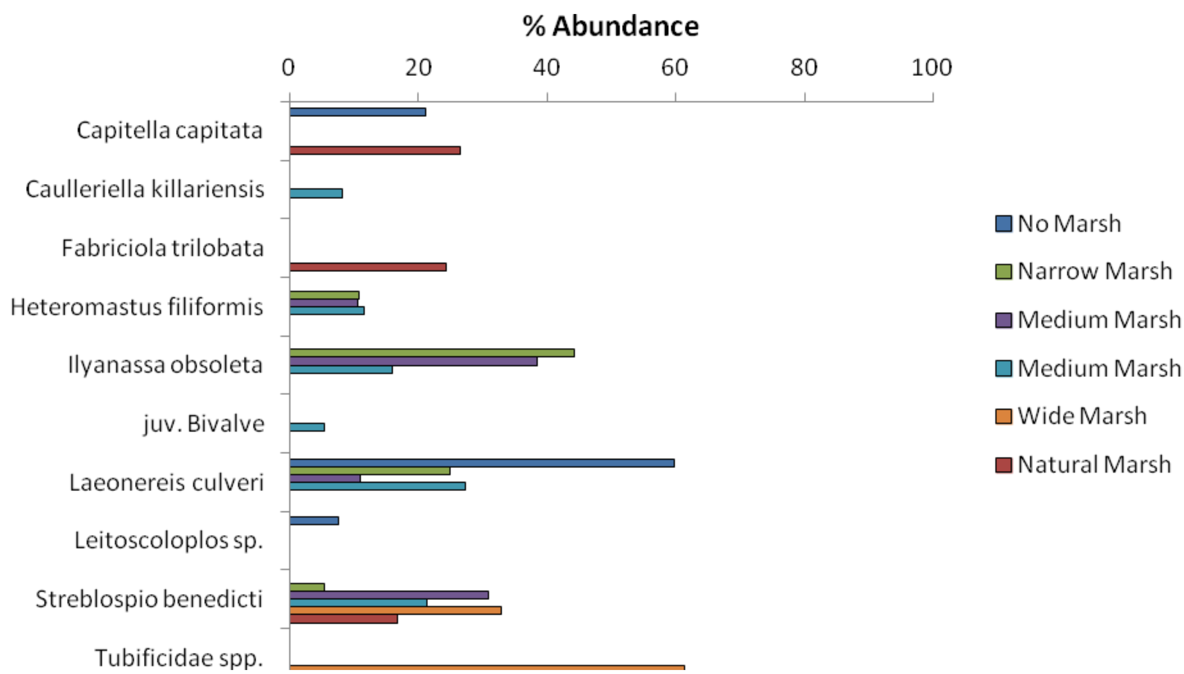

Figure 36: Fauna comprising > 5% of total faunal abundance at the SoCo sites in 2009.

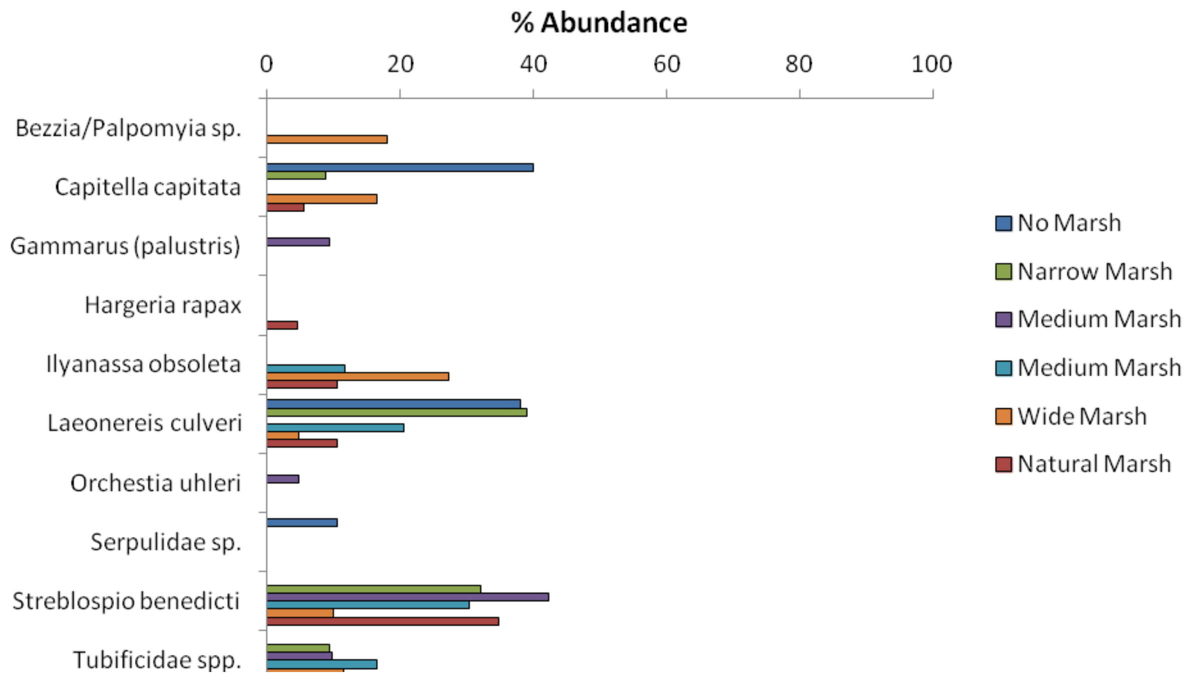

Figure 37: Fauna comprising > 5% of total faunal abundance at the CeCo sites in 2009.

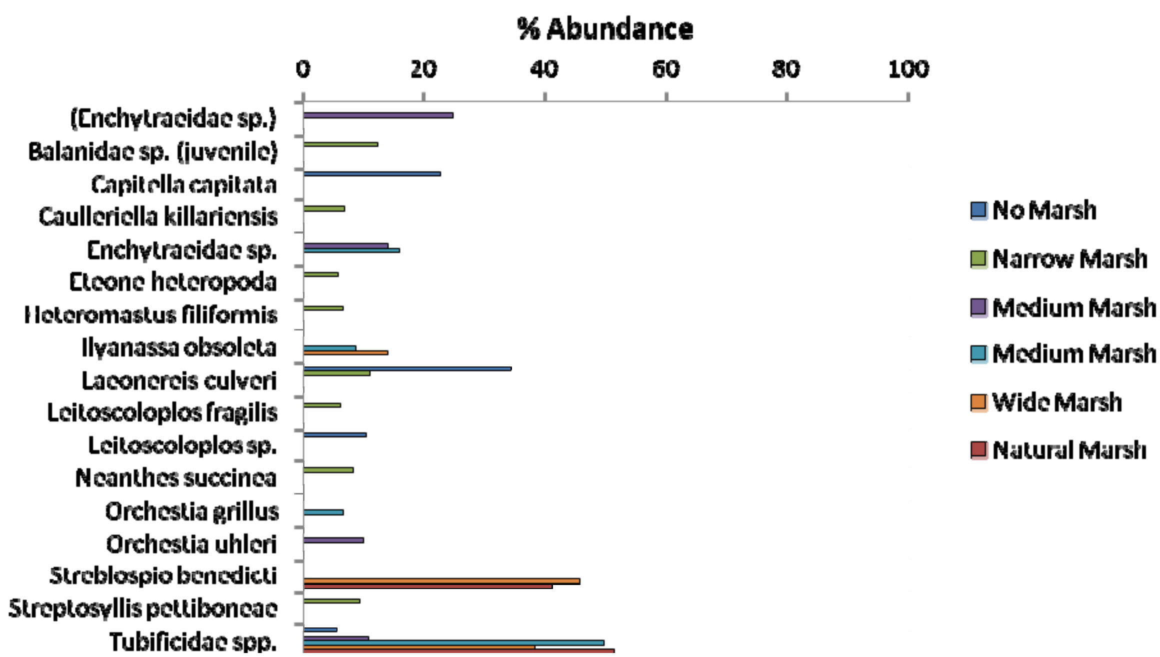

Figure 38: Fauna comprising > 5% of total faunal abundance at the SoCo sites in 2010.

