COASTAL RECREATIONAL FISHING LICENSE

FINAL REPORT

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Grant Title: Fisheries Habitat Impacts of Marsh Sills (Living Shorelines) as a Shoreline Stabilization/Restoration Alternative to Bulkheads

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Abstract/Executive Summary

Tidal salt marshes provide vital services to the coastal ecosystem and to human welfare, particularly by providing habitat to fish and crustaceans. With increasing coastal development, tidal salt marshes and other shoreline habitats of North Carolina are increasingly modified by artificial shoreline stabilizations structures, such as bulkheads and riprap revetments. Bulkheads interfere with salt marsh function and inhibit upwards migration of shoreline habitats, thereby leading to the loss of habitats critical to fish production. The Coastal Habitat Protection Plan (CHPP) has identified the issue of promoting marsh sills, a shoreline restoration strategy and alternative to bulkheads, as a current top priority. Unfortunately, few data exists to assess the performance of marsh sills. The purpose of this CRFL project is to assess the effectiveness of marsh sills in restoring and sustaining viable shoreline habitats for fish and mobile crustaceans. This was achieved through completion of four components: (1) Evaluation of the ecological function of the permitted and constructed marsh sills in North Carolina; (2) Assessment of the shoreline stabilization performance of marsh sills relative to traditional stabilization structures; (3) Quantification of fish and crustacean (nekton) use of coastal habitats adjacent to marsh sills; and (4) Comparison of the abundance and species composition of epibiota and nekton associated with marsh sills, bulkheads, and control (unstabilized) marshes to determine their relative habitat use and value.

Surveys of 25 marsh sills reveal that marsh sills are constructed using a variety of materials and designs in geographically diverse settings. The subset of marsh sills and control sites selected for further surveying and sampling do not differ in elevation, slope, marsh width, sediment OMC, marsh composition or seagrass density as a function of the presence of absence of a marsh sill. However, there is significant variation in slope, marsh width, marsh composition, and seagrass density between sites. These differences are attributed to site age (sills only) and small-scale differences in the physical characteristics of each site. The mean change in elevation, slope, sediment OMC, and marsh stem density did not differ between marsh sill and control sites pre- and post-landfall of Hurricane Irene. Individual sites were affected differently by the hurricane, but no or minimal damage or erosion was observed at any site post-Hurricane. On the contrary, post-hurricane damage surveys reveal that over 1/3 of the approximately 20km of bulkheads along the Outer Banks back-barrier shoreline were damaged or had collapsed completely. No damage was observed to marsh sill or riprap shorelines, indicating that marsh sills may provide better erosion protection than bulkheads during storm events. Nekton abundance, biomass, and diversity are greater in the marsh at sill sites than control sites, but are equivalent between sills and controls in seagrass/mudflat habitat. Epibiota community composition differs between bulkheads, sills and controls at upper elevations, with oysters dominating the community at sill and control sites and barnacles making up a large percentage of the cover at bulkhead sites. Nekton using habitat directly adjacent to bulkheads are less abundant, have less biomass, and are less diverse than nekton found adjacent to sills. Sills are more structurally complex than bulkheads and are likely serving as a predation refuge for juvenile transient and small resident species.

Through this project, we have provided the missing information on fish habitat function needed to reassure resource agencies that marsh sills restore and sustain fish habitat services and provide equivalent if not better erosion protection than bulkheads. We recommend that resource agencies consider and promote marsh restoration as the first option for shoreline stabilization, followed by carefully designed and reviewed marsh sills in lieu of bulkheads.

Introduction

In recognition of the reliance of fish on the habitats that produce them, the North Carolina General Assembly passed the Fisheries Reform Act of 1997 with a provision requiring the Department of Environment and Natural Resources (DENR) to prepare and then implement a Coastal Habitat Protection Plan (CHPP). The legislative intent for the CHPP is long-term enhancement of coastal fisheries associated with explicitly identified fish habitats. Salt marshes, seagrass beds, oyster reefs, and mudflats serve as important habitat for numerous marine fishes and crustaceans at various life stages (Grabowski et al. 2005, Rountree and Able 2006, Stunz et al. 2010). These habitats serve both as predation refuges and as foraging grounds, yet they are under threat from numerous anthropogenic stressors (Boesch and Turner 1984, Turner et al. 1999, Beck et al. 2001, Minello et al. 2003).

Coastal development and climate change are adversely affecting these coastal ecosystems and potentially altering their habitat value (Harley et al. 2006, Hoegh-Guldberg and Bruno 2010). Shoreline erosion caused by storms may prevent coastal habitats from keeping up with rising sea level, forcing habitats to transgress landward (Titus 1998, Tebaldi et al. 2012). While artificial shoreline stabilization can reduce erosion, structures such as bulkheads are thought to have long-term negative effects on fisheries habitats, in particular preventing salt marsh from migrating up-slope as sea level continues to rise (Figure 1) (Titus 1998). The current recommended action stated in the completed 2005 CHPP is to "protect fish habitat by revising estuarine and public trust shoreline stabilization rules using best available information, considering estuarine erosion rates, and the development and promotion of incentives for use of alternatives to vertical shoreline stabilization measures" (Street et al. 2005). Marsh sills are intertidal breakwaters typically constructed seaward of the salt marsh, with gaps or drop-downs between each sill length to allow for inundation of the marsh behind the sill (North Carolina Estuarine Biological, Physical Processes Work Group, and North Carolina Division of Coastal Management 2006). The marsh sill is intended to sustain, enhance, and restore salt marsh habitat, while still providing erosion protection, yet few studies have been completed to support these claims (Currin et al. 2007). Although some progress has been made in determining the effects of various types of stabilization on salt marshes and fish and mobile crustaceans, the results have been mixed (Bozek and Burdick 2005, Seitz et al. 2006, Currin et al. 2007).

The NC General Assembly has also acted directly with legislation to address this CHPP recommendation by mandating the Division of Coastal Management (DCM) to develop a General Permit for construction of marsh sills to facilitate their use in lieu of vertical bulkheads as a means of shoreline protection. The resultant Marsh Sill General Permit has now been in place for six years, but is rarely used by private property owners. This is in large part because of restrictive requirements from reviewing agencies who lack reassurance that the marsh sills do indeed meet their promise of enhancing and sustaining salt marsh and other associated fish and wildlife habitats. This CRFL project focuses on the impacts of shoreline stabilization on tidal salt marshes and adjacent intertidal and subtidal fish habitat. For this project, we collaborated with the NC Division of Coastal Management (DCM) and with Dr. Carolyn Currin's research group at the NOAA lab in Beaufort to conduct an integrated physical and biological assessment of marsh sills in North Carolina.

Objective: The overall objective of this project is to gather and analyze field data to determine how the ecological functions and fish habitat values of shorelines stabilized by marsh sills compare to those of natural shorelines occupied by salt marshes. This objective was accomplished through four interconnected components, which address the following questions:

1) What is the spatial distribution and quality of fish habitat associated with marsh sills in North Carolina?

2) How do marsh sills perform in terms of shoreline stabilization relative to other stabilization structures and marshes without artificial stabilization?

3) What are the effects of marsh sills on fish and crustacean (nekton herein) use of nearshore habitats (salt marsh, seagrass beds, and mudflats)?

4) What is the relative habitat value of marsh sills for nekton and epibiota (e.g., oysters, mussels) when compared to bulkheads and marshes without stabilization structures?

The components of the project objective were revised from those originally included in the proposal and an explanation and justification for these revisions is provided in the Discussion section of this report.

Procedures

We have provided a brief summary of our approach to completing each component, followed by a description of the study sites and component-specific procedures**.**

Component 1

To determine the spatial distribution of fish habitats associated with marsh sills, we visited 25 marsh sill sites in North Carolina in 2010 to assess the range of design techniques and geographic settings in which sills are used. We then selected three marsh sill sites, referred to herein as control-impact (CI) sites, that we deemed to be representative of appropriately constructed sills (after consultation with DCM staff). To ensure that we have the ability to detect differences in coastal habitats correlated with the presence or absence of marsh sills, we selected sites with similar geographic settings (wave exposure, tidal inundation patterns, and sediment type). We selected three marsh sites that are similar in geographic setting and habitat spatial distribution to serve as control sites.

Component 2

To assess the ability of marsh sills to stabilize the shoreline and prevent erosion, we surveyed the CI sites selected under Objective 1 prior to (2010) and post-landfall (2011) of Hurricane Irene's landfall in August 2011 and measured site characteristics (surface elevation, vegetation cover, and sediment parameters) at four sill-control site pairs located in the northern, central, and southern NC coastal regions pre- and post-sill construction, referred to as Before-After-Control-Impact (BACI) sites herein. To compare the stabilization performance of marsh sills to more traditional techniques (i.e. bulkheads and riprap revetments), we conducted visual, post-Hurricane Irene damage assessments of directly impacted shorelines in 2011.

Component 3

To determine if and how temporal patterns of nekton (fish and mobile crustaceans) utilization vary in response to the presence and consequences of marsh sills, we intensively sampled nekton in 2010 at CI sites and at BACI sites pre- and post-sill construction in 2010, 2011, and 2012.

Component 4

To test how hard substrates introduced to stabilized estuarine and sound shorelines are utilized as habitats by epibiota (macroalgae and invertebrates) and nekton, we sampled epibiota and nekton at replicate bulkheads, sills, and control sites (no stabilization) in 2011.

Description of study sites

CI sites consist of three existing granite marsh sills and three control marsh sites that lack artificial stabilization. The three stone sills and paired control sites are located in Pine Knoll Shores, NC (Figure 2c). At each site, a low sill, consisting of granite boulders was constructed at a base elevation near the mean low water mark, extending to a height just above mean sea level. Marsh grass, *Spartina alternaflora* and *S. patens*, was planted behind the sill at elevations consistent with nearby natural marshes. Sill sites 1 and 3 were constructed and planted in 2002, while sill site 2 was constructed in 2008 and planted in 2010. Control sites were selected near each marsh sill site based on physical similarity and proximity to the marsh sill sites. All sites were located within 500 m of one another, ensuring similar hydrology, geomorphology, tidal range, water quality, orientation and fetch.

BACI sites are located in Hatteras, NC (35°13'18.97"N, 75°41'35.21"W), Pine Knoll Shores, NC (34°42'11.58"N, 76°48'21.21"W), Swansboro, NC (34°41'49.90"N, 77° 6'24.61"W), and Holly Ridge, NC (34°28'12.30"N, 77°30'28.37"W) (Figure 2 a-d). At each site, a low sill, consisting of granite boulders (Hatteras and PKS) or oyster shell bags (Swansboro and Holly Ridge) was constructed at a base elevation near the mean low water mark, extending to a height just above mean sea level. *S. alternaflora* and *S. patens* (except the PKS site) was planted behind the sill at elevations consistent with nearby natural marshes. The Swansboro sill was constructed in the September 2010 and planted in May 2011, the Hatteras sill was constructed in March 2011 and planted in May 2011, the Holly Ridge sill was constructed in November 2011 and planted in May 2012, and the Pine Knoll Shores sill was constructed in April 2012 and will be planted in May 2013. All control sites were selected based on physical similarity and are located within 50 to 100 m of the paired sill site, ensuring similar hydrology, geomorphology, tidal range, water quality, orientation and fetch. When evaluating the stabilization performance of the marsh sill sites when compared to control sites, we had to exclude control site 2 because we were unable to obtain permission to revisit the site post-Hurricane Irene. Instead, we resurveyed the control site used for the BACI comparison in Pine Knoll Shores (referred to as CI control site 4 under Component 2).

For the Hurricane Irene damage surveys (Component 2), we selected sections of shoreline along Bogue and Pamlico Sounds, based on the path of Hurricane Irene in August 2011. We selected approximately 20 km of shoreline on Bogue Banks, a barrier island approximately 34 km in length, which runs east to west, and is bordered by Bogue Sound (north) and the Atlantic Ocean (south) and 60 km of shoreline on Hatteras Island, a barrier island approximately 320 km in length, bordered by Pamlico Sounds (west) and the Atlantic Ocean (east) (Figures 3 and 4, respectively).

We quantified epibiota and conducted edge habitat nekton sampling (Component 4) at CI stone sill and control sites surveyed under Components 1, 2, and 3, as well as at three bulkhead sites located in PKS along the same shoreline (Figure 2b).

