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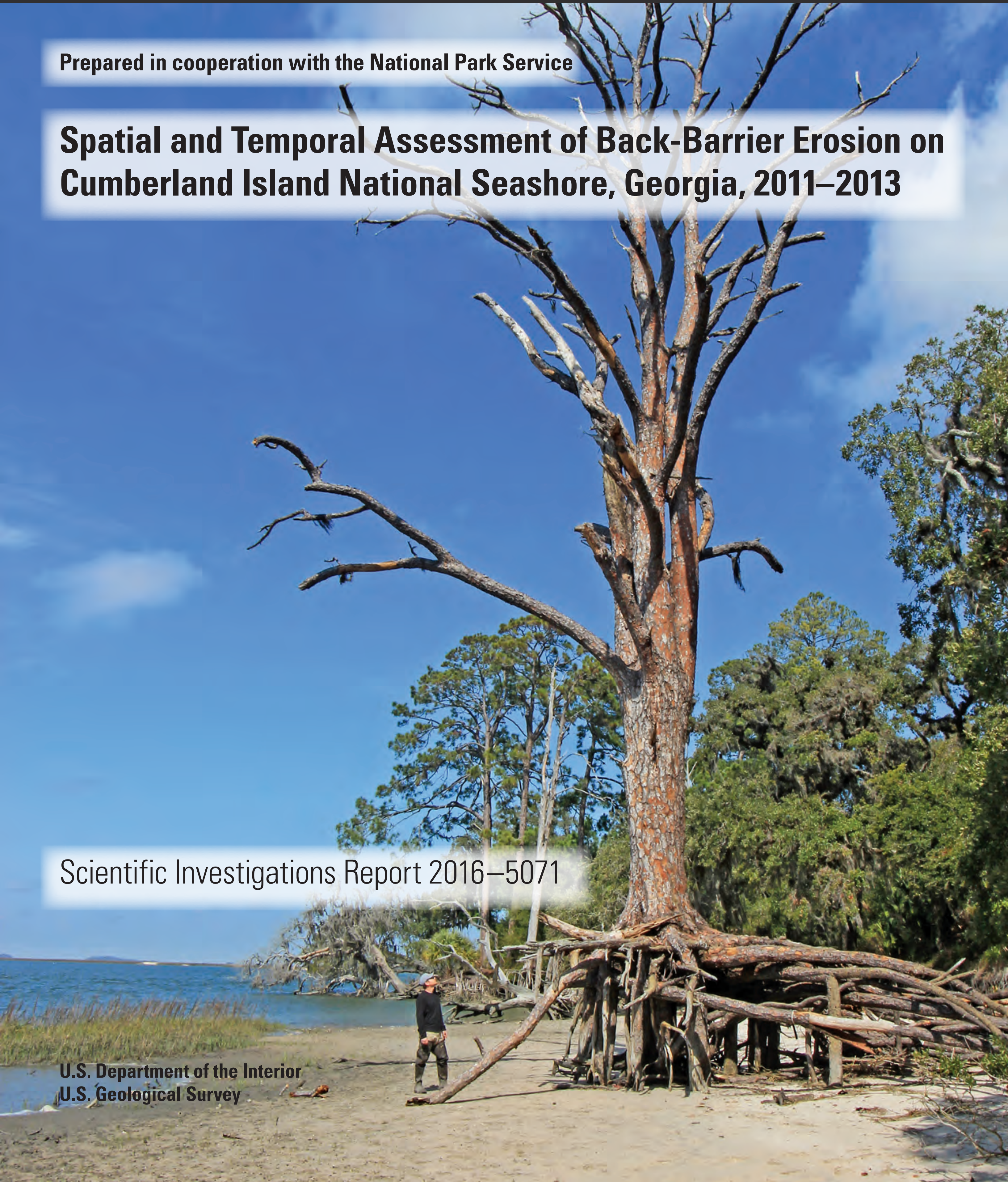
Spatial and Temporal Assessment of Back-Barrier Erosion on Cumberland Island National Seashore, Georgia, 2011–2013



Scientific Investigations Report 2016–5071

U.S. Department of the Interior
U.S. Geological Survey

Cover. Back-barrier erosion as seen from Brickhill Bluff, Cumberland Island National Seashore. Photograph by Alan M. Cressler, U.S. Geological Survey.

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By Daniel L. Calhoun and Jeffrey W. Riley

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Acknowledgments

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Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Flow rate	
meter per year (m/yr)	3.281	foot per year (ft/yr)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)

Inch/Pound to International System of Units

Multiply	By	To obtain
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) Universal Transverse Mercator (UTM) Zone 17N.

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AMBUR	Analysis of Moving Boundaries Using R
BB	Brickhill Bluff
CUIS	Cumberland Island National Seashore
CW	Cumberland Wharf
dBFS	decibels relative to full scale
DCP	data collection platform
DW	Dungeness Wharf
EPR	end point rate
Esri	Environmental Systems Research Institute
GADNR	Georgia Department of Natural Resources
GPS	global positioning system
Hz	hertz
ICW	Intracoastal Waterway
IPCC	Intergovernmental Panel on Climate Change
NPS	National Park Service
PEEP	Photo-Electronic Erosion Pin
PO	Plum Orchard
RK	Raccoon Key
RTK GPS	Real-Time Kinematic Global Positioning System
SLR	sea-level rise
SD	standard deviation
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

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Abstract

Much research has been conducted to better understand erosion and accretion processes for the seaward zones of coastal barrier islands; however, at Cumberland Island National Seashore, Georgia, the greater management concern is the effect that erosion is having on the resources of the island's western shoreline, or the back barrier. Catastrophic slumping and regular rates of erosion greater than 1 meter per year threaten important habitat, historical and pre-historical resources, and modern infrastructure on the island. Prior research has helped National Park Service (NPS) staff identify the most severe and vulnerable areas, but in order to develop effective management actions, information is needed on what forces and conditions cause erosion. To this end, the U.S. Geological Survey, in cooperation with the NPS, conducted two longitudinal surveys, one each at the beginning and end of the approximately year-long monitoring period from late 2011 to early 2013, along five selected segments of the back barrier of the Cumberland Island National Seashore. Monitoring stations were constructed at four of these locations that had previously been identified as erosional hotspots. The magnitude of erosion at each location was quantified to determine the relative influence of causative agents. Results indicate that erosion is, in general, highly variable within and among these segments of the Cumberland Island National Seashore's back barrier. Observed erosion ranged from a maximum of 2.5 meters of bluff-line retreat to some areas that exhibited no net erosion over the 1-year study period. In terms of timing of erosion, three of the four sites were primarily affected by punctuated erosional events that were coincident with above-average high tides and elevated wind speeds. The fourth site exhibited steady, low-magnitude retreat throughout the study period. While it is difficult to precisely subscribe certain amounts of erosion to specific agents, this study provides insight into the mode of erosion among sites and the interaction among factors that set up conditions that may be leading to punctuated events.

Estimates of sea-level rise were incorporated into the results of this study to project conditions that could be in place by the end of the 21st century. When using the erosion rates observed in this study to extrapolate future shoreline position, results indicate an average retreat (across all monitored locations) of 15 meters by 2050 and approximately 37 meters by 2100.

Introduction

The majority of geomorphological studies in coastal environments have focused on beach and shoreline erosion and accretion (Pendleton and others, 2004; Hapke and others, 2011); however, increased attention is being placed on the mainland sides—back barriers—of barrier islands because of the wealth of natural resources and the functional stabilizing roles held therein. Chronic erosion has been identified along the back barrier, or western side, of Cumberland Island National Seashore (CUIS; fig. 1), which is the southernmost barrier island along the Georgia coast in the Southeast United States (Alber and others, 2005). Here, coastal marshes and island uplands are bounded by the Cumberland River to the north and Cumberland Sound to the south over a distance of almost 30 kilometers (Frick and others, 2002). The western shore of CUIS and its back-barrier marshes and uplands hold tidal creeks, rich ecological habitat, abundant wildlife, historical and archaeological sites, National Park Service (NPS) and private structural property, and a constantly changing physical environment dominated by erosion. As reported in Foyle and others (2003), a data gap exists in erosional processes on unaltered barrier islands of Georgia. These authors urged the creation of a Georgia coastal monitoring program that would address some of the issues inhibiting detailed process-level analysis of coastal change. Concern has been expressed by resource management personnel and researchers regarding the potential for the erosion (in locations such as CUIS) to be exacerbated by

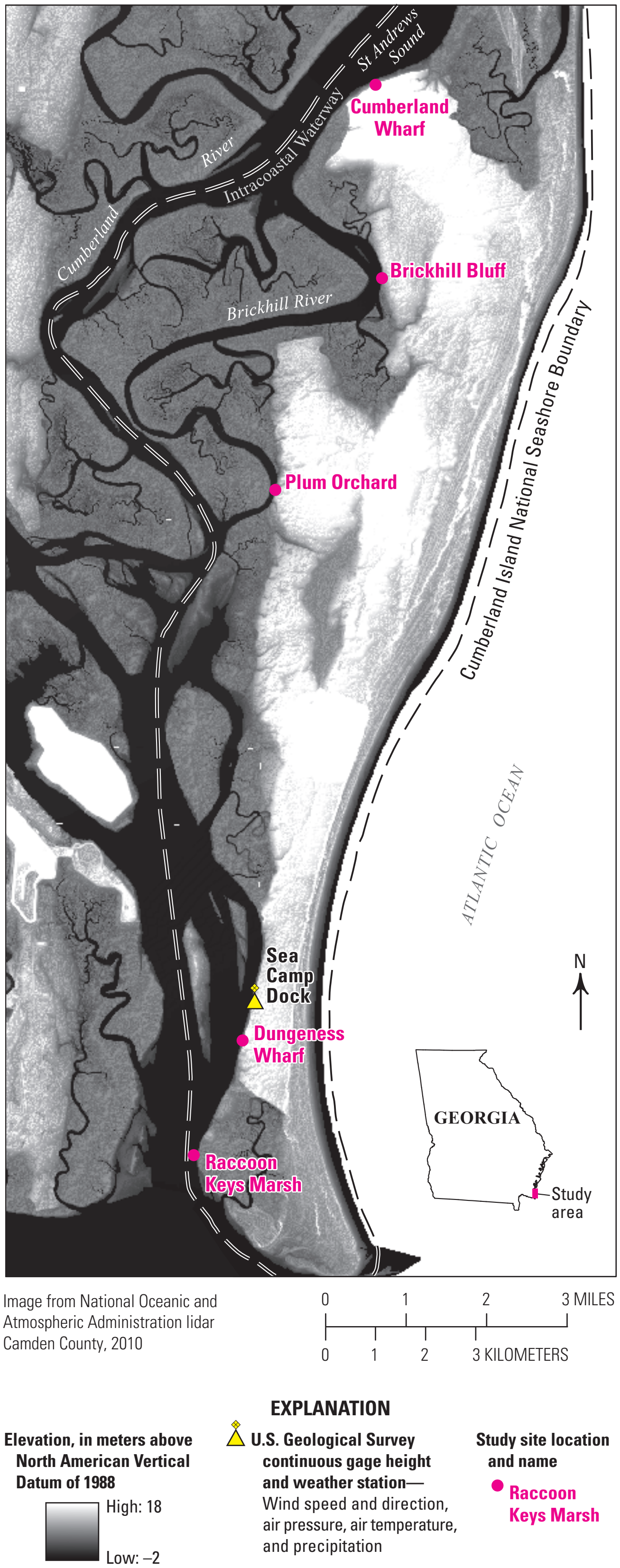

Figure 1. Location map showing back-barrier erosion study sites on Cumberland Island National Seashore (CUIS), Georgia.

existing and potentially increasing boat traffic, storms, natural geologic controls, erosional response to historical sea walls (end-around effects), rainfall runoff from developed nearshore structures, geomorphic processes such as migrating tidal creeks, animal traffic, and (or) sea-level rise (SLR). Effects from erosional processes on archaeological sites within CUIS have been noted (Dougherty and Fry, 2003; Jackson, 2006; John Fry, Resource Manager, CUIS, oral commun., 2006; Jackson and others, 2007). Adverse effects to natural systems such as marsh-grass habitats are known, but the extent has yet to be fully determined (Alber and others, 2005).