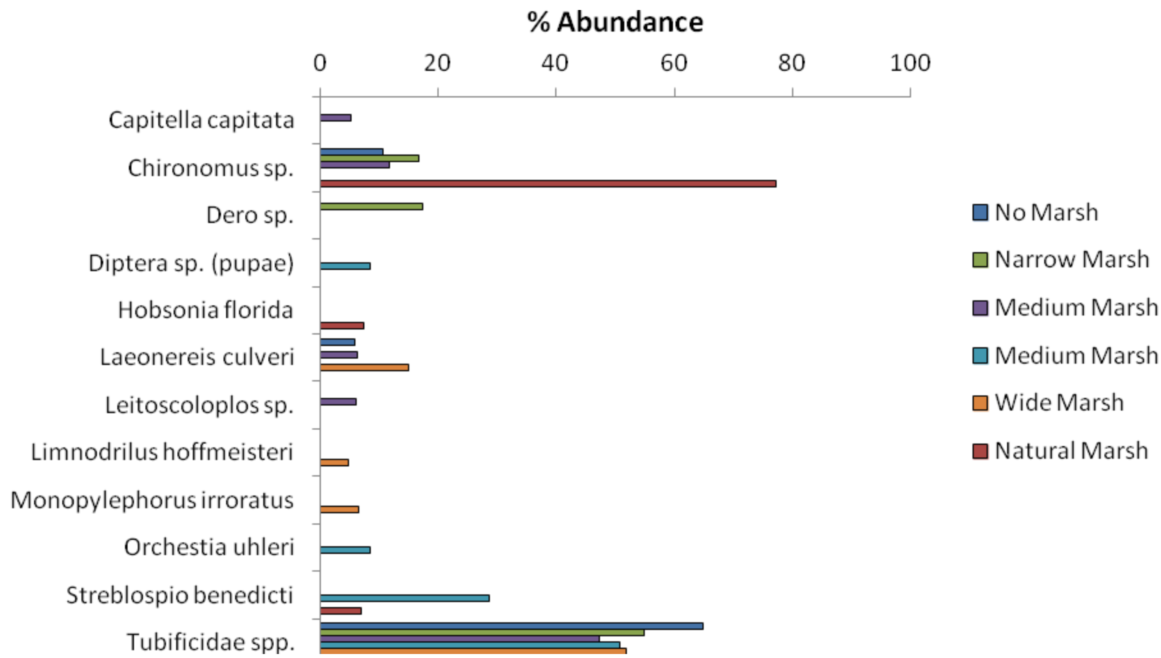

Figure 39: Fauna comprising > 5% of total faunal abundance at the NoCo sites in 2010.

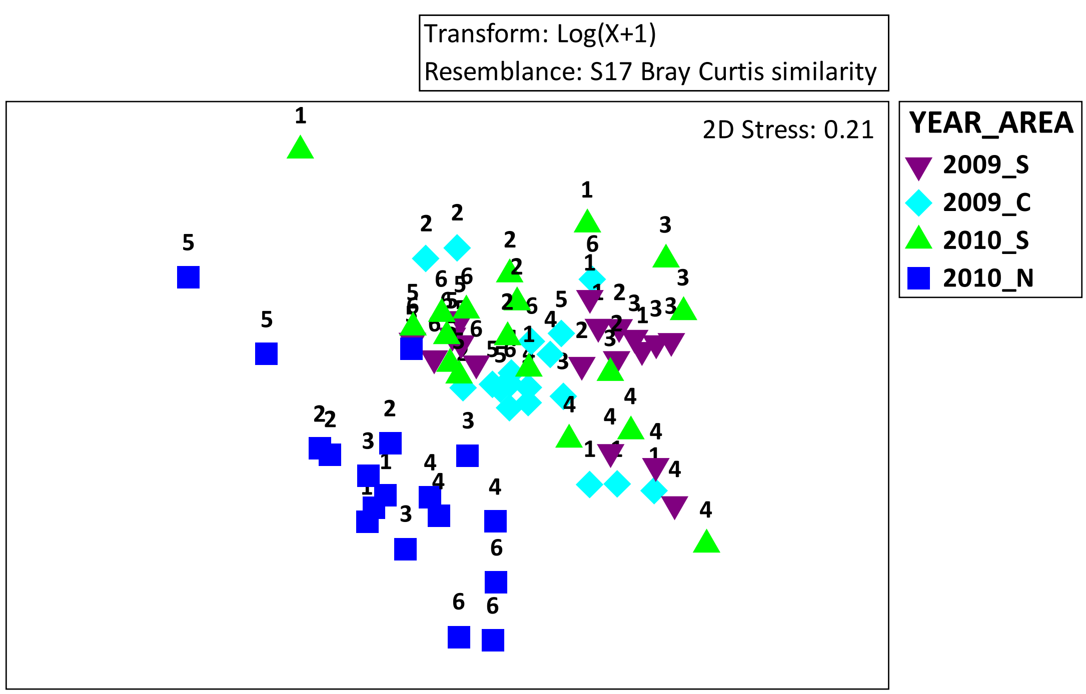

Figure 40: MDS plot of samples from the 3 regions (S=SoCo, C=CeCo, N=NoCo) over the two years. Numbers next to symbols indicate specific sites as referenced in Appendix 3.

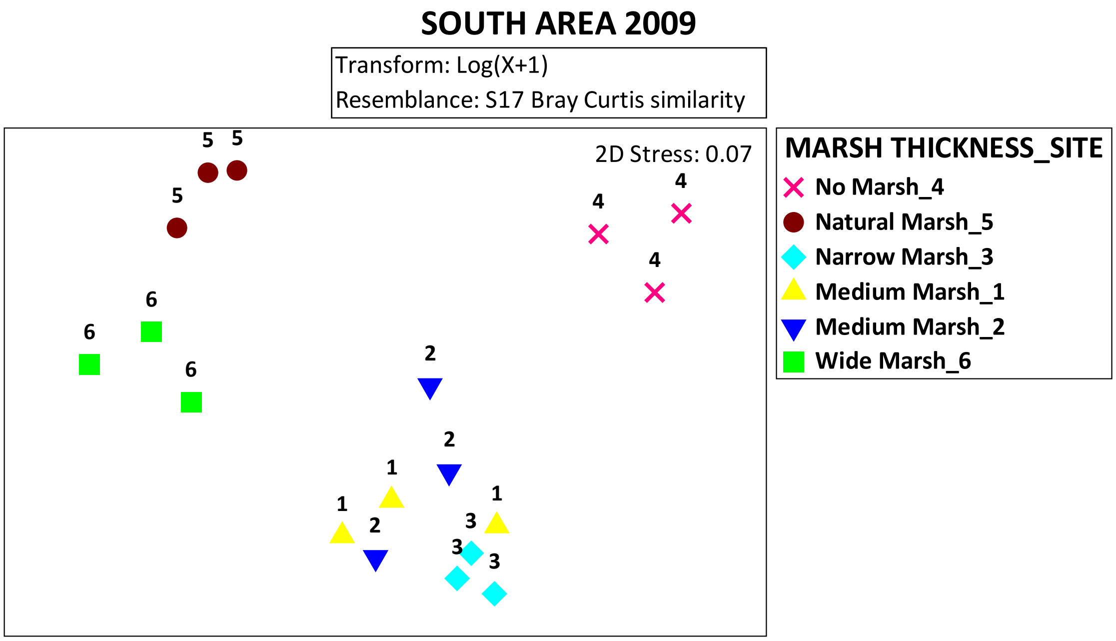

Figure 41: MDS plot of samples from the SoCo region in 2009.