Components 1 and 2: Assessing fish habitat availability and stabilization performance of marsh sills

Marsh sill statewide site assessments with NC DCM

We participated in the NC DCM marsh sill evaluations conducted from June to August 2010. The evaluations consisted of site visits to each marsh sill that had been permitted and constructed within North Carolina. For each site visit, we completed a questionnaire developed by DCM regarding the physical and biological performance of the marsh sill site. We participated in 25 of the 30 site visits. The methods and questionnaire for the evaluations can be found here: http://dcm2.enr.state.nc.us/estuarineshoreline/marshsill.html. In addition to completing the evaluations, we selected three sills that are representative of appropriately designed and permitted sills and were located with the same geographic setting to assess whether marsh sills affect fish habitat availability. The survey methods for these sites are described below.

Surface elevation, slope, and marsh width

We measured surface elevation at each site using a leveling rod and rotary laser level in the plots along five permanent transects and referenced the measurements to semi-permanent benchmarks with elevations determined using a Trimble Virtual Reference Station (VRS), Real Time Kinematic (RTK), Global Positioning System (GPS). The average slope (ratio of height over distance) of the marsh was calculated for each site. We calculated the maximum mean inundated (2cm or greater) marsh width (m) each site at one monthly spring high tide using marsh surface elevation data, additional width measurements taken using aerial photographs in ArcGIS, and water level data recorded every six minutes using a stationary HOBO continuous water level recorder located at Pine Knoll Shores Aquarium. Water level data was not available for the July spring tide due to an error with the water level recorder during that sample period. Therefore the maximum inundated marsh width (m) for the July sampling period was calculated by averaging the maximum marsh width of each site for June and August.

Sediment organic matter content

We took sediment organic matter samples by coring the top 3-5 cm of sediment layer at every plot on all site transects and taking the cores back to the lab to be frozen for later analysis. A subsample of approximately 30 g (wet weight) was dried overnight in a 100°C oven, and then placed in a 450°C oven for 6–8 h to obtain ash weight. Percent organic matter was calculated by subtracting the ash weight from the dry weight and then dividing by the total dry weight.

Salt marsh community characteristics

To compare marsh plant community composition at marsh sill sites and control sites, we measured salt marsh stem densities, maximum stem heights, and percent cover by species during the period of peak marsh biomass (July-August) at each site pair. Five transect locations were selected using restricted random sampling, which has been shown to produce better density estimates than simple random sampling (Neckles et al. 2002). Marsh transects began at the seaward edge of the marsh and continued to the start of upland vegetation or property owner landscaping, which reached no more than 20 m from the start of the transect at most sites. The length of each transect within a site depended on the extent of the marsh and the distance of the sill from shore. Marsh sampling plots began at the lower marsh edge and samples were collected at 1, 3 or 5 m intervals along each transect, depending on total transect length. We recorded percent cover by species within each 1-m^2 plot and stem density by species and stem heights of

the five tallest plants by species per 0.25-m^2 quadrat (Daoust and Childers 1998, Craft et al. 2003).

Seagrass community characteristics

We surveyed subtidal areas up to 30 meters seaward of the marsh edge at each site and quantified percent cover of seagrass by species, live oyster, loose shell, and mudflat. The length of each transect within a site depended on the extent of the seagrass beds and the distance of the sill from the estimate high water line. Subtidal sampling plots began at the lower marsh edge and samples were collected every 3 or 5 m along each transect, depending on total transect length. Seagrass shoot density was estimated by counting the total number of shoots per species enclosed by 0.25 m^2 quadrats using a snorkel and mask (Hauxwell et al. 2001).

Visual damage surveys

To assess the stabilization performance of different shoreline stabilization structures during Hurricane Irene, we conducted visual surveys of 20 km of continuous shoreline from Atlantic Beach, NC to Emerald Isle, NC, and 60 km of shoreline in Hatteras Village, Rodanthe, Waves, and Salvo on Hatteras Island, NC (Figures 3 and 4, respectively). We recorded GPS points using a Trimble GeoExplorer (2008 series), took photographs for each change in shore type (e.g., marsh, beach, bulkhead, riprap), and categorized each instance of visible shoreline erosion or damage (Table 1). The GPS data, photos, and category assignments were then used to determine the percentage of armored shoreline by type and the percentage of damaged shoreline by type.

Plotting GPS points along shoreline and comparison to 2012 NC DCM digitized shoreline

We imported the GPS points into ArcGIS as shapefiles overlaid on 2010 aerial imagery of the Bogue Banks and the Outer Banks shoreline. Each GPS point was classified according to shoreline type (e.g., marsh, beach, bulkhead, sill) using the aerial imagery, GPS coordinates, field notes, and field photos. After digitizing the shoreline based on our visual surveys and aerial imagery, we then reconciled our shoreline to the shoreline digitized by NC DCM in 2011 and 2012. We overlaid the DCM polylines onto our shapefiles and the 2010 aerial imagery of the Outer Banks and Bogue Banks coastlines. At each GPS point from our surveys, we classified the corresponding shoreline and structure polyline segments with a habitat or armoring descriptor. NC DCM classified the shoreline using 2007 aerial imagery for Dare and Hyde counties and 2010 aerial imagery for Carteret County, producing ArcGIS continuous polyline shapefiles that include the shoreline type (marsh, sediment bank, modified, miscellaneous) and shoreline structure type (boat ramp, vertical structure, breakwater, groin/jetty, sill, sloped structure). We did not receive the shoreline data for Carteret County until June 2012; therefore the results of the Bogue Banks analysis will not be presented in this report.

Component 3: Evaluating nekton use of fish habitats associated with marsh sills

Salt marsh nekton sampling

We sampled nekton during one night spring tide per month between June and October 2010 to determine nekton utilization of the marsh and subtidal habitats at each site. We sampled nekton utilizing the marsh during high tide by simultaneously setting two fyke nets at a paired marsh sill and natural marsh sites during a dusk or night spring tide. Fyke nets were placed at the sill gaps at the marsh sill sites and at random locations at the edge of natural marshes, with the fyke net opening set at approximately the same distance from the high water line at each paired site (Rozas

and Minello 1997, Currin et al. 2007). The fyke nets consist of a 0.9m by 0.9m by 5.1m compartmentalized net bag with 0.9m by 5.1m wings that stretch out from the bag. Fyke net wings were set at the same distance apart at marsh sill and control site and were collected simultaneously in order of setting at each site. Species were identified, counted, weighed, and the first twenty of each species were measured for standard length (fish and shrimp) or carapace length (crabs) either in the field or in the lab (after being transported using buckets and air bubblers) and then released to minimize mortality. We calculated catch per unit effort (individuals or grams per soak time, hours) for nekton caught by each net.

Seagrass/mudflat nekton sampling

To determine nekton utilization of subtidal habitats adjacent to marsh sills and natural marshes, we seined two times during an afternoon spring low tide each month (June to October 2010). Seining occurred parallel to the shoreline over a standard distance (typically 20 m intervals) at each site. Seines consisted of a 7.3m by 1.8m net with a 1.8m by 1.8m by 1.2m bag. Species were identified, counted, weighed, and the first twenty of each species were measured for true length (fish and shrimp) or carapace length (crabs) either in the field or in the lab (after being transported using buckets and air bubblers) and then released to minimize mortality. We calculated catch per unit effort (individuals or grams per area, m^2) for nekton caught by each net.

Component 4: Quantifying epibiota and nekton at bulkhead, marsh sill, and control sites

To test how hard substrates introduced to stabilized estuarine and sound shorelines are utilized as habitats by epibiota (macroalgae and invertebrates) and nekton, we sampled replicate bulkheads, stone sills, and control sites (n=3) in September 2011. We determined the percent cover (using the point-intersect method, with 16 intersections within a $0.25m^2$ quadrat) and species composition of epibiotic species attached to the introduced sections of hard substrates that are only submerged at high tide (high elevation) and completely submerged except during low tide (low elevation).

Nekton utilization of the substrate was assessed by setting replicate (n=10) minnow traps at the edge of each shoreline type two hours before high tide and collecting the traps two hours after high tide monthly from June to October 2011. Nekton species handling, identification, measurement were the same as for Component 3. We calculated catch per unit effort (individuals or grams per soak time, hours) for nekton caught by each net.

Statistics

We performed two-factor, nested (sill vs. control, nested site) analysis of variance (ANOVA)s to test for significant differences in marsh sediment OMC, total marsh plant stem densities, changes in sediment OMC, and changes in total marsh stem density. Data were averaged by plot before conducting these analyses. We conducted pairwise comparisons among sites using Tukey's HSD comparisons. Because of the violations of the assumptions for parametric statistical testing, two-factor (sill vs. control and site) permutational analysis of variance (PERMANOVAs) on Euclidean distance matrices were performed to test for significant differences in marsh species diversity indices, marsh elevation, marsh slope, maximum inundated marsh width, seagrass shoot densities, and epibiota total percent cover. PERMANOVA pairwise comparisons were performed to elucidate site differences. To decipher significant community differences between marsh sill and control sites, we performed two-factor, nested PERMANOVAs on the Bray-Curtis similarity matrices of marsh plant densities and epibiotic community composition. Marsh plant densities and epibiotic cover were log (x+1) transformed to reduce the effect of the most abundant species

when testing for differences in community composition.

The abundance and biomass of each species of fish and decapods were pooled separately for each habitat (marsh from fyke nets or seagrass/mudflat from seines) per month, per site. We compared nekton species diversity for each habitat between CI marsh sill and control sites by calculating species diversity indices. We performed two-factor (sill vs. control and sample month) PERMANOVAs on the Bray-Curtis similarity matrices of nekton abundance and biomass to decipher significant community differences in each habitat between CI marsh sills and control sites. Nekton species abundances were log (x+1) transformed to reduce the effect of the most abundant species when testing for differences in community composition. To test for significant differences in fish and decapod abundance, biomass, and on raw diversity indices, we performed two-factor ANOVAs on box-cox transformed pooled fyke net, seine, and minnow trap data. We performed Wilcoxon sign rank tests on individual abundances and biomass (pooled by net and month) of each species of fish and crustacean to compare individual species use of sill and control sites. An alpha level of 0.05 was used for all hypothesis testing. Analyses were conducted using JMP 9.0 (SAS 2012) and PRIMER-E software (Clarke and Gorley 2001).

Results

Component 1: State-wide marsh sill evaluations and selected marsh sill surveys

NC DCM statewide marsh sill evaluations

The results of the statewide marsh sill evaluations conducted in conjunction with NC DCM can be found in the final report completed by NC DCM (http://dcm2.enr.state.nc.us/estuarineshoreline/marshsill.html).

CI site surface elevation, slope, and marsh width

Mean elevation (m), slope, and maximum inundated width (m) of the marsh found at marsh sill sites was not significantly different from that of the marsh found at control sites ($P>0.05$, each metric, Table 2). Elevations are relative to NAVD88. However, the average slope of sill site 1 was less than the slope of control sites 1 and 3 ($P<0.05$) and the maximum inundated marsh width of sill site 2 and control site 2 was smaller than the other sill and control sites ($P<0.05$).

CI site sediment organic matter content

The organic matter content (OMC) of marsh sediments ranged from 2.1 to 3.4% at control sites and from 2.2 to 3.1% at marsh sill sites (Figure 5). Mean OMC did not differ by treatment (sill vs. control) or by site ($P>0.1$).

CI site marsh plant community characteristics

The community composition, species richness, evenness, and Shannon diversity of marsh plant species did not differ as a function of the presence of a marsh sill ($P>0.05$, each metric). However, there were differences in the community composition between sites, with the composition of sill site 2 differing from sill sites 1 and 3, as well as control site 3 ($P<0.05$, Figure 6). Mean total marsh plant stem density did not differ between sill and control sites, but the total density of marsh plants at sill site 2 was less than the density of sill site 1 (Figure 6, $P<0.05$). To avoid redundancy with stem density data, percent cover data is not presented in this report, but is included in the raw data files.

CI site seagrass community characteristics

Two species of seagrass were present at the CI sites, *Halodule wrightii* and *Zostera marina,* with *Z. marina* only present at sill site 3. The total seagrass density varied among some sites ($P<0.05$, Figure 7), but the mean density was not different between sill and control sites ($P>0.05$). To avoid redundancy with shoot density data, percent cover data is not presented in this report, but is included in the raw data files.

Component 2: Marsh sill stabilization performance

CI site comparison pre- and post-Hurricane Irene

Marsh surface elevation at CI control increased by 2.0 cm, while elevation of the sill sites decreased by 0.78 cm from August 2010 to October 2011 (Figure 8a). Elevation changes were more variable at marsh sill sites, ranging from -11.0 cm to 7.4 cm. Control site mean elevation changes ranged from -2.7 cm to 7.0 cm (Figure 8b). The slope of the marsh at sill and control sites increased by 0.0033 and 0.065, respectively (Figure 9a). Changes in slope at marsh sill sites ranged from -0.085 to 0.057 and changes in slope at control sites ranged from -0.089 to 0.28 (Figure 9b).