Erosion and accretion are natural processes that control barrier-island evolution and migration (Riggs and Ames, 2003; FitzGerald and others, 2008); however, the processes that cause back-barrier erosion along islands such as Cumberland Island are poorly understood. Portions of CUIS, along with many locations on other Atlantic coast barrier islands, have been classified as currently existing in a regressive state. A regressive state is described as the condition where the width and elevation of portions of an island prevent wave overwash and breach from the ocean margin during extreme events (Timmons and others, 2010). Without the sediment supply to the back barrier of the island from such events (or from long-term estuarine sources), steady erosive action over time will narrow—and lower—the island to the point at which it can receive back-barrier replenishment from oceanside sources (Riggs and Ames, 2003; Timmons and others, 2010). The period of barrier-island evolution thus entered is referred to as a transgressive state where the island begins a migration towards its mainland. Riggs and Ames (2007) found that the majority of change to the Core Banks barrier islands of North Carolina has occurred during storm-driven periods—over decades—where ocean-sourced sediments have overwashed the islands supplying material to build the back barrier, which subsequently has been stabilized by growth of aquatic vegetation. Lacking a connection to ocean sources of sediment, the back barrier of complex islands (such as CUIS), defined by having physical structure substantial enough to prevent overwash, can become dominated by erosion driven by multiple factors, including fetch (the distance of open water facing the margin), the type of material making up the margin, type and density of vegetation along the margin, and anthropogenic influences such as boat wakes and structural emplacements. Strandplain aprons can form from eroded materials or estuarine sources that will protect further incursion, providing that the material is not removed during successive erosional events (Riggs and Ames, 2003). Evidence that much of CUIS currently exists in a regressive state can be found in studies of shoreline change, which show that long-term accretion to the ocean margin is averaging approximately 2 meters per year (m/yr) (Morton and Miller, 2005; Jackson, 2010a, 2015) and is not contributing to stabilization of the western shore.

Processes driving barrier-island evolution are expected to be exacerbated due to accelerations in mean SLR caused by climate change (Intergovernmental Panel on Climate Change, 2007; FitzGerald and others, 2008; Wong and others, 2014) and may be the single largest threat to the integrity of the coastal margins of the United States (Saunders and others, 2012). However, agreement on how that single component can be attributed to predicted net changes has been debated (FitzGerald and others, 2008; Williams, 2009). Predictions of SLR for the 21st century vary based on many of the possible factors involved. The Intergovernmental Panel on Climate Change (IPCC) (2007) estimates of global increases in relative sea level generally conform to the rates derived from empirical data measured during the 20th century and the estimated increased rates that are expected to be caused by thermal expansion of the oceans from increases in global temperature. From 1961 to 2003, the average rate of SLR was 1.8 millimeters per year (mm/yr). This rate was higher during 1993 to 2003, averaging 3.1 mm/yr (Intergovernmental Panel on Climate Change, 2007). The IPCC projects that the rate of SLR during the 21st century will be between 1.8 and 5.9 mm/yr. These estimates do not include any increases in the rates of melting from polar or extra-polar sources. When more possible melt sources are considered, these estimates double (Rahmstorf, 2007). Through these various estimates, by the end of the 21st century, the range of predicted increases in relative mean sea level would be between 0.2 and 1.2 meters (m). These values are in the range of estimates used by the U.S. Army Corps of Engineers for required coastal project planning (U.S. Army Corps of Engineers, 2011). The lower boundary of this estimate is coincident with measured increase in tide elevations from the Fernandina, Florida, tide gage (located just south of CUIS) from the period 1897–2011, which totaled 0.18 m for a 100-year interval (Church and White, 2011) and is slightly less than the 2.4-mm/yr increase during 1939–1992 reported by Kraus and others (1997).

Erosion to locations on the western margin of CUIS that hold important archaeological resources was assessed by Dougherty and Fry (2003), and rates of change between 0.15 and 0.5 m/yr were noted. A recent University of Georgia study conducted in conjunction with the Georgia Department of Natural Resources (GADNR) Historical Resources Division used remotely sensed data to determine the amount of erosion (and [or] accretion) for the Georgia coast and its back-barrier islands (Alexander and others, 2008; Robinson and others, 2010). The purpose of the study was to determine which archaeological sites were most in danger of being destroyed or compromised by erosion. The analysis provided average long-term and short-term erosion and accretion rates for the island's beach side as well as for the back barrier. However, the authors suggested that although the results could indicate a general susceptibility, it could not substitute for monitoring individual locations of concern as the patterns of erosion and deposition are highly variable in time and space. The authors reported that, for the Georgia barrier islands, when long- and short-term rates of erosion and accretion are taken into account, there does not appear to be a net change in island position.

Jackson (2006, 2010a, 2015), using similar methods as the Dougherty and Fry (2003) study, performed a detailed analysis of back-barrier shoreline change specific to CUIS covering a period of 150 years. Jackson identified zones of erosion and accretion along the back barrier and showed that rates of change were specific to periods of time status shifted from one state to another in some locations. Areas of the island that contained important archaeological resources and had steady erosive change were singled out by NPS staff as areas of concern requiring more detailed information to enable assessment of potential management remediation (John Fry, Resource Manager, Cumberland Island National Seashore, written commun., 2011).

Purpose and Scope

The current study was initiated to evaluate the magnitude and rates of erosion along discrete points of interest to NPS management (fig. 1) and to identify factors that may be leading to erosion as it occurs along the back barrier of CUIS. Sites were selected based on their current state and susceptibility to continued erosion, and priority was given to sites where marsh and upland ecosystems are immediately threatened by further land loss and possibly where cultural and historical resources could be damaged by continued erosion. The results of this study should be viewed with respect to the fact that sites were chosen because they had already been identified as erosion hot spots, and findings should not be extrapolated for the entire back barrier of CUIS.

Determination of rates of change during a short period, such as a day or less, at a high resolution both spatially and temporally coupled with monitoring conditions during which erosion is noted was expected to enable some attribution of the specific causes of the eroding back barrier of CUIS. Factors influencing back-barrier erosion at CUIS could include fluvial-driven erosion from high rainfall inundation events, the daily rise and fall of tides, storm-driven tides, SLR, and wave action from recreational boating and shipping traffic that travels through the Intracoastal Waterway (ICW) and other channels. Dredging to accommodate shipping through Cumberland Sound has occurred throughout the 20th century (Alber and others, 2005), and studies indicate that alterations in the current velocity and sediment dynamics within the sound occurred during this time (McConnell and others, 1983); however, water level in Cumberland Sound has been unaltered during the period of dredging with respect to background rates of increase (Kraus and others, 1997). Additionally, animal traffic, including wildlife, feral horses (Simon and others, 1984; Jackson and others, 2007), and hogs, as well as human activities involved in accessing the shoreline of CUIS during recreation, could be increasing denudation of the shoreline and loosening the consolidation of soils in the erosion-prone areas. Potential drivers of erosional forces are varied, and interactions among the various sources may result in an intensification of back-barrier erosion. Areas of high erosion also may coincide with geologic characteristics specific to the location, including local lithology and degree of consolidation of sediments. These site-specific differences may create preferential areas of armoring and transfer of kinetic energy to areas with less consolidated materials. Although it was not possible to monitor all of these potential drivers of erosion along the back barrier of CUIS, efforts were made to assess those factors deemed feasible and most likely to be contributing to the rates, magnitudes, and timing of erosional events during the time span of the study.

Field studies were initiated by the U.S. Geological Survey (USGS), in cooperation with the NPS, in December 2011 and were concluded in May 2013. The goal was to monitor conditions over at least an entire year to capture possible seasonal variability. The study period had to be extended longer than a calendar year to meet the desired monitoring duration after an equipment malfunction. Throughout this report, the term "margins" is used to define the westernmost extent of uplands and (or) the near-vertical soil profile at the land-water interface that is susceptible to erosive forces. Approaches taken included longitudinal surveys of margin position along five segments of various site-specific lengths near the beginning and end of the field assessments, more detailed point-specific estimates of erosional scarp retreat through erosion pins, and continuous measures of erosion at selected locations at each of four sites using Photo-Electronic Erosion Pins. Continuous data were recorded for tidal fluctuations and for hydroacoustic energy during the majority of the study period. Existing and co-occurring instrument-based data were used that provided meteorological information such as wind speed and direction from a single point on the western margin of the island. Data collected during this study that were used to support the interpretations herein are available at http://dx.doi.org/10.5066/F7Z60M4M (Riley and Calhoun, 2016).

Methods

The methods of investigation that were used in this project included traditional as well as innovative techniques to assess change in landscape position and environmental conditions. Surveys of longitudinal segments at each of five sites that were selected for study were conducted at the beginning and end of the study. At four of these sites, more intensive and targeted measurements occurred throughout the study period and included the use of standard bank pins and Photo-Electronic Erosion Pins. Measurement of tidal and meteorological conditions and hydroacoustics coincided with the erosion estimates from the pins with the intent to assess the conditions during which erosion occurred. Estimates of erosion were then used to project where the margins that were studied likely would be located if the rates of positional change observed continued over the course of the current century.

Margin Position

The term "margins" is used in this report to define the westernmost extent of uplands and (or) the near-vertical soil profile at the land-water interface that is susceptible to erosive forces. To determine margin position, points were surveyed along the edge of the margin scarp using either a Trimble R8 Real-Time Kinematic Global Positioning System (RTK GPS) unit, a Trimble S6 total station, or both. Horizontal position data are referenced to the North American Datum of 1983 (NAD 83) UTM Zone 17N, and vertical data are referenced to the North American Vertical Datum of 1988 (NAVD 88) computed using GEOID09. Project benchmarks were installed at each monitoring location to serve as the origins for margin surveys. Benchmarks were constructed using a 1-m-long, 0.1-m-diameter polyvinyl chloride pipe buried 1 m below the ground surface then filled with concrete and capped with a brass tablet set in the center. Positional data for these benchmarks are included in table 1. Point spacing was variable depending on the size of the feature and the presence of obstructions that may have prevented observation of a point. In general, point spacing was 1–5 m over most of the margin with closer spacing occurring over the areas where other instrumentation was located. Point data were collected and exported as Esri shapefiles so linear features could be hand- or on-screen digitized in ArcMap. This procedure was conducted for the initial shoreline position at the start of the project and was also conducted near the end.

To quantify the change in margin position, the computing software R and the Analysis of Moving Boundaries Using R (AMBUR) package (Jackson, 2010; Jackson and others, 2012) were used. AMBUR uses shapefiles as the input data and can be used to cast perpendicular transects between the beginning and ending shoreline positions. The package allows for many positions to be evaluated, but the current study only used the two surveys conducted in the beginning and near the end of the study period. The "cast transect" function and the "near transects" function in AMBUR were used to automatically project end points on each digitized margin line rather than overlapping them. The transect lengths were then used to evaluate the change in margin position. All margins were visually evaluated to ensure that transects were cast to appropriate locations on each margin position. If problems were encountered, the "filter transects" function was used to average the azimuth of three adjacent transects to improve the perpendicularity of transects. To further evaluate consistency in transect position, transects were spaced horizontally at 1, 3, and 5 m, and summary statistics were then calculated from the transect lengths for each spacing. Positional surveys were also conducted to characterize specific features at the locations, which helped determine where equipment would be installed and relative heights of the erosional margins and their relation to other data collected during the study (table 1).

