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RETROSPECTIVE ANALYSIS AND SEA LEVEL RISE MODELING OF COASTAL HABITAT CHANGE IN CHARLOTTE HARBOR TO IDENTIFY RESTORATION AND ADAPTATION PRIORITIES

L. Geselbracht(1), K. Freeman(1), E. Kelly(2), D. Gordon(1), and A. Birch(1)

(1)The Nature Conservancy, 222 S. Westmonte Drive, Altamonte Springs, Florida 32714
(2)10418 Nottingham Forest Drive, Brooksville, FL 34601
Corresponding author's e-mail: Lgeselbracht@tnc.org

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Abstract: *Charlotte Harbor, Florida, is a series of interconnected shallow estuaries surrounded by low-lying uplands and a population of approximately 780,000 people. Direct and indirect impacts of human development as well as an accelerating rate of sea level rise have had and will continue to have dramatic effects on the distribution of this system's coastal habitats. The long term sustainability of this estuarine system and surrounding human communities depends on understanding past and predicted future coastal scenarios, allowing effective adaptation, restoration and management decisions. To understand historical changes, we compared recent coastal habitat distribution information to that reported in an earlier study (Harris et al., 1983) using geospatial analysis. To understand likely future conditions, we applied the Sea Level Affecting Marshes Model (SLAMM) over a 100 year period using slower, moderate and faster sea level rise (SLR) scenarios of 0.7 m, 1.0 m and 2.0 m, respectively. Our analyses show that while some coastal wetland habitats increased over the sixty year period from 1945 to present, modeling results through 2100 predicted net losses of tidal flat, coastal forest and inland freshwater marsh under all three SLR scenarios. Mangrove swamp and saltmarsh decreased under the fastest rate of SLR modeled.*

Key Words: Adaptation, coastal systems, marsh, oyster reef, restoration, seagrass, Sea Level Affecting Marshes Model (SLAMM), sea level rise (SLR)

The purpose of this retrospective and prospective study was to spatially characterize and quantify both past and future changes in coastal habitats throughout the Charlotte Harbor system to support effective resource management, restoration and climate change adaptation decisions. Charlotte Harbor is located in southwest Florida (Fig. 1) and consists of a series of interconnected estuaries surrounded by low-lying wetlands and uplands, making the region sensitive to sea level rise (SLR). Since the 1940's, coastal habitats in the Charlotte Harbor system have been substantially altered by human development (Beever et al., 2009; Harris et al., 1983) and these alterations are expected to continue into the future as development and sea level rise progress (http://www.esterofl.org/EsteroLife/growth/taxbase.htm, 3/27/12; Beever et al., 2009). In southwest Florida, alteration of coastal systems will continue whether sea level rises 18–59 cm by 2100, as predicted by the Intergovernmental Panel on Climate Change (IPPC, 2007), or at the higher rates predicted by models that include the melting of polar ice caps and other

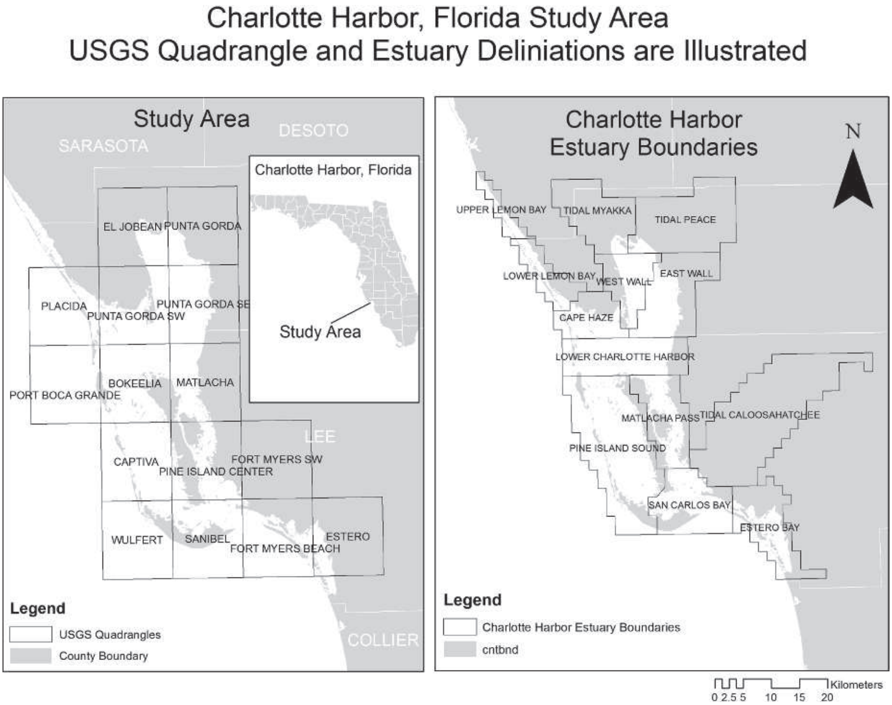

FIG. 1. Study area showing USGS quadrangle names on the left and Charlotte Harbor National Estuary Program (CHNEP) estuaries on the right.

factors (e.g., CCSP, 2008; Mitrovica et al., 2009; Overpeck et al., 2006; Rahmstorf et al., 2007).

Estuaries are especially vulnerable to environmental changes because their productivity varies with the qualities and quantities of water exchanged between the ocean and the adjacent uplands and watersheds (Nicholls et al., 2007). As with many Gulf of Mexico estuaries, the Charlotte Harbor estuaries are bounded in places by urbanized lands (CHNEP, 2008). The human altered landscapes limit the opportunities for intertidal and coastal wetland systems to migrate to higher elevations in response to SLR (Harris and Cropper, 1992). SLR impacts will be observable over decadal time scales (CCSP, 2008; IPPC, 2007; Mitrovica et al., 2009; Overpeck et al., 2006; Rahmstorf et al., 2007), which is within the planning horizons for coastal development. Coastal communities would benefit economically, socially and environmentally by implementing climate change adaptation strategies such as redirecting development away from those natural areas that will be impacted by SLR and maintaining sediment transport to marsh systems (Titus et al., 2009; USEPA, 2009). Understanding how SLR is likely to affect the distribution of coastal natural habitats provides an opportunity to assess the vulnerability to both natural and anthropogenic environments. Better decisions now will result in healthier and safer natural and human communities into the future.

Among the useful tools available to enhance understanding of the effects of SLR on coastal wetland systems is the Sea Level Affecting Marshes Model (SLAMM). SLAMM was developed by the U.S. Environmental Protection Agency (USEPA) in the mid-1980s (Park et al., 1986). SLAMM v6.1 beta dated March 2011 (http://warrenpinnacle.com/prof/SLAMM/index.html), was used for these analyses. SLAMM employs a decision tree that integrates geometric and qualitative relationships between elevation–submergence and wave action–erosion to simulate the dominant processes involved in wetlands change and shoreline modifications during SLR. The five primary processes used to predict wetland changes with SLR are inundation, erosion, overwash, saturation, and accretion.

SLAMM has been applied in different locations around the United States (Glick and Clough, 2006), but several early applications used relatively low resolution elevation (1.5 m contours) based on National Elevation Data (NED). The coarse resolution elevation data requires SLAMM to extrapolate elevations based on other factors, such as land cover data provided by the National Wetlands Inventory (NWI). Comparison of SLAMM results using inferred elevation information versus the recently available high resolution Light Detection and Ranging (LiDAR) elevation data revealed differences in predicted habitat distributions between the two methods of over 170% depending on the habitat type (Geselbracht et al., unpublished data). However, a hindcast of SLAMM using high resolution LiDAR elevation data in the Waccasassa Bay area of the Florida Gulf Coast found that SLAMM predicted the same patterns of coastal forest loss as that observed in 30 years of field plot data (Geselbracht et al., 2010).

Consistent with other areas of Florida's Gulf of Mexico coast, the Charlotte Harbor estuaries have extremely low relief geomorphology. The 1.0 m elevation contour extends inland from the shore as far as 3 to 10 km. These low elevations make the southwest Florida coast particularly vulnerable to SLR (Titus and Richman, 2000) and emphasize the need for accurate elevation data for SLAMM analyses in the Charlotte Harbor region.

To characterize past coastal system changes, we conducted a retrospective (1945 – most recently available) geospatial analysis of habitat trends over a 258,500 ha area of the greater Charlotte Harbor estuaries (FIG. 1). The geospatial analysis compared data derived from aerial photo-interpretation of historic and contemporary conditions. We conducted the analysis to determine long term trends in coastal habitat extent which can be utilized in coastal restoration, conservation and management decision-making.

We also conducted a prospective (2008–2100) SLAMM analysis to predict future coastal habitat conditions for the same areas examined in the historical analysis and compared results to spatially characterize and quantify changes. For the prospective SLAMM analysis, we used recently available high resolution LiDAR-derived elevation data. We evaluated the impacts of 0.7 m (IPCC A1B Maximum scenario), 1.0 m, and 2.0 m SLR by the year 2100. Both the retrospective (1945 – most recently available) and prospective (2000–2100)

TABLE 1. USGS quadrangle maps and associated estuaries in the study area.

USGS Quadrangle	Associated Estuary	Estuary Size (hectares)
El Jobean	Tidal Myakka River	16,804
Punta Gorda	Tidal Peace River	25,056
Placida	Lower Lemon Bay	8,318
Punta Gorda SW, El Jobean	Charlotte Harbor West Wall	11,011
Punta Gorda SE	Charlotte Harbor East Wall	19,273
Placida, Punta Gorda SW	Cape Haze	10,405
Port Boca Grande, Bokeelia, Matlacha	Lower Charlotte Harbor	18,372
Wulfert, Bokeelia, Captiva	Pine Island Sound	39,095
Pine Island Center, Matlacha	Matlacha Pass	15,018
Fort Myers SW	Tidal Caloosahatchee	42,907
Ft. Myers Beach, Sanibel	San Carlos Bay	17,033
Estero, Fort Myers Beach	Estero Bay	16,578

analyses are provided to assist with development of restoration, management and sea level rise adaptation strategies that can be employed to sustain and improve coastal habitat productivity and resiliency while better protecting human communities and economic opportunities. The most recently data available was used, ranging from 1999 to 2007, depending on location and habitat type, as described below.