Mean marsh sediment OMC decreased by 0.73% at control sites, while mean OMC increased at marsh sill sites by 0.12% from August 2010 to October 2011, although these differences in OMC change were not significant ($P>0.1$). The change in sediment OMC ranged from -1.3 to 0.025% at control sites and from -0.24 to 0.63 at marsh sill sites (Figure 10).

The total marsh stem density decreased for all sites from August 2010 to October 2011 (Figure 11). There was no significant difference in the change in stem density between sill and control sites, with stem loss ranging from 13 stems to 62 stems per $0.25m^2$ at control sites, and stem loss ranging from 13 to 78 stems per $0.25m^2$ at sill sites ($P>0.1$, Figure 11). Losses in stem densities spanned all elevations of the marsh, with the mean loss at the marsh edge being 21 stems per $0.25m^2$ and the mean loss at the uppermost marsh plot being 51 stems per $0.25m^2$.

BACI site comparison

The results of the BACI site comparison pre- and post-sill construction will be presented in the publication associated with this project upon the completion of the post-construction sampling of the BACI sites. Post-construction sampling was beyond the original scope and award period of this grant. These results and data will be delivered per the guidelines of the CRFL grant program.

Hurricane Irene Damage Surveys

Of the approximately 60 km of shoreline surveyed along the back-barrier portion of the Outer Banks, 35% (~21 km) of shoreline was stabilized by bulkhead (Figure 12a). Other shoreline structure types (sills, riprap, and hybrid riprap/bulkhead) made up only 14% (~8km) of the shoreline, with the remaining shoreline being marsh or beach (Figure 12a). We did not find any visible damage (structural failure, landward erosion) to sill, riprap, or hybrid shorelines surveyed. Of the 21 km of bulkhead shoreline surveyed, 33% was damaged (Figure 12b) with damage ranging from landward erosion to complete bulkhead collapse. A majority of the damage was classified as structural damage to the bulkhead itself. We did not attempt to quantify damage to marsh or beach shorelines. The results of the Bogue Banks damage surveys will be presented in the manuscript to be submitted for publication in a peer-reviewed journal upon completion of the

shoreline analysis.

Component 3: Nekton habitat use

Abundance, biomass, and composition of nekton at CI sites

Salt marshes landward of marsh sills promoted a higher abundance, biomass, richness and diversity of fish and crustaceans than control sites ($P<0.05$, Figures 13a-c, respectively). Juvenile transient species, such as mojarra (*Eucinostomus spp*.), brown shrimp (*Penaeus spp.)* and flounder (*Paralichthys spp.),* as well as small resident species, such as mummichogs (*Fundulus heteroclitus*), killifish (*Fundulus majalis*), and grass shrimp (*Hippolyte spp.)* were more abundant at sill sites than control sites ($P<0.05$, Figure 14a).

There was no difference in abundance, biomass, or community composition of fish and crustaceans using mudflat or seagrass habitat adjacent to sills or control sites ($P>0.1$, Figure 15a-b). There was a correlation between seagrass percent cover for the area seined and total fish and crustacean abundance (adjusted r^2= $P<0.05$, Figure 16).

Abundance, biomass, and composition of nekton at BACI sites

The results of the BACI nekton use pre- and post-sill construction will be presented in the publication associated with this project upon the completion of the post-construction sampling of the BACI sites. These results and data will be delivered per the guidelines of the CRFL grant program.

Component 4: Epibiota and nekton use of bulkheads and marsh sills

The total epibiotic percent cover did not differ between marsh sill, bulkhead, and control sites at either the high or low elevation plots ($P>0.05$, Figure 17a-b). At the high elevation plots, the community composition of epibiota was different between bulkhead and sill sites and between bulkhead and control sites ($P<0.05$, Figure 17a). At the low elevation plots, epibiotic community composition was different between control and sill sites ($P<0.05$, Figure 17b). Although the mean community composition of low elevation plots on bulkheads appeared to be different from that of sill and control sites, high variability in the total percent cover and community composition between bulkhead sites resulted in the difference being non-significant (Figure 17b).

Unvegetated habitat directly adjacent to bulkheads exhibited lower abundance and biomass of fish and crustaceans than habitat adjacent to sills (Figure 18a-b). The community composition of nekton caught at bulkhead sites, marsh sills, and controls sites was different ($P<0.05$). No mummichogs or killifish (*Fundulus spp.)* were caught at bulkhead sites, while the mean number of individuals caught at marsh sills sites and control sites was 124 and 8, respectively.

Discussion

Interpretation of results

Component 1: Statewide marsh sill evaluations and selected marsh sill surveys

The results of the statewide marsh sill evaluations are discussed in the final report on the NC DCM webpage. The surveys of the selected marsh sill and control sites in Pine Knoll Shores reveal that there are no overall differences in the physical or ecological characteristics sites with

marsh sills when compared to control sites. However, the youngest sill site, sill 2, had a lower marsh density and different marsh community composition than a majority of the control and other sill sites. This is likely due to the age of the restored marsh and the eroded state of the existing marsh at the site prior to the sill construction relative to the other sites. Previous studies of marsh restoration (e.g., (Boyer et al. 2000, Zedler and Callaway 2000, Currin et al. 2007)) have shown that it may take several years for the vegetation of a restored marsh vegetation to resemble that of a natural marsh.

Sediment OMC is relatively low at all sites, when compared to sediment OMC values reported for previously studied mature marshes on the Atlantic coast (e.g. (Craft et al. 1988)) but are consistent with those values reported by Currin et al. 2007. Although, there was no difference in OMC between control and sill sites, the reduction in wave energy caused by the presence of the sill may result in retention of higher amount of organic matter within the marsh over time. Once complete, the results of the BACI study will be used to further test this hypothesis.

Seagrass density was highly variable across sites, making it difficult to determine if the presence of a marsh sill may affect adjacent seagrass density. Other factors such as wave exposure, boat activity, and water depth (*see* (Fonseca 1998)) may have a greater affect on the seagrass community than the presence or absence of a marsh sill. The results of the BACI surveys of seagrass habitat under Component 2 may provide additional insights and will be considered in the final publication.

Because the marsh sill and control sites were selected within the same geographic setting, factors other than stabilization, such as tidal inundation, geomorphology, and wave exposure, were not expected to result in site differences. However, small differences in these and other factors may have resulted in some of the site differences (e.g., slope, marsh width, seagrass cover) observed. Currin et al. 2007 observed differences in marsh density, community composition, elevation between sites within the same NC region, but these sites were more geographically dispersed and had greater variation in shoreline orientation and fetch. All of these factors should be considered when determining the potential impacts of marsh sill construction on the adjacent habitats. Wave exposure, inundation time, and proximity to channels will be considered as covariates in the final analyses included in a future publication.

Component 2: Marsh sill stabilization performance

The landfall of Hurricane Irene in August 2011 occurred during high tide at the CI marsh sill and control sites. The high tide, combined with the storm surge, resulted in the entire marsh being inundated during the storm (as confirmed by HOBO water level data). The changes in marsh elevation and slope were highly variable across the control and sills sites surveyed (Figures 8 and 9, respectively). While some sites increased in overall elevation and slope (control sites 1 and 4 and sill sites 1 and 2), other sites saw a decrease in elevation and slope (control 3 and sill 3). Sites with a net increase in elevation saw the greatest increases at upper plots where sediment was most likely transported and deposited from landward unvegetated areas present at those sites (Gittman 2011, *personal observation*). Sites with a net decrease in marsh elevation saw the greatest elevations losses at both the highest and lowest elevation plots, indicating that sediments were scoured from the upper marsh edge and the lower marsh edge where vegetative cover is lower. Vegetation can stabilize sediments and prevent erosion along shorelines (Conaway 2005), but we did not find a correlation between vegetation density pre-Hurricane Irene and the overall change in elevation. The relationship between the change in elevation and vegetation percent cover or marsh plant species-specific densities will be explored in a future manuscript.

Changes in sediment OMC were highly variable across sites (Figure 10) and were not correlated with elevation change or marsh stem density change. Marsh density decreased for all sites post-Hurricane Irene and this may be as a result of Hurricane damage to the marsh, as well as seasonal (August to October) or annual differences (2010 to 2011) in stem density (Figure 11). Hurricane damage was visually apparent in some sites where vegetation had been scoured away, but these scoured areas were small (less than 1 m^2) and infrequent within the marsh (Gittman 2011, *personal observation*). Sites will be resurveyed in September 2012 to determine if losses in stem density remain after one growing season.

The results of the BACI site comparison pre- and post-sill construction will be discussed in the publication associated with this project upon the completion of the post-construction sampling of the BACI sites.

The results of the Hurricane Irene damage surveys conducted for shorelines along the Outer Banks, NC, reveal that over 1/3 of the properties with bulkheads were damaged at the time of the survey (Figure 12b). Bulkheads are the most common shoreline stabilization feature along the surveyed shoreline (Figure 12a). Riprap and marsh sills are less common than bulkheads along the Outer Banks shoreline, making up only 3.6% and 2.2% of the shoreline, respectively. No damage was visible to any shoreline protected by riprap or a marsh sill. Although the sample size of riprap and marsh sills is far less than that of bulkheads, the large difference in damage between the structure types (33% for bulkheads and 0% for other structures) may indicate the bulkheads do not provide the best protection against shoreline erosion and damage during storm events. Because the combined high tide and storm surge associated with Hurricane Irene overtopped the shoreline stabilization structures, much of the damage to the bulkheads was likely as a result of scouring of sediment landward of the bulkhead and then subsequent failure of the structural integrity of the bulkhead in the most extreme cases.

In many cases along the Outer Banks and Bogue Banks, NC, the slope of the shoreline landward of the bulkhead is steep (nearly vertical) when compared to marsh sill, riprap, or natural shorelines. This steep grade can result in a large loss of sediment if the stabilizing structure (the bulkhead) collapses or is breached. This result was evident at a majority of the damaged bulkheads surveyed (Gittman 2011, *personal observation*). One property owner in Bogue Banks, NC, reported that replacement of his bulkhead and restoration of his shoreline to its previous elevation and width after Hurricane Irene required 22 truckloads of clean sand fill (epibiota bulkhead 2, Acree 2012, *personal communication*). Marsh sill site 2, located approximately100 meters from this collapsed bulkhead saw an increase in overall marsh elevation and only a slight increase in the slope of the shoreline (Figures 8b and 9b, respectively). Additional analysis and interpretation of the results of the damage surveys will be included in the publication upon completion of the Bogue Banks shoreline analysis.

Component 3: Nekton habitat use

Fyke net data reveal that nekton are more abundant, have more total biomass, and are more diverse at sites with marsh sills than sites with just a fringing marsh (Figure 13a-c). Greater fish and crustacean abundance, biomass, and diversity may indicate that sills increase the structural complexity of the habitat, which could benefit small resident and juvenile fishes (Grabowski 2004). Some of the species that are more abundant at marsh sill sites, such as mummichogs and killifish (*Fundulus spp.*), are known to be marsh residents (Able et al. 2012), while others, such as flounder (*Paralichthys spp*.), are transient species that only enter the marsh at high tide (Rountree and Able 1992). It is unclear whether sills are serving as a predation refuge or as a potential foraging habitat, in the form of epibiota on the sill structure itself. Natural fringing oyster reefs

are thought to serve both roles (Peterson et al. 2003) and marsh sills may be serving as a substitute for natural oyster reefs lost to overharvesting and habitat degradation. Further discussion of the role of sills as a predation refuge or food source is provided under Component 4 discussion section. Results of the nekton sampling of BACI sites may clarify the mechanisms by which marsh sills enhance marsh habitat because the newly constructed and sampled sills have low densities of epibiota in the first year after their construction (Gittman 2011, *personal observation*).

Seine net data suggest that the presence of a marsh sill does not affect nekton use of seagrass or mudflat habitats seaward of the marsh sill (Figure 15a-b). The variability in seagrass cover at marsh sill and control sites may have masked the effect of marsh sills on habitat use. However, inclusion of seagrass cover as a covariate did not result in significant differences in marsh sill and control site nekton abundances or biomass. We did find a positive relationship between the percent cover of seagrass in the area seined and the abundance of nekton caught in the associated seine pull (Figure 16). However, because the area to perimeter ratio of seagrass cover was not determined, the relationship between nekton abundance and seagrass cover may not be as a result of greater seagrass area, but could be due to greater availability of seagrass edge habitat (Macreadie et al. 2009). We intend to use survey data and data available from NC DMF to determine if the relationship is a result of seagrass area or available seagrass edge for the final publication. Additionally, results of the nekton sampling of BACI sites may clarify the effects of marsh sills on seagrass habitat and the relationship between nekton abundance and seagrass cover.