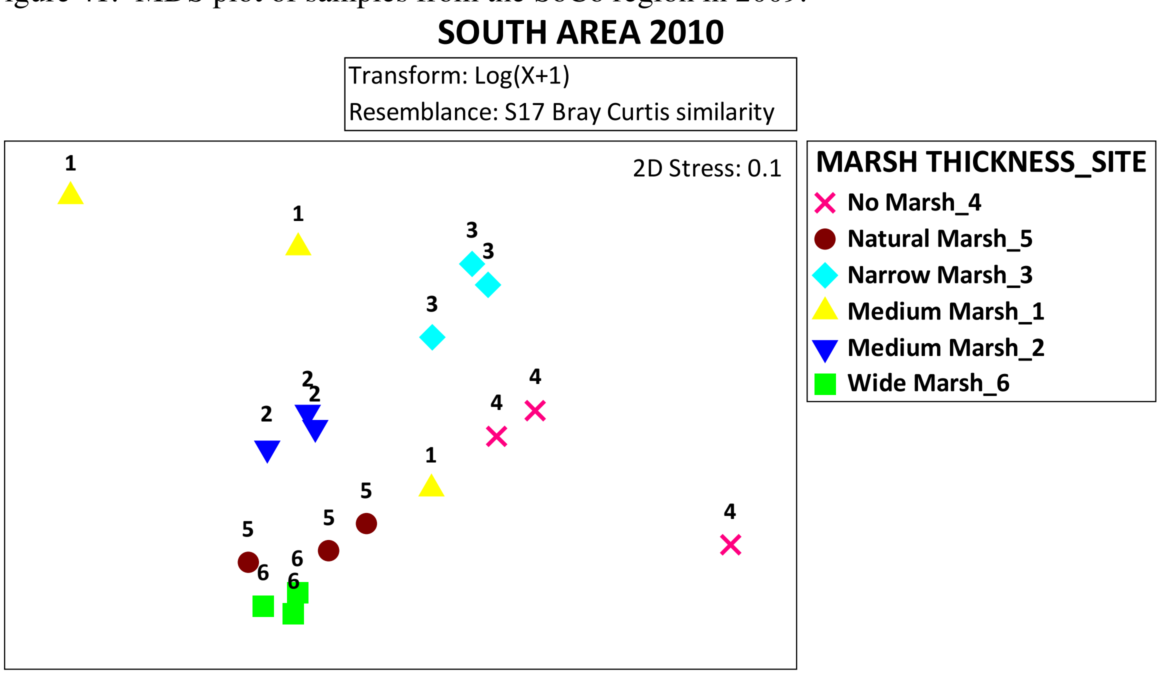

Figure 42: MDS plot of samples from the SoCo region in 2010.

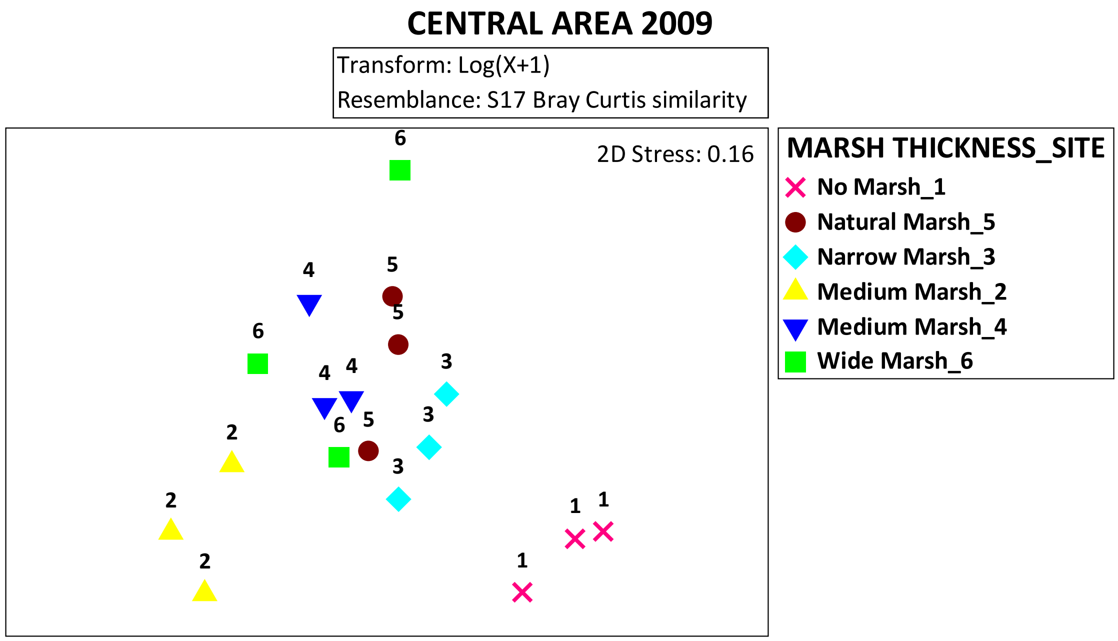

Figure 43: MDS plot of samples from the CeCo region in 2009.

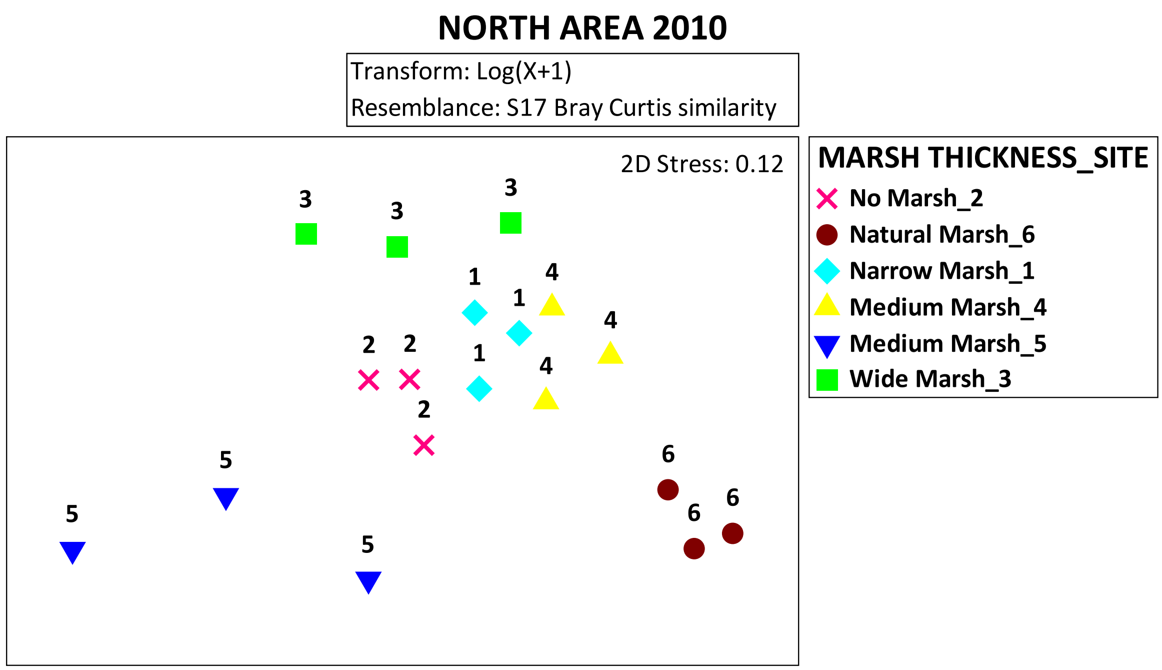

Figure 44: MDS plot of samples from the NoCo region in 2010.

Sediment grain size

Grain size analysis from two CeCo sites were analyzed using a CILAS laser particle size analyzer. All sediments were sandy, with average grain sizes of >100 um, and the bulkhead site without marsh had average grain size of over 250 um. Average grain size of sediments at a bulkhead site with marsh was significantly less than that at a bulkhead with fringing marsh.

Sediment analysis was conducted at the upper and lower edge of SoCo and NoCo sites in 2010. All sites had low percent organics (<6%) except for the wide marsh in the SoCo area). At this site sediment % organic content was 16% near the bulkhead structure, but not at the seaward edge of the marsh. Sediment grain size was in the fine to medium sand range (125 to 500 um) for all sites and there was little evidence for consistent difference in grain size near the bulkhead structure versus the seaward edge of the marsh).

Infauna discussion:

Cumulative measures of the infaunal community, including total infaunal abundance and diversity, showed mixed patterns among marsh types, regions, and years. For the SoCo sites in 2009, the natural marsh had higher per sample abundance than any of the bulkhead sites and the no marsh site had lower faunal abundance. However, in 2010 there was little distinction among medium marsh sites and the natural marsh, though low abundances were still observed in the no marsh site. Diversity did not differ consistently among marsh types for SoCo in 2009. However, in 2010 higher per sample diversity was observed in the narrow marsh site. The CeCo sites showed total faunal and diversity patterns similar to SoCo sites in 2009. NoCo sites in 2010 showed few differences among sites for either total faunal abundance or diversity to marsh size.

