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Late Holocene marine transgression and the drowning of a coastal forest: Lessons from the past, Cape Cod, Massachusetts, USA

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ABSTRACT

Extra-tropical storms in the spring of 2010 swept the New England coastline resulting in significant erosion along South Cape Beach, a barrier system located on Cape Cod, Massachusetts. The erosion revealed 111 subfossil stumps and a preserved peat outcrop. We hypothesize that the stumps represent an ancient Eastern Red cedar, *Juniperus virginiana*, stand growing in a back-barrier environment and drowned by episodic storm events and moderate rates of sea-level rise. Stumps, bivalves, and organic sediments, were radiocarbon dated using traditional and continuous-flow Atomic Mass Spectroscopy methods. Six sediment cores elucidated subsurface stratigraphy and environmental setting. Subfossil stumps ranged in age from 413 ± 80 to 1239 ± 53 calibrated years before present. We assume that this age represents the time at which the ancient trees were drowned by marine waters. Based on elevation and age, an 826 year rate of submergence was calculated at 0.73 mm/yr with an R^2 value of 0.47. Core stratigraphy, microfossil assemblages, and radiocarbon ages indicate a dynamic barrier environment with frequent overwash and breaching events occurring during the past 500 years. Shoreline change analysis showed that between 1846 and 2008, the shoreline retreated landward by 70 m at a long-term rate of 0.43 m/yr. Future increases in the rate of sea-level rise, coupled with episodic storm events, will lead to the destruction of terrestrial environments at rate orders of magnitude greater than that during the time of the paleoforest.

1. Introduction

1.1. Background

General questions about the spatial and temporal response of barrier beach systems to marine transgression during the late Holocene remain unanswered. This leaves society vulnerable to ongoing and future climate change. When preserved in submerged paleolandscapes, remnants of coastal forests can yield a record of environmental change as the death of particular species and its replacement by more salt tolerant flora, can serve as a proxy for determining the character and timing of inundation (Hunter et al., 2006). Paleolandscapes submerged under coastal and marine sediments are a diminishing and important resource providing signatures of environmental change and a guide for locating cultural resources in coastal settings (Momber, 2004). Submerged terrestrial landscapes can also be used to determine a rate of transition between freshwater and saltwater environments elucidating local sea-level fluctuations (Long et al., 2006). In the light of accelerated rates of sea-level rise (SLR), information about coastal evolution may forewarn coastal managers and decision makers, thus enhancing their ability to anticipate future change (Orson and Howes, 1992; Momber, 2004). Failure to anticipate future changes, due to a lack of understanding about past changes, leaves society vulnerable to coastal hazards associated with climate change.

The drowning and preservation of ancient coastal forests can occur in response to both passive and active mechanisms. Relative SLR caused by gradual land subsidence, uplift, or eustatic changes occurring over centurial to millennial time scales is the primary passive mechanism of submergence (Belknap et al., 2005). Active mechanisms can occur at time scales as little as hours and include episodic flooding events brought on by sudden crustal movements and storm surges associated with tropical and extra-tropical storms (Atwater and Yamaguchi, 1991; Donnelly, 2005). As there is little known about how coastal forests respond to passive and active mechanisms of change, and what their preservation along continental shelves can tell us, it is important to investigate paleolandscapes that may illuminate the response of coastal forests to late Holocene sea-level rise and storminess.

Hunter et al. (2006) deciphered important chapters in the coastal evolution of Lake Heron based on a submerged conifer forest. In that

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study, dendrochronological analysis of subfossils deciphered lake level fluctuations and paleoclimate conditions during the mid-Holocene approximately 7300 years before present (ybp). Lyon and Harrison (1960) used the radiocarbon age and elevation of several *Pinus strobus* stumps from three drowned forests in coastal New England to determine an average rate of submergence for the region and substantiate the geomorphic evidence of transgression during the past few thousand years. Through comparing local submergence rates with rates of eustatic SLR, areas of crustal stability and downwarping were identified (Lyon and Harrison, 1960; Harrison and Lyon, 1963).

Similarly, Bloom (1963) documented fluctuations of relative sea level and crustal rebound using submerged tree stumps along the New England coastline dating to between approximately 1280–4200 ybp. Assuming the trees grew with their roots above the high-tide level, Bloom (1963) concluded that the stumps provided a minimum value of marine submergence during the past 4200 years.

Along the coast of Plymouth, Massachusetts, Gontz et al. (2013) documented the presence of 18 preserved *J. virginiana* stumps along the mudflats and fringing saltmarsh of Duxbury Bay. In that study, AMS radiocarbon dating revealed that the trees had been submerged between 2219 ± 94 and 2867 ± 79 calibrated years before present (cal BP), with the topographically highest sample returning the youngest date. Based on radiocarbon age and subfossil elevation, an approximate rate of landscape transgression for the site was calculated at 1.4 mm/yr with an R^2 value of 0.97. (Gontz et al., 2013).

Active submergence, brought about by flooding events caused by tectonic movements of the crust or catastrophic tsunamis, can also rapidly drown coastal forests (Atwater and Yamaguchi, 1991; Dawson, 1994). Along the Washington coastline, Atwater and Yamaguchi (1991) documented that buried marshes and forests record episodic inundation during the Holocene. At that location, the transition between fresh and marine environments was attributed to catastrophic tectonic subsidence combined with a tsunami (Atwater and Yamaguchi, 1991). Their findings were based on radiocarbon dated subfossil stumps, which showed marine flooding occurred rapidly, too quickly to attribute to passive SLR (Atwater and Yamaguchi, 1991). In their study, Atomic Mass Spectroscopy (AMS) radiocarbon analysis of subfossil cedar stumps provided valuable insights into prehistoric coastal response to active flooding events allowing for a greater awareness about potential future scenarios of marine submergence (Atwater and Yamaguchi, 1991).

There have been several studies documenting how hurricanes can catastrophically change the physical and biological structure of coastal forests existing in the modern environment (Conner et al., 1997; Boose et al., 2001). Coastal forests are impacted during hurricanes through high winds, surged and blown saltwater intrusion, and barrier breaching (Baker, 1978). An early documentation of the impacts of hurricanes on coastal forests is provided by Hawes (1939), who reported that as a result of the 1938 Hurricane there was widespread destruction of several acres of cedar trees in Voluntown, Connecticut. In 2003, Hurricane Isabel caused widespread damage in the Great Dismal Swamp National Wildlife Refuge, located in North Carolina (Belcher and Poovey, 2006). Isabel resulted in the immediate destruction of 85% of the 1000 ha of mature cedar stands within the refuge. In another study, McCoy and Keeland (2006) documented high winds from Hurricane Katrina damaged at least 32% of the cedar trees within Grand Bay National Wildlife Refuge, located in Mississippi.

Surging marine waters often causes the most damage to coastal forests during storm events especially if topographical conditions allow for the pooling and infiltration of saltwater into underlying soils (Pezeshki and Chambers, 1986). Hook et al. (1991) documented the destruction of a South Carolina coastal forest as a result of Hurricane Hugo in 1987. In addition to heavy wind damage, wind-blown waves and storm surge carried saltwater into the forest causing significant tree mortality. At this location, a storm surge of 3 m was recorded and resulted in the destruction of over 3.47 ha of coastal forests.

1.2. Study site

During March 2010, the U.S. northeast coast experienced a series of large, slow moving extra-tropical storms, locally referred to as Nor'easters. The storm systems resulted in large amounts of precipitation and widespread flooding and coastal erosion. Along the south facing shores of Cape Cod, many beaches experienced an excess of 20 cm of beach and shallow shoreface lowering. Erosion along a 200 m section of the eastern end of South Cape Beach (SCB) barrier system revealed the presence of 111 preserved subfossil stumps in growth position in intertidal and subtidal areas within an intermittent peat deposit (Fig. 1). Areas containing drowned coastal forests in New England are often in transition to saltmarshes as soil salinity increases and then later buried by landward retreating barrier sands (Lyon and Goldthwait, 1934). In more recent times, the preserved remnants of forests became exposed by the retreat of the shoreline due to SLR and storms resulting in the scouring away of the foreslope (Lyon and Goldthwait, 1934).

The study site is located along the eastern end of the SCB barrier system on the south shore of Cape Cod, Massachusetts centered at 41°33′ 07.50″ north latitude and 70° 29′ 49.30″ west longitude (Fig. 1). The paleoforest site is part of the South Cape Beach State Park, managed through a partnership between the Massachusetts Department of Conservation and Recreation (DCR) and the Waquoit Bay National Estuarine Research Reserve (WBNERR). SCB is a 2.9 km barrier system adjacent to Nantucket Sound. Sediment supply arrives via wave and current transport from offshore shoals and eroding bluffs to the east. Net littoral transport generally trends from east to west (Berman, 2011).

The western end of the barrier is known as Dead Neck and terminates at the navigable entrance to Waquoit Bay which has been stabilized with jetties. Washburn Island extends the barrier further westward from the main channel. Looking to the east, the barrier protects an extensive saltmarsh system which connects two salt ponds, Sage Lot Pond to the west, and Flat Pond to the east (Fig. 1). The eastern end of the barrier becomes welded to uplands and has been heavily modified through the development of a private golf course and large estates fronted by seawalls and groins.