METHODS—*Study area*—Charlotte Harbor is located in southwest Florida (26°44′58.14″N, 82°07′32.89″W) and is a large, subtropical, estuarine complex approximately 56 kilometers in length comprised of interconnected estuaries, coastal bays and tidal rivers, as shown in FIG. 1 and TABLE 1 Harris et al., 1983; Stevens et al., 2007). This large estuarine system contains at least 71,680 ha of open water and 320 km of shoreline not including the numerous mangrove islands. Water depth of the system averages approximately 1.8 m. Several state Aquatic Preserves are designated in Charlotte Harbor, which is considered one of the most pristine and productive estuarine systems in Florida (FDEP, 2009; Pierce et al., 2003). Three large rivers flow into Charlotte Harbor, the Caloosahatchee, the Peace and the Myakka together draining approximately 78,800 ha. The thirteen estuaries and coastal bays that comprise the Charlotte Harbor system are diverse and productive and are designated as the Charlotte Harbor National Estuary Program (CHNEP). Each of the estuaries has unique biological, geomorphological, water quality and watershed conditions, and associated resource management priorities. Throughout the estuaries, there currently exist tens of thousands of hectares of freshwater and salt water marshes, mangrove swamps, coastal forests, tidal flats, cypress, tidal swamps, beaches and oyster reefs (Pierce et al., 2003). For purposes of our analyses, we used the same study area as in Harris et al. (1983), which encompasses a 258,500 ha portion of the Charlotte Harbor area (somewhat less than the CHNEP area) and is identified by the USGS quadrangle maps illustrated in FIG. 1. We conducted both retrospective and prospective analyses of coastal system change to better understand long term changes in the system. Having a better understanding of past and likely future changes is valuable information that can be used to guide restoration and coastal resilience decisions.

Retrospective analysis (1945–2007*)—We conducted a quantitative, comparative geospatial analysis of coastal habitat change in the 258,500 ha study area over the period 1945 to the most recently available data, which ranged from 1999 to 2007 depending on the location and habitat type. We compared distribution of saltmarsh, mangrove swamp, tidal flat, seagrass and oyster reef habitat from the period 1945 to 1982 as reported in Harris et al. (1983) to the most recent distribution information for these coastal systems. USGS quadrangle maps were used as comparison units to be consistent with the unit of measurement in Harris et al. (1983). In 1983, Harris et al., quantitatively assessed change in coastal system extent through interpretation of 1982 aerial photographs taken at a 1:24,000 scale and compared them to data collected in 1945 using photographic and photo-interpretation techniques. To determine the most recent spatial extent of saltmarsh, mangrove swamp and tidal flat habitat, we used the Florida Natural Areas Inventory (FNAI) Cooperative Land Cover 1.1 (CLC) map which uses the Florida Land Cover Classification System (FLCS) categories to describe various wetland and upland land cover types including developed dry land (http://myfwc.com/research/gis/data-maps/terrestrial/fl-land-cover-classification/). The CLC map pieces together all the latest land cover datasets available statewide. The northern part of the study area is within the Southwest Florida Water Management District (SWFWMD) and the FNAI data were generally collected in 2008. The southern portion of the study area is within the South Florida Water Management District (SFWMD) and these data were generally collected in 2004. To determine recent seagrass distribution, we utilized geospatial data from the SWFWMD and SFWMD collected in 2008 (SWFWMD, 2008). For the most recent oyster reef distribution, we used the geospatial oyster reef coverage available from the Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWC-FWRI, 2008), which was collected in the Charlotte Harbor area in 1999.

Prospective SLAMM analysis—The prospective coastal system analysis was conducted by modeling the impacts of sea level rise (SLR) using the Sea Level Affecting Marshes Model (SLAMM). The modeling was conducted for a 100 year period covering the years 2000 through 2100 using three SLR scenarios: the Intergovernmental Panel on Climate Change A1B Maximum, which is equivalent to 0.7 m, 1.0 m and 2.0 m. As in previous versions, SLAMM 6.1 beta (http://warrenpinnacle.com/prof/SLAMM6/ SLAMM6_Technical_Documentation.pdf) requires a set of raster input files, a table of site parameters specific to the study area, and a set of model parameters that are entered when a simulation is run. In this study, the raster inputs were a digital elevation model (DEM), a slope layer, and a land cover layer which includes natural communities. The non-spatial, site specific input parameters required to run SLAMM include the photo date of the land cover layer, the date the DEM was created, direction offshore that the subsite faces, historic trend in sea level rise, several tidal elevation parameters (NAVD88 correction, salt elevation, and great diurnal tide range) and the rates of erosion, sedimentation, and accretion for certain wetland types. To accommodate the varying tidal elevations within the Charlotte Harbor system, we created four subsites (i.e., defined polygons over which site parameters are held constant) within the overall study area (see FIG. 2). The "global site" is the remainder of the study area, i.e. the area outside of the subsites. The four subsites include: Peace and Myakka River Estuaries, Estero Bay, Caloosahatchee Estuary and Cape Haze. Site specific information on all SLAMM input parameters is provided below and summarized in TABLE 2. While tidal elevations varied among the site/subsites, the DEM and slope were held constant.

Prospective SLAMM analysis input, land cover raster—The FNAI Cooperative Land Cover (CLC) map (www.fnai.org) was used to classify natural communities and land cover types in the SLAMM analysis. The source data used to create this map are the same as the vegetation data used for the above described retrospective analysis and represents the most recently available land cover conditions. FNAI uses the Florida Land Cover Classification System (FLCS) categories to describe various wetland and upland land cover types including developed dry land (http://myfwc.com/research/gis/data-maps/terrestrial/fl-land-cover-classification/). We examined the FLCS categories and assigned the SLAMM category that most closely matched the vegetation or land use description, as summarized TABLE 3 and shown in FIG. 3. The National Wetlands Inventory (NWI) wetland types were also compared and assigned to SLAMM categories (Clough et al., 2010). Areas identified by the NWI as tidal flats replaced the CLC classification if they overlaid water. Small areas of coastal forest and marsh in the Peace River were coded by the NWI as tidal categories and were designated as tidal categories in our vegetation cover. In addition, the beach distribution data were inconsistent between the SWFWMD and SFWMD data. The SWFWMD dataset did not

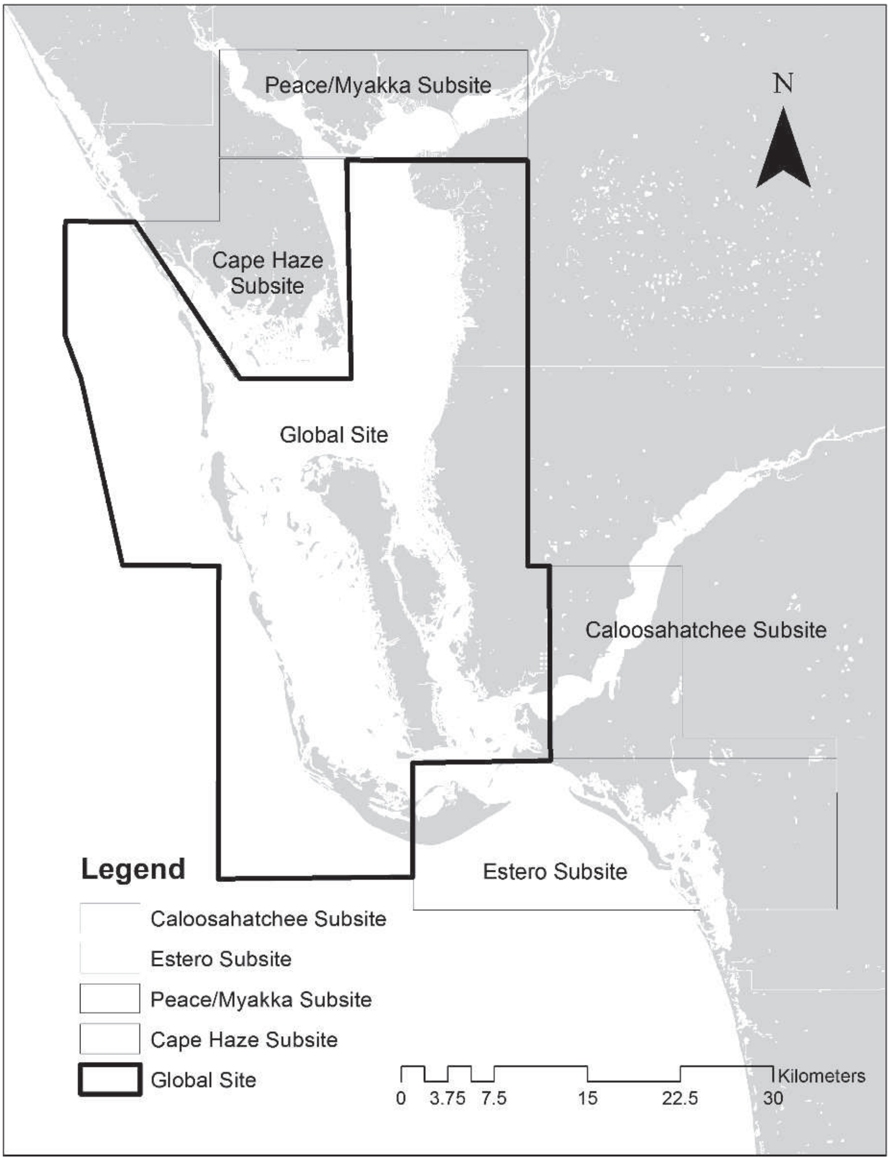

FIG. 2. The study area used in the SLAMM analyses is made up of a global site and subsites. Boundaries are illustrated. Subsites were created to accommodate variations in tidal elevations in the study area. The global site is the portion of the study area outside of subsites.

show beach distribution data along the barrier island in the northern portion of the study area. To correct this, we eliminated the beach information from the vegetation raster and added in the FWC-FWRI beaches layer, which originated from the FWC-FWRI's 2003 Florida Vegetation and Land Cover dataset (http://www.fnai.org/gisdata.cfm).