The lack of relation among cumulative community measures and marsh type may be related to both the location of sampling and varying species composition. Samples for this project were taken along the lower fringe of the marsh to allow comparability among sites. However, marsh infauna are known to vary as one moves from the edge to the interior of the marsh, often changing from domination by opportunistic polychaetes and amphipods on the edge to oligochaetes in the interior (Whaley and Minello 2001, Novak 2011). Sampling in the interior of the larger marshes may have shown very different patterns related to interior subhabitat differences in sediment composition and faunal dominance and the lack of this habitat in the narrower marshes. Moreover, edge areas may be expected to experience greater wave disturbance than more protected interior areas, especially along exposed shorelines such as sampled in this study, leading to domination by a disturbance tolerant subset of species.

Analysis of species dominance patterns as well as Analysis of Similarity of faunal composition and abundance confirms differences in the infauna taxa present even along this lower edge habitat. For the SoCo sites, there tended to be distinct faunal composition groupings that included samples from the natural marsh areas, wide marsh areas, no marsh areas, and the narrow/medium marsh areas. These groupings reflected greater abundance of oligochaetes in the natural and wide marshes and dominance by opportunistic polychaetes in the no marsh and narrow marsh sites. Although not as pronounced, a similar pattern was observed at the CeCo sites. The NoCo sites were dominated primarily by oligochaetes at all bulkhead sites, with the natural marsh site having a high dominance by insect larvae. Dominance by oligochaetes and insect larvae is typical of low salinity tidal marshes and reflects the different environmental conditions in this region. The difference in faunal composition observed here indicates that there are differences in the infaunal community with changes in marsh width. Larger marshes tended to have taxa more characteristic of interior, well established marsh habitats even along the edge areas sampled while narrower marshes and non marsh areas were dominated more by opportunistic taxa. Though some taxa became dominant only in the largest marsh or no marsh areas, others showed a gradient in abundance as marsh width decreased. Since the availability of oligochaetes, burrowing polychaetes such as *Capitella*, shallow burrowing polychaetes such as *Laeonereis*, and tube dwelling polychaetes such as *Streblospio* may be very different for epibenthic predators, this change in community dominance can be expected to have significant upward trophic impacts.

Results discussion:

Objective 2: Design and install a demonstration project utilizing alternative shoreline stabilization approaches for research and education purposes.

Collaboration with stakeholders greatly influenced the results of this objective. As the collaborations occurred prior to the construction of the demonstration project and its resultant monitoring, it is most efficient to report on how the collaborations shaped the objective and then discuss the actual objective results.

During the second project advisory panel, the advisory panel was unanimously concerned with the idea of the demonstration project as originally envisioned by the project team. The homeowner on our panel did not see how a demonstration project on a National Estuarine Research Reserve related to property owners since it would not be protecting anything (i.e., a structure). The marine engineer liked the idea but was concerned the planned location of the demonstration project may not be ideal due to unfavorable energetics. He also thought there were insufficient funds to appropriately construct the demonstration project. The resource agency members of the panel were concerned that the project not impact potential seagrass beds, and were concerned about the implications if the project failed, as that might solidify even more the idea that bulkheads are the only solution that work in the minds of the public. One final point that was mentioned during the advisory panel meeting was that, the area of the Rachel Carson component of the NCNERR where the demonstration project is slated to go is a relict dredge spoil cell. Thus, the upland that is present is not really "natural" and that the area is just trying to return to equilibrium and the question was raised: Why would you try to stop that?" These were all good points that made the project team think very hard about the demonstration project.

To alleviate the energetics concern, Co-PI Mark Fonseca compared the energy dynamics of the proposed demonstration site to those of naturally occurring fringing salt marsh in Carteret County. This analysis was conducted using bathymetry data collected by NOAA and the Wave Exposure Model (WEMO; http://www.ccfhr.noaa.gov/docs/WEMo_V3_manual.pdf) to calculate relative wave energy at shoreline marsh sites. The results of this analysis are shown in (Fig. 45). The assessment showed that the area energetics have the potential to sustain marsh grass.

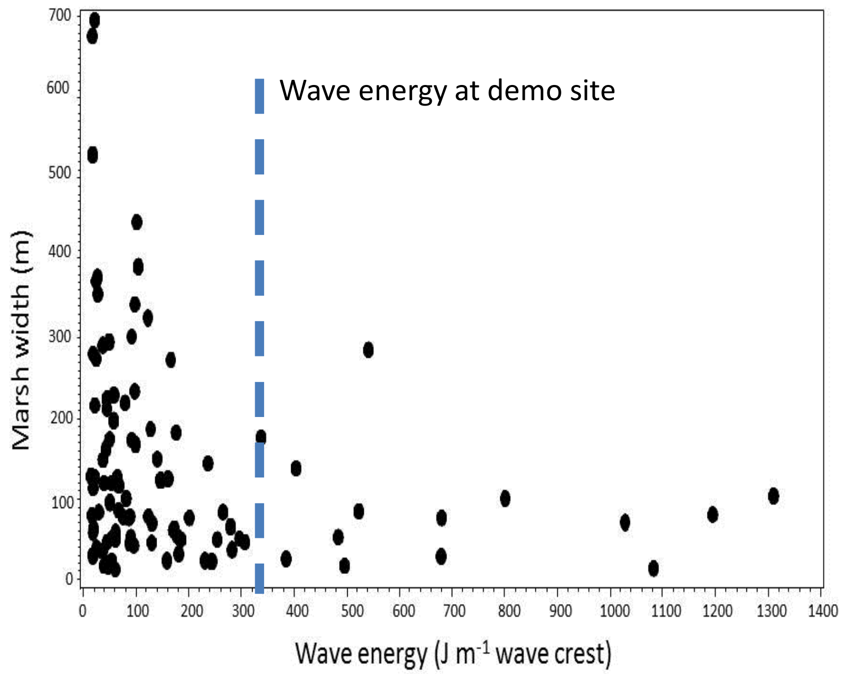

Figure 45: Analysis of marsh width (m) vs. wave energy setting for Carteret County shorelines. Marsh width determined using aerial imagery and ArcGIS, and wave energy calculated using WEMO. Dotted line shows calculated wave energy at the proposed demonstration site.

After showing the advisory panel the energetics assessment, it was jointly decided that a small pilot "proof of concept" project was warranted. This was conducted at no cost to the project through a partnership with the N.C. Division of Marine Fisheries. The pilot project successfully showed that loose shell would stay in place at the site. One final adjustment was done to account for the advisory panel concern that we were trying to protect an unnatural shoreline (the dredge spoil cell). The project was moved slightly to the west to avoid the dredge spoil cell. All these modifications allowed the project to move forward meeting the original intent of the objective: to design and construct an alternative to a vertical bulkhead to stabilize an eroding estuarine shoreline and to do it in a high traffic location so that many people will be able to see and learn from it.

All oyster reefs constructed as part of this project (both patch and sill) are shown in Figure 46. Reefs were installed in May 2012. Prior to construction, a DEM was created of the project area to use as a preconstruction baseline and to identify locations for oyster shell placement. The preconstruction DEM for the sill reefs area depicts a low sloping bathymetry with one narrow band of rapid slope change between -0.1 and -0.5 m below MSL (Figure 47).

Figure 46: Locations of oyster reefs constructed as part of the demonstration project.

Previous research has shown that restored intertidal reefs fair best when placed in this depth range (Fodrie et. al unpublished). Shell placement occurred in May 2012. In August 2012, the first post construction DEM was created. The post construction DEM for the sill reefs area showed that the deployed shell has remained where placed and that the tops of the sill reefs are in the critical zone for maximum success. It also shows a narrow band of deeper water just on the front side of the created oyster sill reefs (Figure 47, bottom). It is too early to attribute this finding definitively, but one potential explanation is that it represents successful sediment trapping behind the reef structure.