Table 1. Sites selected for this back-barrier erosion study, including locations and characterizations of installed instrumentation and feature descriptions, Cumberland Island National Seashore, 2011–2013.

[Horizontal datum: North American Datum of 1983; vertical datum: North American Vertical Datum of 1988; Universal Tranverse Mercator Zone 17N; m, meter; N/A, not applicable]

Site	Abbreviation used in this study	Northing of installed benchmark (m)	Easting of installed benchmark (m)	Horizontal precision of benchmark (m)	Survey segment length (m)	Generalized matrix material	Height of central erosional feature (m)	Transducer elevation (m)	Elevation of base of erosional margin (m)	Height of base of erosional margin above transducer (m)
Cumberland Wharf	CW	3421835.77	457343.23	0.36	170	Sand	10	N/A	N/A	N/A
Brickhill Bluff	BB	3418166.10	457535.11	0.14	230	Sand with midden overlay	1.5	–1.05	1.15	2.20
Plum Orchard	PO	3413647.54	455428.46	0.06	250	Sand and clay with midden overlay	1.1	–1.79	0.80	2.59
Dungeness Wharf	DW	3402554.12	454788.71	0.03	200	Sand with midden overlay	2.8	–0.25	1.30	1.55
Raccoon Key	RK	3401184.27	454264.91	0.02	400	Dense clay and sand	0.6	–1.45	–0.01	1.44

Standard Bank Pins

In addition to GPS-based surveys, standard bank pins were installed along each of the four site margins. Bank pins are metal rods, cylindrical in shape, and initially set flush with the margin; as erosion occurs, the length of pin exposure is measured to determine the distance of margin retreat. Bank pins are often used in fluvial studies to evaluate streambank erosion (Wolman, 1959; Gabet, 1998). Bank pins have been used in many different environments subject to erosion and deposition that vary by dominant type of erosion and cover several orders of magnitude (Gabet, 1998; Lawler, 2005). Along selected margin areas, bank pins were installed in a nested fashion to capture the variability in erosion vertically and horizontally along the erosional surface. Pins consisted of 1-m-long and 4-millimeter (mm)-diameter steel rods and were irregularly spaced along the entire margin that was surveyed. Painting of the rods with fluorescent paint facilitated the relocation of the pins. Pins were purposely placed on steep sheer areas of the margin face (fig. 2*A*). Large unconsolidated aprons were often present where upper material had failed on the lower portion of the margin or on the upper margin. Tree roots were supporting material further out than the actual margin face, making installation conditions poor. Because data collection visits occurred only quarterly, standard bank pins allowed the greatest amount of data to be collected with less chance of information loss through equipment malfunction or displacement. The number and configuration of pins varied by location, and generally, pins were nested vertically with one low on the margin face 10–30 centimeters (cm) above the toe, one approximately in the center, and another 10–30 cm from the top. At Cumberland Wharf (CW; fig. 1) the scale of the margin (approximately 10 m high) and magnitude of erosion and instability of the slope prohibited the use of bank pins. The erosion margin at Raccoon Keys Marsh (RK; fig. 1) differed the most in several respects, namely that its height (less than 1 m) and highly bioturbated sediments allowed only two pins to be installed, one near the toe and one near the center. On each visit, pins were measured to the nearest millimeter then reset flush with the margin face. Often, bottom pins were buried, and these pins would be recorded as so. If the amount of material covering the pin was small, an attempt would be made to excavate the pin to determine if erosion had occurred prior to burial. No attempt was made to excavate the pin when large failures were present so as to prevent unnatural removal of the failed material that was then acting to protect the margin toe. On each subsequent visit, every pin would be visited and measured or recorded as still buried. When large failures occurred resulting in pin loss or making the previous location of pins unsuitable for re-installation, pins would be placed in the closest location suitable for installation. In the case of complete removal of pins by erosion, the full length of the pin in question was used as the erosional change.

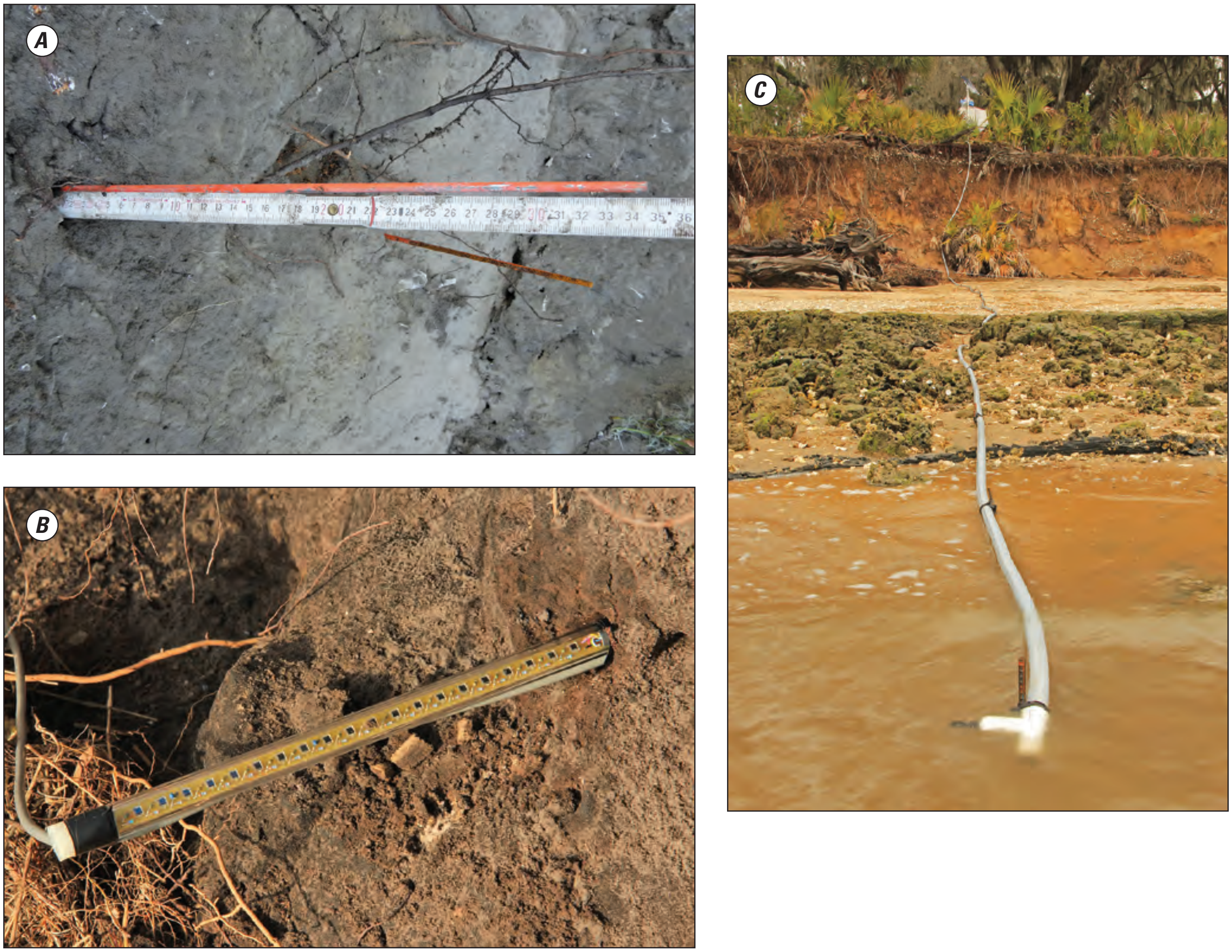

Figure 2. *A*, Standard bank pins at Brickhill Bluff (BB) and technique used to measure between inter-visit bluff erosion; *B*, in situ Photo-Electronic Erosion Pin (PEEP) extended out of its installation location (when installed, only the outermost photo diodes are exposed); and *C*, pressure transducer, hydrophone, and data collection platform at Dungeness Wharf (DW), Cumberland Island National Seashore. (Photograph *A* by Jeffrey W. Riley, USGS; photographs *B* and *C* by Alan M. Cressler, USGS.)

Photo-Electronic Erosion Pins

Paired Photo-Electronic Erosion Pins (PEEPs; fig. 2*B*) were installed at each site to allow erosional rates to be monitored at a finer temporal interval (2 minutes [min]) than could be possible with the standard bank pins (PEEP-3T; Hydro Scientific LTD Stratford-upon-Avon, UK) (Lawler, 1991, 1993, 2001, 2002, 2003, 2005, 2008; Mitchell and others, 1999; Lawler and others, 2001; McDermott and Sherman, 2009). This continuous monitoring allowed precise timing of erosional events to be captured and allowed for the evaluation of possible thresholds or lags in erosional response. PEEPs are a series of photodiodes arranged along sealed 0.7-m-long pins that are installed horizontally (in this case) into the erosional margin by using a coring device. Sequential diodes record the changing exposure of the rod to ambient light as it relates to an outermost reference diode. Full exposure of the measurement length (approximately 0.25 m) is recorded as an equal ratio of the voltage of the measurement diodes to that of the reference diode (see fig. 2*B*). PEEPs were field calibrated in the lighting conditions under which they were to operate at the installation locations by pushing the rods into cored holes in the erosional margin. Output voltages of the sensors at multiple lengths of exposure were recorded, and regression equations were derived relating voltage to exposed length according to manufacturer instructions (Hydro Scientific, 2010). Calibration data are included in appendix 1. Calibration equations were applied to the raw voltage outputs across the measurement data and are reported in millimeters of exposed lengths of the rods. The data were recorded to a Campbell Scientific CR850 data collection platform (DCP) coupled to an AM16/32B Multiplexer. The Campbell Scientific program and wiring diagram used at the four locations are included in appendixes 2 and 3, respectively.

Monitoring Hydrodynamics

The detailed temporal estimates of erosion were examined in the context of hydrodynamic factors that are known to affect coastal processes. The factor believed to most affect coastal erosion is wave action. Wave action and the associated energy available at the water/land boundary are highly variable. Wave energy is directly proportional to wave height; therefore, factors presumed to assist in data analysis were tidal period and range and wind speed and direction.

The primary parameter monitored in this study to relate to wave action was water level. For this study, water level refers to average water level as well as the height of waves. As water level increases and more of the bank becomes inundated, greater pressure is applied to the bank; the bank material may then become saturated below the submergence level. Julian and Torres (2006) note that many fluvial studies show that as the water levels begin to fall and the pressure is released from the bank, failures may occur. In addition to this mode of erosion, waves that impact the banks and bluffs may mechanically remove sediment through physical contact. The effect of these two processes may be compounded by two different actions. During periods of low water, waves may remove material at the toe of the margin. During the following high-water event (such as spring tides or a low-pressure system), when the upper surface becomes saturated, the soil matrix may no longer support the weight of itself and the water due to the undercutting by wave action, and thus collapses. Additionally, if large wind-driven waves occur during a high-water event, the upper banks and bluffs may experience the same action that removes material at the toes.