Component 4: Epibiota and nekton use of bulkheads and marsh sills

Although the total epibiotic cover does not differ between bulkheads, sills, and control sites, the community composition did vary between bulkheads and sill and controls sites at high elevation plots and between control and sill sites at low elevations (Figure 18a-b). Within high elevation plots eastern oysters, *Crassostrea virginica,* made up the majority of the community at sill and control sites, while barnacles (*Balanus spp.)* constituted the majority of cover at bulkhead sites. Within the low elevations, marsh sill and control sites cover was dominated by eastern oysters, with ribbed mussels, *Geukensia demissa*, occupying a smaller portion of the cover at sill sites. In contrast, cover at bulkheads sites consisted of a mixture of barnacles, oysters, green macroalgae (*Enteromorpha spp.)*, and bryozoans. High variability between low elevation plot cover at bulkhead sites resulted in the differences in community composition from sills and control sites not being significant. Differences in community composition among shoreline stabilization structures may be caused by differences in substrate type, water flow, and sediment suspension.

Epibiota settlement and growth is driven by numerous physical and ecological factors, including, but not limited to availability of suitable substrate, salinity, tidal inundation, sedimentation, wave exposure, competition, and predation (McDougall 1943, Sutherland and Karlson 1977, Ortega and Sutherland 1992, Pineda and Caswell 1997, Olivier et al. 2000). Elevations were standardized across structure type into high and low elevation plots. However, unlike bulkheads, the orientation of the substrate surface changes with height for sills, therefore the suitable area for barnacles to occupy may be reduced when compared to bulkheads. The orientation and structure of marsh sills more closely resembles that of natural oyster reefs, which may explain the higher cover of oysters on sills than on bulkheads. Additional comparisons between stone sills and oyster reefs need to be made to determine if granite sills can be considered substitutes for natural oyster reefs. The BACI analysis of stone and oyster bag sills may provide further evidence that stone sills can serve a similar function to that of an oyster reef. The results of this comparison will be presented in a future publication.

Nekton abundance and biomass was higher within the unvegetated mudflat directly adjacent to marsh sills than adjacent to bulkheads (Figure 18a-b). However, neither bulkheads nor sills had significantly higher nekton abundance or biomass than control sites. These results indicate that more structurally complex habitats, defined as those habitats with more cover to serve as a predation refuge per unit area (Bartholomew and Diaz 2000), may support higher abundances and biomass of small resident and juvenile nekton. Control sites have an intermediate level of structural complexity with *S. alternaflora* marsh edge and loose oyster found adjacent to the area sampled. Therefore, nekton abundance and biomass from low (bulkhead) and high (sill) complexity would be expected to be intermediate at control sites. A majority of the nekton caught at marsh sill and control sites were small marsh resident species that depend structurally complex, resource-rich habitats, such as mummichogs (*Fundulus heteroclitus*) and grass shrimp (*Hippolyte spp*.) (Kneib 1997, Rountree and Able 2006). Bulkhead sites did not support any individuals of the aforementioned species. However, other common fish, pinfish (*Lagodon rhomboides*) and pigfish (*Orthopristis chrysoptera*), were found at bulkhead sites, as well as sill and control sites, indicating that all sites may serve as foraging habitat for these generalist consumer species. However, if only generalist species are supported by low complexity structures such as bulkheads, then the role of habitat structural complexity must be considered when assessing fish habitat quality.

Data limitations

The marsh sills we sampled were selected because they are considered to be appropriately designed, therefore conclusions drawn from data regarding fish habitat sustainment, stabilization performance, fish utilization, and epibiota coverage should only be applied to similarly designed sills in similar geographic settings. Additionally, this was a short-term survey of the habitats and supported nekton, additional years of surveying and sampling would be needed to examine long-term changes in habitat or nekton use associated with marsh sills or other stabilization methods. Finally, the mechanisms by which marsh sills have the potential to enhance fish habitat were not clearly identified by the results presented in this report. Further sampling and analysis is needed to determine if the sills serve as a predation refuge for juvenile and resident nekton or as foraging habitat.

Final analyses and interpretation of the results of this project will be presented in peer-reviewed publications to be completed in the near future. Once published, the results and interpretation of results presented in those publications should be used for management decisions in lieu of the results and interpretations presented in this report if those results differ.

Adherence to proposed project objectives

This project adhered to the primary objective provided in the proposal: "The overall objective is to gather and analyze field data to determine how the ecological functions and fish habitat values of shorelines stabilized by marsh sills compare to those of natural shorelines occupied by salt marshes," (Peterson and Bruno 2009). However, we revised the components necessary for achievement of this objective based on the availability of suitable marsh sill sites, preliminary field results, the addition of improved methods for achieving the proposed objective, and the opportunity to sample pre- and post-construction of marsh sills and pre- and post-landfall of Hurricane Irene. The original components proposed (*from* Peterson and Bruno 2009) are as follows, with revisions to each outlined below each component:

(1) To test the hypothesis that the abundance and distribution of fish habitats (salt marsh, SAV, soft bottom, and shell bottom=oyster reef) are modified by marsh sills as a function

of geographic environmental setting (surface elevation, sediment composition, wave exposure, and tidal prism), we will plot the spatial distribution of fish habitats and measure the marsh species composition and biomass for the estimated 30 permitted and completed marsh sill sites (exact number of sites will determined through DCM site visits in August and September 2009) and paired control marsh sites in North Carolina over 2 years. To characterize the geographic environmental setting, we will also measure the surface elevation, estimate the tidal prism and wave exposure, and determine sediment characteristics of each sill-control pair. Differences in physical site characteristics have implications for function, even determining the fish habitat type itself if sufficient deposition or erosion occurs. Additionally, a 2 year, multi-seasonal habitat assessment will reveal temporal and seasonal variation in geographic environmental setting and subsequent fish habitat distribution.

Revisions: In collaboration with NC DCM, we conducted site visits and questionnaire-based assessments of 25 or the 30 permitted and constructed sills identified in NC in 2009. We selected a subset of sill and control sites for further evaluation and sampling over the 2-year study period. Additionally, we selected sites planned for marsh sill construction in the northern, central and southern regions of NC to further evaluate the effects of marsh sill construction on fish habitat distribution and function. Sediment grainsize analysis is also only being completed for BACI sites, rather than for all survey sites. Finally, completion of damage survey assessments was also not included in the proposal and because NC DCM could not provide shoreline data before until June 15, 2012, only the results of the Outer Banks damage surveys are presented in this report. Further data analyses and interpretation of results from this component with be presented in subsequent peer-reviewed publications.

(2) To determine if and how temporal patterns of nekton (fish and mobile crustaceans) utilization vary in response to the presence and consequences of marsh sills, we will intensively sample nekton in the spring, summer, and fall of year 1 at 3 stone sill-stabilized marshes and in 3 control marshes, including sites studied by Currin's NOAA team. We will sample nekton over 3-day periods (1 day and night for each of 3 sill-control site pairs) during spring tides from May to October using fyke nets. By sampling nekton frequently through the spring-summer-fall seasons of fish and crustacean use, we will develop the first integrated data set on fishery habitat value of sill-stabilized vs. natural marshes.

Revisions: We completed this component for sites surveyed under components 1 and 2. However, we sampled nekton during night spring tides only to maximize the number of sites we could sample and night sampling proved to produce a higher abundance and diversity of nekton (Young et al. *unpublished data*). This revised component is listed as Component 3 in this report.

(3) To quantify variation in nekton use of distinct fish habitats in response to marsh sills, we will sample nekton in the marsh interior, marsh edge, and adjacent seagrass beds using throw traps at the sites mapped and sampled in Objectives 1 and 2. We will adopt the Objective 2 sampling period, alternating throw trap sampling with fyke net sampling by full tidal cycle at each site, thus allowing us to sample nekton in each habitat during spring tides. We will collect 30 throw trap replicates per habit type per site beginning at low tide to quantify temporal nekton use as a function of the spatial distribution of important fish habitats.

Revisions: We completed this component for sites surveyed under Components 1 and 2. Instead of using throw traps, we used seines to sample seagrass habitat and due to the small size of the marshes sampled (less than 10 m width on average), distinction between marsh interior and marsh edge was not deemed to be necessary to achieving the goals of the project.

(4) To test the hypothesis that marsh sills affect nekton utilization of available fish habitats as a function of geographic environmental setting, we will sample nekton of a large suite of the 30 sill-control sites in the spring and fall of year 2. By sampling nekton at sites throughout the North Carolina coast, we can determine whether the affects of marsh sills on shoreline habitat and use of habitat by nekton are specific to the geographic environmental setting in which the marsh sills are constructed.

Revisions: In lieu of sampling additional existing marsh sills, we elected to sample sites pre- and post-construction of marsh sills along north, central and southern NC coasts and to conduct post-hurricane damage surveys of the NC shorelines to evaluate relative stabilization performance of different stabilization structures. These revisions are represented as Components 2 and 3 in this report. Because completion of the BACI sampling was not included in the original proposal and sill construction extended beyond the project award period, only pre-construction data is being provided to NC DMF at this time.

(5) To test how hard substrates introduced to stabilized estuarine and sound shorelines are utilized as habitats by epibiota (macroalgae and invertebrates) and nekton, we will sample replicate bulkheads, riprap revetments, and sills (both stone and oyster-bag) in year 2. We will determine the percent cover and species composition of epibiotic species attached to the introduced hard substrates that are continuously submerged. Nektonic utilization will be assessed by suction dredge sampling of volumetrically isolated samples using throw traps to establish a fixed sample during both day and night. From this sampling, specific conclusions could be drawn about the suitability of stone as compared to oyster bags for oyster colonization, thus indicating the best substrate for creating new fish habitat (oyster reef), as well as utilization of this habitat by nekton.

Revisions: We completed this component of the project. However, instead of sampling epibiota and nekton on riprap revetments, we sampled control sites without artificial stabilization to compare to marsh sills and bulkheads. Additionally, minnow traps were used instead of suction dredge sampling to sample nekton because it is less time intensive, destructive, and minimizes nekton mortality. This revised component is listed as Component 4 in this report.

Applicability of study results to CRFL Strategic Plan and priorities

This CRFL project is applicable to the Habitat goal to "enhance coastal fisheries through the protection, enhancement, and restoration of coastal fish and fish habitats" and to the following Habitat objectives outlined in the CRFL Strategic Plan:

- Improve effectiveness of existing programs;
- Identify, designate, and conserve fish habitat and Strategic Habitat Areas (SHAs); and
- Enhance habitat and protect it from physical harm (DMF 2007).

More specifically, this project is applicable to the following habitat strategies (DMF 2007):

- **Strategy H.1.1.** In cooperation with other DENR agencies and university scientists, conduct coastal habitat status assessments using standard indicators of estuarine and near shore ocean conditions.
- **Strategy H.1.4.** Enhance education of fishermen and the public concerning fish habitats, how they function, and what people can do to protect them.
- **Strategy H.2.4.** Conduct research to clarify the linkages between coastal fish habitat and fish production and identify the key aspects of habitat function and how these functions are affected by human activities.
- **Strategy H.2.5.** Coordinate mapping and monitoring of fish habitats to delineate causes of and effects of habitat disturbance and loss.
- **Strategy H.3.1.** Identify degraded fish habitat and implement restoration measures
- **Strategy H.3.2.** Initiate monitoring programs to evaluate success of restoration and enhancement projects.
- **Strategy H.3.3.** Conduct research on restoration techniques in order to improve the quality and function of created or enhanced habitat.
- **Strategy H.3.4.** Refine materials and deployment techniques to maximize long- term ecological function and structural integrity of restoration efforts.

Through this project, we have achieved the following:

- Conducted coastal habitat assessments in collaboration with NC DMF and NC DCM (H.1.1);
- Provided information necessary to educate the public on alternative shoreline stabilization techniques (H.1.4);
- Identified how shoreline stabilization can affect coastal habitat function (H.2.4);
- Monitored fish habitats to determine if shoreline stabilization can adversely affect coastal habitats (H.2.5);
- Identified degraded habitats associated with bulkheads (H.3.1);
- Monitored habitat characteristics and nekton use of restored marshes associated with marsh sill construction (H.3.2);
- Conducted research on the effects of marsh sills on coastal fish habitats (H.3.3); and
- Made recommendations to NC DCM and NC DMF for marsh sill construction techniques for long-term sustainment of coastal ecosystem function through presentations and personal communications (H.3.4).