TABLE 2. SLAMM input parameters for the global site and subsites. The global site is the area outside of the subsites within the study area.

	Global Site	Subsites			
Parameters	Charlotte Harbor	Peace/Myakka River	Estero Bay	Caloosahatchee River	Cape Haze
Land cover photo date	2004	2007	2004	2004	2008
DEM Date	2007	2005	2007	2007	2007
Direction Offshore	West	South	West	West	West
Historic trend in sea level rise (mm/yr)	2.4	2.4	2.4	2.4	2.4
NAVD correction [MTL - NAVD88 (m)]	−0.178	−0.142	−0.185	−0.127	−0.171
Great diurnal tide range (m)	0.529	0.624	0.75	0.401	0.461
Salt elevation (m above MTL)	0.434	0.511	0.615	0.527	0.378
Marsh erosion rate (horizontal m/yr)	0.23	0.23	0.23	0.23	0.23
Coastal forest erosion rate (horizontal m/yr)	0.23	0.23	0.23	0.23	0.23
Tidal flat erosion rate (horizontal m/yr)	0.7	0.13	0.7	0.13	0.13
Saltmarsh accretion rate (mm/yr)	7.2	7.2	7.2	7.2	7.2
Brackish marsh accretion rate (mm/yr)	7.2	7.2	7.2	7.2	7.2
Tidal FW marsh accretion rate (mm/yr)	7.2	7.2	7.2	7.2	7.2
Beach sedimentation rate (mm/yr)	0.3	0.3	0.3	0.3	0.3
Frequency of overwash (years)	31	31	31	31	31
Used elevation pre-processor [True, False]	FALSE	FALSE	FALSE	FALSE	FALSE

TABLE 3. FNAI Cooperative Land Cover (CLC) codes and land cover types assigned for SLAMM analyses throughout the study area. Where NWI and CLC tidal features corresponded, the SLAMM vegetation assignment was changed. Tidal swamp was assigned to the entire CLC polygon with which it overlapped.

CLC Land Cover Code	SLAMM Category
1110–1150, 1210–249, 1311–1330, 1400–1410, 1500, 1610–1660, 1710–1740, 1811, 1831, 1880, 2114, 2221, 2410, 7000–300, 18311–18323, 22311, 183111–183252, 222111, 1832121–1832151	Undeveloped Dry Land
1670	Ocean Beach
1821–822, 1832–1877, 3240–260, 18211–18225, 18324, 182111–182136	Developed Dry Land
2100–2113, 2120–2141, 2300	Inland Freshwater Marsh
2210–2214, 22131–22132, 221311–221312	Cypress Swamp
2215–2220, 2222–2242, 2420–2450, 7400, 22211–22212, 22312–22332	Coastal forest
3100–3115, 3117–3118, 3200–230, 4100–140, 4200–210, 8000	Inland Open Water
3116, 4160, 5000	Estuarine Water
4170	Inland Shore
5200–5220, 9100	Tidal Flat
5230, 52111	Rocky Intertidal
5240	Regularly Flooded Marsh
5250	Mangrove
5251, 21112–21212	Inland Freshwater Marsh
6000	Open Ocean
21231	Tidal Fresh Marsh
22151	Tidal Swamp

Prospective SLAMM analysis input, elevation raster—Digital elevation models (DEMs) derived from high resolution LiDAR data collected by the SWFWMD the Florida Division of Emergency Management (FDEM) Coastal LiDAR Project were downloaded from the NOAA Coastal Services Center's Digital Coast website. The elevation data were downloaded as a DEM in the State Plane Coordinate System (Florida West 1983), with a vertical datum of NAVD88 by averaging ground points within a 5 m cell. The floating-point DEM data were converted to an ArcGIS grid format (Esri ArcGIS 9.3), re-sampled to 30 m cell size, and clipped to the study area. The LiDAR from which the DEM was derived meets or exceeds a 1.2 m horizontal accuracy and 0.20 m fundamental vertical accuracy at the 95% confidence level. Metadata with links to the technical reports for the LiDAR data collection are available at (http://www.csc.noaa.gov/digitalcoast/data/coastallidar/index.html).

Areas of open ocean and tidal creeks that contained ''no data'' values were set equal to 0. A slope raster in degrees from the DEM was then defined. In all of the model runs, LiDAR-derived elevation data were used; therefore, use of the SLAMM preprocessor was not required.

Prospective SLAMM analysis inputs, site specific parameters—As discussed above, two sets of land cover data were used for this study and photo date varied among the ''global site'' and subsites (see TABLE 2). The Charlotte Harbor, Estero Bay and Caloosahatchee Estuary global site and subsites fall within the SFWMD boundaries and the land cover data for these site/subsites were collected in 2004. The Peace/Myakka River Estuaries and Cape Haze subsites fall within the SWFWMD boundaries and the land cover data for these subsites were collected in approximately 2007/2008.

The LiDAR data used to create the DEM used for our analysis was collected in 2007, except for the Peace subsite which was collected in 2005. The land cover and DEM dates allow SLAMM to calibrate initial land cover condition to the latest land cover photo date. The direction offshore parameter is used by the SLAMM decision tree to determine the context of a particular cell in relation to offshore areas and informs the direction of habitat conversion. For all but the Peace/

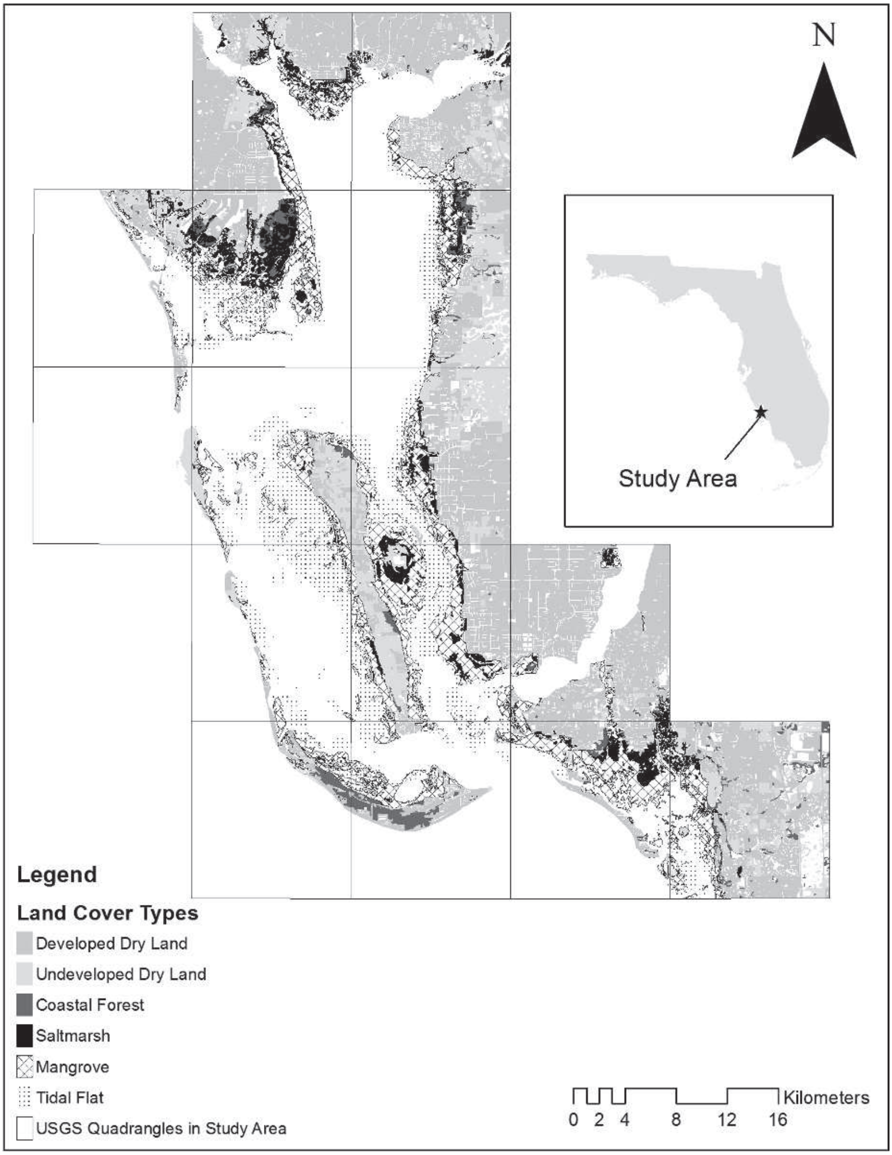

FIG. 3. Land Cover Types in the Charlotte Harbor Study Area. Source is the Cooperative Land Cover, Florida Natural Areas Inventory (FNAI, 2010).

Myakka River Estuaries subsite this direction is west. For the Peace/Myakka River subsite, direction offshore is predominantly south. Historic trend in sea level rise provides SLAMM with the information required to calibrate both the land cover and DEM rasters to the initial condition (year 2007).