The water-level data were collected through the use of one pressure sensor at each site (Campbell Scientific CS455 pressure transducer, 0–14.5 pounds per square inch) installed as far into the water as practical from the base of the studied erosional scarp and recorded to the same DCP as were the PEEPs described previously (fig. 2*C*). The pressure sensors were set to scan at 10-second intervals, and values were averaged over a 2-minute interval. Maximum, minimum, and standard deviation of the 10-second scans were also recorded every 2 minutes. The high rate of data collection enabled not only determination of tidal cycle but also enabled the characterization of wave height and wave period data. These data were evaluated in the context of climatic conditions estimated from an anemometer (for wind speed and direction) as well as precipitation data and tidal height from a gage located at the Sea Camp dock (USGS/NPS cooperative gage 02228295) that records every 15 minutes.

Heights of the erosional margin of the central erosional feature at the locations where the PEEPs were installed are included in table 1. The positions of the transducers were also surveyed with respect to the elevation of the respective erosion margin base. This enabled a determination of when—and how often—the tidal height was coincident with the margin. The conditions during which tide was high enough to reach and possibly exceed the height of the base of the margin were expected to provide information related to when erosional events would be instigated.

Monitoring Hydroacoustics

To collect data related to boat traffic and wave action, programmable acoustic recording devices were employed at the study locations (Peterson and Dorcas, 1992, 1994). HTI-96-MIN hydrophones (underwater microphones) were mounted in proximity to the pressure transducers at each site (fig. 2*C*) and were monitored continuously by SM2 Acoustic Recording Devices (Wildlife Acoustics, Inc.) housed in the same shelters as the DCPs. Comparisons were made between the intensity, frequency, and periodicity of the boat and wave sound to the physical measurements taken in this study to inform conclusions regarding the timing of erosion events determined through the physical measurements.

The Song Scape routine within the Song Scope software program (Wildlife Acoustics, Inc.) was used to analyze the daily acoustic files. It was noted through initial analysis of the acoustic files that boat traffic generally was detected in the 180–330-hertz (Hz) range, and this, in part, bounded the parameters of the analysis. A single bin was chosen to constrain all sound within that range, and outputs of the sound intensity (in decibels relative to full scale [dBFS]) over 2-minute, hourly, and daily intervals were made from the software. Comparisons to the full range measured (0–4,000 Hz) were made, and it was determined that sound data required filtering to allow analysis of information collected only during the times when the tidal range—as measured by the pressure transducers at each site—reached the base of the erosional margin. This approach ensured that the sound recorded was more applicable to any detected erosion events measured through the means previously mentioned and not attributable to sound generated by such things as airplanes or wave crash and boat noise during lower tides. It was also determined that the full measured range of sound was more interpretable than the windowed range.

Projecting Future Conditions

In an effort to provide an estimate of future conditions, shoreline positions were projected based on erosion rates from the longitudinal surveys from the present study. While these projections are based on empirical data, they cover a short period and do not take into account longer term variability, possible changes to driving mechanisms, or the interaction between retreat and the possibility of encountering geologic controls that may alter erosion rates. These projections should only be used as a tool to help inform management decisions of near-shore problems and possible timeframes for action and not necessarily used as absolute location of shoreline positions.

Shorelines positions for each of the monitored locations were projected for the year 2050 and 2100 by using the AMBUR package (Jackson, 2010b) for the computing language R. Projections were based on the average retreat observed at each site multiplied by the number of years until 2050 (37 years) and 2100 (87 years). For this analysis, projected shoreline configurations were generalized, and hard structures were treated as mobile boundaries. The rationale for the above approach is based primarily on the timeframe of consideration. First, the monitoring period covers only about 1 year, and while this provides valuable insight, it precludes an understanding of the longer term variability of erosional behavior. Second, when projecting over relatively large temporal periods, one must make assumptions about the stability/variability of causal mechanisms. For these reasons, the average erosion rates at a site were selected over erosion rates at individual transects. The choice to project shoreline change over hardened structures stems from the fact that based on current rates, unless seawalls/revetments are extended along the margin or other management actions are taken, it is probable that end-around erosion will effectively create an “island” by eroding around the structure so that the structure may no longer remain attached to the margin. The shoreline would likely retreat to occupy a similar position to the adjacent margin.

Before shoreline positions can be projected, several data processing steps are required to derive input to the function. These steps are described in the AMBUR documentation (Jackson, 2010b); however, additional factors were considered. First, between the two GPS surveys, some discrete locations at all of the sites had experienced slumping of upper bluff material. As surveys followed the margin edge, a few points along slumps were occupying positions slightly further away from the land than during the initial survey, which appears as aggradation in the shoreline position. When these slightly aggrading areas are summed over a 37- or 87-year span, the results indicate areas of substantial, albeit false, accretion. Thus, the first step was to edit the input shorelines to remove the aggrading points by simply making the ending shoreline position equal to the beginning shoreline in these areas. Next, transects would be re-cast and filtered and capture points would be created where perpendicular transects intersect the shorelines (Jackson and others, 2012). The length of transects was then divided by the time period, from initial survey to end survey, to yield the end point rate (EPR). The mean of all transects at a site was used to represent the erosion rate at a site. The projected shorelines from AMBUR were edited to better reflect the general shape and morphology of the current shoreline. In some cases, a transect or transects would occur in a slight bend or erosional alcove along the shoreline leading to an azimuth different from the average direction of retreat, resulting in misconfiguration of the resulting shoreline. When this occurred, corresponding points were removed and the adjacent points connected.

Site Selection and Description

Site selection was based on specific resource needs rather than on a random sampling design. Previous work (Jackson, 2006, 2010a; Jackson and others, 2007) had identified areas of chronic erosion that were of concern to CUIS management. Primarily, sites were selected within these areas where fragile upland and marsh habitat and (or) archaeological or historical sites were being threatened due to shoreline erosion. The sites spanned the length of the island (fig. 1) and covered the diverse back-barrier conditions present at CUIS.

The level of monitoring at each site was dependent on site characteristics (table 1). For example, at Raccoon Key (RK), which is a site with no trees, a 400-m margin survey was conducted. In contrast, at Dungeness Wharf (DW), thick vegetation and large trees limited the margin survey to approximately 200 m. Similar site-level modifications had to be made in the installation of equipment. Issues encountered primarily were caused by tree roots in bluffs and by unconsolidated material unsuitable for pin installation. At CW, the feature scale and magnitude of shoreline change precluded the use of discrete monitoring devices so that margin surveys had to be used as the sole determinant of change. The remaining sites all received the full instrumentation to monitor water level, for time discretized erosion, bank pins for inter-visit erosion, and margin position surveys at the beginning and end of the project. Due to large electrical power requirements for the type of instruments being used, early failures were encountered, and the temporal continuity of the datasets was, at times, compromised. Specifically, erosion pin data collection began in February 2012, and stable data collection from the continuous instruments was not possible until May 2012. For this reason, summary comparisons between approaches were based on erosion rates rather than on absolute distance eroded.

Cumberland Wharf

Cumberland Wharf (CW) is the northernmost site and is located near the highest elevation upland portions of the island, with elevations up to 10.5 m (NAVD 88; GEOID09) (fig. 1). The CW site is bordered to the north by St. Andrews Sound. The CW site had the highest bluff height (10 m) of the study sites (fig. 3*A*). Because of this relatively high bluff, not all of the techniques used at other sites were applicable here. Large rotational and slump failures were observed that were several times larger in thickness than erosion pins could quantify; therefore, a margin survey was the sole determinant

Figure 3. Study locations: *A*, Cumberland Wharf (CW), March 13, 2012; *B*, Brickhill Bluff (BB), June 20, 2012; *C*, Plum Orchard (PO), November 8, 2013; *D*, Dungeness Wharf (DW), November 6, 2012; and *E*, Raccoon Keys and Marsh (RK), June 19, 2012, Cumberland Island National Seashore.

of shoreline change. The upper margin was heavily vegetated with shrubs and intermittent large trees. At low tide, a relatively large strandplain platform is present below the base of the bluff. This platform is most likely material that has eroded from the bluff and then sorted by tidal action. The bluff is composed of fine to medium sands with little organic material and appears to have been a part of a series of ancient dunes that are now slumping into the sound due to the action of erosive forces. The bluff is more subject to gravitational forces—based on the height and slope angle of the feature and on the non-cohesive sandy matrix—than any of the other sites in this study.

Brickhill Bluff

Brickhill Bluff (BB) is located in the northern portion of the island and is bordered on the west by the Brickhill River (fig. 1). This site is located on a meander bend and may be subject to fluvial erosion at high tides during tidal fluctuations. The BB site has substantial tree cover along the margin, and in several locations, large trees have toppled that are protecting areas of the bluff (fig. 3*B*). The bluff matrix is composed of a very fine sand with a thin layer of shell midden near the surface and has a bluff 1.5 m high (table 1). This site contains a designated group campsite and may sometimes be accessed by motor boats and kayakers, which potentially exacerbate bluff erosion. Campers exploring along the shore may also contribute to soil and material instability. Erosion pins were installed horizontally in the bluff, nested in vertical sets of three, and evenly spaced along the segment studied. PEEPs were installed in a relatively high-banked cove north of the area where the majority of camping activity occurs.

Plum Orchard

Plum Orchard (PO) is near the midpoint of the island along the Brickhill River (fig. 1). In contrast to the two sites further south that are located along Cumberland Sound and primarily affected by waves and tides, PO may be subject to the additional effects of fluvial erosion, because it is positioned in a meander bend. Additionally, concerns have been expressed that upland-sourced rainfall runoff may be contributing to erosion along the margin edge (Dr. Chester Jackson, Georgia Southern University, written commun., 2015). This site includes a dock that is used by some of the private residents of the island, by park operations, and by the public and is subject to a greater degree of boat traffic than BB. Of the sites in this study, PO has the second lowest bluff face at 1.1 m (table 1) and is mostly bordered by a grassy lawn with large trees in several locations (fig. 3*C*). The matrix is composed of consolidated sands with high clay and organic content and is topped with a layer of midden materials. The PO site has several manmade structures along the shore. In addition to the dock, a wooden seawall protects a historical outbuilding, and a pile of rip-rap protects another. Immediately north of the rip-rap, the margin consists of a thin strip of marsh extending to the uplands. Bank pins were installed and monitored along the margin except where hardened structures were in place.

Dungeness Wharf

Dungeness Wharf (DW) is located near the southern extent of uplands and is bordered by Cumberland Sound to the west (fig. 1). As the primary arrival point for visitors, employees, and deliveries, DW experiences substantial boat traffic. The margin is heavily vegetated with large live oaks, juniper, and sable palms (fig. 3*D*) and is immediately north of a concrete seawall. Of the five monitoring locations, DW has the second highest bluff face at 2.8 m (table 1) and is composed of fine to medium sand where slightly coarser material below may be acting, at times, to support the more erodible material above. A thin layer of midden material is present at the surface and forms an overhang when eroded below, until the point where it fails when support is lost. Out from the bluff is a relatively long, flat platform with many large toppled trees from past erosion events that may act to reduce wave energy and provide shoreline protection in some locations. Monitoring at DW employed all of the techniques previously described, and bank pins were installed in the top, middle, and bottom of the bluff face as described in the text.