Recommendations

We recommend that the results of this CRFL project be considered when making new priorities for habitat protection, research needs, and education and outreach goals within the CRFL Strategic Plan and future revisions to the Coastal Habitat Protection Plan. Marsh sills are a viable alternative to traditional shoreline stabilization techniques, such as bulkheads and riprap revetments. Marsh sills combine marsh habitat restoration with shoreline stabilization that is equivalent, if not superior to that provided by bulkheads. Nevertheless, careful site evaluation, engineering design, and agency review of potentially affected coastal habitats is necessary for the appropriate design and construction of marsh sills. In many sites with only minor to moderate erosion and low to intermediate wave energy, marsh planting may be the most appropriate shoreline stabilization technique. Only when stabilization through planting is not sufficient should any form of artificial stabilization be employed. If possible, stabilization through oyster shell or oyster bags should be considered and recommended by permitting agencies.

Additional research is needed on the long-term effects of all forms of artificial shoreline stabilization, particularly in the context of sea level rise and reoccurring major storm events. Although the results of this project provide evidence for the ability of marsh sills to support habitat function and short-term stabilization during a major storm event, it is still unclear if marsh sills (or any stabilization structure) will provide the protection against future storm events and erosion caused by sea level rise. NC DMF and DCM should consider long-term monitoring programs for coastal habitats most vulnerable to the combined effects of shoreline stabilization and sea level rise, particularly salt marshes and seagrass beds.

Finally, regardless of the findings of this project in favor of marsh sills over other artificial shoreline stabilization strategies, marsh planting and marsh sill construction will likely not increase in NC in lieu of bulkhead construction if the public is not adequately informed and educated. NC DMF and DCM have made strides in educating the public about estuarine shoreline stabilization options and procedures for obtaining the appropriate permits, but many property owners and contractors are still unaware of bulkhead alternatives. We recommend the continued use of estuarine shoreline stabilization workshops like those held in 2012 and continued improvements to the educational NC DCM and DMF webpages. Additionally, we also recommend streamlining the permit review process for shoreline stabilization in a way that maximizes efficiency without sacrificing the review and careful planning necessary for shoreline stabilization projects.

Figures

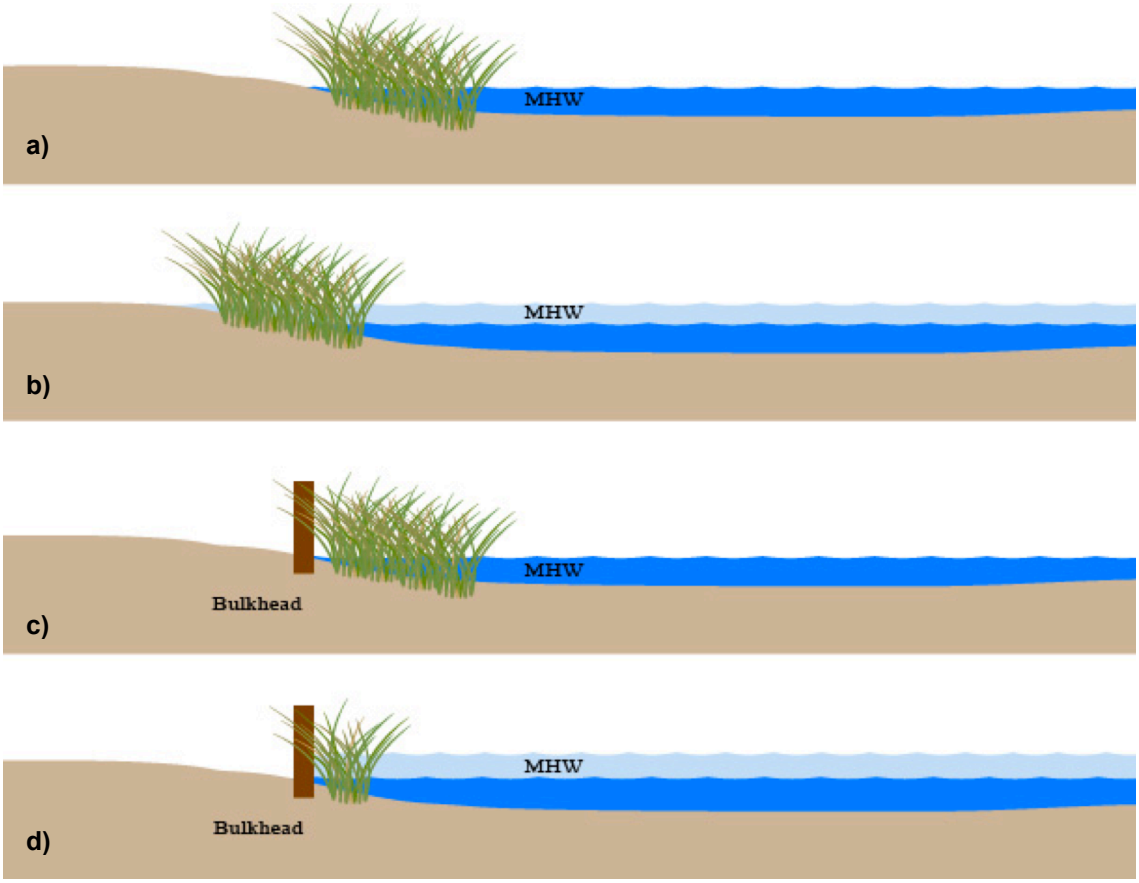


Figure 1. Schematic showing the loss of marsh in front of a bulkhead as sea level rises. **a)** Salt marsh position at the current sea level. **b)** The marsh retreats up the shoreline as sea level rises. **c)** The marsh position at current sea level with a bulkhead located landward of the marsh. **d)** The marsh is unable to retreat up the shore because of the presence of the bulkhead. Symbols are courtesy of the Integration and Application Network (ian.umces.edu/symbols/).

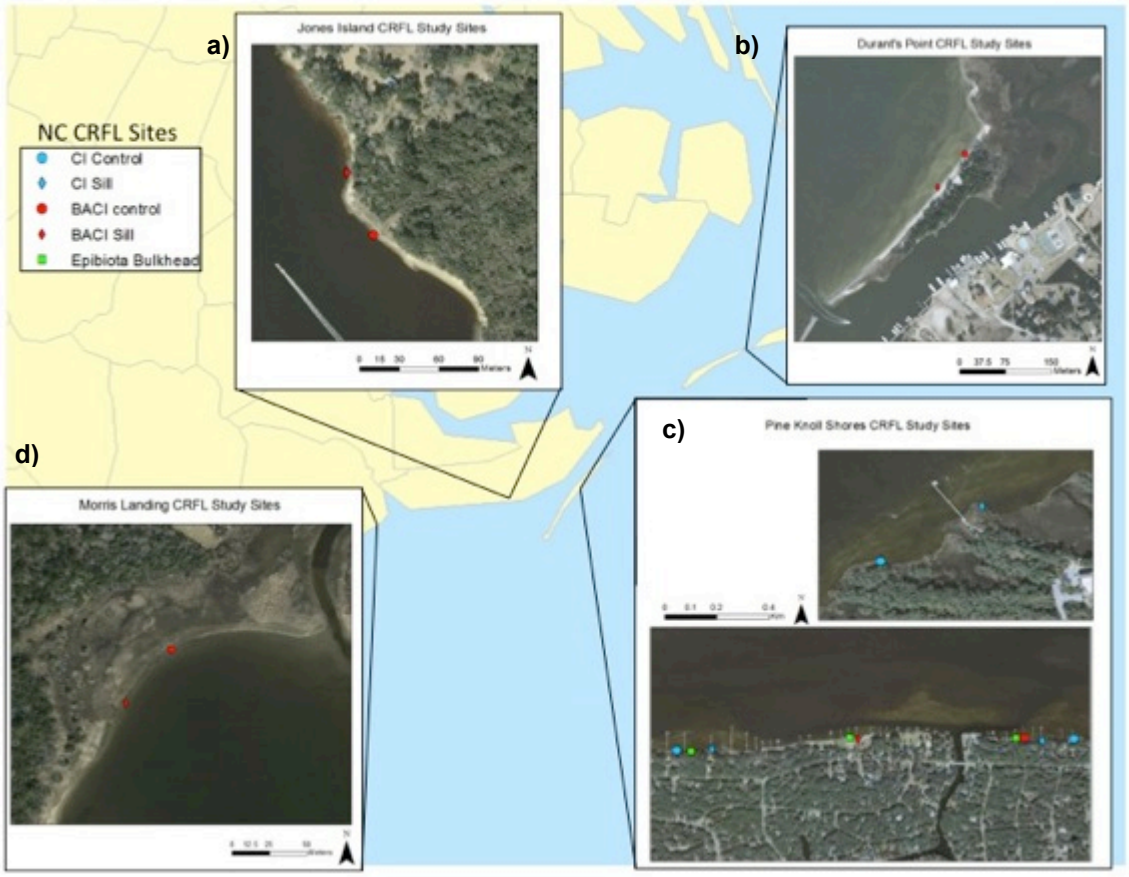


Figure 2. a) BACI study sites on Jones Island in Swansboro, NC. **b)** BACI study sites on Durant's Point in Hatteras, NC. **c)** CI and BACI study sites in Pine Knoll Shores, NC**. d)** BACI study sites at Morris Landing in Holly Ridge, NC.

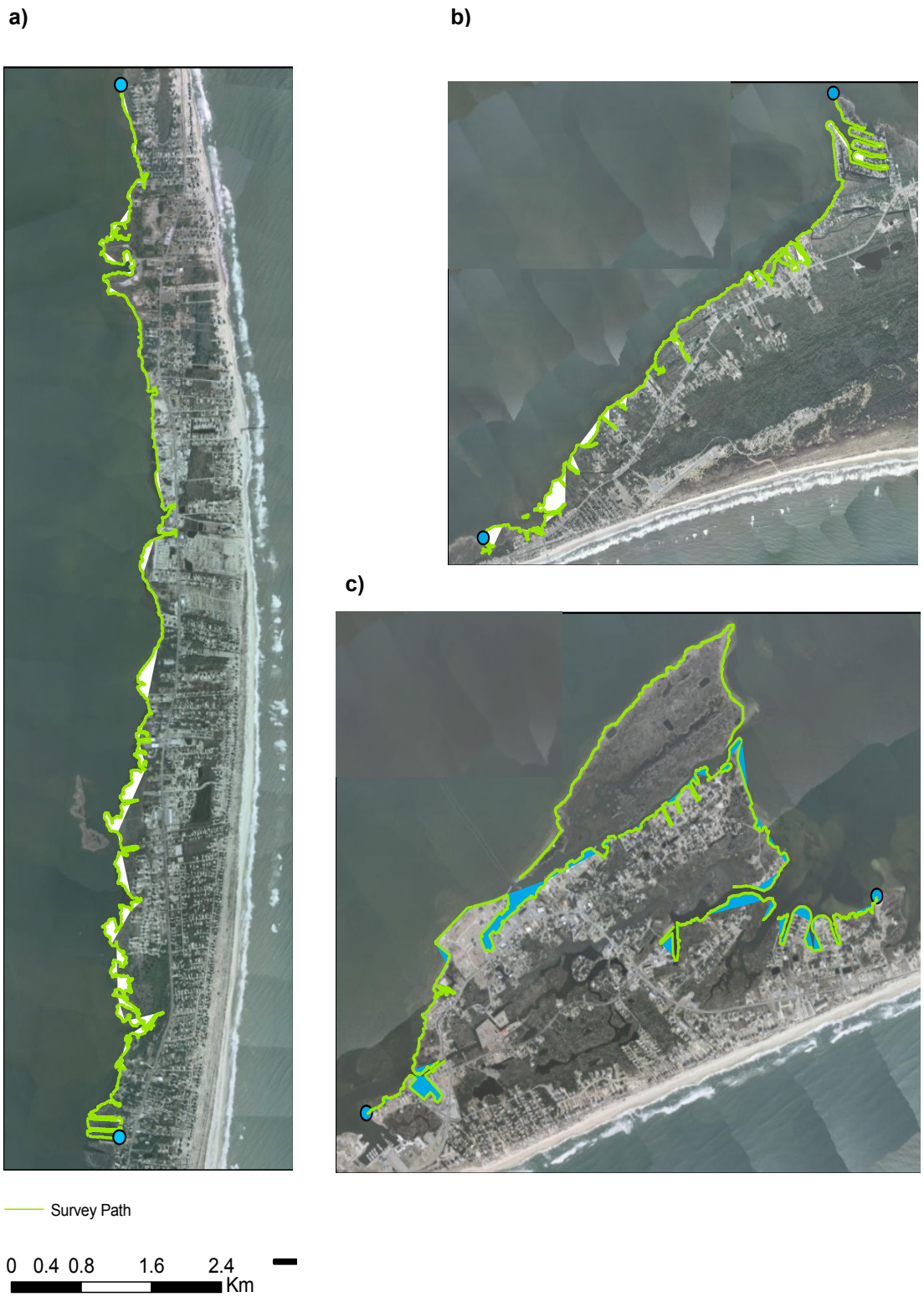


Figure 3. Shoreline surveyed on Hatteras Island post-Hurricane Irene**. a)** Salvo to Rodanthe **b)** Frisco **c)** Hatteras Village

Figure 4. Shoreline surveyed on Bogue Banks post-Hurricane Irene.