A narrow 20–30 m wide by 2–3.5 m high dune system lies between the active beach and the Flat Pond marsh system. Using ground penetrating radar and historic cartographic sources, Maio et al. (2012b), identified two buried channels within the barrier which formally connected Flat Pond to Nantucket Sound. The presence of buried channels indicates that there have been repeated morphologic and hydrologic changes likely resulting in rapid fluctuations between salt and fresh hydrologic regimes in the back-barrier environment (Orson and Howes, 1992). Currently, the only tidal input entering Flat Pond arrives through a restored culvert system on the eastern side and saltwater intrusion through the barrier.

1.3. Barrier plant communities

Today the plant communities along the barrier are typical of other New England coastal systems and generally include low marsh, high marsh, marsh fringe, upper boarder, and upland (Clark and Patterson, 1985; Orson and Howes, 1992). Along the SCB barrier, the regularly flooded low marsh areas fall below MHW and are often dominated by stands of short and long form *Spartina alterniflora*. High marsh falls at or above MHW and has plant communities dominated by *Distichlis spicata* and *Spartina patens*. Short-form *S. alterniflora* as well as *Juncus gerardi* are also found in this zone. The marsh fringe is co-dominated by *Iva frutescens* and *J. gerardi* and often contains dead or dying *J. virginiana* trees and stumps marking the lower threshold of this species (Clark, 1986). The upper boarder marks a transitional zone between the brackish fringe marsh and terrestrial upland. The upper boarder contains healthy stands of *J. virginiana*. Moving landward from the

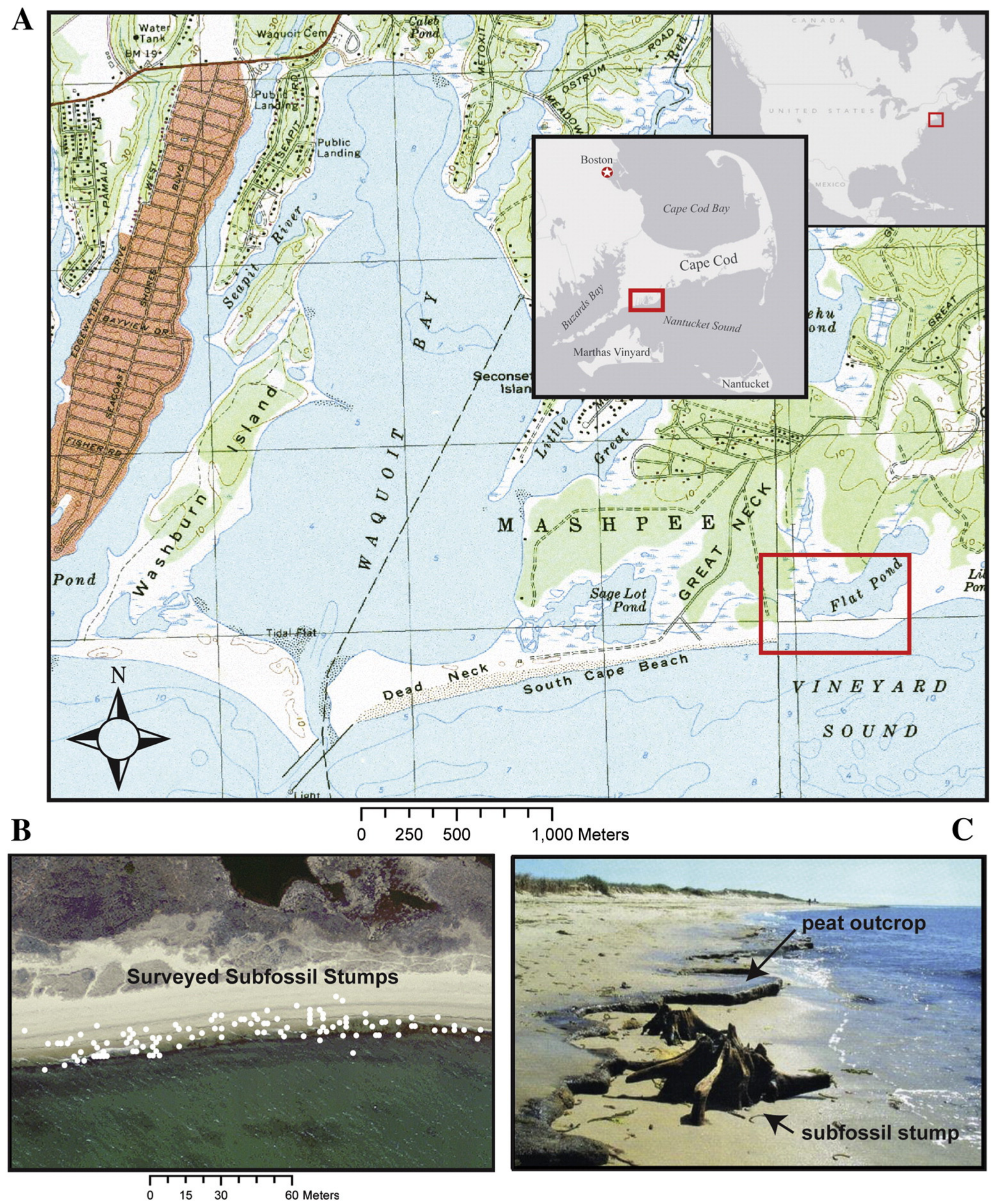

Fig. 1. (A) USGS topographical map (MassGIS, 2012) showing paleoforest study site identified with a white star. The paleoforest is located on the shoreface of the South Cape Beach barrier system, located in the town of Mashpee, Massachusetts. Insets show the context of the Waquoit Bay site in relation to southeast Massachusetts and North America coastal systems. (B) 111 Subfossil stumps (white circles) surveyed in growth position after storm erosion. (C) Subfossil stumps photographed at low tide with associated outcropping peat.

upper boarder into the upland, numerous tree and shrub species are present including *Quercus ilicifolia* and *Pinus rigida*.

1.4. Geologic history

The SCB area has a framework of relict glacial topography subsequently altered by fluvial, coastal, and aeolian processes (Gutierrez et al., 2003; Uchupi and Mulligan, 2006). During the end of the Wisconsin Glacial, the Laurentide Ice Sheet reached its southern terminus at Nantucket and Martha's Vineyard islands approximately 23,000 ybp (Balco et al, 2002). The subsequent coastal evolution of southeast Massachusetts occurred in response to the melting and northward retreat of the ice sheet beginning approximately 18,000 ybp (Oldale, 1982; Uchupi et al., 1996; Gutierrez et al., 2003). During these initial periods of ice retreat, outwash and ice contact debris were deposited along the Mashpee Pitted Plain, composed mostly of glacial contact and outwash deposits with numerous kettle basins (Oldale, 1992). The subsequently reworked outwash deposits provide the geologic framework for the SCB barrier system (Mather et al., 1942). During this time, global sea-levels were approximately 130 m below current levels (Lambeck and Chappell, 2001).

After the area became ice free, large portions of the inner continental shelf remained subaerially exposed allowing for the development and subsequent submergence of numerous terrestrial ecosystems including shorelines, deltas, lakes, coastal forests, and saltmarshes (Barnhardt et al., 1995; Belknap et al., 2002). In some locations, remnants of formerly terrestrial environments became preserved in nearshore sediments and provide a signature of the rapid environmental changes (Shaw et al., 2009). During the period between 12,000 and 10,000 ybp, rates of SLR were as high as 17 mm/yr dropping gradually to approximately 3 mm/yr by 6000 ybp (Oldale and O'Hara, 1980).

After 6000 ybp, the rate of SLR continued to decelerate and coastal and aeolian processes played a larger role in modifying the shoreline forming the coastal features most associated with Cape Cod, including barrier beaches, dunes, saltmarshes, and spits (Fairbanks, 1989; Uchupi and Mulligan, 2006). Based on pollen analysis, the Waquoit saltmarshes transitioned from fresh to brackish systems approximately 4000 ybp, marking the time period when marine waters began to flow into the low-lying basins of the area (Orson and Howes, 1992).

1.5. Landuse history

The extensive coastal resources found along the south shore of Cape Cod have attracted human populations for millennia. The once exposed seafloor undoubtedly held early human settlements exploiting the available resources (Bell, 2009). Evidence of submerged paleo-landscapes associated with Native American habitation in the waters surrounding Cape Cod included drowned forests, peat deposits and artifacts dredged by fishermen (Bloom, 1963; Bell, 2009). Dated macro-fossil artifacts from an ancient Native American midden pile, located at the head of Waquoit Bay, 3 km from the paleoforest site, provided evidence of human use of marine resources between 200 BC to 1400 AD (Maio, unpublished data).