SLAMM requires parameters for: converting elevation values to the MTL datum (NAVD88 correction); for the maximum daily tide range (great diurnal tide); and for the elevation at which freshwater wetlands and dry land begin (salt elevation). The SLR rate along with the NAVD88 correction, great diurnal tide range and salt elevation are either published on the NOAA Tides and Currents website (http://tidesandcurrents.noaa.gov/), or are calculated from data found on this website. The NAVD88 correction (MTL-NAVD) was calculated for NOAA stations that had published values for these datums; otherwise, the correction was calculated using NOAA's vdatum program (vdatum.noaa.gov).. Great diurnal tide range was from published station values. These values were averaged within subsites to produce the final SLAMM input parameters.

Salt elevation was also derived from data published on the NOAA tides and currents website. Salt elevation is the elevation boundary between salt water, saltmarsh or brackish marsh and freshwater marsh or dry land. It was calculated by examining 3 years of tide data for the Naples tide station (NOAA tides and currents website). We used the Naples station because the Fort Myers tide station, while within the study area, is substantially influenced by the Caloosahatchee River, limiting its applicability for estimation in the remainder of the study area. From the 3 years of tide data, we calculated a frequency distribution to identify the elevation at which the high tide occurred no more than once a month (i.e., the salt elevation). For the Naples tide station, we then calculated the ratio of 'salt elevation' to mean high water (MHW) and applied this ratio to short-term tide stations in the study area to estimate salt elevation at these stations. The salt elevations for all tide stations within the global site and each of the subsites were then averaged to derive the salt elevation for the study area and each subsite.

For erosion rates, the most proximate data to our study area in the literature was from the Crystal Bay area approximately 230 km north of Charlotte Harbor. In that area, Hine and Belknap (1986) found that saltmarsh eroded at a rate of 0.2 horizontal m/year for coastal embayments. In our study area, coastal forest is set back from the coast except for a small stand found in northern Estero Bay. Because we were unable to identify erosion rate data for coastal forest in the study area or region, the same saltmarsh erosion rate (0.2 horizontal m/year) was also used for coastal forests.

To calculate tidal flat/beach erosion rate, we downloaded long-term coastal erosion rate data from the National Assessment of Shoreline Change (Morton et al., 2004). These data are only applicable to the beaches and tidal flats facing the Gulf of Mexico, not tidal flats located within Charlotte Harbor and its associated estuaries. Using the National Assessment of Shoreline change dataset, we were able to calculate the average erosion rate of 0.7 horizontal m/yr. for the Charlotte Harbor global site and Estero Bay subsite which have Gulf-facing beaches and tidal flats. Because no erosion data for the interior tidal flats and beaches could be located, we applied the same erosion rate calculated above to the Peace/Myakka River Estuaries, Caloosahatchee River Estuary and Cape Haze subsites.

SLAMM is sensitive to the accretion rate parameter and so this rate is a significant source of uncertainty in SLAMM applications (Chu-Agor M.L et. al 2010). In addition, little published information is available on accretion rates along Florida's Gulf Coast. The closest marsh accretion rate data was from Cedar Creek near Crystal River, Florida approximately 230 km north of the study area. In this area, Leonard et al. (1995) measured an accretion rate of 7.2 mm/yr. in saltmarsh, the predominant type of marsh in our study area. Accretion rate was not specifically available for brackish and tidal freshwater marsh, so the rate for saltmarsh was used for all marsh types.

For beach sedimentation rate, we used data from the most proximate source, the Southwest Florida Everglades, estimated to be 0.3 mm/year (Scholl et al., 1969). Frequency of overwash was calculated from historic hurricane information available from NOAA's Coastal Service Center website (http://www.csc.noaa.gov.hurricanes). We conducted a query of all recorded tropical storms passing through the Charlotte Harbor "bay" area. The first recorded tropical storm passing through this area was recorded in 1888. Since that time, 3 tropical storms and 8 hurricanes have passed through this area. We assumed hurricanes rated as a category 2 or higher resulted in overwash of the barrier island system. Since 1888, 4 category 2 or higher hurricanes have passed through the area, so on average approximately 1 overwash event has occurred every 31 years over the 123 year period of record (1888 to 2011).

SLAMM model runs—Because LiDAR-derived elevation data were used, use of the SLAMM preprocessor was not required. In addition, the soil saturation algorithm was turned off, the connectivity algorithm was enabled, and the SLAMM default elevations for coastal wetland system types were utilized (see SLAMM technical documentation for additional information; Clough et al., 2010). All scenarios were run with developed dry land set to "protected". This setting assumes developed areas are surrounded by a dike that will protect them from sea level rise. SLAMM can also be run with developed dry land not protected. We utilized the "protect developed dry land" setting as we assumed efforts will be made to protect existing developed dry land from inundation. We ran SLAMM using the scenarios 0.7 m, 1.0 m, and 2.0 m SLR by the year 2100. The 0.7 m SLR scenario was chosen because it is an IPCC (2007) scenario (A1B maximum). The other two SLR scenarios were selected based on recent projections of the magnitude of SLR to the year 2100 (CCSP, 2008; Mitrovica et al., 2009; Overpeck et al., 2006; Rahmstorf et al., 2007).

SLAMM model output—SLAMM provides output in both tabular and graphic formats. For each output SLAMM predicts the spatial distribution of each wetland system, open water area and upland land type (developed and undeveloped dry land) so change in spatial distribution over time can be calculated by comparing output to the initial condition. The graphic output provides a spatial depiction of where habitat changes are simulated to occur. As with the tabular output, change over time can be described quantitatively and qualitatively by comparing initial condition with output years.

Comparison of historic and prospective coastal habitat analyses—Although we used a global site and subsites to best approximate existing conditions in the study area as input into SLAMM, SLAMM does not provide model results by global site/subsite. Therefore, we used geospatial analysis to compare historic changes in coastal wetland distributions to SLAMM simulated future changes and presented the results for each USGS quadrangle map in the study area to allow comparison to the earlier study by Harris et al (983).

RESULTS—*Retrospective analysis (1945 – most recently available)*—The results of the retrospective analysis of habitat changes between 1945 and the most recently available habitat data are shown in TABLE 4 by USGS quadrangle map. To reference the estuaries associated with each quadrangle map, please see TABLE 1. Results are presented for five habitat types (saltmarsh, mangroves, tidal flats, seagrass and oysters) and three period comparisons (1945–1982, 1982–most recent and 1945– most recent). For this study, we defined substantial changes as those greater than 10% or 100 ha. Where habitat increased from "none present", we reported the results in hectares rather than percent change. The results indicate that throughout the study area, from 1945–1999/2004/2007, saltmarsh and tidal flat habitat increased substantially (+123% and +927%, respectively), while seagrass, mangrove swamp and oyster reef habitat decreased substantially (−25%, −25% and −86%, respectively). It should be noted that the large observed increase in tidal flat extent is more likely due to differences methods and conditions between years than a real gain in tidal flat habitat. Possible differences in methods include tide stage during image collection, photographic methods and/or photo interpretation methods. Because the tide stage and/or time of day for the 1945 and 1982 aerial photography is not available, a comparison of the historic and recent photography is not possible and would be required to better estimate change in extent of tidal flat habitat. For the period 1982–1999/2004/2007, throughout the study area, seagrass habitat remained relatively stable (+6%), saltmarsh increased substantially (+356%), and mangrove swamp and oyster reef declined (−32% and −75%, respectively). Again, caution is advised for interpreting the tidal flat data due to methodological differences.

Over the period 1945 to the most recent year habitat data were available, change in extent of coastal habitats by sub-area did not always follow the pattern of change observed for the study area as a whole. While saltmarsh increased by 123% throughout the study area, a substantial decrease (−68%) was observed in the Fort Myers SW USGS quadrangle (Tidal Caloosahatchee River). Saltmarsh extent remains relatively unchanged (−6%) in the Punta Gorda (Tidal Peace River) quadrangle area. The Port Boca Grande (Lower Charlotte Harbor) and Captiva (Pine Island Sound) quadrangle areas continue to have very little salt marsh habitat. Over the same period (1945–2004/2007), saltmarsh increased substantially in the following quadrangle areas: Bokeelia/ Pine Island Sound (+385%), El Jobean/Tidal Myakka River (+13%), Estero/ Estero Bay (+17%); Fort Myers Beach/Estero Bay (+183%), Matlacha/ Matlacha Pass (+301%), Pine Island Center/Matlacha Pass (+231%), Placida/ Cape Haze (+433%), Punta Gorda SE/Charlotte Harbor East Wall (88%), Punta Gorda SW/Charlotte Harbor West Wall/Cape Haze (+878%) and Sanibel/San Carlos Bay (+162%).

Over the study period (1945–2004/2007), while mangrove swamp decreased by 25% in the study area as a whole, mangrove swamp increased substantially in the following USGS quadrangle areas: Estero/Estero Bay (+26%), Fort Myers SW/Tidal Caloosahatchee River (+37%), Matlacha/Matlacha Pass (+25%) and Port Boca Grande (+44%). During the same period, substantial decreases in mangrove swamp were seen in these quadrangle maps: Bokeelia (−56%); Captiva (−13%;), Fort Myers Beach (−32%), Pine Island Center (−36%), Placida (−55%;), Punta Gorda (−41%), Punta Gorda SE (−51%;), Punta Gorda SW (−47%;) and Sanibel (−30%). And, mangrove swamp remained fairly stable in the El Jobean (−3%) and Wulfert (−2%) quadrangle areas.