All reef sites were monitored for biotic composition during the first week of August, 2012. Large grids were mapped over each reef and sill to determine percent cover of live oysters and other epifaunal organisms (as well as reef length and width). Furthermore, randomly chosen plots were sampled to quantify spat settlement (for the three sills, these included samples on the seaward side, crest and landward side). These constitute our initial baseline data against which future survey data collected well beyond the end of this project will be compared. While data processing and analyses remain underway, our initial comparison of spat settlement shows several distinct patterns between restored and reference sites, as well as among landscapes. For the small, 60-bushel patch reefs, shell cover and spat density were considerably higher at restored sites relative to non-restored reference sites (Figure 48). Among restored reefs, however, spat settlement was greatest on the reefs constructed along the marsh ramp, with 2-3 times fewer spat per-unit-area on the reefs built along marsh scarps or creek banks. Variability was also apparent at smaller scales, with spat density 2 times higher on the creek reefs at the entrance of tributaries relative to those on creek banks, and spat density on “blowout” reefs only 1/5 of that observed on adjacent ramp reefs (Figure 49). On the sill reefs, spat and associated faunal densities were greatest on the seaward side of the sills, and decreased across the crest and to the landward side of the sills (Figure 50).

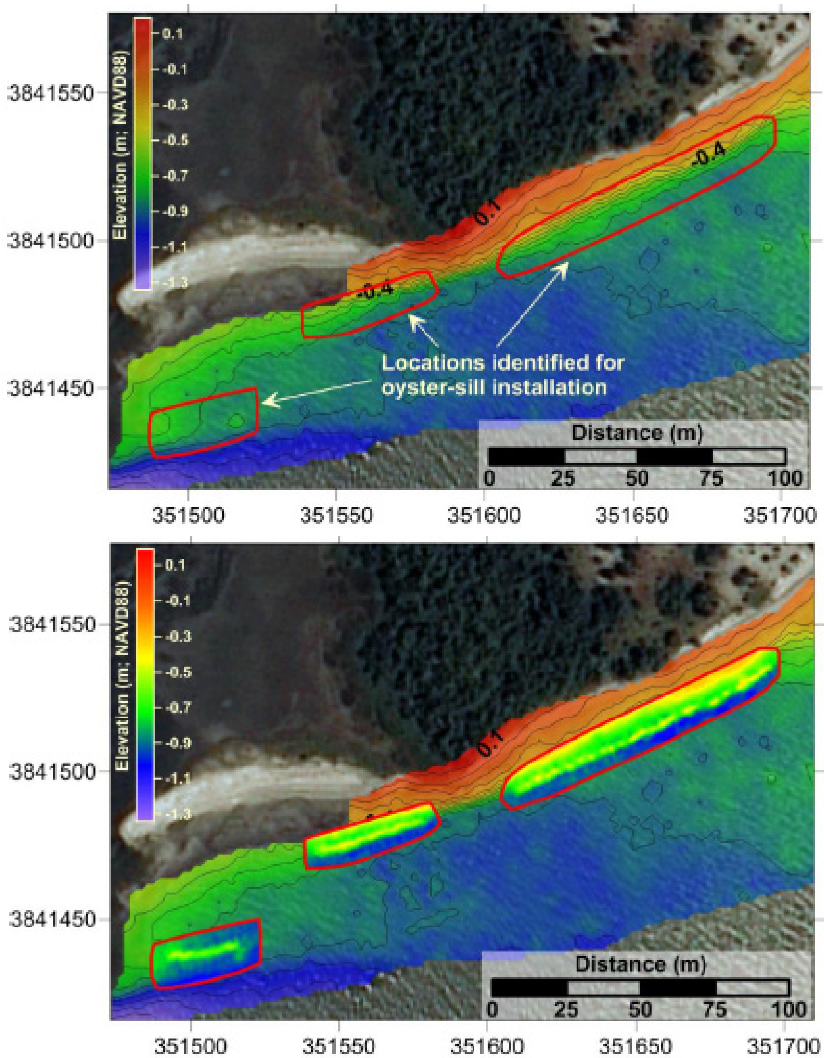

Figure 47: Demonstration site DEM pre construction DEM (top) and post construction (bottom) for oyster sill reefs.

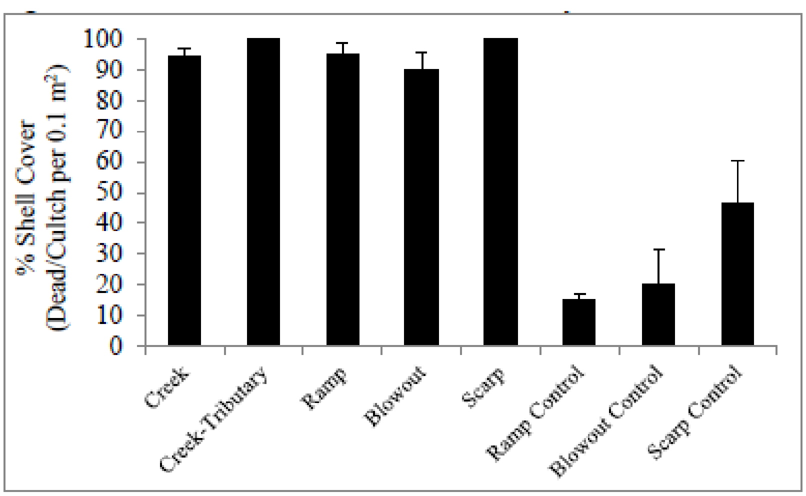

Figure 48: Shell cover at restored and non-restored reference sites at Carrot Island.

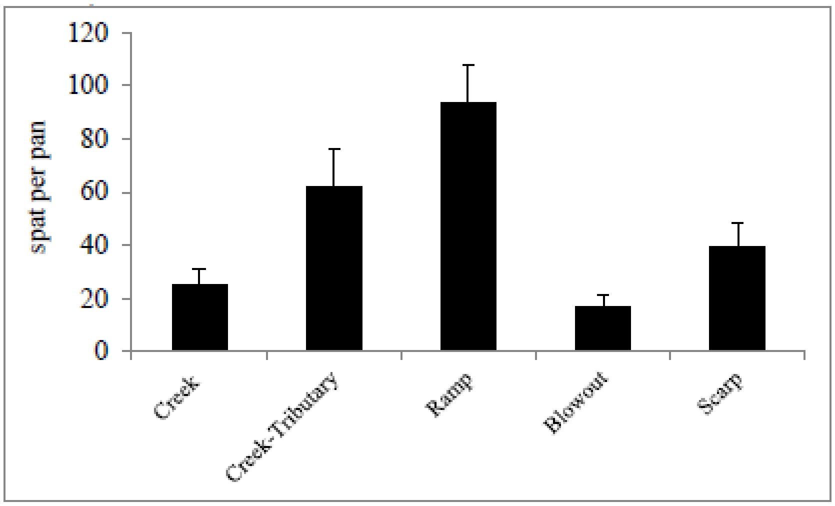

Figure 49: Oyster spat density on small patch reefs at Carrot Island among a diversity of marsh landscapes. Pans used to quantify spat density covered an area of 0.05 m^2 (i.e., data are spat * 0.05 m^{-2}).

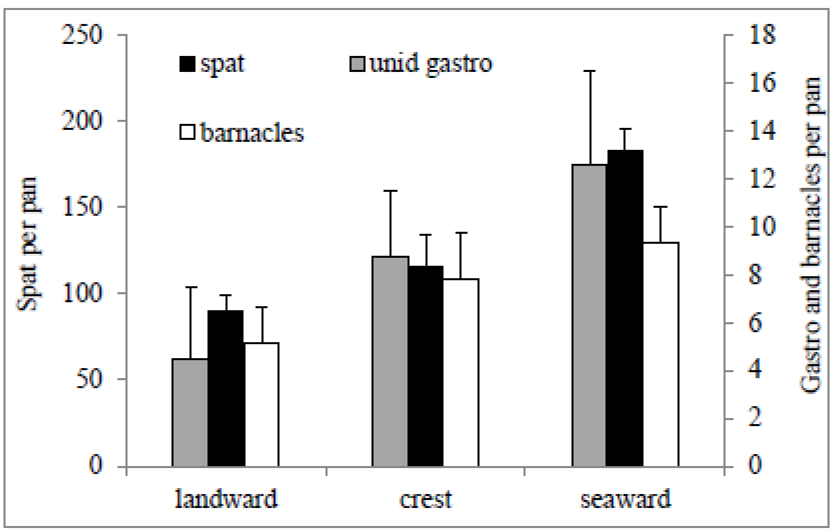

Figure 50: Oyster spat (and some associated taxa) density across the recently constructed Carrot Island sills. Pans used to quantify faunal density covered an area of 0.05 m^2 (i.e., data are fauna * 0.05 m^{-2}).