In 1930, the Army Core of Engineers enlarged the natural entrance into Waquoit Bay and stabilized it with large jetties (Keay, 2001). The largest human modifications of the barrier came during the height of WWII, when in the early 1940's, the U.S. Army began extensive use of the SCB barrier and Washburn Island as a secret training ground for amphibious landings (Keay, 2001). Military infrastructure included roads, bridges, barracks, and other training facilities. Both the Great New England Hurricane of 1938 and the Hurricane of 1944 caused widespread damages to the area's existing military infrastructure, including the destruction of numerous buildings, roads, and an important causeway connecting Washburn Island to the mainland (Keay, 2001). Slated for development in the 1970's, the area was established as a State Park and in 1988 was incorporated into the National Estuarine Research Reserve System. The Waquoit Bay National Estuarine Research Reserve (WBNERR) contains nearly 1000 ha of protected coastal lands designated for research, education, recreation, and fishing.

2. Methods

2.1. Radiocarbon aging

The use of Atomic Mass Spectrometry (AMS) radiocarbon methods to determine the age of drowned forests and decipher the style and timing of submergence has been well documented (Lindström, 1990; Catto et al., 2000; Lacourse et al., 2003). Radiocarbon methods have been employed in this investigation to age subfossil wood material, macrofossils, and bulk sediments. All samples were sent to the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at the Woods Hole Oceanographic Institution (WHOI) in Woods Hole, Massachusetts, for AMS radiocarbon dating and isotopic carbon analysis. All samples were processed according to NOSAMS specifications. NOSAMS utilizes a 3.0 MV tandetron based AMS system for traditional radiocarbon dating using graphite accepting sputter sources (NOSAMS, 2012). In addition to the traditional method, NOSAMS also has developed a 500 kV pelletron based AMS system with a novel gas-accepting ion-source that was employed for the aging of all shell samples (Von Reden et al., 2011). This new continuous flow AMS (CF-AMS) method is capable of directly analyzing CO_2 gas and, hence, skips the conversion to graphite process (Roberts et al., 2013).

We employed traditional AMS methods to determine the time that surveyed subfossil stumps died. Thirteen stumps were located visually at low tide during the summer of 2010 for sampling. Sample locations were chosen based on our attempt to provide maximum coverage of the surveyed subfossils in both shore parallel and shore normal directions. Once subfossils were chosen for sampling, their location was determined using a Trimble GeoXH handheld GPS unit with positional accuracy of $\pm$ 20 cm. Stump elevations were determined using a Sokia Auto level and Philadelphia Rod and tied to WBNERR benchmark #4. The elevation for each subfossil stump was taken from the highest root coming off the main trunk and made relative to the North American Vertical Datum of 1988 (NAVD88). Based on modern analogs, this best represented the elevation of ground surface during the time the trees were alive. Samples were taken from preserved roots using a carpenter saw and placed in a labeled plastic bag. The main trunk was not used, as it was, generally, the most degraded portion of the subfossil material. The samples were cleaned thoroughly in deionized water. Subsamples were then selected from outer portions of the cleaned samples to best represent the time at which the tree died.

2.2. Tidal fluctuation determination

The absence of a NOAA tide station within close proximity to the study site necessitated the development of local tide datums for use within the GIS and assessing the elevation of the subfossil stumps below the current mean high water (MHW). The datums, including MHW, mean high higher water (MHHW), mean low water (MLW), mean low lower water (MLLW), mean sea level (MSL), great diurnal tide range and mean tide range, were calculated using data recorded at the WBNERR operated Menhaunt, Massachusetts tide station located at 41° 33.156′ north latitude and 070° 32.912′ west longitude, approximately 4 km west of the study site. Tide data provided in 30 min increments was obtained for the two month time period between March 29th and May 29th 2001. The mean was taken for all high, highest, low, and lowest tides occurring over the two month period to determine the MHW, MHHW, MLW, and MLLW. These values were converted to meters relative to NAVD88 (Table 1).

2.3. Sediment cores

We obtained two sediment cores from the active beach just landward of the subfossil stumps using a Geoprobe Systems model TR54 coring devise mounted on a 4115 John Deere tractor. The two sediment cores (WB1 and WB2) were obtained at approximately 0.87 m above MHW and separated by a shore parallel distance of 60 m. WB1 and WB2 reached a below surface depth of 3.22 m and 3.56 m respectively and were contained in 5 cm clear polycarbonate tubes retrieved consecutively in 1 m sections. Percussion cores from Flat Pond were obtained using 7.6 cm PVC pipe driven into the marsh sediment using a sledge hammer and extracted by hand and rope. The lithostratigraphy of all cores was recorded and photographed in the laboratory where they were stored at 4° C. Organic samples were collected and prepared for radiocarbon dating. Four samples were taken from the peat and fine sand layers were analyzed through a 50X powered microscope to identify plant and animal microfossils.

2.4. Geospatial analysis

The integration of multiple datasets within a GIS allows for the mapping and quantification of the spatial and temporal aspects of coastal change (Maio et al., 2012a). All geospatial processing and analysis

Table 1
Tidal datums for study site shown relative to the North American Vertical Datum of 1988.

Tidal datum	Elevation relative to NAVD (cm)
Mean sea level (MSL)	0.6
Mean tide range	50.8
Great diurnal tide range	76.5
Mean high water (MHW)	22.9
Mean high high water	29.6
Mean low water	−27.9
Mean low low water	−46.9

was carried out using Esri ArcGIS version 10.1 software. Geospatial data sources included high resolution orthophotographs, a 2011 LIDAR-derived digital elevation model (DEM), USGS topographical maps, and a georeferenced 1846 U.S. Navy Coast Survey (Coast Survey) map. The Coast Survey maps represent the most accurate historical cartographic source for areas along the Massachusetts coastline (Mague, 2012; Maio et al., 2012c) and allowed for an accurate determination of landscape change occurring between 1846 and present. The landward and seaward differences between the historical and contemporary HWL's were measured and a long-term rate of change was calculated. The rate only takes into account two shorelines in time, and, therefore, only determines long-term trends rather than the mechanisms driving the change.

3. Results

We surveyed 111 subfossil stumps along the shallow shoreface of SCB. The stumps spanned a shore parallel distance of 200 m and a shore normal distance of 26 m encompassing a total area of about 0.5 ha. Within six months of their discovery, many of the subfossil stumps were reburied by the shifting sands until another series of storms in 2012 and 2013. Hurricane Sandy (2012) and subsequent Nor'easters resulted in wide scale erosion of the peat outcrop and subfossil material from the shoreface, revealing the paleoforest to an even greater extent than previous.

3.1. Subfossil wood identification

Based on physical attributes and preservation, the subfossil stumps are characteristic of cedar trees. Whether they represented Atlantic White Cedar, *Chamaecyparis thyoides* (*C. thyoides*) or Eastern Red Cedar, *Juniperus virginiana* (*J. virginiana*) was more difficult to discern. There are many similarities between *C. thyoides* and *J. virginiana*, both of which are native to coastal Massachusetts. Both types of cedar wood have natural preservatives, greatly enhancing their preservation potential in a variety of environmental settings (Lawson, 1985). The growing conditions are very different between the two species as *C. thyoides* is restricted to coastal freshwater swamps with peat soils overlaying sandy deposits, while *J. virginiana*, thrives in well aerated sandy soils and can be found from the saltmarsh upper boarder to mountain sides.

We had initially identified the wood as *C. thyoides* based on physical characteristics. The subfossil material had a light physical weight, was soft and when sectioned and, viewed under a microscope, there was no apparent heartwood. Looking at modern samples, these qualities are characteristic of *C. thyoides* and not *J. virginiana*, which is considerably denser and has prominent heartwood (Christopher Wood, Personal Communication, September 1, 2012). However, due to the potential for degradation of the wood's physical characteristics within the harsh coastal environment and other supporting factors, the *C. thyoides* hypothesis was eventually dismissed in support of an identification of *J. virginiana*.

A major factor supporting the *J. virginiana* hypothesis is the abundance of modern analogs for its presence along the SCB barrier and the absence of modern analogs for the presence of a *C. thyoides* swamp. Today, along the upper boarder surrounding the saltmarsh, *J. virginiana* can be observed in healthy stands. At lower elevation areas within the marsh fringe it is common to see *J. virginiana* stumps or dying trees encroached upon by high marsh plant communities and saline soils.

In addition to the modern analogs for *J. virginiana* forests along the SCB barrier, the presence of a preserved high marsh peat bed outcropping 25 cm in depth from the foreshore in the vicinity of the stumps also played a role in our identification. Its presence around the stumps was advantageous to this study as peat can often play a crucial role in reconstructing paleolandscapes due to the wealth of information that often remains preserved within (Plets et al., 2007). *Distichlis spicata* rhizomes and foraminifera assemblages were sampled every 5 cm throughout the 25 cm outcrop indicating a high marsh brackish water environment directly overlying sandy terrestrial soils.