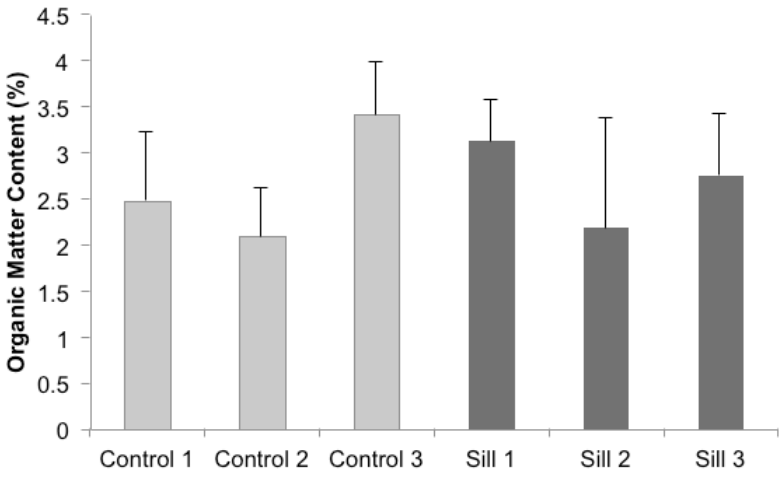


Figure 5. Sediment organic matter content (%) by site. Values are means (+SE).

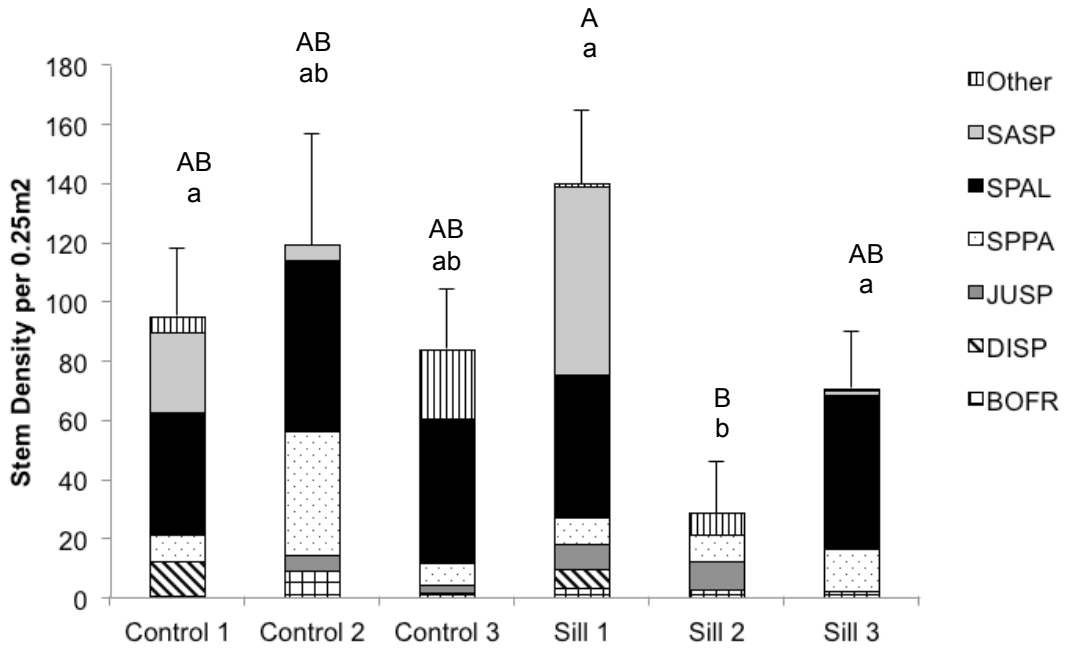


Figure 6. Mean marsh stem density by species. Error bars are + SE of total stem densities. Functionally similar species were combined for display purposes and only the six most common species groups are shown, all others are grouped as "Other": SASP= *Salicornia species*, SPAL= *Spartina alternaflora*, SPPA=*Spartina patens*, JUSP= *Juncus species,* DISP= *Distichlis spicata* BOFR= *Borrichia frutescens.* Sites with different capital letters "A" and "B" have significantly different total marsh densities (P<0.05). Sites with different lower case "a" and "b" have significantly different marsh plant community compositions (P<0.05).

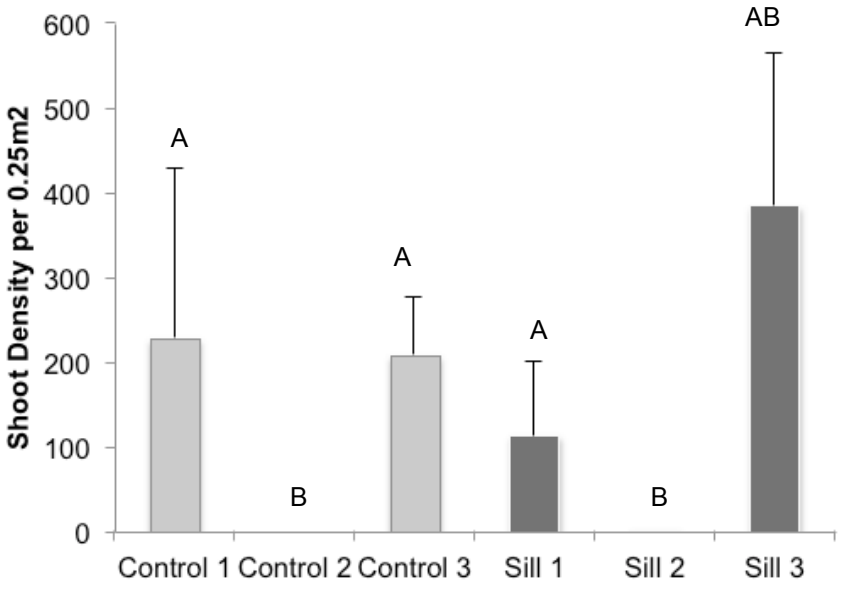


Figure 7. Mean seagrass shoot density by site. Error bars are + SE. Sites with different letters ("A" or "B") are significantly different (P<0.05).

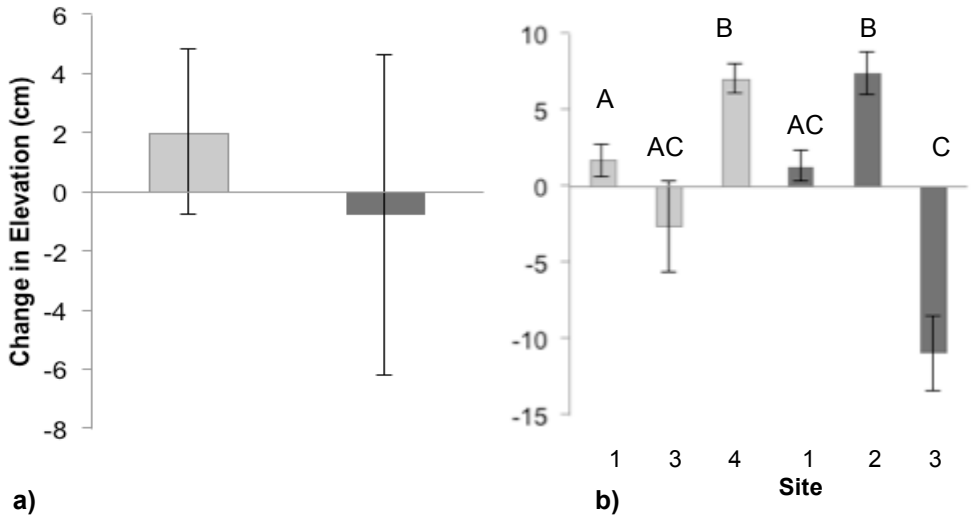


Figure 8. a) Change in marsh surface elevation from August 2010 (pre-Hurricane Irene) to October 2011 (post-Hurricane Irene) at control sites (light gray) and sites with sills (dark gray) along Bogue Sound, NC. **b)** Change in marsh surface elevation by site. Values are means (+SE). Control site 4 (BACI control site) was surveyed in lieu of control site 2. Sites with different letters ("A", "B", or "C") are significantly different (P<0.05).

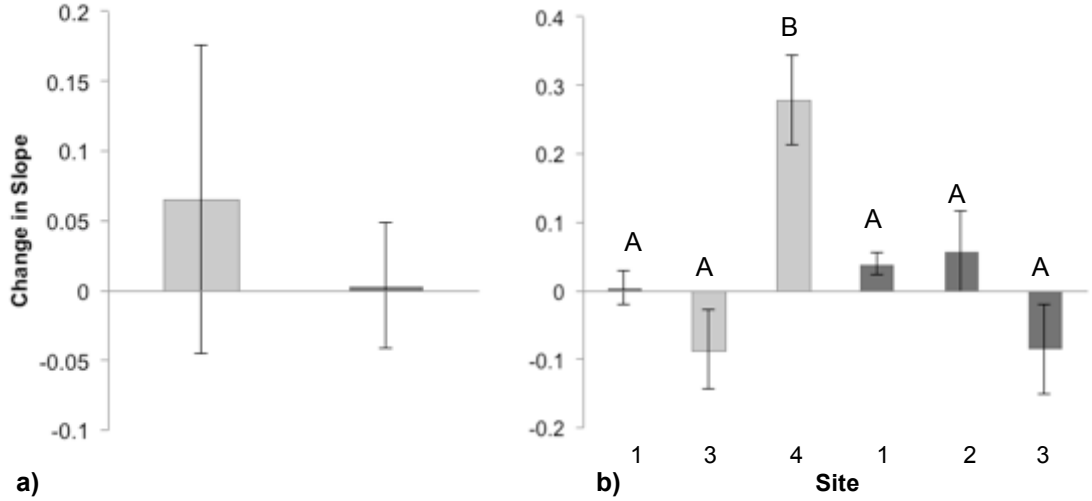


Figure 9. a) Change in marsh slope from August 2010 (pre-Hurricane Irene) to October 2011 (post-Hurricane Irene) at control sites (light gray) and sites with sills (dark gray) along Bogue Sound, NC. **b)** Change in marsh slope by site. Values are means (±SE). Control site 4 (BACI control site) was surveyed in lieu of control site 2. Sites with different letters ("A"or "B") are significantly different (P<0.05).

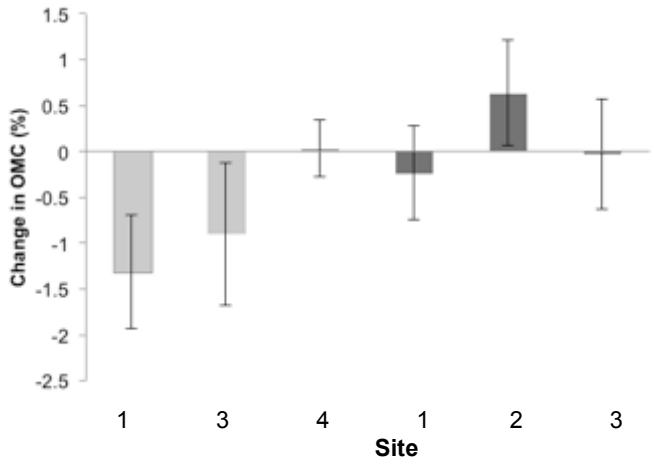


Figure 10. Change in sediment organic matter content from August 2010 (pre-Hurricane Irene) to October 2011 (post-Hurricane Irene) at control sites (light gray) and sill sites (dark gray). Values are means (±SE).