Raccoon Key and Marsh

Raccoon Key (RK) is a low-elevation, narrow strip of uplands that is surrounded by marsh (fig. 3*E*). To the west, RK is bordered by the Cumberland Sound (fig. 1), and directly north of RK is a large circular mound of dredge spoils creating an artificial upland area. Of all the monitoring locations, RK resides at the lowest elevation and has the lowest bluff face at 0.6 m (table 1). The RK site is unique in that the bluff is rather limited in the vicinity of the actual key where the upland is present. A lower face is composed of highly bioturbated marsh-like sediments with high clay and organic content that coarsens up to the higher elevation surface. In addition to the limited bluff, the northern edge of the key margin is composed of shell midden. This lower bluff face and small exposed area of shell midden were the focus of monitoring efforts in the vicinity of the key. To put the shoreline change of the key area into perspective, the shoreline margin surveys were extended to include the adjacent marsh, which is identical in material composition to the small bluff face in front of the key. Margins extended a total of 400 m with most of the length lying north of the key. Furthermore, due to the short stature of the bluff face, erosion pins were only installed in two vertical positions at each location.

Back-Barrier Erosion and Causative Agents

Results of the various methods of investigation in this study included estimated change in the longitudinal segments at each of the five sites where surveying was conducted. At four of these sites, more intensive and targeted measurements occurred throughout the study period and included erosion estimations through the use of standard bank pins and PEEPs. Measurement of tidal and meteorological conditions and hydroacoustics coincided with the erosion estimates and allowed for the assessment of the conditions during which erosion occurred.

Margin Position

GPS surveys along a standardized segment at each site were conducted near the beginning and ending of the field component of this study. The initial surveys were conducted during December 2011 at PO and RK and during March 2012 at DW, BB, and CW. Ending surveys were conducted during February 2013 at all sites. The changes over those time periods were normalized to meters per year of margin change (table 2). At all sites, portions of the segments had little to no change while at other portions, erosive change exceeded 2 m horizontally. Average changes across all segments were between 0.3 and 0.8 m. The mean change estimates were lowered in some locations because of hardened structures within those segments such as a sea wall at PO and locations where large trees were present that proved to be less likely to show change over the interval observed, although many trees have been uprooted and toppled in many instances along the study margins. These average estimates of change (along with other results below) are presented alongside the estimates obtained from Jackson (2006) for the same locations albeit over somewhat longer segments (zones). The Jackson (2006) study derived estimates from historical aerial photography and other data sources, as well as those summarized to include the time period during 1983 to 2002, were used herein for comparison purposes. The estimates obtained in this study were collected with a much greater degree of precision (millimeters or centimeters) compared to the estimates made through photo analysis (meters or greater) and were for a constrained time period that likely did not include as high a degree of perturbations and variability as over the 20-year time span of Jackson (2006).

Standard Bank Pins

As was seen with the GPS survey estimates of margin change, values for the annual erosion detected by use of the standard bank pins ranged from no discernable movement to greater than 2 m (table 2) out of the 93 pins that were installed. Furthermore, variability in erosion rates measured by standard bank pins was quite similar among sites, with standard deviations (SD) ranging from 0.35 to 0.54 m/yr. The SD among erosion rates estimated by GPS surveying ranged from 0.36 to 0.80 m/yr. Erosion rates at RK have the greatest SDs for both measurement approaches. Agreement between the averages and maximums for the two techniques was generally within 0.5 m. The strong agreement between the mean and median of these results indicates that the pins that underwent little to no change or those that indicated the highest levels of erosion were not skewing the summary results. This difference was approximately the same when compared to the Jackson (2006) study for these locations except in the cases of DW and RK, where the estimates in this study were on the order of one-half (or less) of those presented in the Jackson study (table 2).

Table 2. Summary of Real-Time Kinematic (RTK) segment surveys of horizontal position change and standard bank-pin measures, Cumberland Island National Seashore, 2011–2013.

[The estimates from Jackson (2006) are from corresponding zones; in the cases of DW and RK, these were the same zones. Units are normalized to meter per year. N/A, not applicable]

Site	RTK repeat surveys (2011–2013)			Standard bank-pin measures (2012–2013)					Estimates of erosion from Jackson (2006)
	Minimum	Maximum	Mean	Number	Minimum	Maximum	Mean	Median	
Cumberland Wharf (CW)	0	1.41	0.25	N/A	N/A	N/A	N/A	N/A	1.87
Brickhill Bluff (BB)	0	1.99	0.47	21	0.08	2.50	1.00	0.87	0.50
Plum Orchard (PO)	0	1.94	0.26	33	0.01	2.19	0.72	0.63	0.65
Dungeness Wharf (DW)	0	2.40	0.37	41	0	1.71	0.59	0.68	1.90
Raccoon Key (RK)	0	2.34	0.77	18	0.32	2.27	1.00	0.86	1.90

Photo-Electronic Erosion Pins

Performance of the PEEPs was highly dependent on factors that prevented full study objectives from being met. Large erosion events, at times, either fully exposed the measurement length of the PEEP or displaced the entire unit, both of which resulted in periods of unmeasured margin position. The PEEPs were also affected by transient ambient lighting conditions during the study that led, at times, to inconsistent voltage outputs and spurious readings. Influences included the western aspect of the sensor installation (based on the north-south alignment of the back barrier), time of day, relative tree canopy shading, and degree of cloud cover. Lighting conditions were most favorable for consistent and interpretable voltage outputs in mid- to late morning when ambient light was developed but not directly shining on the erosion front. Lighting effect was most notable at RK where bioturbation from hermit crabs was widespread and at sites where soils were observed to be composed of more clay and organic material and less sand (RK and PO). The margin heights at RK and PO were much lower in elevation with respect to the high tides, resulting in more frequent inundation of the sensor locations. Interference in PEEP readings was caused by an erosional widening (between visit intervals) of the cored hole in which the sensor was installed—through channeling of the daily tidal inundation—allowing light to enter the gap between soil and sensor, skewing the apparent position. In addition, the tidal submergence of the erosion margin at RK created differential lighting through the water during those periods that also affected the consistency of the voltage outputs of the PEEPs. Many of the limitations to these instruments were noted by Bertrand (2010). In order to derive comparable datasets, a time window was established that was site specific, and the average output from the sensor was arithmetically averaged over that time period to reflect the margin position for a given day. This resulted in reduced ability to discretize events from the expected 2-minute data series to a wider 24-hour period.

Physical measurements were taken of the exposed PEEP lengths during site visits to verify the continuous records collected during that time. A correction was then applied to the continuous data to obtain final estimates of erosion when the margin had been eroded past the measurement length of the PEEP. Data were processed based on every site visit and verification measurement; an additive record at each site for each of the two installed PEEPs (P1 and P2) and for standard bank pins placed near PEEP locations can be seen in figures 4*A–D*. Where displacement events were observed and the original cored hole was fully eroded, the total length of the PEEP became the correction value. The final record should be viewed as a conservative estimate of the total erosion that occurred for a given PEEP based on the conclusion that more erosion likely occurred than what was observable. Relative percent differences between the PEEP values at the time of a site visit and the actual measured values varied across sites and by instrument (table 3). Positive and negative estimates of variability likely were, in part, the result of the previously mentioned observation of installation hole widening at the margin surface and the various interferences from lighting conditions. Through analysis of standard erosion pins that were placed near the locations of the PEEPs and at coincident elevations, the corrected PEEP values for total erosion over the course of the study show general agreement across all of the sites (table 3; figs. 4*A–D*). Data from the standard bank pins present an improved visual estimate of erosion over time because the bank-pin data are free from the additive corrections necessary for data from PEEPs. Figures 4*A* (BB), 4*C* (DW), and 4*D* (RK) illustrate how both PEEPs and the respective adjacent erosion pins track over the course of the study. In contrast to the graphs for these sites, figure 4*B* (PO) highlights the disparity in erosion between the north and south PEEPs and the corroboration with adjacent erosion pins.

The continuous margin position data indicate that the four sites had differing erosion patterns. An estimation was made to determine rates of change that were the result of rapid movement of the margin versus that of a much more gradual nature.

Table 3. Measurement summaries from Photo-Electronic Erosion Pin (PEEP) instruments (two per site), percent differences from physical measures, and summary of near-PEEP standard bank pins, Cumberland Island National Seashore, 2011–2013.

[Values for estimated gradual change are estimates of the percentage of erosion attributed to gradual erosion rather than punctuated events. mm, millimeter; m, meter; %, percent]

Site	PEEP change per day (mm)		PEEP change per year (m)		Difference between uncorrected PEEPs and measured value (%)		Change per year at near PEEP standard bank pins (m)	Estimated gradual change (%)
	P1	P2	P1	P2	P1	P2		
Brickhill Bluff (BB)	1.8	2.8	0.67	1.01	19	31	0.86	4
Plum Orchard (PO)	4.8	2.0	1.77	0.72	28	41	1.62	15
Dungeness Wharf (DW)	3.0	3.8	1.09	1.37	24	8	1.31	3
Raccoon Key (RK)	1.7	1.9	0.62	0.71	10	4	0.53	55

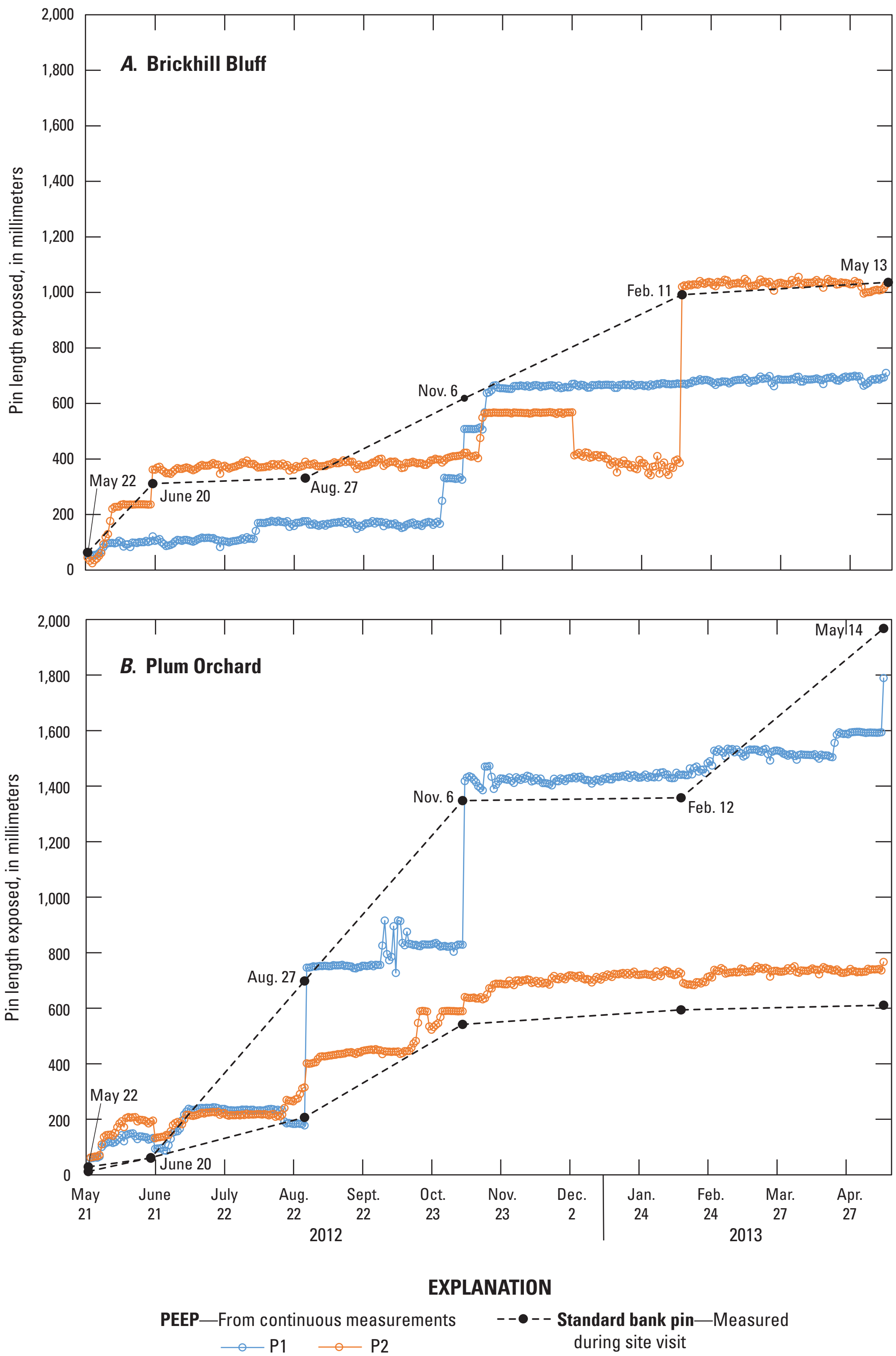

Figure 4. Measured exposed Photo-Electronic Erosion Pin (PEEP) lengths and standard bank pins at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); *C*, Dungeness Wharf (DW); and *D*, Raccoon Key (RK), Cumberland Island National Seashore, 2011–2013. Large changes mostly reflect correction of record from displacement events that occurred between site visits. Data loss for RK was caused by malfunction of P2 from March 2013 to end of record.