Both foraminifera and thecamoebians microfossils remain well preserved in Holocene sediments and have been widely used as paleoenvironmental proxies (Scott and Medioli, 1978). Foraminifera are ubiquitous in most marine environments and provide a good indicator of elevation and other environmental factors (Gehrels, 1999; Murray, 2006). Five peat samples were extracted from the 25 cm peat outcrop for microfossil analysis. Species associated with brackish water environments identified in the samples include *Haplophragmoides maniliensis*, *Tiphotrocha comprimata*, and *Jadammina macrescens* (Scott and Medioli, 1978). Due to the presence of brackish water plant and animal species, and the absence of freshwater peat, the presence of a freshwater *C. thyoides* swamps is unlikely at this particular location.

3.2. Radiocarbon dating

All radiocarbon ages were calibrated using Calib version 6.1.1 used with the IntCal09 calibration data set in conjunction with Reimer et al. (2009). A marine reservoir correction (ΔR) of $\Delta R = -95 \pm 45$ ^{14}C years was applied to all shell macrofossils (Stuiver and Braziunas, 1993; Little, 1999). This ΔR value was input into Calib's Marine09 calibration data set. Radiocarbon ages are reported in calibrated years before present (cal BP) and calibrated years AD–BC (AD or BC) with a 1 sigma (1σ) range in uncertainty.

Subfossil stumps ranged in ages from 413 ± 80 cal BP to 1239 ± 53 cal BP and elevation from −63 cm to −165 cm below MHW (Table 2). A linear regression rate of 0.73 mm/yr with an R^2 value of 0.46 was calculated using the calendar age as the explanatory variable and subfossil elevation below MHW as the dependent variables (Fig. 2). This rate does not necessarily reflect the rate of relative SLR as trees may have been killed by a variety of other factors such as storm driven flooding or fire. However, they do provide useful spatial and temporal information about the leading edge of the transgression and provide a terrestrial limiting factor to local SLR.

3.3. Sediment cores

The lithostratigraphy of sediment cores WB1 and WB2 collected on the active beach contained both littoral and terrestrial facies (Fig. 3). The upper 65 cm of both cores, identified as Unit A, are characteristic of a modern beach facies with medium and coarse sands interspersed with narrow beds of very course sand and fine grained heavy metal deposits synonymous with storm deposition. Below 65 cm, both cores contain an organic rich peat bed containing *D. spicata* rhizomes. This facies is identified as Unit B and spans 45 cm in WB1 and 33 cm within WB2. Peat that overrides subfossil stumps is often heavily compacted due to upper shoreface sediments that have rolled over the site during the barriers landward migration (Bloom, 1963). Within WB1, Unit B is discontinuous and split into three sections by deposits of medium to coarse sand. These sand intervals are likely associated with washover events. Within WB2 Unit B is continuous with no sand beds. Two radiocarbon dates from bulk organics (71–72 cm) and *D. spicata* rhizome (77–79 cm) from within WB2 Unit B date to 364 ± 63 and 415 ± 81 cal BP respectively (Table 3).

Foraminifera microfossil species identified within the WB2 peat bed include *H. maniliensis*, *T. comprimata*, and *J. macrescens*, and are all indicative of brackish water environments. These were the same three species identified within the peat outcrop samples. A limited number of thecamoebians were identified within the same core sample and included *Centropyxis aculeate* and *Centropyxis constricta*. These species are more indicative of freshwater marshes but are associated with very high marsh settings (e.g., Medioli and Scott, 1983).

Below Unit B, both cores have approximately 60 cm of fine sand mixed with granules and small rootlets. The fine sand beds in both

Table 2
Radiocarbon ages of subfossil stumps. ^{14}C age was calibrated using a 1 σ probability range. The median calibrated year before present (cal BP) and calibrated calendar year (BC/AD) are shown for each sample. The elevation and distance from the present MHW is also shown.

Lab no.	Sample no.	^{14}C age	1 c Cal BP (Probability)	lo Median cal BP	lo Median BC/AD	Elevation below MHW(cm)	Distance from MHW(cm)	Material dated
OS-94178	UMBWB001	390 ± 25	338–348 (0.141) 458–502 (0.859)	420 ± 82	1530 ± 82	−63	254	Subfossil stump
OS-94179	UMB_WB_002	845 ± 30	727–786 (1)	757 ± 30	1194 ± 30	−83	631	Subfossil stump
OS-97574	UMB_WB_003	570 ± 25	540–558(0.421) 602–628 (0.579)	584 ± 44	1366 ± 44	−79	774	Subfossil stump
OS-89821	UMB_WB_004	370 ± 25	333–352 (0.266) 435–492 (0.734)	413 ± 80	1538 ± 80	−76	20	Subfossil stump
OS-97573	UMBWB005	1160 ± 25	1007–1029(0.217) 1053–1092(0.476) 1106–1136(0.263) 1162–1167 (0.042)	1087 ± 80	863 ± 80	−57	601	Subfossil stump
OS-94180	UMBWB006	1320 ± 30	1186–1202 (0.234) 1257–1292(0.766)	1239 ± 53	711 ± 53	−132	130	Subfossil stump
OS-89818	UMB_WB_007	1240 ± 25	1141–1160(0.164) 1168–1187(0.207) 1201–1259(0.628)	1200 ± 59	750 ± 59	−165	151	Subfossil stump
OS-94181	UMB_WB_008	1280 ± 25	1181–1208(0.442) 1231–1268(0.558)	1225 ± 44	726 ± 44	−146	140	Subfossil stump
OS-97580	UMB WB 009	1280 ± 40	1179–1213 (0.415) 1223–1273 (0.585)	1226 ± 47	724 ± 47	−115	101	Subfossil stump
OS-89820	UMBWB010	1010 ± 30	918–959 (1)	939 ± 21	1012 ± 21	−102	553	Subfossil stump
OS-97572	UMBWBO11	1160 ± 35	1005–1030(0.211) 1052–1096(0.419) 1102–1140(0.309) 1161–1168(0.062)	1087 ± 82	864 ± 82	−85	645	Subfossil stump
OS-89819	UMB_WB_012	970 ± 25	802–810(0.108) 830–857 (0.426) 904–928 (0.466)	865 ± 63	1085 ± 63	−118	103	Subfossil stump
OS-101084	UMBWB13	610 ± 25	556–566(0.182) 585–607 (0.400) 624–646 (0.416)	601 ± 51	1349 ± 51	−77	389	Subfossil stump

All calibrations carried out using Calib version 6.1.1 used with the TntCal09 calibration data set (Reimer et al., 2009).

cores, identified here as Unit C, have a deep red color indicative of a subaerially exposed oxidizing environment formed through aeolian deposition in back-dune environments. Unit C was barren of foraminifera and thecamoebian species in both cores. A fragment of wood obtained from Unit C between 200 cm to 201 cm of WB2 provided a radiocarbon age of 1365 ± 92 cal BP predating the oldest aged stump (1239 ± 53 cal BP). Unit D consists of medium to very coarse sands. Within Unit E the stratigraphy of the two cores consist of a variable pattern of medium to fine sand interspersed with silty sand beds.

The four cores taken along the fringing marsh of Flat Pond reveal a dynamic back-barrier environment (Fig. 4). Unit 1 consists of a peat horizon that continuous in all cores except FPM4, where it is separated

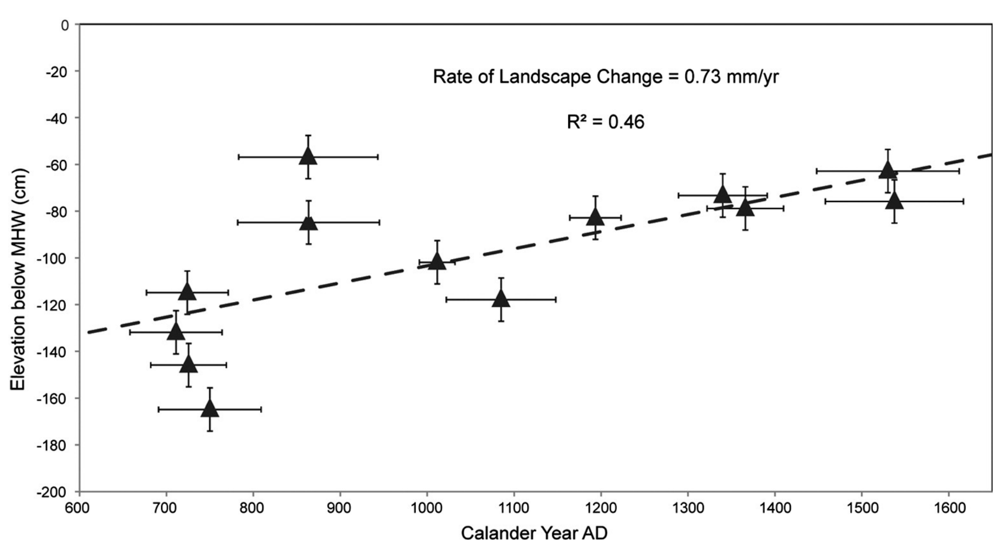

Fig. 2. Calibrated radiocarbon ages AD of subfossil stumps and their vertical relationship to present MHW. We assume the radiocarbon age represents the approximate point in time when saltwater drowned the ancient trees. A linear regression rate for the data (dashed line) provided a rate of 0.73 mm/yr with an R^2 value of 0.46. This represents a long-term rate of change between fresh and saltwater environments. Horizontal error bars represent age uncertainties while vertical error bars represent uncertainties associated with the elevation survey techniques.