Demonstration project discussion:

So far the oyster reef creation has been successful. The oyster reefs are being colonized with spat, and the shell has not been scattered. The saltmarsh planted behind the oyster sill reefs is growing and spreading. All indications to this point are that the combination oyster reef/planted saltmarsh will be a viable erosion protection structure.

Results discussion:

Objective 3: Develop and refine approach for evaluating ecological and socioeconomic costs and benefits of shoreline erosion & protection alternatives.

Similar to the demonstration project above, collaboration with stakeholders greatly shaped this portion of the project. Most have been detailed in the methods section above, however a few additional ones need to be relayed here. During the 2nd advisory panel meeting, the homeowner on our panel made it very clear that the only real economic metric that he cared about was how much was a stabilization structure going to cost him and how long would it perform its function. The economics associated with ecosystem services were not of interest to him. This mirrored the sentiment given to us at the 1st advisory panel meeting by our developer representative. The group did agree that ecosystem services were a valuable commodity even if secondary to the primary concerns noted above. This knowledge helped guide the development of the *Weighing Your Options* booklet.

A second critically important change occurred during the 3rd advisory panel meeting when the panel was presented with the draft of the Weighing Your Options booklet. The developer and engineer disagreed with how we had bulkheads described. We had originally described bulkheads as causing erosion. They stated emphatically that bulkheads prevented erosion. Clarifying discussion revealed that we were looking at the issue from different points of view. They were looking at it from the land perspective, and were correct; bulkheads do prevent erosion from the land. We were looking at bulkheads from the water perspective and were trying to relay that they reflect wave energy causing scour of the shallow subtidal. This miscommunication was clarified in the final version of the booklet.

The final *Weighing Your Options* booklet is included as Appendix 2. Inside the booklet are comparison tables that depict the pros and cons of each stabilization option in an easy to understand format. The booklet is in full distribution and feedback received thus far form stakeholders is positive.

Results discussion:

Objective 4: Develop effective communication methods for exchanging information between scientists, regulatory agencies, business community, politicians and general public in regard to costs-benefits of various short-term and long-term shoreline stabilization plans.

The full results of the conducted needs assessments are included as Appendix 1. A few key results are included here. For the estuarine property owner needs assessment we mailed out 866 surveys. We only received 75 back providing a 9% return rate. This return rate was lower than what we were hoping but enough for us to quantify this particular audiences' views and opinions. The survey result corroborated the DCM permit information that bulkheads are the most used stabilization structure. Of our survey respondents 68% of those that have shoreline stabilization reported that they had a bulkhead. Of the respondents that currently do not have a stabilization structure, the most frequently considered option to install was a bulkhead. When asked what factors would be most influential in determining the type of stabilization structure they would choose to construct, 82% of the responses were "protection from erosion", compared to 58% for the cost of the structure (Figure 51). For the project team this was an important result as it implies if you can show property owners that something besides a bulkhead will provide the same or better erosion protection, they would consider utilizing it. Also of particular interest to the project team, when asked how they would like to receive new information, the most frequent response received was “online resources” (Figure 52). Consequently, many of the project products have targeted this medium (see outreach methods section).

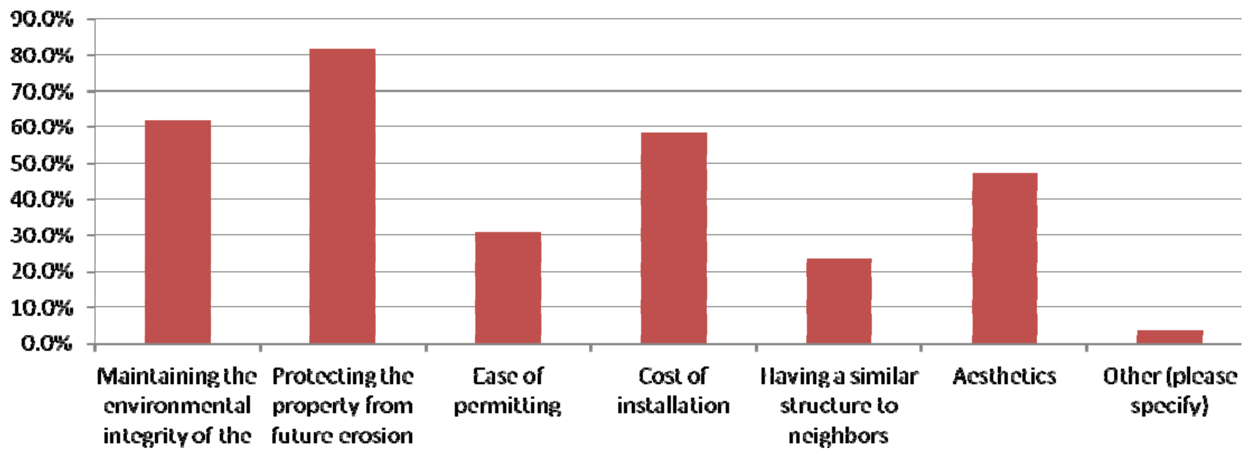

Figure 51: Estuarine property owner survey result to question: What would most influence your choice of structure to stabilize your shoreline?

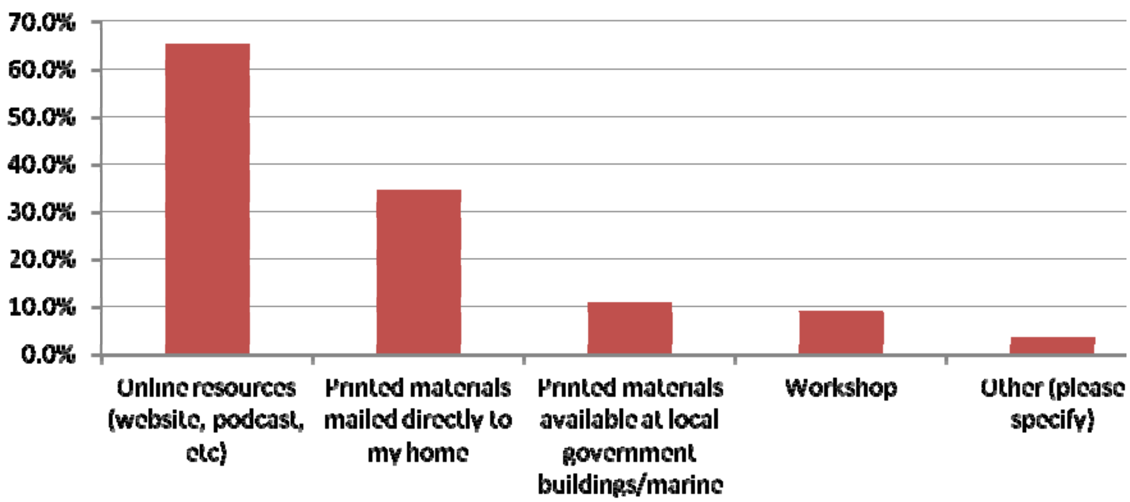

Figure 52: Estuarine property owner survey results to question: How would you prefer to receive information on various shoreline stabilization structures and their pros and cons?

For the marine contractor survey, we contacted 41 companies/individuals via email and received 19 responses for a response rate of 46%. The full results of this survey are included as Appendix 1. The most recommended structure by contractors was a bulkhead (Figure 53).