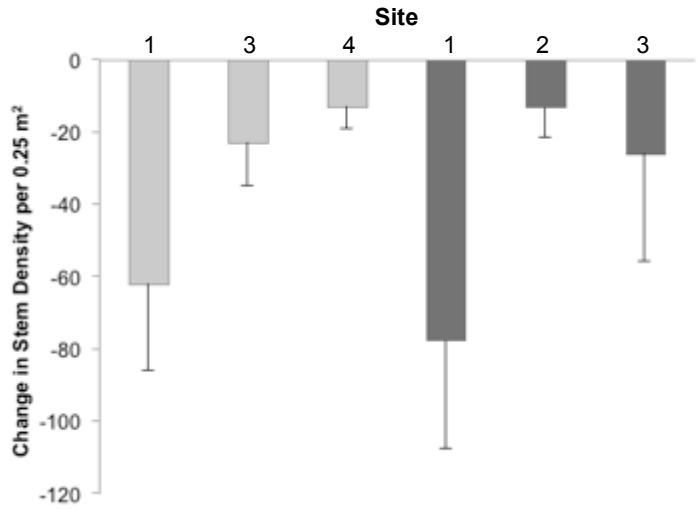
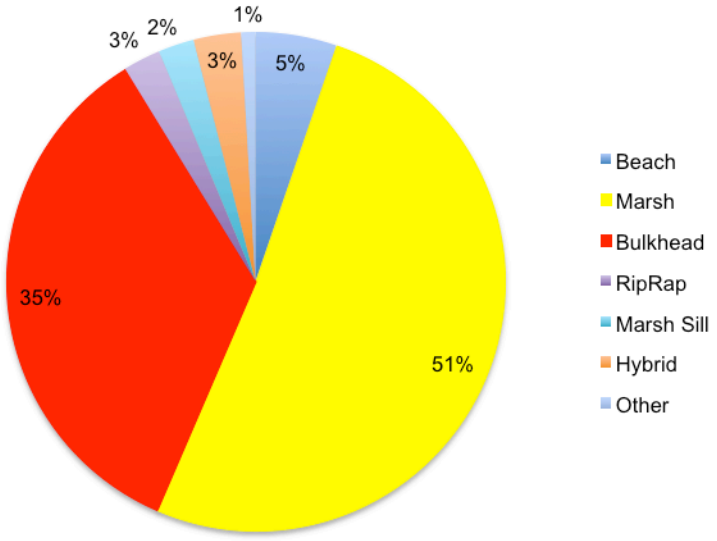
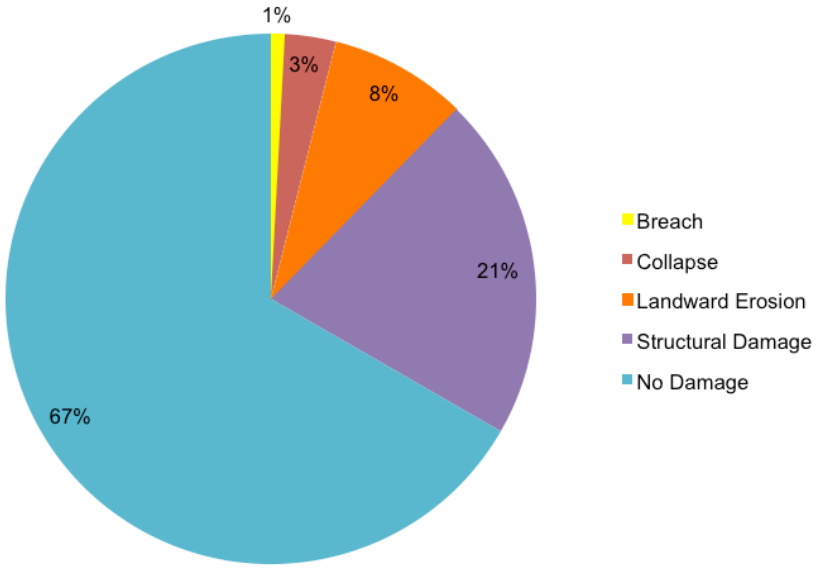


Figure 11. Change in total marsh stem density from August 2010 (pre-Hurricane Irene) to October 2011 (post-Hurricane Irene) at control sites (light gray) and sill sites (dark gray). Values are means (-SE).



a)



b)

Figure 12. a) Percentage of shoreline by type for ~60 km of back-barrier shoreline surveyed in the Outer Banks, NC (Hatteras Village, Frisco, Salvo, Waves, and Rodanthe) post-Hurricane Irene. **b)** Percentage of bulkhead shoreline by damage category for Outer Banks back-barrier shorelines.

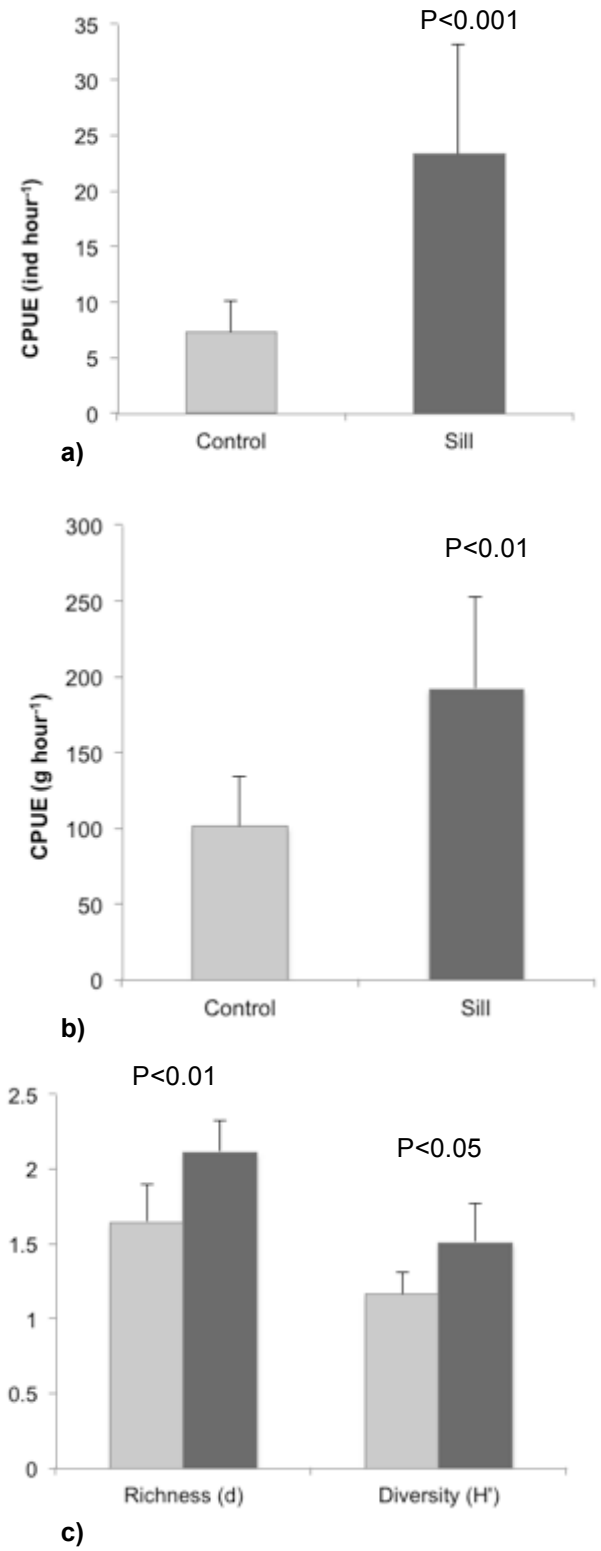


Figure 13. a) Fish and crustacean abundance (CPUE) from fyke net catches (salt marsh) at control (light gray) and sill sites (dark gray), n=3. **b)** Fish and crustacean biomass (CPUE) from fyke net catches (salt marsh) at control (light gray) and sill sites (dark gray), n=3. **c)** Species richness and Shannon Diversity for fyke net catches at control and sill sites. Values are means (+SE).

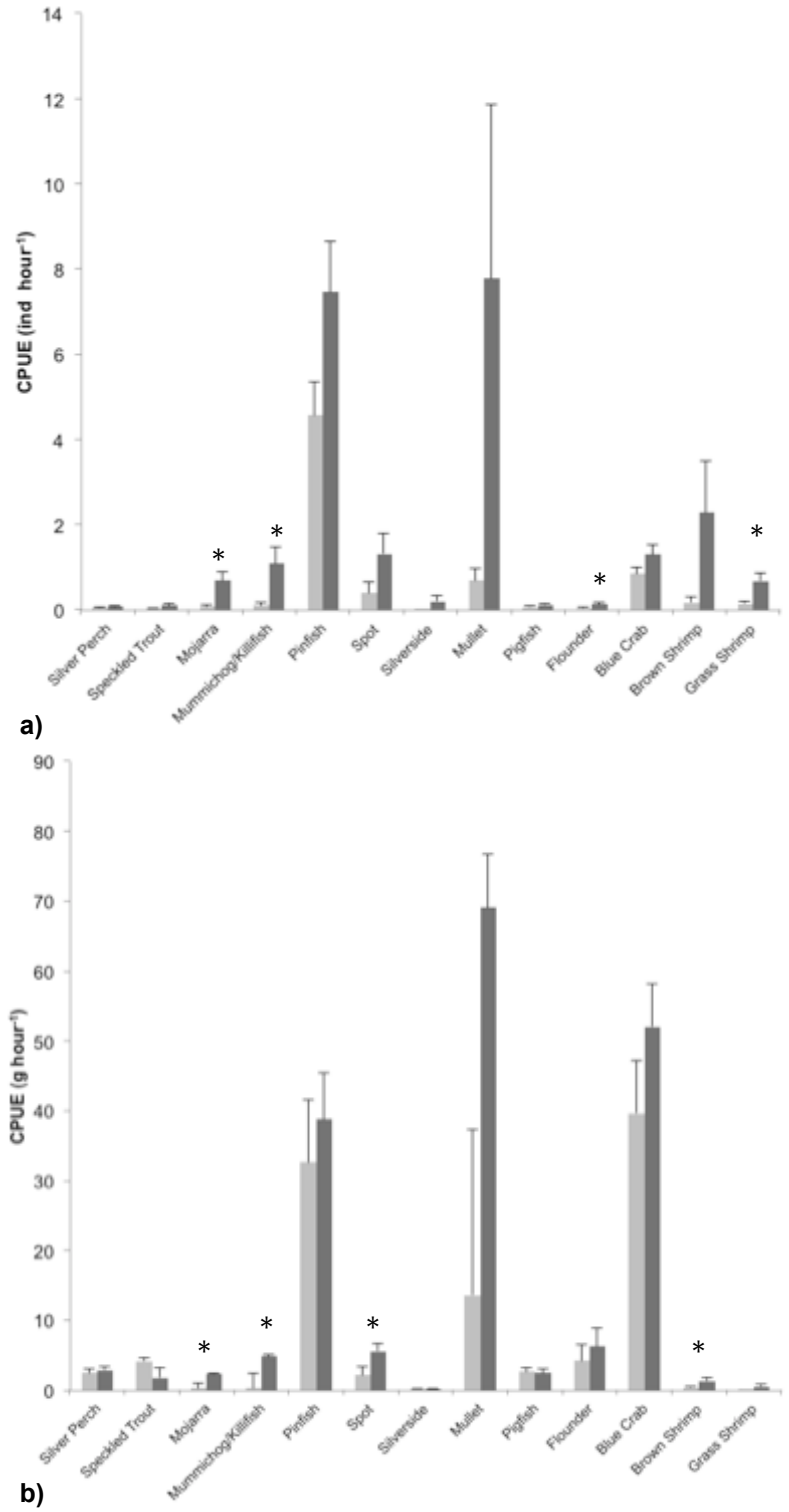


Figure 14. a) Fish and crustacean abundance (CPUE) from fyke net catches by species at control (light gray) and sill sites (dark gray). **b)** Fish and crustacean biomass (CPUE) from fyke net catches by species. * indicates significant difference in control and sill means ($P<0.05$). Values are means (+SE).