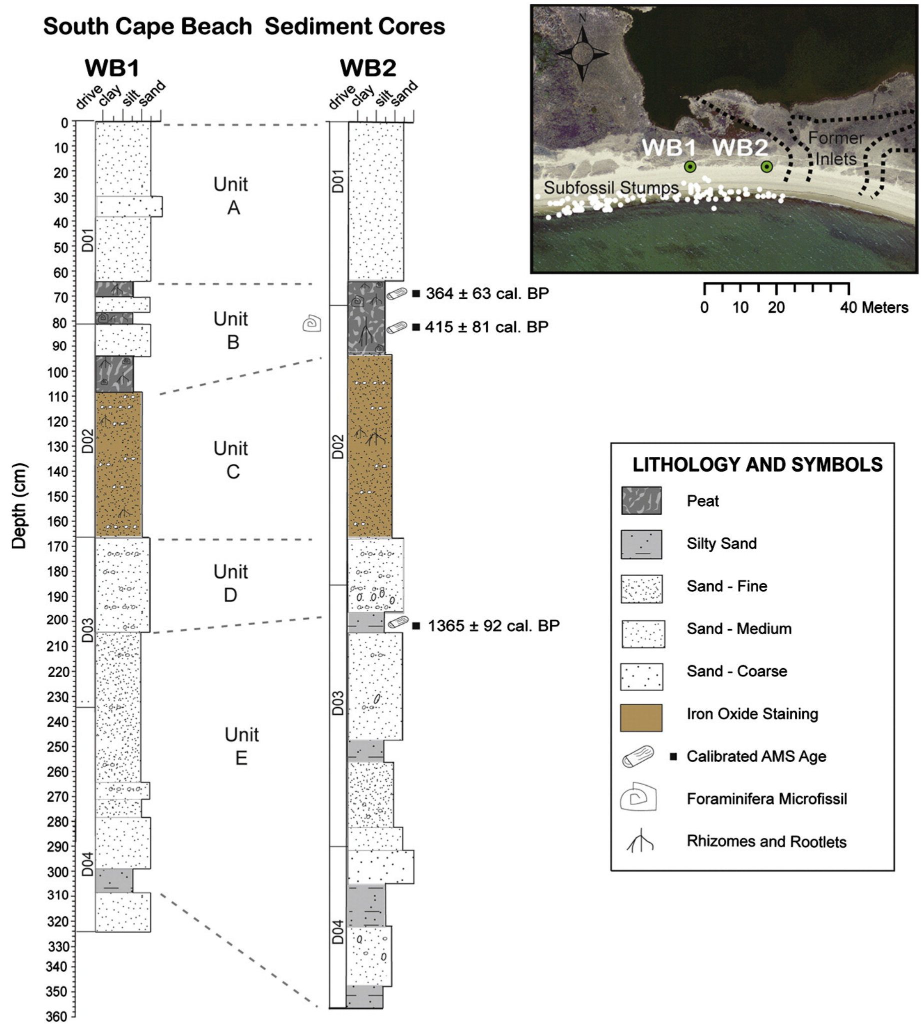

Fig. 3. Lithostratigraphy of sediment cores WB1 and WB2. Core locations in relation to the stumps and former tidal inlet (insert). Unit A is characteristic of a modern beach deposit with medium to coarse sand interspersed with narrow beds of very coarse sand and magnetite. Unit B consists of a peat deposit with rhizomes. Within WB1 Unit B deposits of medium to coarse sand indicate storm driven overwash. Two radiocarbon dates from bulk organics and rhizomes from WB2 returned to 364 ± 63 and 415 ± 81 cal BP respectively. Microfossil assemblages from Unit B WB2 (spiral shell symbol) indicate a brackish high marsh environment when deposited. Unit C consists of red oxidized fine sands and was barren of microfossils. Unit D consists of medium to very coarse sands. A fragment of wood material just below Unit D returned 1365 ± 92 cal BP. Unit E consists of a variable pattern of medium to fine sand intersected by beds of silty sand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Calibrated radiocarbon ages returned from sediment core samples. ^{14}C age was calibrated using a 1 σ probability range. The median calibrated year before present (cal BP) and calibrated calendar year (BC/AD) are shown for each sample along with in core sediment depth. All carbonate bivalves were dated using continuous flow (CF-AMS) methods.

Lab no.	Sample no.	Radiocarbon method	Core	Depth (cm)	^{14}C Age	1 σ cal BP (probability)	1σ Median cal BP	1 σ Median BC/AD	Material dated
OS-94184	WB2D202	AMS	WB2-D1	71–72	290 ± 25	301–319 (0.351) 380–386 (0.050) 392–426 (0.598)	**364 ± 63**	**1539 ± 92**	Bulk sediment
OS-94182	WB2D101	AMS	WB2-D2	77–79	375 ± 25	334–349(0.227) 438–496 (0.772)	**415 ± 81**	**1580 ± 81**	Rhizome
OS-94513	WB2D403	AMS	WB2-D4	199–201	1480 ± 25	1340–1389 (1)	**1365 ± 92**	**591 ± 46**	Wood
OS-95585	FPM657	AMS	FPM6	56–57	2930 ± 25	3005–3014(0.058) 3030–3052 (0.156) 3060–3083 (0.221) 3089–3144 (0.529) 3151–3156 (0.035)	**3075 ± 70**	**1132 ± 76 BC**	Bark
OS-105392	FPM490	CF-AMS	FPM4	89–90	724 ± 108	320–525(1)	**423 ± 103**	**1528 ± 103**	Bivalve
OS-95582	FPM4J00	AMS	FPM4	99–100	240 ± 30	−0–1 (0.012) 153–168 (0.329) 282–307 (0.658)	**230 ± 77**	**1720 ± 77**	Wood
OS-105393	FPM5J37	CF-AMS	FPM5	136–137	574 ± 108	149–161 (0.033) 196–209 (0.032) 225–451 (0.934)	**300 ± 151**	**1650 ± 151**	Bivalve
OS-95584	FPM5J67	AMS	FPM5	166–167	460 ± 25	503–520(1)	**512 ± 9**	**1439 ± 9**	Rootlets

All calibrations carried out using Calib version 6.1.1 used with the IntCal09 calibration data set (Reimer et al., 2009). A marine reservoir correction (ΔR) was applied to all shell samples of ΔR = −95 ± 45 (Stuiver and Braziunas, 1993; Little, 1999). The ΔR correction was input into Calib's Marine09 calibration data set. Bold data indicates median calibrated years before present and median calibrated years AD/BC.

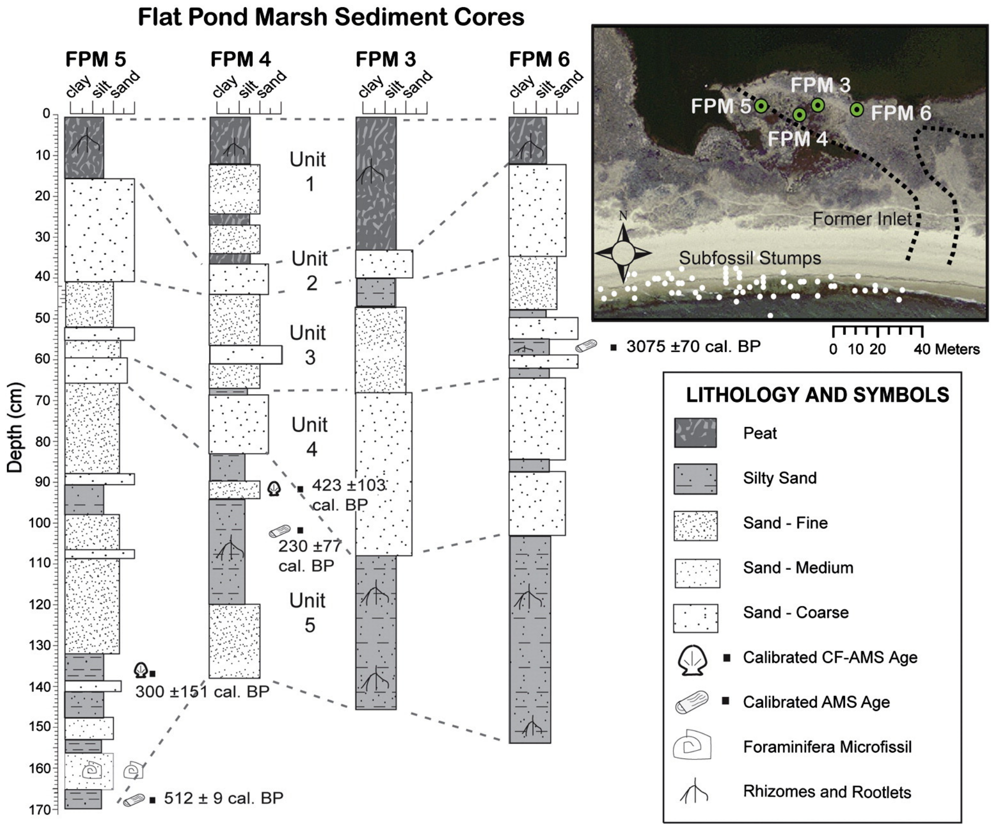

Fig. 4. Stratigraphy of the four Flat Pond Marsh cores (FPM3–FPM6). Core locations are shown relative to the stumps (white circles) and former inlet (dashed black line within insert). Unit 1 consists of peat that is continuous in all cores except FPM4. Unit 2 consists of coarse sand and may represent overwash or a remnant flood tide delta. Unit 3 consists of silty sand. A piece of bark (log symbol) from Unit 3 in FPM6 returned an age of 3075 ± 70 cal BP. Unit 4 and Unit 5 consist of alternating coarse sand and silty sand deposits. Microfossil (spiral shell symbol) analysis of a silty sand deposit from Unit 5 FPM5 showed foraminifera species associated with offshore marine environments.