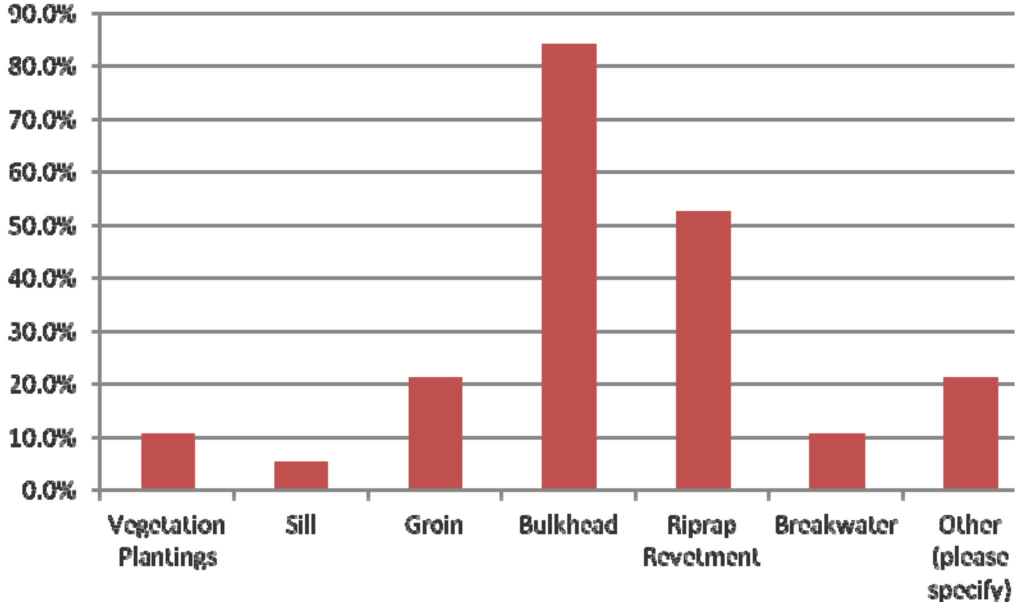

Figure 53: Marine contractor survey results to question: What type of structure(s) do you most commonly recommend?

This and the homeowner result above that noted bulkheads were considered most often shows the large amount of inertia that must be overcome to increase the use of other stabilization structures. This highlights the need for education and outreach activities to try and overcome this inertia.

Interesting, the contractors reported that cost was the primary concern for their clients in picking a stabilization structure. This could represent a contradiction to the results from the homeowner survey (see Figure 51), but more likely, represents the contractors reaction to the negotiation over price that often occurs in construction projects. Similar to the homeowners, the surveyed marine contractors preferred to receive new information via online resources (Figure 54).

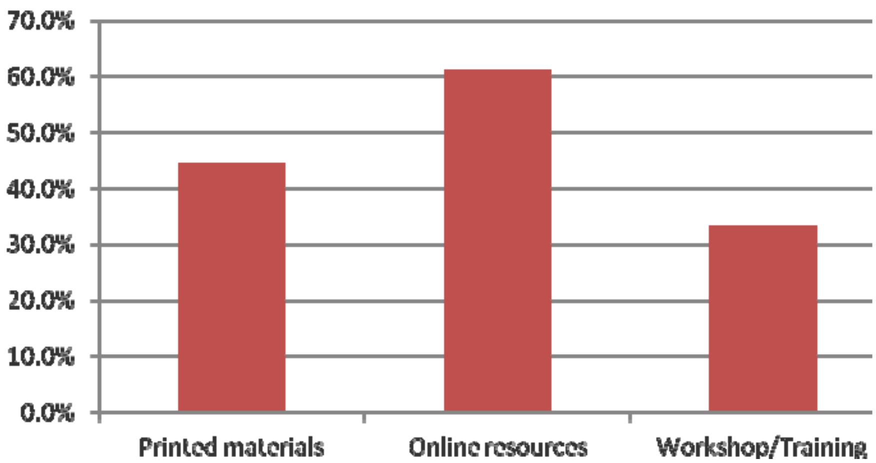

Figure 54: Marine contractors survey results for question: In what format would you prefer to receive information?

Beyond the needs assessment results, the key deliverables of this objective were to relay the project results to key stakeholders. A complete list of all project products (booklets, curriculum, presentations, workshops, fact sheets, etc.) that have been produced/are in production is included below.

- Marine contractor needs assessment survey results report, November 2009 (Appendix 1).
- Estuarine property owner needs assessment survey results report, November 2009 (Appendix 1).
- Four technical 2 page fact sheets designed for general public reading: 1) Submerged Aquatic Vegetation (SAV); 2) What are Ecosystem Services?; 3) Marsh on the Fringe; and 4) Living Shorelines.
- CICEET project website.
- K-12 activity booklet *Our Living Estuaries*.
- *Weighing Your Options*, How to Protect Your Property from Shoreline Erosion: A handbook for estuarine property owners in North Carolina (Appendix 2).
- NCNERR Coastal Training Program, *Estuarine Shorelines: Value, Regulations, and Stabilization* Workshops, Sept 2011 NoCo, April 2012 CeCo and SoCo. NoCo and CeCo workshops, PI Fear presentation: *Wetlands Function and Value*. SoCo workshop, NCNERR Research Assistant, Byron Toothman: *Wetlands Function and Value*.
- PI Fear, presentation to the CRC Feb 2009 meeting (CICEET project overview).
- PI Fear presentation to the CRC Sept 2010 meeting (CICEET project update and results from year 1).
- PI Currin presentation: *The living shoreline approach to estuarine shoreline stabilization in North Carolina* at the Puget Sound Shorelines and Impacts of Armoring: State of the Science conference. May 12-14, 2009.
- PI Fear, presentation at the 22nd annual Coastal Society meeting, Wilmington, NC, June 13-16, 2010 (CICEET project overview and initial results).
- PI Fear, presentation to the N.C. Coastal Habitat Protection Plan (CHPP) steering committee in Jan 2011 (project overview and initial results).
- PI Fear, presentation to ECU Coastal Policy graduate student class in Feb 2011 (project overview and initial results).
- PI Fear CHPP Habitat and Water Quality Advisory Committee in Feb 2011 (project overview and initial results.
- PI Fear, Sea Grant Inner Coast Study Committee in Apr 2011 (project overview and initial results).
- O'Meara, Teri (project graduate student, UNC-IMS), poster presentation, "*Effects of Shoreline Hardening on Nitrogen Processing in Salt Marshes*" May 2011 at the 11th annual International Estuarine Biogeochemistry Symposium, Atlantic Beach, NC.
- PI Fear, CRC Estuarine and Ocean Systems Subcommittee, panel discussion on estuarine shoreline and current policy, Aug 2011.
- PI Currin, presentation to CRC, *Impact of Hurricane Irene on Pivers Island Natural and Stabilized Marsh Shorelines*. Oct 2011.

- PIs Fear and Currin, and Rachel Gittman all gave presentations at the Southeastern Estuarine Research Society (SEERS) meeting held in Beaufort, NC, Apr 11-13, 2012, and participated as invited panelist at a special session to discuss shoreline stabilization and research activities related to shoreline stabilization.
- PI Currin, presentation at NOAA-sponsored Hurricane Awareness Workshop on July 17, 2012 (estuarine shoreline stabilization which included results from the CICEET-project).
- Gittman, Rachel, CRC presentation Nov 2012 meeting: *Evaluating the effects of shoreline stabilization on fish habitat value and erosion of estuarine shorelines in North Carolina*.
- Gittman, Rachel, presentation to the N.C. CHPP steering committee in March 2011: *Evaluating the effects of shoreline stabilization on fish habitat value and erosion of estuarine shorelines in North Carolina.*
- Gittman, Rachel, presentation: *Evaluating the effects of shoreline stabilization on fish habitat value and erosion of estuarine shorelines in North Carolina.* At the Benthic Ecology Meeting. Norfolk, VA. March 2012.The list of project products included in the methods section above are the results from this effort.
- Young, Erika (project graduate student, UNC-IMS), presentation on nekton results at the Benthic Ecology Meeting in Birmingham, AL. April 2010.
- Young, Erika, seminar series presentation on nekton and bird results at Western Carolina University in March 2011 and UNC-Pembroke in April 2011.
- Young, Erika, presentation on nekton and bird results to the Student to Academic Professoriate for American Indians (SAPAI) in Pablo Montana in June 2012.
- O'Meara, Teri, et.al. (in prep), *Impacts of shoreline hardening on salt marsh vegetation.*
- Co-PI Piehler, Michael, et. al, (in prep), *Impacts of shoreline hardening on denitrification in salt marshes*.
- Ridge, Justin, (project graduate student, UNC-IMS) (in prep), *Exposure time determines oyster reef success*.
- Gittman, R.K. (project graduate student, UNC-IMS), Popowich, A.M., Peterson, C. H., and Bruno, J.F. (In prep). *To armor or not to armor: an evaluation of the performance of shoreline armoring during Hurricane Irene*.
- Young, Erica, et. al (in prep), *Fish utilization of fringing marsh associated with bulkheads compared to natural marhses.*
- Young, Erica, et. al (in prep), *Bird utilization of fringing marsh associated with bulkheads compared to natural marshes*
- Young, Erica, P.h.D. dissertation, UNC-CH, 2012.
- Co-PI Peterson, Charles., et. al (in prep), *The role of oyster filtration and biodeposition in stimulating a variety of organisms at different trophic levels.*
- Currin, C.A., Chappell, W.S, and Deaton, A., 2010, *Developing alternative shoreline armoring strategies: The living shoreline approach in North Carolina*, in Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S., eds., 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 91-102.