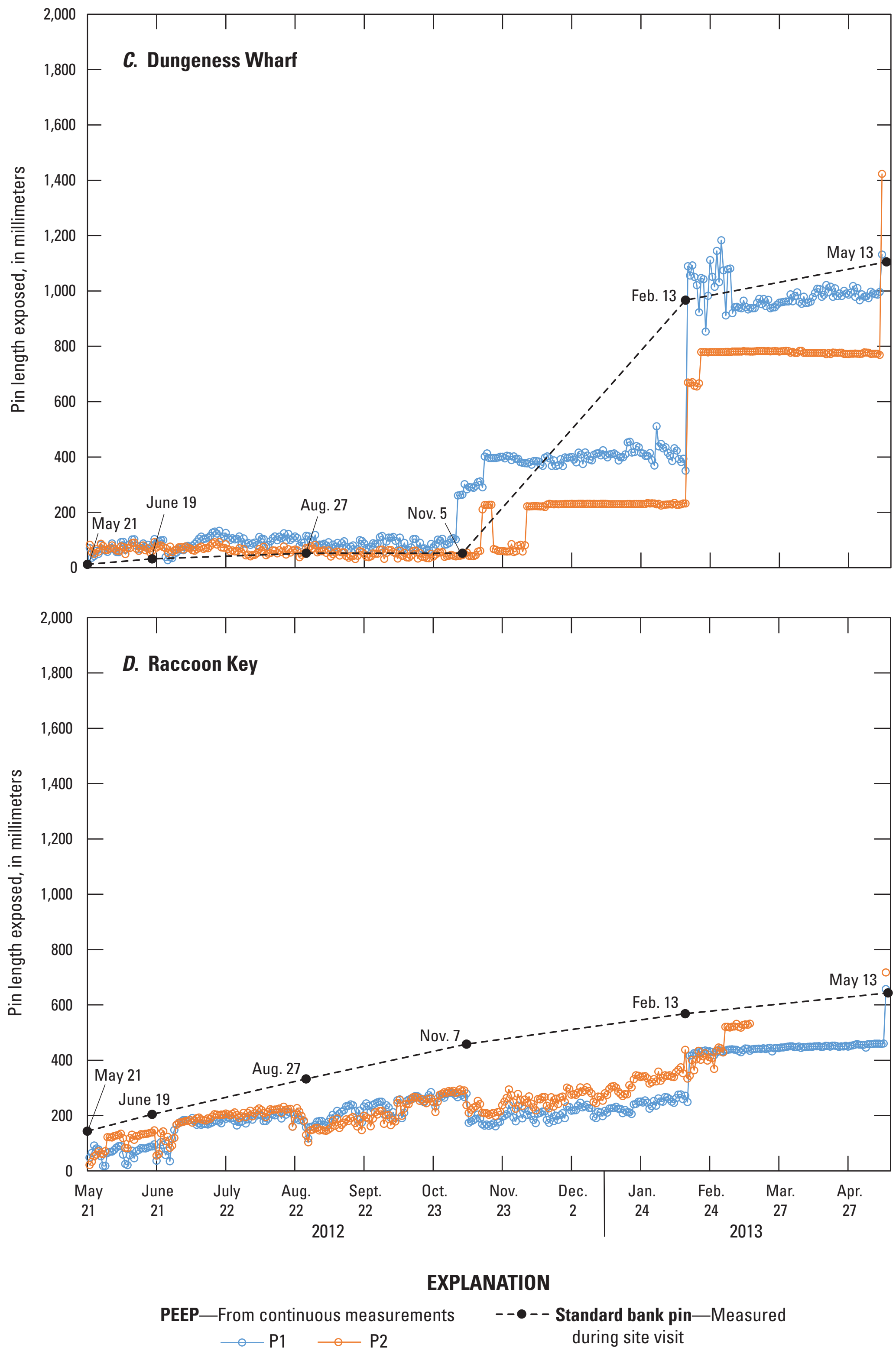

Figure 4. Measured exposed Photo-Electronic Erosion Pin (PEEP) lengths and standard bank pins at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); *C*, Dungeness Wharf (DW); and *D*, Raccoon Key (RK), Cumberland Island National Seashore, 2011–2013. Large changes mostly reflect correction of record from displacement events that occurred between site visits. Data loss for RK was caused by malfunction of P2 from March 2013 to end of record.—Continued

Periods of PEEP measures that did not discernibly experience abrupt changes were used (through linear regression) to obtain estimates in change per day attributable to influences that may be ongoing, such as daily tidal fluctuations or material loss through wind or rainfall on the face of the erosional scarp. Two differing patterns of erosion were seen between RK and DW. The RK site appears to be undergoing a gradual and consistent erosion showing little response to storm events that occurred. The DW site, however, underwent periods of no change in margin position that were punctuated by significant displacement events. The PO and BB sites had characteristics of both types of responses, but were also dominated by displacement events. Gradual erosion at BB and DW is responsible for approximately 4 and 3 percent, respectively, of the change measured during the study period—based on the average total change recorded by two PEEPs at each location (table 3). At PO and RK, gradual erosion was responsible for approximately 15 and 55 percent, respectively, of the total erosion.

Hydrodynamics and Meteorological Factors

Where short-term changes could be discerned from the continuous PEEP data, continuous data from the measurement of tidal height from the pressure transducers and from meteorological readings from the Sea Camp gage (fig. 1) were used for comparison with the continuous measure of erosion. The large displacement events in the continuous record of the PEEPs seen in figures 4*A–D* are primarily the result of the corrections that were made to the data upon site visit (as previously mentioned). The actual material displacements—and occasional data loss—occurred earlier in the record than can be readily noted in the graphs because the ability of the sensor to record the change was compromised when that change exceeded the 0.25-m measurement length of the photodiodes. Essentially, when the sensor data show no change in the graphs, all of the PEEP photodiodes were fully exposed and therefore no longer measured the erosional margin. When abrupt downward shifts or highly variable day-to-day data were recorded, the sensor was displaced and likely was buried under the collapsed apron of eroded material from above.

Single storm events occurred over the course of multiple days at BB, PO, and DW, and figure 5 includes tidal-height, wind-direction, and wind-speed data. Wind speeds not illustrated were less than 10 kilometers per hour (km/h) and were not expected to generate appreciable wind-driven wave heights. The elevation at which the base of the scarp has been exceeded by the tidal height is illustrated in the graph. The events at BB and DW occurred over the same period of time. Substantial erosion appears to be occurring when multiple factors coincide, such as when tidal height is above the base of the scarp and high sustained winds, primarily from a southwest to northwest direction, occur. This effect is particularly the case at DW where once tidal cycle reaches sufficient height, interactions of the wind-driven waves with the unconsolidated soils that make up the margin produce infrequent but abrupt events of material loss. Although only one erosional event is included in figure 5 for each of the three sites where abrupt changes were noted, there were approximately three other episodes during the continuous records where the largest portion of change was seen. Unfortunately, these events seemed to have occurred soon after site visits took place, resulting in situations where the timing of the event was known, but full quantification of the exact sequence of events was not possible.

Readings from the installed transducers were used to determine where tidal cycle corresponded to measured erosion. From RTK surveys of elevation of the transducer location and elevation of the base of the four study margins, it was possible to determine when, how often, and for what duration the tidal cycle surpassed the point at which direct effects would be predicted to occur. Direct effects could take the form of removal of consolidated material or removal of material that had collapsed from above when unsupported by previous erosion events. Comparative results for the percentage of time at a site that tides exceeded the base of the margin are included in table 4. By using the tidal data collected at each site during this study and the projected rate of increase in relative sea level of 1.8–5.9 mm/yr (Intergovernmental Panel on Climate Change, 2007), it was possible to project the percentage of time that the base of the current erosional margin at each of the monitored locations would be inundated by daily tidal sequences (table 4).

Table 4. Exceedance percent of tidal record above base of erosional margin for current conditions and those based on projections of increases in relative sea level under two scenarios, Cumberland Island National Seashore, 2011–2013.

[Low projection from Intergovernmental Panel on Climate Change (IPCC; 2007); high projection from Rahmstorf (2007); m, meter]

Site	Percent exceedance		
	Tide above margin base	IPCC low projection 0.2 m	Rahmstorf high projection 1.2 m
Brickhill Bluff (BB)	7	16	54
Plum Orchard (PO)	15	25	61
Dungeness Wharf (DW)	0.5	3	45
Raccoon Key (RK)	42	49	90