by two 10 cm beds of fine sand. Unit 2 consists of a coarse sand deposit running though all four cores and may represent a large overwash event or flood tide delta. We identified a deposit of sandy silt within the four cores as Unit 3. A well preserved piece of bark sampled from Unit 3 of FPM6 provided an AMS radiocarbon date of 3075 ± 70 cal BP, representing the oldest age documented in this study.

Unit 4 consists of a coarse sand deposit while Unit 5 contains overlapping silt and fine sand deposits with intermittent thin beds of coarse sand. A piece of wood sampled within Unit 5 from the bottom (170 cm) of FPM5 provided an age of 512 ± 9 cal BP. Another piece of wood sampled from Unit 5 within FPM4 (99–100 cm) provided an age of 230 ± 77 cal BP. Two shell samples obtained from 136–137 cm

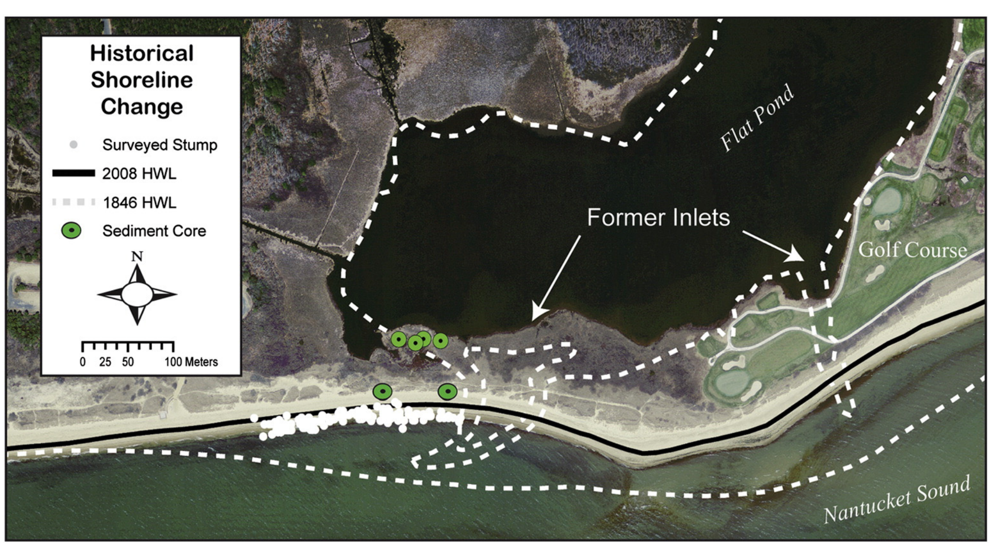

Fig. 5. Historical shoreline change occurring between 1846 and 2008. Subfossil stumps are shown with white circles. The 1846 HWL and outline of Flat Pond (dashed white line) were derived from an 1846 U.S. Navy Coast Survey map. The 2008 HWL derived from the displayed orthophotograph is shown with the black line. During the 162 year period, the shoreline retreated landward by 70 m. While there was considerable erosion along the beach fronting Flat Pond and the adjacent golf course, the shoreline to the west remained relatively stable. Former inlets that existed in 1846 but no longer exist today are shown with the white arrows.

of FPM5 and 89–90 cm of FPM 4 provided ages of 300 ± 151 and 423 ± 102 cal BP respectfully (Table 3). Radiocarbon dates and core stratigraphy provide evidence of frequent overwash and breaching events. A sample from Unit 5 FPM5 showed foraminifera species associated with offshore marine environments including *T. comprimata*, *Elphidium excavatum*, *Elphidium williamsoni*, and *Cibicides sp*.

3.4. Geospatial analysis

Coastal changes occurring between 1846 and 2008 were determined by the comparison of HWL delineated within the GIS from the 2008 orthophotographs and the Coast Survey map. The results show that during the 162 years, the area was eroded by 70 m ± 10 m with an end point rate of 0.43 m/yr (Fig. 5). Though locally along the SCB barrier it is an accelerated rate, with much of the 3 km barrier stable or accreting during the same time, the calculated rate is similar to the average rate (0.40 m/yr) for all of Cape Cod during the past century (Hapke et al., 2010).

4. Discussion

4.1. Paleoenvironmental evolution

We developed a conceptual model depicting coastal changes occurring in the area of the paleoforest during the past 1500 years (Fig. 6). The model is based on our results including radiocarbon ages, sediment core stratigraphy, microfossil assemblages, and documented historical shoreline change. Modern observations of current environmental changes impacting *J. virginiana* populations along the SCB barrier were also integrated into the model.

The radiocarbon ages of surveyed stumps shows that the paleoforest existed for at least 800 years with the first tree dying at 711 ± 53 AD and the last in 1538 ± 80 AD. Based on our field surveys of visible stumps, the extent of the forest when alive encompassed a minimum area of 0.5 ha. Surveyed subfossil stumps found in coastal settings are often the only visible part of a more extensive occurrence as stumps further seaward are destroyed due to continued erosion and those more landward remain buried under beach sands (Bloom, 1963). The large