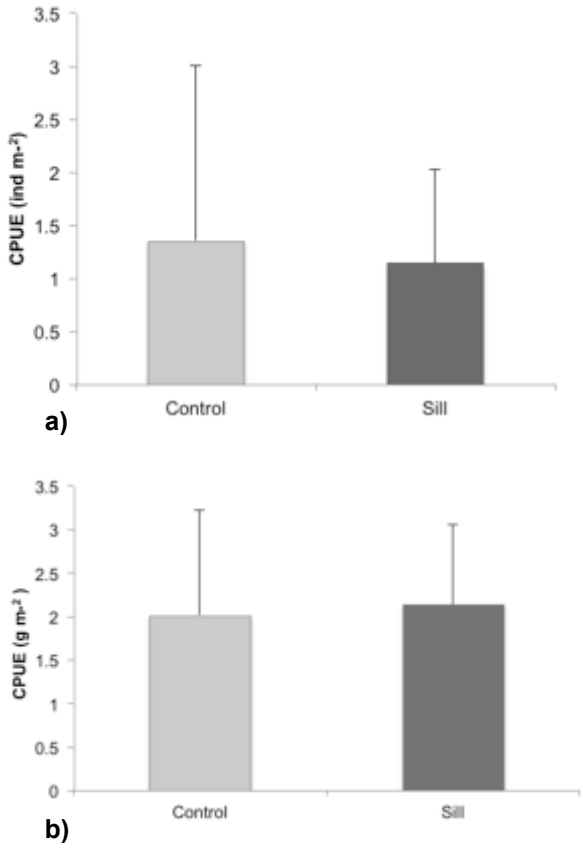


Figure 15. a) Fish and crustacean abundance (CPUE) from seine net catches (seagrass/mudflat) at control and sill sites (n=3). **b)** Fish and crustacean biomass (CPUE) from seine net catches (seagrass/mudflat) at control and sill sites. Values are means (+SE).

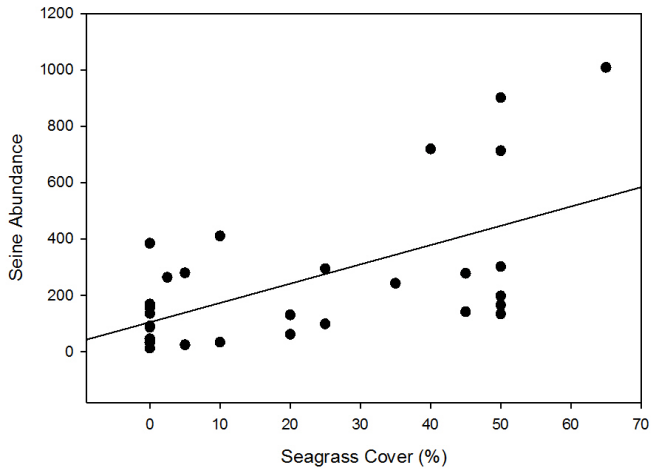


Figure 16. Relationship between seagrass percent cover within the area seined at each site and the total abundance of fish and crustaceans caught within that seine pull. Adjusted r^2= 0.343, P<0.001.

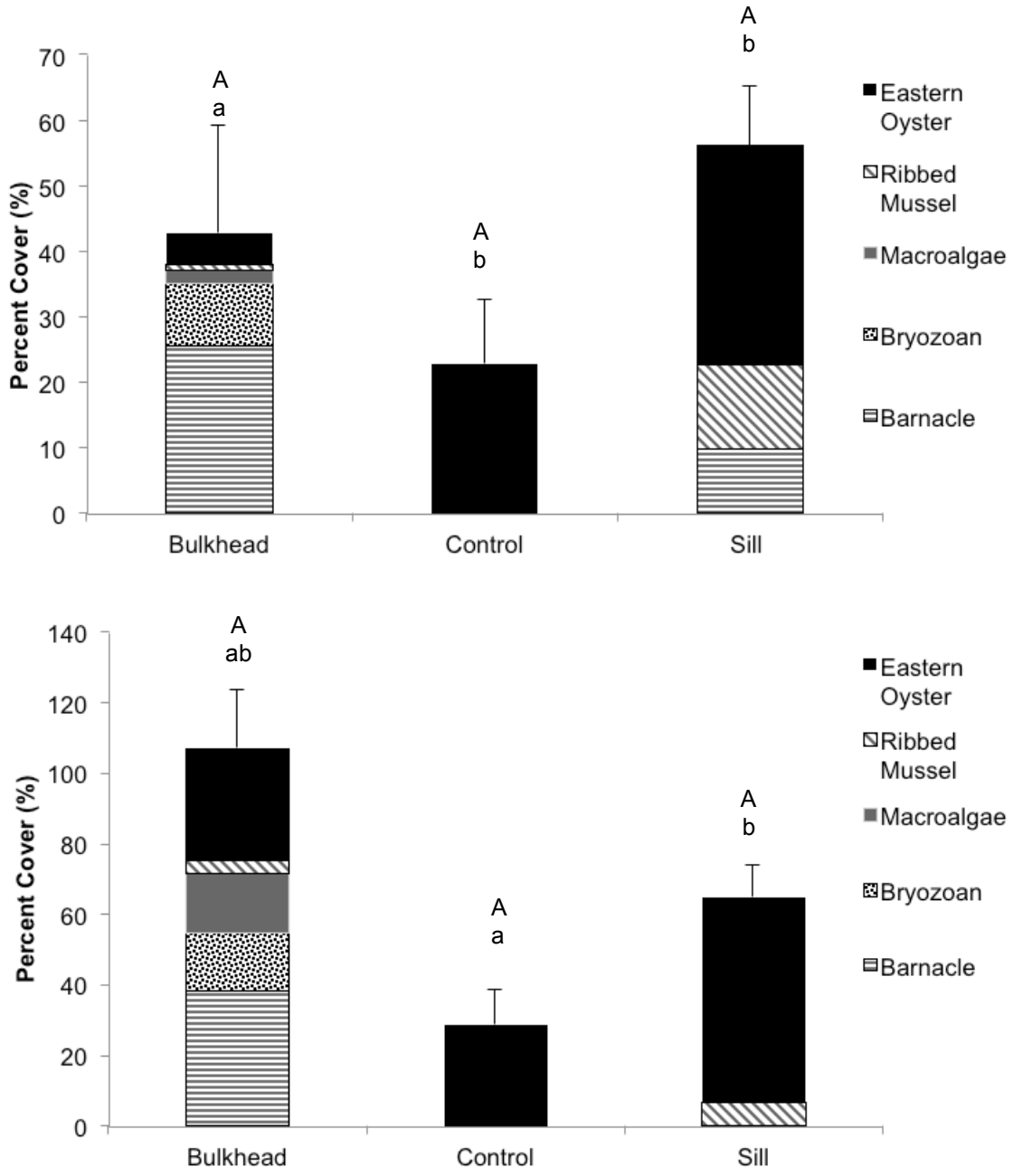


Figure 17. a) Community composition for bulkhead, control, and marsh sill epibiota (high elevation) (n=3). **b)** Community composition for bulkhead, control, and marsh sill site epibiota (low elevation). Means greater than 100% indicate multiple groups were found at each intersection within the $0.25m^2$ quadrat. Values are means (+SE of total percent cover of all epibiota). Sites with different capital letters "A" and "B" have significantly different total epibiota cover ($P<0.05$). Sites with different lower case "a" and "b" have significantly different epibiota community compositions ($P<0.05$).

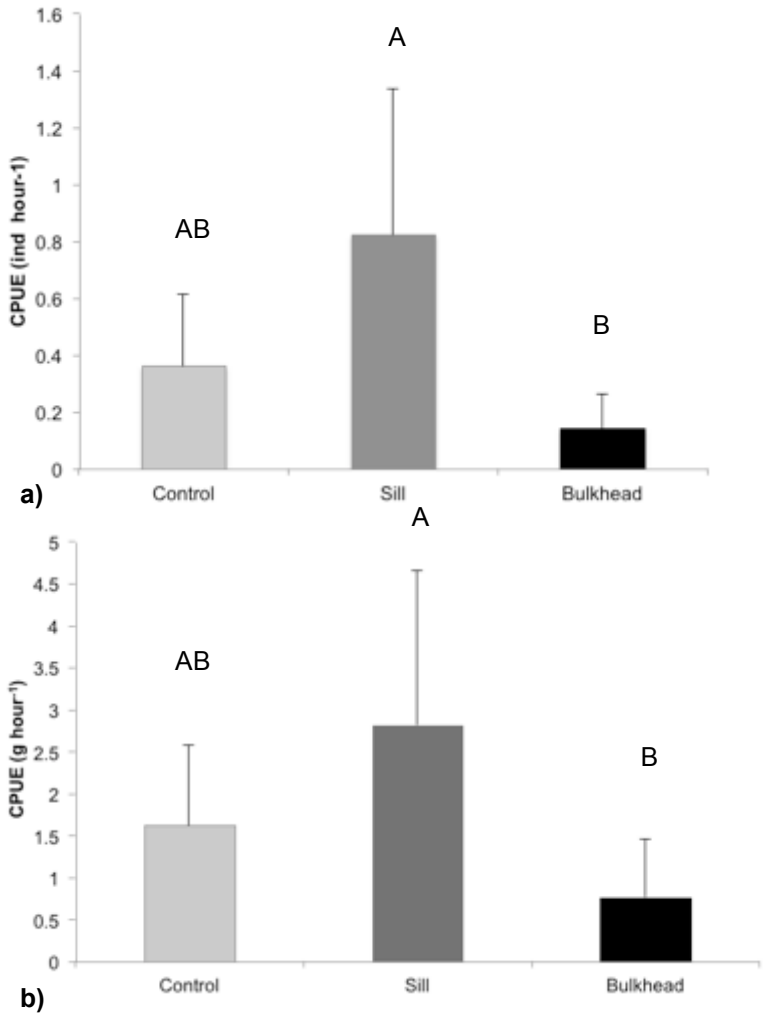


Figure 18. a) Fish and crustacean abundance (CPUE) from minnow trap catches at control, sill, and bulkhead sites (n=3). **b)** Fish and crustacean biomass (CPUE) from minnow trap catches at control, sill, and bulkhead sites Values are means (+SE). Sites with different capital letters "A" and "B" have significantly different total nekton abundance or biomass ($P<0.05$).

Tables

Table 1. Shoreline stabilization damage classifications.

Stabilization Type	Damage Category	Description
Bulkhead	Landward Erosion	Erosion occurred above and behind the bulkhead.
	Collapse	The bulkhead failed completely.
	Breach	The bulkhead has a breach or partial collapse, where sediment has been scoured out.
	Structural damage	Bulkhead is warped or pieces are missing, but no breach has occurred.
Riprap	Landward Erosion	Erosion occurred above and behind the riprap.
	Breach	Rocks have been displaced and a gap is visible in the riprap.
Marsh sill/breakwater	Landward Erosion	Erosion occurred above and behind the marsh sill.
	Breach	Rock or wood is missing from the sill and a gap (unplanned) is visible in the sill.
All	No damage	No noticeable damage.

Table 2. Mean marsh surface elevation, slope, and maximum inundated marsh width for CI sites. Elevations are relative to NAVD88, ± SE.

	Elevation (m)			Slope			Max. Inundated Marsh Width (m)		
Control Average	**0.033**	**±**	**0.016**	**0.370**	**±**	**0.043**	**10.3**	**±**	**1.5**
Control 1	0.051	±	0.057	0.331	±	0.020	11.6	±	1.8
Control 2	0.046	±	0.063	0.325	±	0.042	7.3	±	2.0
Control 3	0.002	±	0.080	0.455	±	0.061	12.0	±	0.8
Sill Average	**0.061**	**±**	**0.056**	**0.292**	**±**	**0.053**	**11.2**	**±**	**3.5**
Sill 1	0.154	±	0.024	0.244	±	0.015	15.3	±	1.2
Sill 2	-0.038	±	0.084	0.397	±	0.124	4.2	±	0.1
Sill 3	0.068	±	0.057	0.235	±	0.090	14.0	±	1.0

Annual Budget expenditures

Category	Year 1 Expenditures	Year 2 Expenditures
Personnel	$70,405	$73,095
Fringe	$10,227	$7,598
Travel	$400	$1,675
Equipment	$0	$0
Supplies	$11,486	$2,309
Construction	$0	$0
Contractual	$0	$0
Other	$3,750	$3,750
Total Direct	$96,268	$88,427
Indirect	$14,441	$13,284
TOTAL	$110,709	$101,711

Budget deviations

We had a budget deviation in year 1, which required a no-cost extension for $1,500 from the Miscellaneous Services (Other) funding category. The details of the budget deviation are provided in the attached Letter of Request for a No-Cost Extension submitted to DMF in 2011.

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