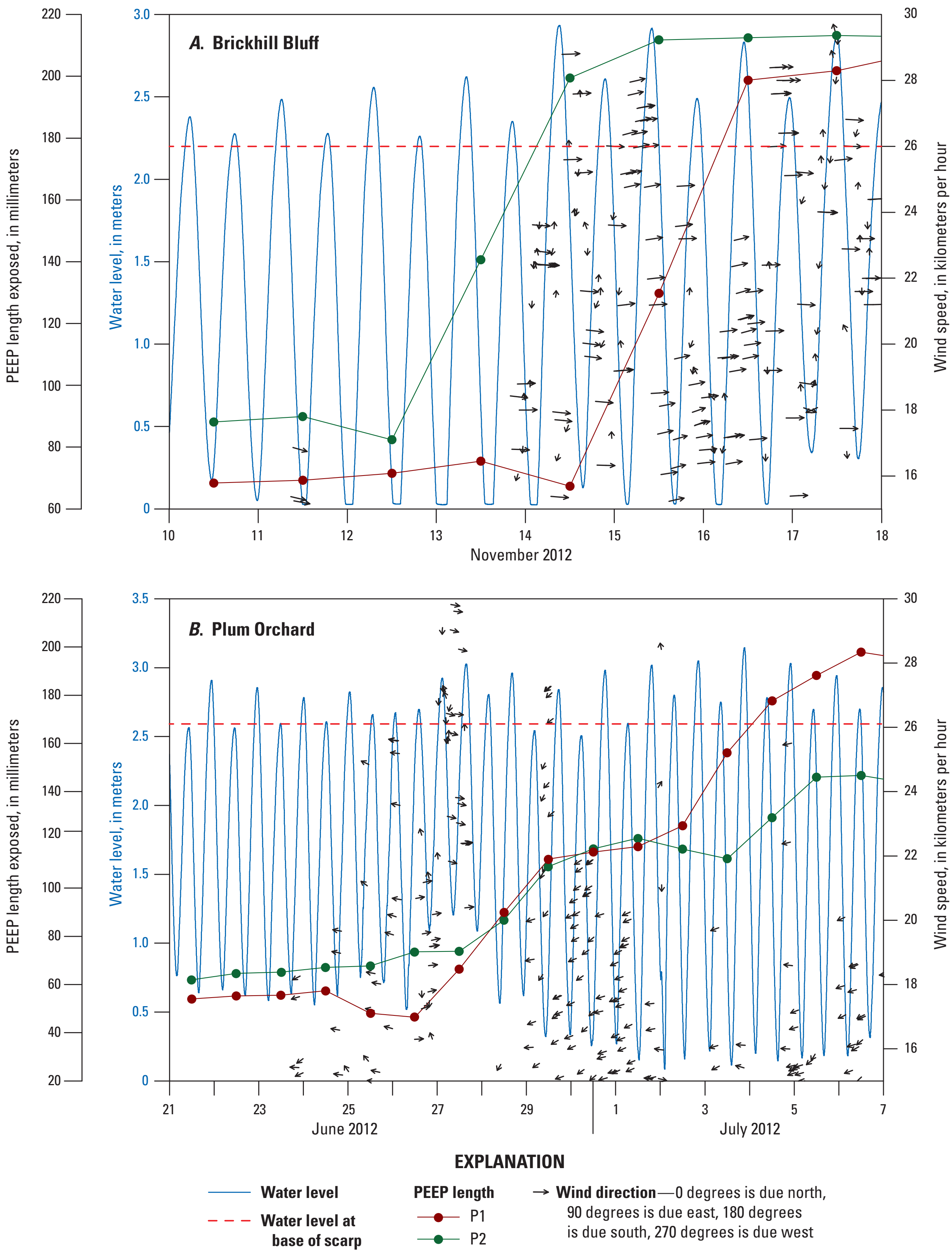

Figure 5. Continuous measurements of exposed Photo-Electronic Erosion Pin (PEEP) length, tide level, wind direction, and wind speed at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); and *C*, Dungeness Wharf (DW), Cumberland Island National Seashore.

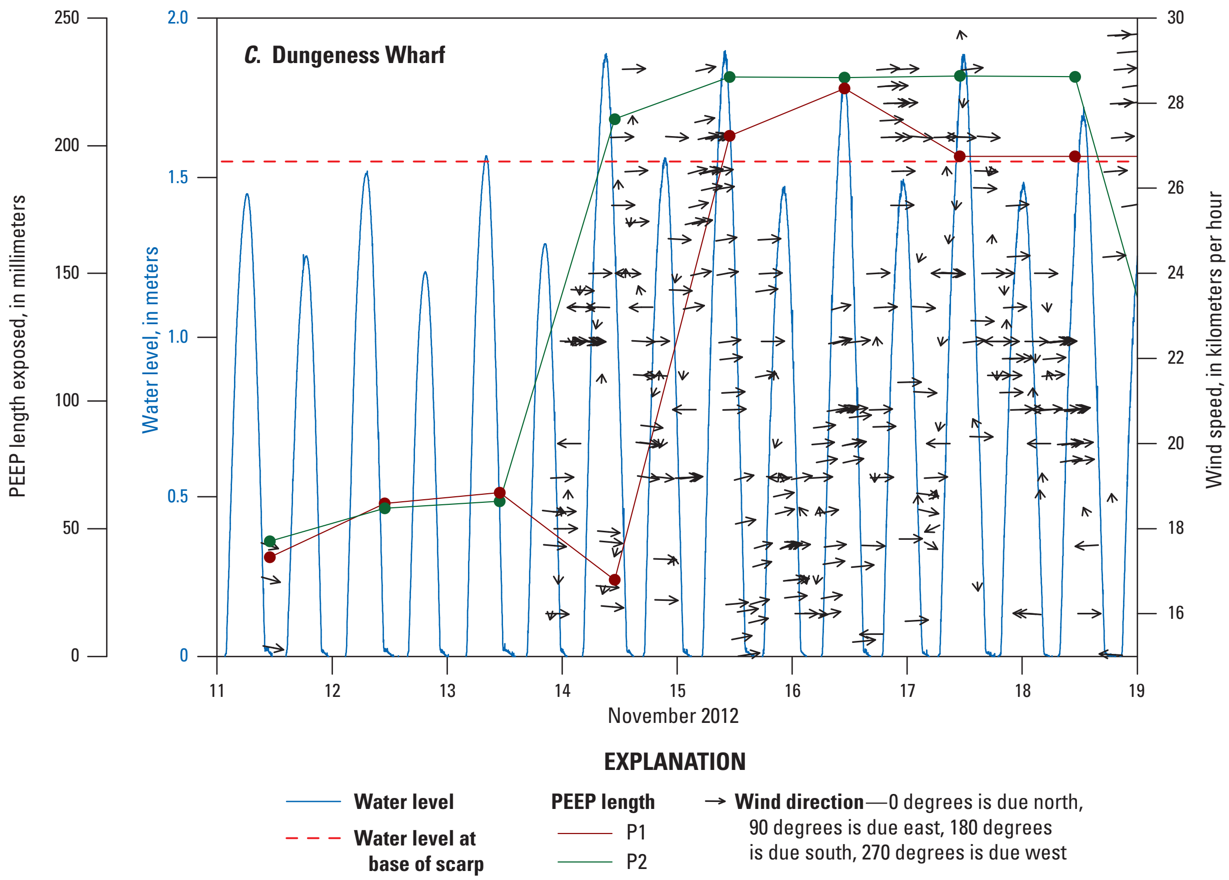

Figure 5. Continuous measurements of exposed Photo-Electronic Erosion Pin (PEEP) length, tide level, wind direction, and wind speed at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); and *C*, Dungeness Wharf (DW), Cumberland Island National Seashore.—Continued

Hydroacoustics

Wind-driven wave energy produced the vast majority of the sound recorded through the hydrophones. In an effort to focus analysis on boat sound, a frequency window between 180 and 330 Hz was selected based on individual sound recordings at sites that were manually scanned. The types of boats passing installation locations produced sound that primarily was contained in this frequency band. Boat passage was apparent in the daily sound files and generally lasted between 15 seconds for small vessels and 3 minutes for those that, by inference, were larger. Wind sound itself was readily recorded at frequencies below 200 Hz, and the majority of the energy detected from waves striking the sensor at the lower tides was generally above 500 Hz. The daily average sound intensity recorded at BB, PO, DW, and RK during the study is included in figure 6. The scale of the sound intensity is in decibels relative to the full scale (dBFS) of the device's configuration (0 to 4,000 Hz) before sound waves are clipped, therefore, the recorded values are based on the reference of the hydrophone and are in logarithmic units. The difference between a −50 dBFS value and that of −40 dBFS value is a ten-fold increase in magnitude according to a power ratio. The annual plot of the daily average sound intensity shows a general pattern of elevated sound in the spring and summer, decreased sound in the fall and winter, then elevated sound again in the spring. The general levels of increased sound were likely associated with boating traffic. Sound levels within the frequencies analyzed (between 180 and 330 Hz) at RK and PO were consistently higher than at the other sites, especially during the summer months (fig. 6). A longer period of acoustic record along with a more sophisticated method of distinguishing among the various sources of acoustic energy could be used to better characterize any general pattern or differences among these sites over seasonal scales.

In the effort to further discretize the acoustic data, averaged 2-minute sound data were filtered to reflect only time periods where the water level was above the base of the erosion margin at each site (table 4). The sound window was opened to the full frequency spectrum that was recorded (0–4,000 Hz) to allow more sound intensity spread between background noise and sounds of interest (figs. 7*A*–*D*). As was noted in relation to the daily average overlays, seasonal patterns of sound emerge, although at DW no pattern was discernible because of the limited time during which the erosional margin was inundated (approximately eight times

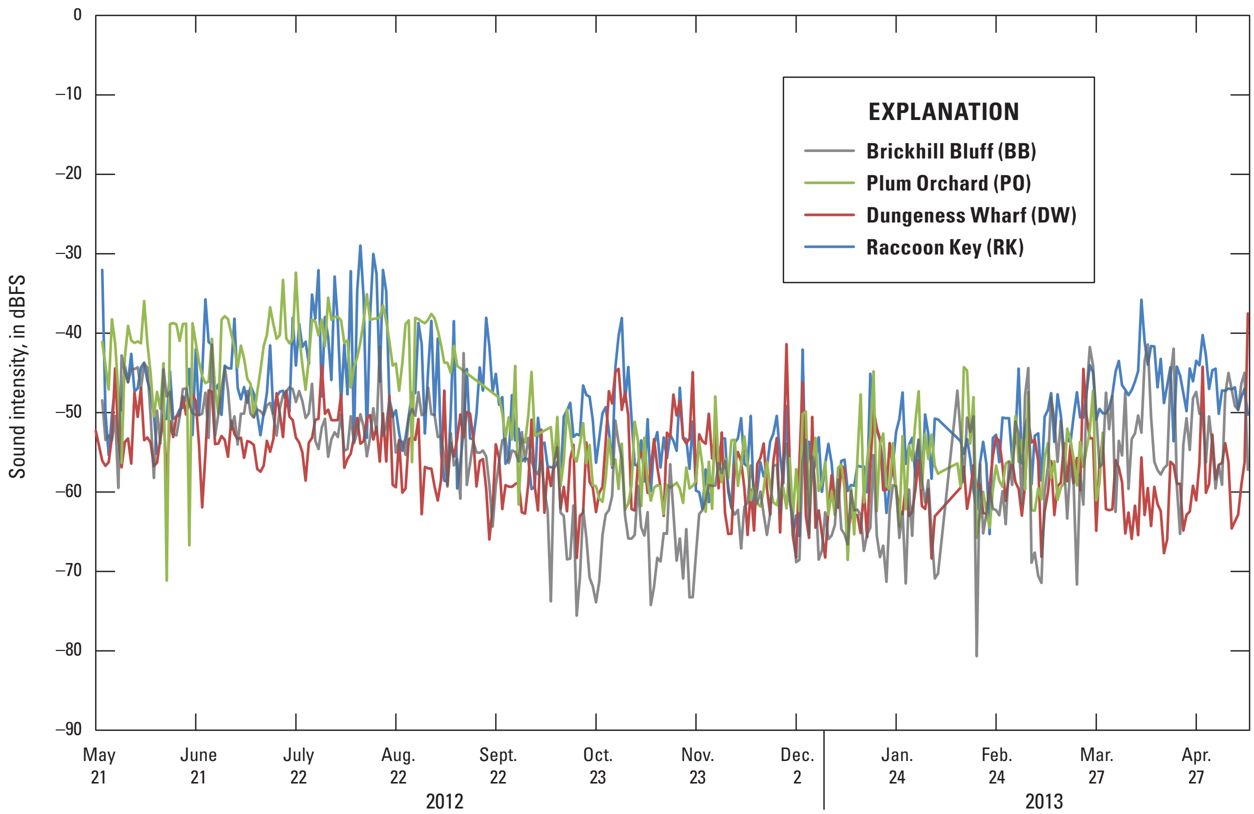

Figure 6. Daily average sound intensity in the 180–330-hertz frequency band, in decibels relative to full scale (dBFS) at four Cumberland Island National Seashore study sites, 2011–2013.

during the course of the study, or less than 1 percent of the time). Sustained sound intensity was highest in late spring to summer and lowest during the winter months. Individual data points in the 2-minute data that appear as outliers with a higher intensity than the majority of data during a given time period were found, in general, to represent boats when manually evaluated. In some cases, the 2-minute data captured the full time period of an individual boat passage—such as when a small boat was recorded—and in other cases, the boat passage exceeded many 2-minute periods of time—such as when larger vessels were in the more open waters off of RK. When data appear grouped together and sequential, sound was usually from storm tides affecting the island margin or high intensity rainfall impacting the water surface.