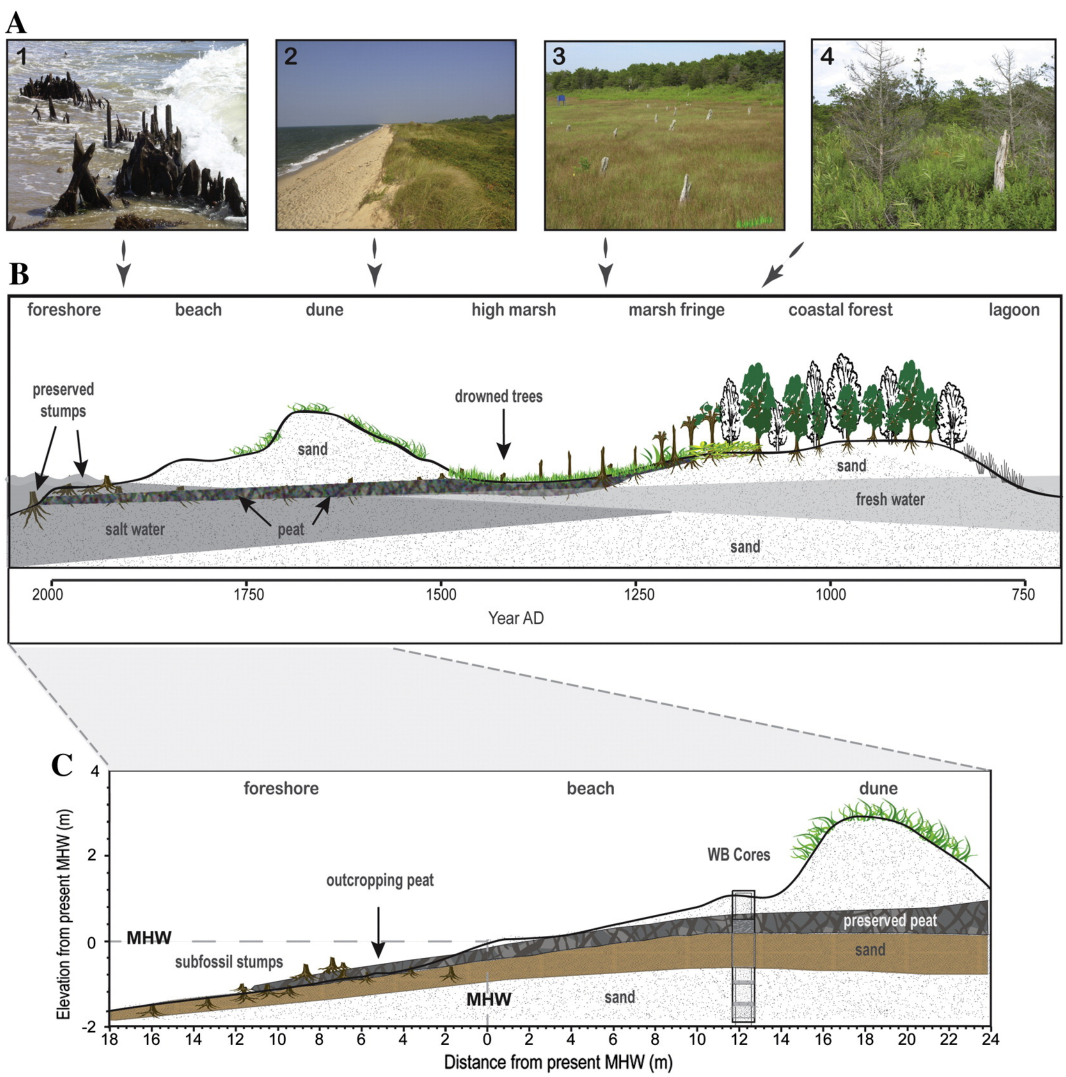

Fig. 6. Conceptual model of environmental evolution of surveyed paleoforest site. A) Photographs of modern analogs for conceptual model including 1) subfossil stumps along eroding shoreface, 2) landward migrating barrier beach and dune system, 3) stumps and preserved tree trunks in the high marsh of Sage Lot Pond, 4) healthy *J. virginiana* trees along upper boarder of Sage Lot Pond marsh system. C) A cross-section of the shoreface depicting the spatial relationship between sediment cores, peat deposits, and surveyed stumps with the current mean high water (MHW). The true position of the cores, stumps, and peat outcrop are in reality spread out along 200 m of the shoreface and do not actually occur along the same shore perpendicular axis. It was therefore necessary to make some generalizations when developing the cross-section diagram. The profile shows the erosion of outcropping peat and subfossil stumps in the shoreface.

spatial extent and temporal longevity of the paleoforest indicates a period of long-term hydrologic stability stochastically disrupted by episodic storm events.

In southern New England, between 4000 ybp to 1000 ybp, there was a deceleration in the rate of relative SLR from 3 mm/yr to less than 1 mm/yr (Donnelly and Bertness, 2001). The 1000 years prior to the 20th century, encompassing the period of time that the surveyed paleoforest existed, saw a near stop to relative SLR with rates as low as 0.52 mm/yr ± 0.62 (Donnelly, 2006). During this period, hydrologic conditions along the SCB barrier would have remained relatively stable and provided for the physical conditions conducive to the development of the paleoforest.

The current environment along the SCB barrier provides a clear analog for the environmental conditions that likely existed in the paleoenvironment. Based on modern observations, *J. virginiana* trees are found growing in healthy stands inhabiting areas of the upper boarder and upland (Fig. 6A). Below these healthy stands lies the marsh fringe, a zone marked by an increase in *I. frutescens*. Within the marsh fringe, numerous preserved stumps and *J. virginiana* trees at various stages of death are common marking the lower boundary of *J. virginiana* (Fig. 6A). Moving landward into the uplands *J. virginiana* trees become less abundant, and quickly become replaced by thick stands of pitch pine, *P. rigada*, and scrub oak, *Q. ilicifolia*.

Core stratigraphy and microfossil assemblages from the WB1 and WB2 cores (Fig. 3) support our environmental interpretation depicted in the conceptual model (Fig. 6). With a transgressing barrier, moisture and salinity concentrations decrease with depth within the cores with drier terrestrial facies positioned below saltmarsh and beach facies. Based on sediment size, the presence of woody rootlets, and its iron-oxidized red color, Unit C is representative of a back-dune terrestrial environment and would have provided habitat for *J. virginiana* trees. The absence of microfossils within Unit C also supports the conclusion that this is a terrestrial facies. Based on a radiocarbon age of 1365 ± 92 cal BP obtained from the lower potions of Unit C, and 415 ± 81 cal BP returned from a sample from the high marsh facies in Unit B, the terrestrial environment existed for at least 900 years prior to its transition a brackish high marsh system (Table 3).

As marine waters continued to move landward and upward during the late Holocene, the physical environment began to change through an upward shift in plant communities. With higher sea levels, and more frequent and longer inundation by marine waters, high marsh plant communities began to expand into higher elevation areas. This would eventually lead to the salinization of the terrestrial environment and the eventual demise of the paleoforest. The signatures of the transition between fresh and saltwater environments are contained within the peat deposits of Unit B and those sampled from the peat outcrop surrounding the stumps. The peat sampled at both locations contains macrofossil rhizomes and microfossil foraminifera indicative of a high marsh brackish environment.

The presence of *D. spicata* rhizomes makes it likely that this facies represents a brackish water environment and provides a good indicator of the approximate time period the ecosystem transitioned from one favorable to *J. virginiana* trees to one favorable to high marsh flora (Miller and Egler, 1950; Orson et al., 1987). Based on the radiocarbon age from the *D. spicata* rhizomes within WB 2 Unit B, the high marsh environment existed at this location until at least 1580 AD prior to being covered by transgressing barrier sands (Table 3). The time period of this transition is also illuminated by the temporal correlation between the radiocarbon ages of Unit B WB2 and the two most landward stumps (#1 and #4). Both trees died between approximately 1530 AD and 1540 AD while two samples from Unit B returned ages between 1539 AD and 1580 AD (Tables 2 and 3). The age correlation between the peat horizon and most landward stumps provides for an approximation of when the surveyed paleoforest site had made a full transition to a brackish system.

Based on the elevations and ages of the thirteen sampled stumps, the area transitioned from a fresh to saltwater environment between approximately 711 AD and 1538 AD at a rate of 0.73 mm/yr (Fig. 2). This rate provides a long-term approximation of the upper boundary of intruding marine waters (Catto et al., 2000) but does not necessarily represent the rate of SLR as the death of the trees may have come through a single disturbance event such as storm surged waters or fire.

By approximately 1500–1600 AD, barrier sands forced their way landwards being deposited over the high marsh peat and paleoforest stumps. Through this process, the surveyed stumps were preserved below anoxic peat and sand deposits (Fig. 6). Once buried, acceleration in the rate of SLR after 1900 resulted in rapid shoreline erosion. According to our shoreline change results, between 1846 and 2008 the HWL had been eroded landward by over 70 m, and, in the process, rolling up and over the preserved stumps. More recently, the continued scouring of the shoreface and landward migration of the barrier revealed the subfossil stumps along the foreshore. The conceptual model depicting these changes provides a useful visualization for landward migration of the shoreline but does little to elucidate the mechanisms driving these changes.

4.2. Mechanisms of change

In this study we sought to decipher the major forcing mechanisms that led to the submergence and death of the paleoforest. Was the ancient forest killed by catastrophic storm events, passive SLR, or a combination of the two? If it was a combination of the two, did one mechanism play a larger role than the other, and how can this information be used to help us understand and anticipate future change? Studies have shown that coastal cedar populations can be closely tied to both episodic storm events and SLR (Clark, 1986). Based on sediment cores, Clark (1986), documented that along the Moriches Bay on the south shore of Long Island, New York, accelerated rates of SLR after 1930 led to the death of a *J. virginiana* forest and its replacement by high marsh flora. This transition was hastened by the Great New England Hurricane of 1938, which caused the immediate death of several trees and a rapid transition to high marsh plant assemblages (Clark, 1986).

4.2.1. Storm driven change

Our results point towards a stochastically driven system where episodic storm events played the primary role in the submergence of the paleoforest. The results also show that on centurial scales SLR also played a role. Storm driven flooding can catastrophically flood brackish and freshwater environments having significant ecological consequences for barrier ecosystems (Clark and Patterson, 1985; Buynevich et al., 2003; Buynevich and Donnelly, 2004; Buynevich, 2007; Boldt et al., 2010).

Previous studies have shown that sedimentary archives of prehistoric hurricane events have been preserved in the back-barrier environments of southern New England (e.g. Emery, 1969; Donnelly et al., 2001; Boldt et al., 2010) with deposition coinciding with the time period that the paleoforest was submerged. During high energy storm events, coarse grain sands are transported landward into back-barrier environments and deposited over in situ fine grained organic rich sediments (Donnelly et al., 2001; Scileppi and Donnelly, 2007; Woodruff et al., 2008). When found in back-barrier saltmarsh or lagoon environments, these coarse grain storm-induced deposits provide a reliable proxy for past overwash events (Scileppi and Donnelly, 2007; Woodruff et al., 2008). In Succotash salt marsh in East Matunuck, Rhode Island, Donnelly et al. (2001) used a series of vibracores to document a 700 year history of intense hurricane strikes that were identified as seven distinct overwash horizons bracketed between organic rich peats. Two of the fans represent prehistoric hurricane events, the first occurring between 1411 and 1433 AD and the second around 1300 AD (Donnelly et al., 2001). Emery (1969) documented a 1000 year record of past hurricane events within Oyster Pond in Falmouth, Massachusetts. The Oyster Pond core contained a record of nine overwash horizons some of which were dated to the prehistoric interval (Emery, 1969). At Mattapoisett Marsh, located 30 km west from the study site, several hurricane events were documented with active intervals occurring between 750–850 AD, 995–1149 AD, and 1443–1618 AD (Boldt et al., 2010). A synthesis of sediment core data from the Atlantic Basin also identifies two periods of increased hurricane activity during the past 2000 years including from 900–1250 AD, and 1350–1450 AD (Mann et al., 2009). These intervals of increased hurricane activity coincide with the submergence of the paleoforest and the death of individual trees.