Regarding seagrass and oyster reef habitat, all quadrangle areas experienced a substantial loss with the exception of Placida (Cape Haze and Lower Lemon Bay) and Punta Gorda SW (West Wall and Cape Haze; +4% and +7%, respectively) for seagrass habitat and Bokeelia (Pine Island Center), Fort Myers Beach (Estero and San Carlos Bays), Fort Myers Southwest (Tidal Caloosahatchee) and Sanibel (San Carlos Bay; +11 ha, +1 ha, +1 ha, and +6%, respectively) for areas that had oyster reef habitat in 1945. Focused seagrass restoration and conservation efforts may explain why this habitat increased by 6% during the period 1982 to 2008. Because of the large uncertainty surrounding how the earlier tidal flat data were collected, we will only say that the only quadrangle area where tidal flat distribution did not increase substantially over the study period 1945 to 2004/2007 is Fort Myers Southwest (−13%; i.e., Tidal Caloosahatchee River).

TABLE 4. Change in coastal habitat distribution over time for (a) saltmarsh, (b) mangrove, (d) tidal flat, (e) seagrass, and (f) oyster habitats. Data sources include: (1) Harris et al. (1983) for 1945 and 1982 all habitats, (2) FNAI Cooperative Land Cover for 2004 and 2007 saltmarsh, mangrove, coastal forest and tidal flat habitats, (3) SWFWMD and SFWMD for 2008 for seagrasses, and FWC for 1999 for oyster habitats.

	1945 (hectares)	1982 (hectares)	1945–1982% Change (ha)	2004/2007 (hectares)	1982–2007% Change (ha)	1945–2007% Change (ha)
(a) SALTMARSH (USGS Quadrangle)						
Bokeelia	12	10	−17%	57	486%	385%
Captiva	0	3		13	349%	(+10)
El Jobean	713	619	−13%	803	30%	13%
Estero	222	160	−28%	261	64%	17%
Fort Myers Beach	311	302	−3%	879	191%	183%
Fort Myers SW	560	138	−75%	181	31%	−68%
Matlacha	187	0	−100%	751	(+751)	301%
Pine Island Center	287	80	−72%	951	1092%	231%
Placida	64	0	−100%	339	(+339)	433%
Port Boca Grand	0	0	0%	2	(+2)	(+2)
Punta Gorda	223	57	−75%	208	268%	−6%
Punta Gorda SE	172	0	−100%	322	(+322)	88%
Punta Gorda SW	177	68	−61%	1726	2423%	878%
Sanibel	9	0	−100%	23	(+23)	162%
Wulfert	0	0	0%	24	(+24)	(+24)
Total Study Area	2936	1436	−51%	6542	356%	123%
(b) MANGROVES (USGS Quadrangle)						
Bokeelia	3544	3731	5%	1572	−58%	−56%
Captiva	1033	1121	9%	898	−20%	−13%
El Jobean	3433	4321	26%	3324	−23%	−3%
Estero	2769	3280	18%	3481	6%	26%
Fort Myers Beach	6032	5955	−1%	4127	−31%	−32%
Fort Myers SW	1936	1190	−39%	2649	123%	37%
Matlacha	4243	5821	37%	5290	−9%	25%
Pine Island Center	8937	11291	26%	5760	−49%	−36%
Placida	1083	968	−11%	483	−50%	−55%
Port Boca Grand	39	32	−18%	56	75%	44%
Punta Gorda	4310	2799	−35%	2532	−10%	−41%
Punta Gorda SE	2821	3502	24%	1377	−61%	−51%
Punta Gorda SW	6885	8251	20%	3645	−56%	−47%
Sanibel	3067	2943	−4%	2137	−27%	−30%
Wulfert	1392	1426	2%	1371	−4%	−2%
Total Study Area	51524	56631	10%	38701	−32%	−25%
(c) TIDAL FLATS (USGS Quadrangle)						
Bokeelia	21	13	−40%	3755	29817%	17735%
Captiva	23	0	−100%	6769		29233%
El Jobean	306	51	−83%	433	748%	41%
Estero	126	68	−46%	980	1341%	678%
Fort Myers Beach	314	147	−53%	786	436%	150%
Fort Myers SW	153	21	−86%	133	519%	−13%
Matlacha	513	21	−96%	4371	21067%	751%
Pine Island Center	941	145	−85%	9711	6600%	932%
Placida	108	57	−47%	1962	3312%	1715%

TABLE 4. Continued.

	1945 (hectares)	1982 (hectares)	1945–1982% Change (ha)	2004/2007 (hectares)	1982–2007% Change (ha)	1945–2007% Change (ha)
Port Boca Grand	0	0		40		
Punta Gorda	347	38	−89%	1577	4001%	354%
Punta Gorda SE	438	103	−76%	2536	2356%	479%
Punta Gorda SW	1186	437	−63%	2407	451%	103%
Sanibel	60	1	−98%	10229	842072%	16971%
Wulfert	0	0		920		
Total Study Area	4537	1102	−76%	46607	4128%	927%
(d) SEAGRASS (USGS Quadrangle)						
Bokeelia	4921	4602	−6%	4442	−3%	−10%
Captiva	8060	4114	−49%	5434	32%	−33%
El Jobean	661	362	−45%	383	6%	−42%
Estero	1586	523	−67%	979	87%	−38%
Fort Myers Beach	1452	1063	−27%	463	−56%	−68%
Fort Myers SW	593	77	−87%	0	−100%	−100%
Matlacha	2340	2000	−15%	1949	−3%	−17%
Pine Island Center	4640	3921	−16%	3566	−9%	−23%
Placida	1057	634	−40%	1100	73%	4%
Port Boca Grand	155	27	−83%	0	−100%	−100%
Punta Gorda	361	313	−13%	183	−41%	−49%
Punta Gorda SE	1719	1442	−16%	1028	−29%	−40%
Punta Gorda SW	2786	2332	−16%	2975	28%	7%
Sanibel	2144	1595	−26%	1915	20%	−11%
Wulfert	1113	678	−39%	634	−6%	−43%
Total Study Area	33587	23682	−29%	25051	6%	−25%
(e) OYSTER REEF (USGS Quadrangle)						
Bokeelia	0	15	(+15)	11	−26%	(+11)
Captiva	23	0	−100%	5	(+5)	−79%
El Jobean	0	2	(+2)	0	−100%	0%
Estero	20	13	−37%	14	14%	−28%
Fort Myers Beach	1	1	50%	2	85%	178%
Fort Myers SW	0	0	0%	1	(+1)	(+1)
Matlacha	0	3	(+3)	0	−95%	0%
Pine Island Center	209	123	−41%	12	−90%	−94%
Placida	22	23	2%	0	−100%	−100%
Port Boca Grand	0	0	0%	0	0%	0%
Punta Gorda	2	2	25%	0	−100%	−100%
Punta Gorda SE	0	0	0%	0	0%	0%
Punta Gorda SW	70	11	−84%	0	−100%	−100%
Sanibel	3	4	25%	3	−15%	6%
Wulfert	0	0	0%	0	0%	0%
Total Study Area	349	197	−44%	49	−75%	−86%

Prospective analysis (2008–2100)—The results of the SLAMM analyses from 2008–2100 are shown in TABLES 5 and 6 and FIG. 4 through FIG. 6. The results indicate substantial changes in coastal wetland systems under all three SLR scenarios modeled. Under the modest SLR scenario of 0.7 m by 2100

TABLE 5. SLAMM results under 0.7 m (IPCC A1B maximum) and 1.0 m SLR scenarios through 2100. Although SLAMM can only use one date as an input parameter, the Initial Condition represents the most recently available data, 2004 or 2007, depending on the location within the study area.

SLR Scenario	Initial	0.7 m	0.7 m	0.7 m	1.0 m	1.0 m	1.0 m
Date	2004/2007	2100	Change	Change	2100	Change	Change
	(hectares)	(hectares)	(hectares)	%	(hectares)	(hectares)	%
Developed Dry Land	50,531	50,507	−24	0%	50,483	−48	0%
Undeveloped Dry Land	17,672	14,964	−2,708	−15%	12,704	−4,968	−28%
Open Ocean	65,946	65,975	29	0%	66,052	106	0%
Estuarine Open Water	63,124	82,635	19,511	31%	86,574	23,450	37%
Mangrove Swamp	22,535	27,072	4,537	20%	27,846	5,311	24%
Tidal Flat	20,490	1,343	−19,147	−93%	647	−19,843	−97%
Saltmarsh	5,770	5,751	−19	0%	5,473	−297	−5%
Inland Open Water	5,455	4,882	−573	−11%	4,584	−871	−16%
Coastal Forest	3,498	1,344	−2,154	−62%	835	−2,663	−76%
Inland-Fresh Marsh	1,695	1,634	−61	−4%	1,379	−316	−19%
Cypress Swamp	1,300	1,298	−2	0%	1,297	−3	0%

TABLE 6. SLAMM results under 2.0 m SLR scenarios through 2100. Although SLAMM can only use one date as an input parameter, the Initial Condition represents the most recently available data, 2004 or 2007, depending on the location within the study area.

SLR Scenario	Initial	2.0 m	2.0 m	2.0 m
Date	2004/2007	2100	Change	Change
	(hectares)	(hectares)	(hectares)	%
Developed Dry Land	50,531	50,283	−248	0%
Undeveloped Dry Land	17,672	7,941	−9,731	−55%
Open Ocean	65,946	66,775	829	1%
Estuarine Open Water	63,124	121,115	57,991	92%
Mangrove Swamp	22,535	3,809	−18,726	−83%
Tidal Flat	20,490	1,488	−19,002	−93%
Saltmarsh	5,770	101	−5,669	−98%
Inland Open Water	5,455	3,949	−1,506	−28%
Coastal Forest	3,498	589	−2,909	−83%
Inland-Fresh Marsh	1,695	750	−945	−56%
Cypress Swamp	1,300	1,294	−6	0%

(IPCC A1B maximum) (TABLE 5; FIG. 4) the model predicted substantial change (>10% and >100 ha) in three coastal wetland systems through 2100: mangrove swamp increased (+ 20%), tidal flat nearly disappeared (−93%) and coastal forest decreased (−62%). Other substantial changes in land and water cover types include a 15% loss of undeveloped dry land, a 31% increase in estuarine open water areas and an 11% decrease in inland open water areas.