Project Results Summary:

Current shoreline policy in N.C., and in many other states in the southeast U. S., follows the U. S. Army Corps of Engineers nationwide permit which authorizes shore protection along eroding estuarine shorelines, based on the assumption that there is no net cumulative adverse impact of shoreline hardening on estuarine habitats (Titus 2009). Although evidence that shoreline hardening has an adverse impact on ecological function of shoreline habitats is available (Currin et al. 2010), few studies have examined the issue from a landscape perspective including impacts of shoreline hardening on estuarine communities and ecosystem services (but see Seitz et al. 2006). Our research targeted the consequences of bulkheads on estuarine shorelines which support fringing salt marsh, which in North Carolina represents over 65% of the states's 12,000 miles of shoreline (DCM, 2012). We found that fringing marshes occurring adjacent to bulkheads generally provided the same ecosystem structure and functions as would be found in natural fringing salt marshes, including sediment, plant and benthic fauna characteristics, utilization by fish and birds, nutrient cycling and N removal, and attenuation of wave energy. However, we also found that the level of these services, particularly N removal, diminished with a decrease in marsh width. The key question is whether the construction of bulkheads leads, over time, to a reduction in marsh habitat. This may result through both loss of marsh through interruption of landward transgression, and by erosion of the marsh via wave energy (Titus 2009). We found reduced surface elevation associated with narrow marshes and bulkheads without marsh, which is consistent with the conclusion that over time, bulkheads reduce marsh width via erosion and ultimately result in a loss of marsh habitat. Our stem density data also support this conclusion as narrower marshes were less dense. Our research showed that bulkheaded shorelines without any fringing marsh had significantly reduced capacity for nitrogen removal, fewer and less diverse bird communities, no ability to attenuate wave energy and trap sediments to maintain surface elevation, and different infaunal communities. While this project was not long enough to quantify if bulkheading leads to decreased marsh, our results do suggest possible support for this model. Our project clearly indicates that many important ecosystem services will be lost if N.C.'s estuarine marsh system is narrowed and/or eliminated.

The outreach portion of our project clearly showed that protection from erosion was the key issue for estuarine property owners. Thus, there should be no impediment to property owners adopting alternatives so long as the alternatives provide similar levels of protection from erosion. Our demonstration project was designed to provide a case study to do just that; show that an alternative structure could protect estuarine property from erosion. All monitoring to date suggest that the loose shell with marsh plantings approach is a viable approach to stabilize an estuarine shoreline in a low – medium energy environment. Continued education is needed to ensure that these findings are provided to estuarine property owners and marine contractors. These groups are the most important as they are typically the ones deciding what type of stabilization structure is to be utilized. Our *Weighing Your Options* booklet is a first step toward providing this information. Only through continued efforts in research, education and policy will the bukheading status quo in N.C. be shifted toward options that both protect property and minimize impacts to coastal marsh and the ecosystem services that they provide.

3. STATE OF THE TECHNOLOGY

Demonstration:

The results of this project are currently being utilized. The list below provides the current real world uses of our technology.

- The demonstration project is constructed and being evaluated in the field currently.
- The *Weighing Your Options* booklet is being utilized and is being distributed to many different audiences. There is already a need to seek funding to reprint additional copies.
- The research results are being incorporated into peer reviewed manuscripts and presented to management bodies like the N.C. Coastal Resources Commission (November 2012).
- The DCM and the Division of Marine Fisheries have been working with their parent organization the N.C. Department of Environmental and Natural Resources (DENR) to establish a Department-level strategy to streamline permitting and develop other actions to facilitate the use of "living shorelines." The DENR has agreed to promote living shorelines with emphasis on several areas, including: a) the investigation of potential financial incentives and cost reductions for living shorelines, b) the continuation of advocacy and public awareness by DCM staff, c) expanded education and outreach efforts, d) the development of a pre- and post- storm research project that will study the effectiveness and stability of riprap sills versus bulkheads, e) the continuation of mapping, monitoring and research efforts, and e) the streamlining of the current general permit for the construction of riprap sills. To facilitate this, a living shorelines implementation team has been established made up of key staff members from Divisions within the DENR. The team is tasked with developing a strategic plan to accomplish these goals. Project PIs Currin and Fear are part of this team, providing a direct link for use of our project results. Many of the goals of this new DENR effort parallel the objectives of this project, providing an extraordinary real world demonstration of our technology.

Application:

The project team has been able to document use of our products by the following individuals. The individuals that have an asterisk next to their name are willing to be contacted by CICEET at the provided email address. The others on this list were not unwilling; we just did not confirm their willingness due to overlap with an already identified end user. This is by no means an exhaustive list, as we are not able to quantify the users that access our information electronically. However, it should be a good representation of the types of users impacted by this project.

* Tracy Skrabal, Coastal Scientist, Southeast Regional Manager, North Carolina Coastal Federation, (tracys@nccoast.org). The N.C. Coastal Federation has been using and advertising the *Weighing Your Options* Booklet to their customers. The N.C. Coastal Federation also has the *Weighing Your Options* booklet available for download from their website. The project team members regularly have interactions with the N.C. Coastal Federation and it was through these interactions that the N.C. Coastal Federation was made aware of the booklet.

* Angie Baylis, Arthur C. Edwards Elementary school, (Baylis-angela.baylis@craven.k12.nc.us). Mrs. Baylis is a 5th grade teacher that has been a regular

customer of the education sector of NCNERR. Mrs. Baylis was told about the student activity booklet, *Our Living Estuaries*, which was developed as part of this project and requested copies for use in her classroom.

Pat McGhee, L.B. Yancey Elementary School. Mrs McGhee is a 5th grade teacher and requested copies of the student activity booklet, *Our Living Estuaries*, for use by her students. She learned about the booklet through the education sector of NCNERR.

* Gloria Putnam, Coastal Resources and Communities Specialist, North Carolina Sea Grant, (gloria_putnam@ncsu.edu). Mrs. Putnam has been using the SAV technical 2 pager developed as part of this project along with other SAV documents available to produce a new SAV information document to inform stakeholders about this important resource. Mrs. Putnam was sent a copy of the SAV 2 pager by PI Fear after PI Fear learned that Mrs. Putnam was working on a new SAV document. Mrs. Putnam and Dr. Fear have regular interactions.

* P.I. John Fear, N.C. Division of Coastal Management, (john.fear@ncdenr.gov), 252-838-0884. P.I. Fear is part of the DENR's, living shoreline implementation team mentioned in the previous section. Project results are being relayed to the implementation team. The implementation team is holding monthly meetings.

4. NEXT STEPS:

While the funded portion of this project is complete. The project team is committed to continuing certain aspects of the project. These will be completed as funding and staffing allow over the next 2-4 years. Additional funding may be needed to complete some of these. In those instances new proposals will be developed that build off the work funded by this project. The next steps currently envisioned by the project team include the following list.

- Continue evaluating performance of demonstration project.
- PIs Fear and Currin will continue working with the Living Shoreline Implementation Team to foster the use of living shorelines in the State.
- PI Fear and Currin will reassess study sites in terms of marsh vegetation and elevation in 3 years to track change since initial baseline data collected (to verify our place for time model depicted in Figure 2).
- Presentations by PI Fear at November 2012 Coastal Resources Commission Meeting to present final project results.
- Presentations at scientific conferences by all project team members to present final project results.
- Continued manuscript submissions based on project results.
- Update project webpage
- Investigate the allocation between fungal and bacteria mediated denitrification (follow up work based on findings from this project. Note that this effort has already secured addition funding to conduct this work)
- Education and outreach trips to the demonstration site by the education staff of NCNERR.
- Incorporate research results into an updated shoreline stabilization workshop for coastal decision makers/marine contractors.

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