Within the Waquoit system, sediment cores indicate that stochastic mechanisms have driven landform evolution and plant community shifts during the late Holocene (Orson and Howes, 1992). Modern marsh sediments within Sage Lot Pond appear to have developed directly over a large overwash fan likely deposited during a single hurricane event occurring approximately 1100 AD (Orson and Howes, 1992). The evidence presented in this study also indicates storm driven mechanisms for environmental change. The stratigraphy and microfossil assemblages within the FPM and WB cores have preserved a record of storm driven changes including barrier breaching, overwash, and sudden shifts in plant community assemblages (Figs. 3 and 4). Sedimentary evidence for overwash events within the cores includes medium to coarse sand beds overlying organic rich peat beds seen in both FPM4 Unit 1 and WB1 Unit B.

The FPM cores were taken within a relict flood tide delta directly landward of the buried inlets (Maio et al., 2012b) (Fig. 5). The 70 m wide inlet shown on the 1846 Coast Survey map flanks the paleoforest on its eastern edge and, when breached, likely led to rapid shifts in the hydrologic conditions within the back-barrier marsh (Orson and Howes, 1992). Additional evidence of overwash within the FPM cores includes the oldest radiocarbon age in this study, 3075 ± 70 cal BP, returned from a piece of bark sampled from within FPM6 Unit 3. One possible explanation for this relatively old age at this shallow core depth is that the bark was derived from a tree located more seaward than surveyed stumps and transported landward by storm driven washover. The more seaward position of the tree would explain its older age and a storm driven transport mechanism would explain its position within the back-barrier environment.

Offshore marine calcareous foraminifera species, identified within FPM Unit 5, also documents past storm events. Because it takes significant wave action to move these offshore species into the nearshore and back-barrier environments, they are often associated with large landward moving storm surges (Hawkes and Horton, 2012). A fragment of wood sampled from the bottom of FPM 5 Unit 6 shows that all of the changes documented in the FPM cores occurred sometime after 1439 AD, covering a time period of 573 years.

The combined stratigraphic, foraminifera, and radiocarbon signatures of environmental change, contained within the FPM and WB cores, support our hypothesis that active mechanisms led to the drowning of the paleoforest. Furthermore, previous research provides evidence that prehistoric hurricanes made landfall in the vicinity of the paleoforest and caused significant environmental changes including the overwash of barrier beaches and the salinization of formally freshwater environments. In addition, individual storm events recorded in marsh cores (i.e. Orson and Howes, 1992; Donnelly et al., 2001) and the intervals of increased hurricane activity (i.e. Mann et al., 2009; Boldt et al., 2010) coincide with the death of individual trees within the paleoforest.

4.3. Ongoing and future coastal change

During the past 3000 years, moderate increases in sea level have led to the building of numerous barrier systems along the Northeast coast (Ashton et al., 2007). Because barrier systems were formed during periods of moderate SLR, accelerated rates of SLR could provide a tipping point at which there would be wholesale reorganizations of barrier dynamics altering coastal processes which have operated for millennia (FitzGerald et al., 2006). In fact, current and future changes will seriously detract from the stability of the barrier systems (Ashton et al., 2007) leaving them especially vulnerable to a predicted increase in Atlantic storminess in response to warmer ocean waters (Emanuel, 2005).

Since 1920, there has been a threefold increase in the rate of SLR, when compared with the previous millennium from 1 mm/yr to 3 mm/yr, resulting in widespread landward migration of coastal ecosystems (Clark, 1986; Donnelly, 2006; Kemp et al., 2011). For example, there has been widespread plant community transition within New England saltmarshes during the past century leading to declines in high marsh plants species such as *Spartina patens* and a landward migration of low marsh *S. alterniflora* (Donnelly and Bertness, 2001). At a coastal site in Anne Arundel County, Maryland, there was a 42% decline in mature cedar trees between 1997 and 2006 (Walbeck et al., 2006). This decline was attributed to increasing salinities, which, if continued at the current rate, would cause the population to become extinct within 5–10 years (Walbeck et al., 2006).

Hurricane Sandy made landfall on the U.S. East Coast in late October 2012. Sandy caused unprecedented damage to barrier systems and urban areas from North Carolina to Maine. Though Massachusetts had limited damage, when compared to New York and New Jersey, a storm surge height of approximately 1.3 m was observed at the Woods Hole tide gauge located 15 km west of the study site (NOAA Tides and Currents, 2012). Further exasperating the erosion caused by Hurricane Sandy, there was a series of Nor'easters topped by the February 2013 Blizzard that caused catastrophic erosion, overwash, and breaching to many Cape Cod beaches.

In response to these storm events, the paleoforest site experienced wide-scale erosion, with dune loss of 2–3 m directly landward of the surveyed stumps. The once preserved paleolandscape was partially destroyed, with much of the peat outcrop and some subfossil stumps being eroded out of the shoreface and deposited along the HWL. This provides further evidence that extreme storm events continue to drive environmental change along SCB. In addition to the erosion and destruction of some of the paleoforest, at least six more preserved paleolandscapes were revealed along Cape Cod's beaches. These new sites provide a time sensitive opportunity to conduct further investigations and conduct educational outreach activities (Maio and Berman, 2013).

5. Conclusions

The SCB paleoforest provided a unique research opportunity to elucidate the timing and character of late Holocene marine transgression. The research has provided evidence of the drowning of a coastal forest in response to transgressing marine waters between approximately 700–1500 AD. The paleoforest is a clear and accessible visualization of marine transgression and also provides for pre-anthropogenic context for coastal change in response to climate driven phenomena.

Based on our results, the paleoforest inhabited a back-dune environment for over 900 years. During this time, sea levels were stable, rising at a rate of only 0.52 mm/yr ± 0.62 (Donnelly, 2006). As hydrologic conditions changed, due to episodic storm driven flooding and long-term SLR, the area transitioned from a freshwater terrestrial environment favoring *J. virginiana* trees to one favoring high marsh brackish flora. Through this process, drowned tree stumps became covered and preserved within a bed of saltwater peat. We calculated the rate of this transition to 0.73 mm/yr (Fig. 2). Eventually barrier beach sands covered and further preserved both the stumps and associated high marsh peats. Modern analogs for this scenario exist along the SCB barrier today with numerous *J. virginiana* trees observed in various stages of death along the marsh fringe (Fig. 6A). After being buried for over 400 years, accelerated rates of SLR during the 20th century and recent storm events have led to the rapid erosion of the shoreface revealing the preserved subfossil stumps (Fig. 6A).

Driving mechanisms behind the drowning of the paleolandscape are tied to both episodic storm events and long-term SLR. Because sea-levels during the late Holocene had stabilized, the drowning of the paleoforest was likely hastened by storm driven flooding. There are numerous modern analogs of how hurricanes can catastrophically change the physical and biological structure of coastal forests (e.g. Clark, 1986; Conner et al., 1997; Boose et al., 2001). Stratigraphic, microfossil, and radiocarbon evidence from the WB and FPM cores as well as modern observations provide signatures of environmental change in response to episodic storm events along the SCB barrier system.

The long-term development of barrier beach systems during a time of stabilized sea levels leaves them especially vulnerable to future increases in the rate of SLR (Ashton et al., 2007). Moving into the future, barrier instability will likely result in the saltwater inundation of freshwater environments at rates orders of magnitude greater than passive flooding alone (Ashton et al., 2007). Rates of SLR along the Massachusetts coastline are predicted to accelerate to as high as 20 mm/yr before 2100 (Parris et al., 2012). This would be a 40-fold increase over rates of SLR during the time of the paleoforest and would undoubtedly exasperate both passive and active coastal flooding (Kirshen et al., 2007). The continued acceleration in the rate of SLR and the increased intensity and reoccurrence of extreme storm events (Emanuel, 2005) will likely result in widespread and catastrophic destabilization of barrier systems resulting in significant land losses and salinization of freshwater environments (FitzGerald et al., 2001).

Drowned paleolandscapes revealed along transgressing coastlines provide a time sensitive opportunity to research the environmental response to SLR and episodic storm events. The subfossil wood, plant macrofossils, and foraminifera microfossil assemblages found within these locations allow for a reconstruction of past coastal changes providing context to ongoing changes. Preserved paleolandscapes also provide a "teaching moment," serving as a powerful education tool for the landward migration of coastal systems in response to continued marine transgression. Public understanding of how the coastal environment responded to climate fluctuations in the past is crucial for the effective development and implementation of appropriate mitigation and adaptation strategies. Without a clear understanding of past changes, there is little hope for anticipating future changes.

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