Under the moderate SLR scenario of 1.0 m by 2100 (TABLE 5; FIG. 5), the predicted changes were for the same coastal wetland systems and open waters, but the magnitude of change was greater. Under this scenario, mangrove swamp increased (+24%), tidal flat all but disappeared (−97%) and coastal forest decreased by 76%. In addition, inland freshwater marsh decreased under this scenario by 19%. Undeveloped dry land, estuarine open water and inland open water areas also changed substantially (−28%, +37% and −16%, respectively).

Under the higher rate of SLR modeled of 2.0 m by 2100 (TABLE 6; FIG. 6), all wetland systems with at least 1,000 ha in the study area currently decreased substantially including mangrove swamp, tidal flat, saltmarsh and inland freshwater marsh (−83%, −93%, −98%, −83% and −56%, respectively). Cypress swamp experienced little change (−6 ha). In addition, undeveloped dry land in the study area decreased by 55%, estuarine open water increased by 92% and inland open water decreased by 28%.

The most significant predicted land type changes by 2100 under the moderate 1.0 m SLR scenario are shown in TABLE 7 and FIG. 7. Reviewing potential changes under this scenario shows that the largest system transition is from tidal flat to estuarine open water (20,041 ha; 7.8% of study area). Other transitions representing at least 500 ha include undeveloped dry land to mangrove swamp (4,092 ha; 1.6% of study area), coastal forest to mangrove

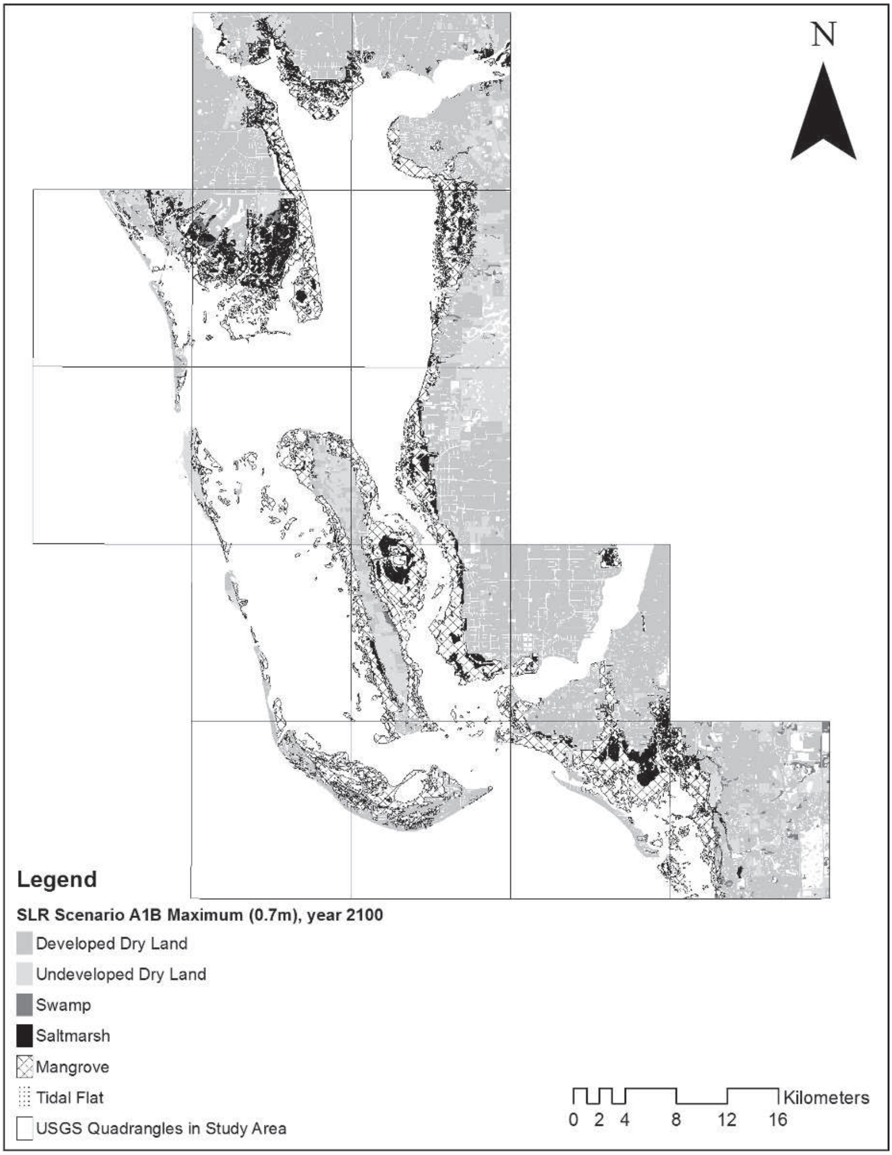

FIG. 4. SLAMM results under 0.7 m SLR scenario through 2100 (IPCC A1B maximum). In this scenario, developed dry land was treated as protected in the model run, assuming there would be no loss of this land type.

swamp (1,921 ha; 0.7% of study area), mangrove swamp to estuarine open water (962 ha; 0.4% of study area) and coastal forest to estuarine open water (704 ha; 0.3% of study area. The quadrangle areas with the greatest transition of tidal flat to estuarine water include Captiva, Pine Island Center, Bokeelia, Matlacha, and Punta Gorda SW and SE (i.e., Pine Island Sound, Matlacha

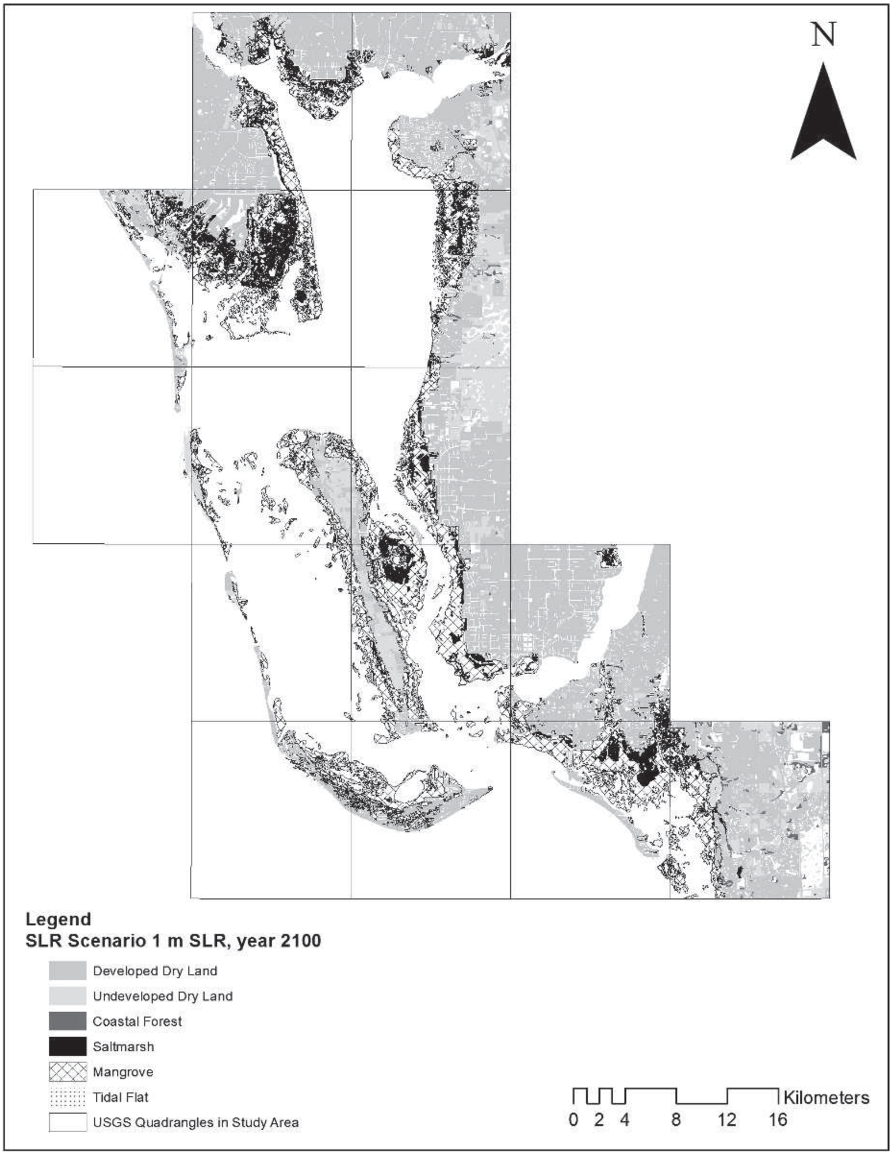

FIG. 5. SLAMM results under 1.0 m SLR scenario through 2100. In this scenario, developed dry land was protected in the model run, assuming there would be no loss of this land type.

Pass, Cape Haze, West Wall and East Wall). The quadrangle areas with the greatest transition of undeveloped dry land to mangrove swamp include Punta Gorda SW and SE and El Jobean (i.e., Cape Haze, West Wall, East Wall and Tidal Myakka River). The transition of coastal forest to mangrove swamp

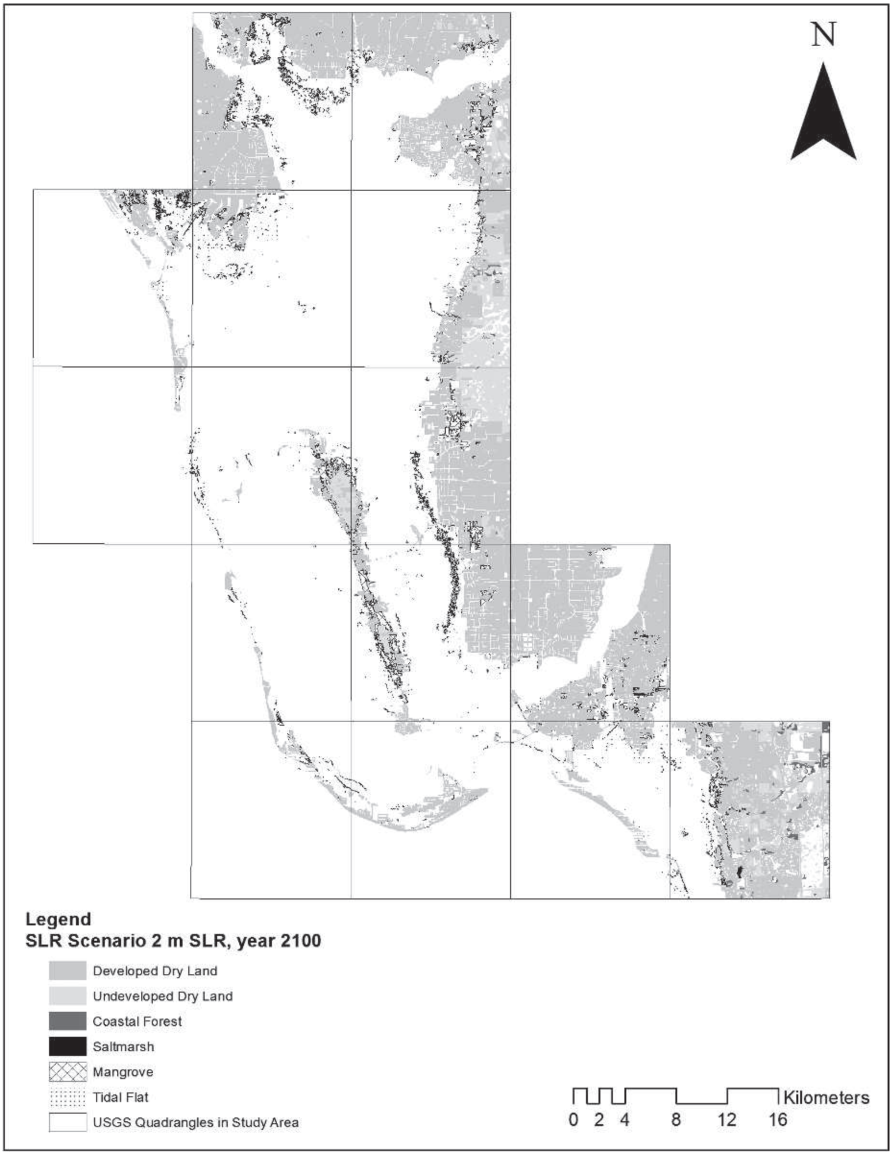

FIG. 6. SLAMM results under 2.0 m SLR scenario through 2100. In this scenario, developed dry land was protected in the model run, assuming there would be no loss of this land type.

primarily occurs in the Sanibel, Punta Gorda SE and SW and Wulfert quadrangle areas (i.e., San Carlos Bay, Cape Haze, West Wall, East Wall and southern Pine Island Sound).

DISCUSSION—From 1945 to 1982, Harris et al. (1983) found a substantial change in some of the coastal habitats examined in the study area, including

TABLE 7. Predicted transition of coastal wetland systems using SLAMM under a 1.0 m SLR scenario by 2100. Only transitions > 500 ha are included.

Transition From/To	Hectares	Percent of Study Area
Tidal Flat to Estuarine Open Water	20,041	7.8%
Undeveloped Dry Land to Mangrove Swamp	4,092	1.6%
Coastal forest to Mangrove Swamp	1,921	0.7%
Mangrove Swamp to Estuarine Open Water	962	0.4%
Coastal forest to Estuarine Open Water	704	0.3%

saltmarsh (−51%), mangrove swamp (+10%), tidal flat (−76%), seagrass (−29%); and oyster reef (−44%; TABLE 4). Harris et al (1983) attributed most of the coastal habitat losses directly or indirectly to coastal development and assumed mangrove swamp expansion was primarily a result of sea level rise and warming temperatures (longer periods between hard freezes). Our analysis shows that since the Harris et al. (1983) analysis, the loss trends for oyster reef habitat have continued (−75% from 1982 to 1999), seagrass extent has slightly improved (+6% from 1982 to 2004/2006), saltmarsh extent has expanded considerably (+302% from 1982 to 2004/2007), and mangrove swamp has declined (−32% from 1982 to 2004/2007; TABLE 4). In the context of this project, it was not possible to assess the change in extent of tidal flat.

Saltmarsh expansion may be at least partially a result of saltmarsh moving into areas that were previously freshwater marsh based on a visual comparison of salt and freshwater marsh distributions in earlier and later land cover maps (i.e., NWI 1999 versus CLC 2008). The retrospective analysis results suggest that given the substantial increase in study area saltmarsh habitat, perhaps at the expense of freshwater wetlands, hydrologic restoration and/or modification where possible may be required to re-establish the diversity of wetland systems that were present prior to extensive urban and suburban development.

Suggested priority restoration areas for coastal wetland systems based on the results of the retrospective and prospective are summarized in TABLE 8 for each estuary (refer to TABLE 1 for associated USGS quadrangle maps). Priority areas for hydrologic restoration and/or modification include the: Punta Gorda SW, Pine Island Center, Fort Myers Beach, Matlacha, Placida and Punta Gorda SE USGS quadrangles. Saltmarsh areas at or adjacent to Cape Haze, West Wall, East Wall, Matlacha Pass and Estero Bay are included within these priority areas.

Despite management practices beginning in the late 1960's that created a buffer system around many of the Charlotte Harbor estuaries and protected mangrove swamps from coastal development, our results show that 25% of mangrove swamp habitat was lost in the study area from 1945 to 2004/2007 (TABLE 4). The quadrangle areas most affected were: Pine Island Center, Punta Gorda SW, Fort Myers Beach and Punta Gorda. These areas include Matlacha

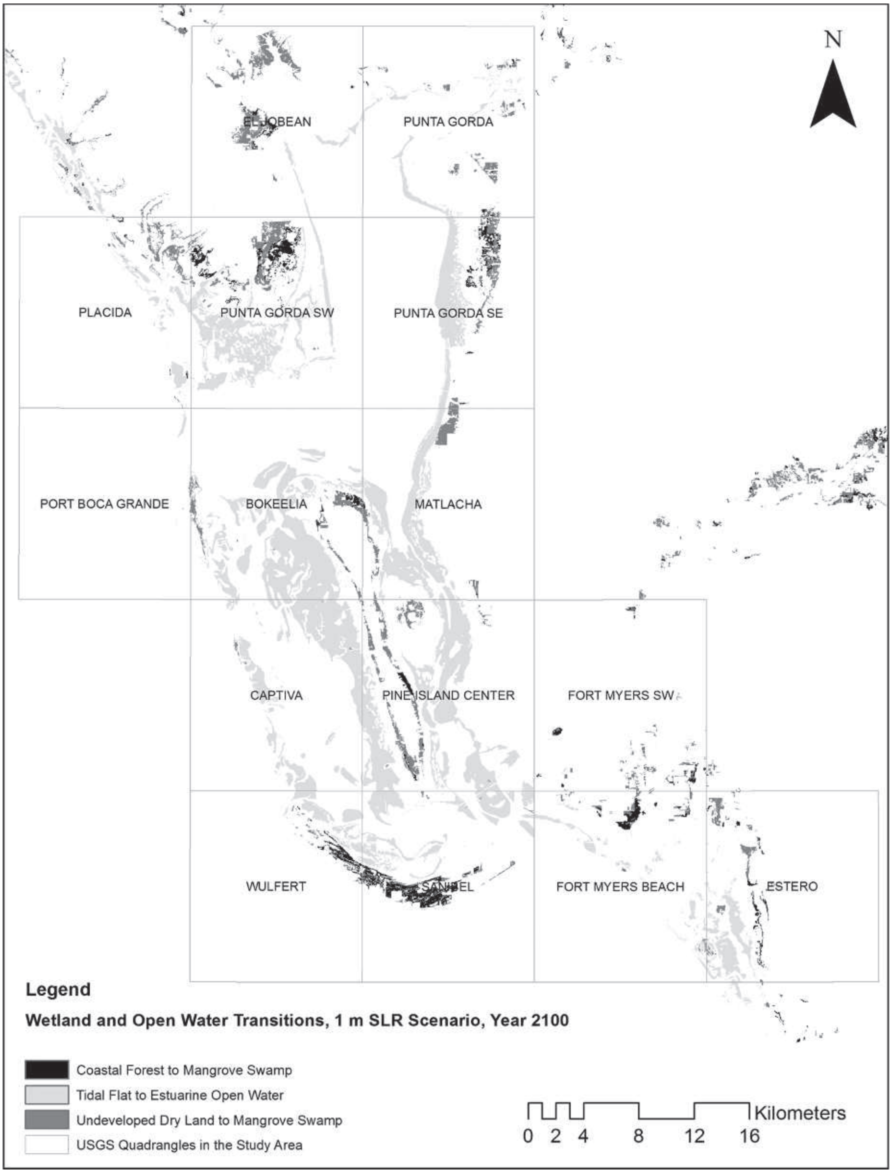

FIG. 7. Greatest land type transitions by 2100 under the moderate 1.0 m SLR scenario. Only changes representing 0.5% or more of the study area are illustrated.

Pass, Cape Haze, West Wall, Estero and San Carlos Bays, East Wall (see TABLE 8). Some of this loss has been attributed to development which required extensive dredge-and-fill activities (Harris et al., 1983). Given the protective nature of mangrove swamps in coastal storms and their relatively high habitat

TABLE 8. Priority restoration areas for coastal wetland systems based on retrospective and prospective analyses of past and predicted future habitat change in the study area.

Estuary	Salt-marsh	Mangrove Swamp	Seagrass	Oyster Reef	Tidal Flat (Facilitate Mangrove Growth)	Coastal Forest	Inland Fresh-water Marsh
Tidal Myakka River		X					
Tidal Peace River							
Lower Lemon Bay							
Charlotte Harbor West	X	X		X		X	
Charlotte Harbor East	X	X			X	X	
Cape Haze	X	X		X	X	X	X
Lower Charlotte Harbor							
Pine Island Sound				X	X	X	
Matlacha Pass	X	X		X	X		
Tidal Caloosahatchee			X				
San Carlos Bay		X	X		X	X	
Estero Bay	X	X	X		X		

value (Das and Vincent, 2009; Odum et al., 1982), opportunities for restoring mangrove swamps in these areas should be explored.

Our results also show that seagrass habitat in the study area has diminished since 1945 in most areas, with the exception of the Placida and Punta Gorda SW quadrangle areas, including Cape Haze and Charlotte Harbor West Wall. However, since 1982, several locations have shown increases in seagrass distribution including: Captiva, Estero, Placida, Punta Gorda SW and Sanibel quadrangle areas, corresponding to Pine Island Sound, Estero Bay, Cape Haze, West Wall and San Carlos Bay. These increases are likely due to the implementation of numerous water quality improvement projects over the last few decades (CHNEP, 2008; SFWMD, 2008; SWFWMD, 2000). Submerged habitats throughout the study area will continue to benefit from implementation of the ongoing water quality improvement efforts and efforts to protect and restore seagrass. Two priority areas for reversing seagrass loss based on past losses are the Fort Myers SW and the Fort Myers Beach quadrangle areas, including the Tidal Caloosahatchee River, San Carlos Bay and Estero Bay (see TABLE 8).

Our analysis indicates that the areas of greatest loss of oyster reefs include Pine Island Center, Punta Gorda SW, Placida and Captiva (i.e., Matlacha Pass, Cape Haze, West Wall and Pine Island Sound; Table 8). Consequently, these areas are candidates for oyster reef restoration. However, current and anticipated future conditions (salinity, substrate and hydrologic regime, etc.) will need further examination to clarify where restoration is likely to be successful. Some of the oyster reef losses may have resulted from direct impacts such as coastal development, filling, dredging and/or harvesting. In other cases, losses may have been a result of indirect impacts such as degraded water quality or modified hydrologic regime (Harris et al, 1983). Ongoing hydrological restoration activities may need to be completed in some areas before oyster reef restoration efforts can be successful.

Looking to the future, the SLAMM results predicted that the Charlotte Harbor system within our study area will lose substantial areas of some coastal systems by the year 2100 under the moderate 1.0 m SLR scenario (FIG. 5 and TABLE 5). Coastal wetland systems that are predicted to lose more than 25% of current area are tidal flat and coastal forest (−97% and −76%, respectively). While it would be difficult if not impossible to slow the transition of tidal flat areas to shallow open water areas as sea level rises, it may be possible to preserve this area as coastal wetlands if mangrove swamp colonization is allowed and/or encouraged. Areas that are predicted to lose the most tidal flat include Cape Haze, East Wall, Pine Island Sound, Matlacha Pass, San Carlos Bay and Estero Bay (TABLE 8). Loss of coastal forest systems with rising sea level could perhaps be slowed by influencing freshwater flows, sedimentation and nutrient loading (Lewis, 1992; Saha et al., 2011; USEPA, 2009; Williams et al., 1999). Areas most vulnerable to coastal forest loss include those adjacent to Cape Haze, West Wall, East Wall, Pine Island Sound and San Carlos Bay where under the moderate 1.0 m SLR by 2100 coastal forest transitions to mangrove swamp and shallow open water areas.

Under the higher SLR scenario (2.0 m by the year 2100), three additional coastal wetland systems suffer substantial area losses. These include saltmarsh (−98%), mangrove swamp (−83%) and inland freshwater marsh (−56%; Table 6). Under this SLR scenario, saltmarsh transitions to shallow subtidal open water and tidal flat habitat. Some of the same approaches noted above to slow the rate of loss of coastal forest (influencing freshwater flows, sedimentation and nutrient loading) could also be used to slow the loss of saltmarsh. In addition, natural habitat restoration and/or creation techniques that reduce shoreline erosion may help slow the rate of saltmarsh loss from some areas. One such technique is the creation and/or restoration of oyster reefs/reef structures along the offshore edge of saltmarshes transitioning to tidal flat or open water. These oyster reef restoration and creation projects have been shown to enhance accretion of sediments and the expansion of marsh vegetation (Dumesnil, 2011). The portions of the study area most vulnerable to saltmarsh loss are those at or adjacent to Cape Haze, Matlacha Pass (Little Pine Island) and northern Estero Bay (Table 8).

While mangrove swamp is able to expand under the 1.0 m SLR scenario by 2100, it is largely replaced by open water under the more rapid 2.0 m SLR by 2100 SLAMM scenario. If SLR occurs at this higher rate, the extensive loss of mangrove systems would increase the vulnerability of both human and natural communities in this area (Das and Vincent, 2009). Mangrove swamps are known to mitigate the effects of storm surge and in the tropics they serve as the base of the estuarine food web (Spalding et al., 2010). In the face of higher rates of SLR, strategies should be implemented to enhance the survival of the protective mangrove systems to the greatest extent possible. One strategy would be to encourage mangroves to migrate onto undeveloped dry land as it becomes increasingly inundated by eliminating as many physical obstacles as possible. Areas where mangrove swamp is most likely to colonize adjacent undeveloped dry land include Lower Lemon Bay, East Wall, Pine Island, Lower Charlotte Harbor, Matlacha Pass and Estero Bay.

Under the 2.0 m SLR scenario, inland freshwater marsh primarily transitions to mangrove swamp, particularly in the Cape Haze area (Table 8). The same techniques noted above for slowing the transition of coastal forest could be applied to slowing the transition of inland freshwater marsh, namely restoring and/or enhancing freshwater flows and facilitating enhanced sedimentation of the system.

The prospective analysis did not address seagrass or oyster reef as SLAMM does not address these habitat types. Seagrass may be able to expand substantially as sea level rises and there are some early indications of migration in Charlotte Harbor (Ott, 2010). Oyster reef may have similar opportunities, but is less likely to expand without human intervention (e.g., additional management measures, oyster reef restoration and/or re-establishment of more natural water flow regimes) as reefs have not naturally rebounded over the last several decades (Geiger, 2009).

The habitat changes noted in the Charlotte Harbor area are not unique to this region. Large areas of coastal wetlands across the Gulf of Mexico are likely to be lost as sea level rises unless adjacent inland habitats are protected from development and hydrologic modification (Geselbracht et al., 2010). The Charlotte Harbor region has an advantage compared to many other regions of the state as large areas of coastal wetlands were protected from development beginning in the late 1960s (USEPA, 1992). These buffer lands will facilitate the upslope migration of some low-lying coastal habitats, but will likely be insufficient under higher rates of SLR. In the developed portions of the study area, where coastal wetlands were largely eliminated, human communities are most vulnerable to SLR impacts including the risks from coastal storms. The vulnerability of these human communities will increase as sea level rises (Shepard et al., 2011) because the coastal wetlands that remain will be unable to migrate to higher elevations where blocked by structures, roads and other development. In such areas, efforts should be made to accommodate upslope migration of coastal habitats such as mangrove swamp as a means of not only preserving ecological values, but as a way of improving the protection of human property and welfare. Where coastal wetlands remain connected to undeveloped lands at a higher elevation, efforts to avert development are advisable. In some areas, coastal wetlands may persist longer than in other areas if mangrove swamp colonization is fostered and oyster reefs are restored in lieu of hardened shorelines where stabilization is required. Mangrove swamps and oyster reef communities can help stabilize sediments, protect shorelines from wave-generated erosion, and mitigate vulnerability of coastal communities to natural hazards and SLR (Das et al., 2009; Meyer et al., 1997; Spalding et al., 2010).

Protecting healthy coastal wetland systems in the face of SLR is of added importance in the context of the Gulf of Mexico Deepwater Horizon BP oil spill in April 2010. The Gulf's healthy coastal wetlands will serve as critical refugia for numerous species following this and potential future spills. Many approaches for mitigating the loss of highly productive coastal wetlands are being suggested including living shorelines and oyster reef restoration to stabilize shorelines and maintaining sediment loads and freshwater flows to maintain marshes and other wetlands (EPA, 2009; IPCC, 1990). Regardless of the approaches adopted, mitigation and adaptation strategies need to be flexible so as to increase the probability that these coastal wetland systems and the services they provide will be conserved into the future. The quantitative and spatial data developed in this study provides a synopsis of the coastal wetland changes that have taken place in the Charlotte Harbor system over the last 60 plus years and the changes that are likely to occur as a result of SLR in the future. Future predictions of habitat distribution changes using SLAMM could be improved if some of the uncertainty regarding marsh accretion in the study area could be addressed through data collection.

The information provided by our retrospective and prospective analyses can be used to identify where specific types of coastal wetland restoration are most needed in the Charlotte Harbor study area and support the climate change adaptation planning and implementation underway in the Charlotte Harbor region (Beever et al., 2009a; Beever et al., 2009b). This work provides the framework for more detailed restoration siting studies that will incorporate such considerations as land use, land ownership, water quality and hydrologic conditions. Taking action now to protect the region's coastal wetland systems will not only result in maintaining a healthy coastal ecosystem, but will maintain the natural system's ability to protect the region's human communities.

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