In one case, where high sound intensity was noted during mid-August at the PO site (fig. 7*B*) and little to no climatic events were detected, one of the largest erosion events was recorded by PEEP 1 (fig. 4*B*). This event indicated the possibility of some correspondence between boat activities and the observed erosion at this time. When the sound data were further scrutinized manually during this period, considerable boat activity was noted near the point of erosional change. A gully-like feature began to form at this position near PEEP 1 after this erosional event and proceeded to extend inland at an increased rate with respect to PEEP 2, as can be seen in figure 4*B*. This resulted in a large disparity—double the estimated erosion—between the two instruments.

In late October and early November 2012, a series of meteorological events (figs. 5*A* and 5*C*) was associated with much of the erosion that was recorded during this study. During this time, the hydrophones recorded periods of increased high sound intensity (figs. 7*A* and 7*C*). Through manually listening to the sound recordings, it was apparent that the sound primarily was caused by wave strikes and elevated winds and rains. Little boat activity could be detected during these periods.

The RK site appears to be experiencing a greater combination of boat traffic and wind and wave energy compared to the other sites (fig. 7*D*). Boat passage is more detectable at RK because the margin is inundated by tides for a longer period of time and because the site is near Cumberland Sound where frequent boat traffic is generally present. The large disparity between the beginning and ending of the data record at PO is difficult to interpret but suggests that a comparatively larger variability in conditions exists over the year along that segment of the Brickhill River. Further north along the Brickhill River, the sound data at BB indicate that during times of margin inundation (only about 7 percent of the time), boat passage was less frequent than at the other sites. As was noted earlier, sound departures from normal conditions appear to be associated with rainfall and elevated tides across the data record; boat passage during times of storm events was not readily discernable because of the high sound intensity of these events.

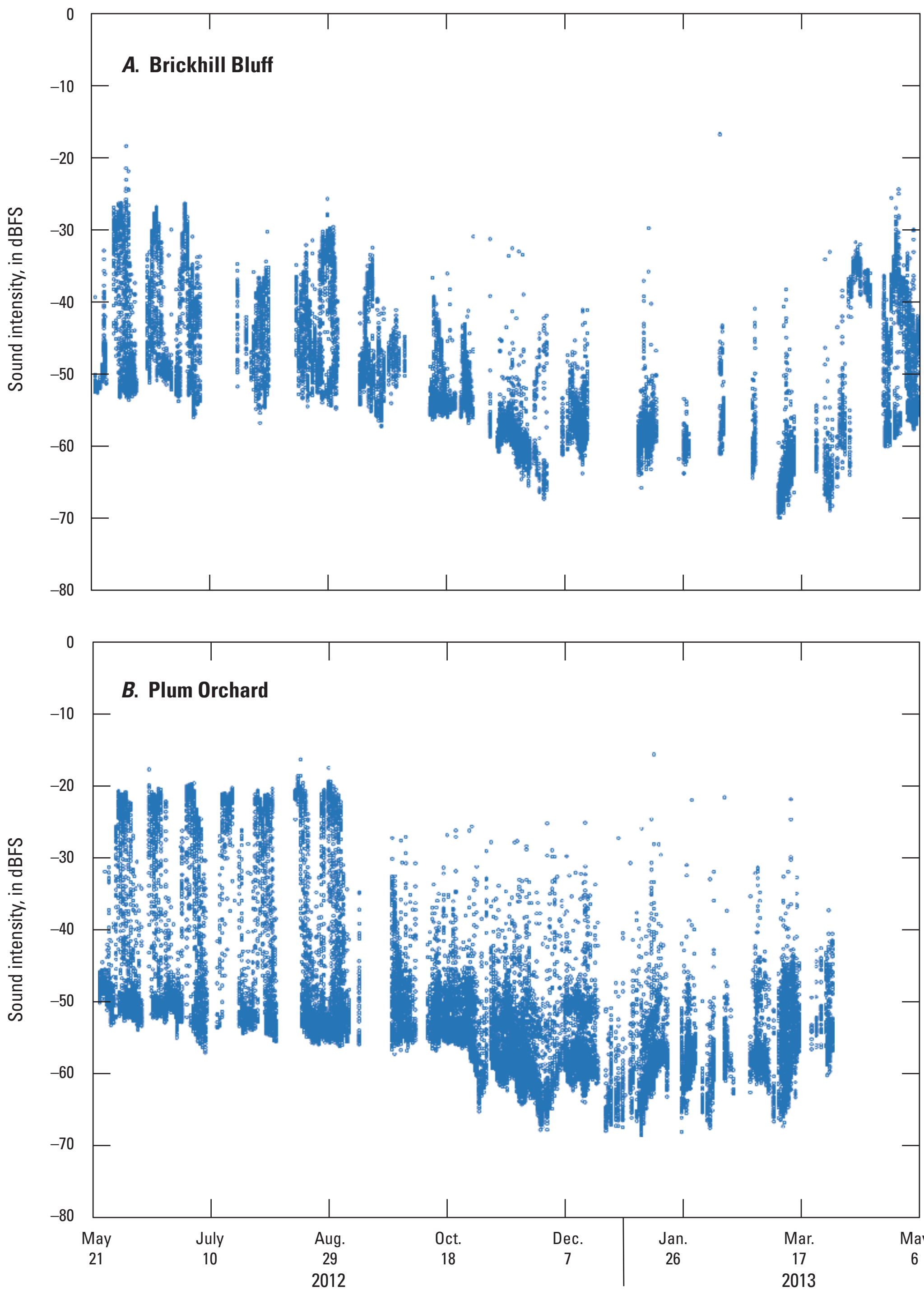

Figure 7. Average 2-minute sound intensity in the 0–4,000-Hz frequency band, in decibels relative to full scale (dBFS), during times of bluff margin inundation at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); *C*, Dungeness Wharf (DW); and *D*, Raccoon Key (RK), Cumberland Island National Seashore, 2011–2013.

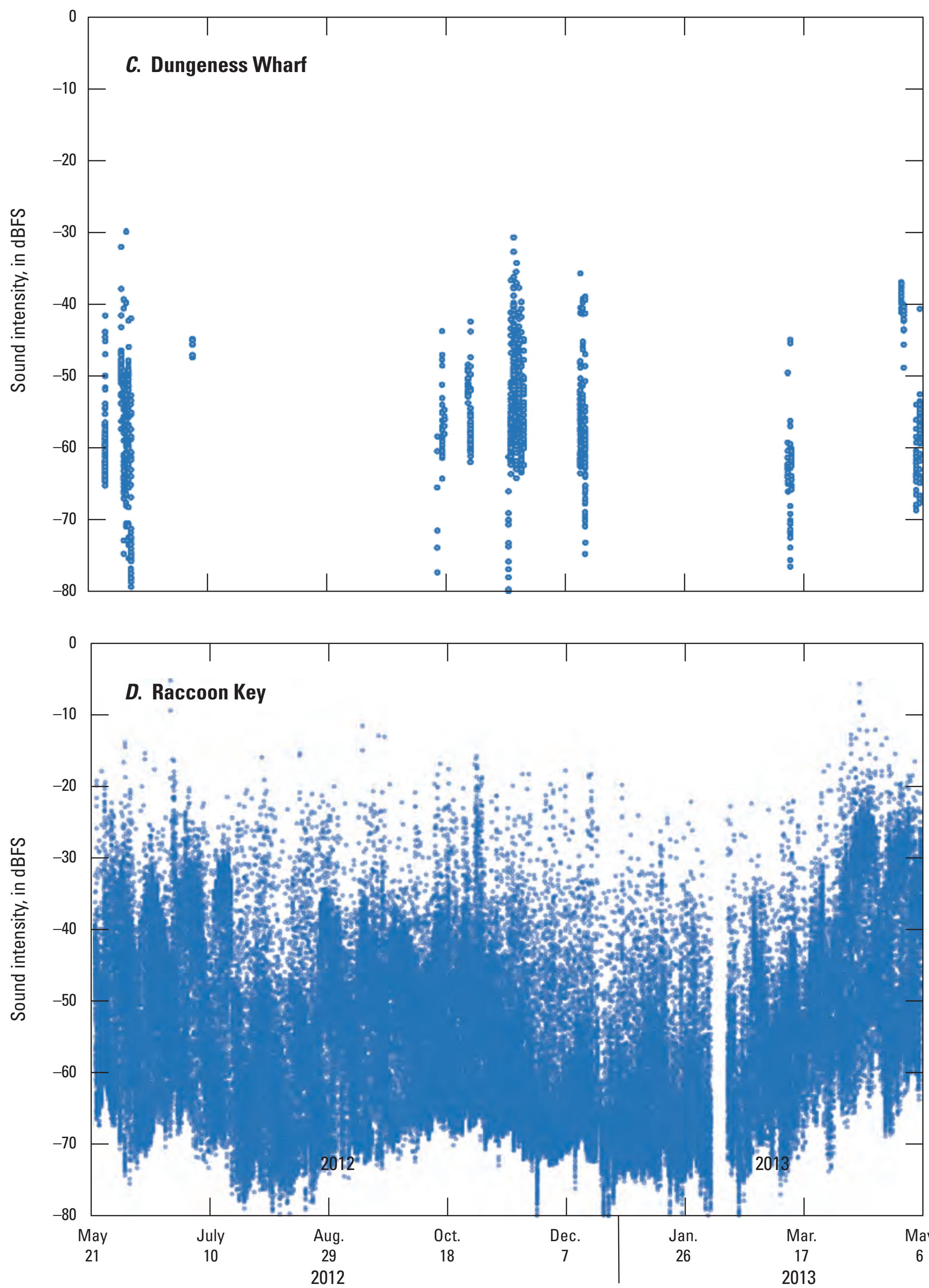

Figure 7. Average 2-minute sound intensity in the 0–4,000-Hz frequency band, in decibels relative to full scale (dBFS), during times of bluff margin inundation at *A*, Brickhill Bluff (BB); *B*, Plum Orchard (PO); *C*, Dungeness Wharf (DW); and *D*, Raccoon Key (RK), Cumberland Island National Seashore, 2011–2013.—Continued

Even though an automated or manual methodology to reliably separate individual boat passages from other sources of sound recorded at the CUIS sites was outside the scope of this study, some general comparisons can be made between boat traffic and measured erosion. Among all the sites, the highest degree of boat traffic and the highest degree of margin retreat were measured at RK (table 2). The correspondence between increased boat traffic and erosion is confounded, however, because RK had the greatest degree of exposure to wind-driven waves out of all of the study sites, and the site was inundated by tides almost half of the study period. Also, erosion was uneven along the margin at RK, indicating that the erosion there could be subject to other factors such as the configuration of the margin. At PO, the opposite occurred; the sound data indicated considerable boat traffic, mostly in the fall and winter, but the PEEP-measured erosion at PO was lowest during that period (fig. 4*B*). No relations were apparent between the time periods of increased erosion and higher than average boat traffic at BB (fig. 4*A*) and at DW (fig. 4*C*).

Projections of Future Shoreline Positions

When using the erosion rates observed in this study to extrapolate future shoreline position, results indicate an average retreat (across all monitored locations) of 15 m by 2050 and approximately 37 m by 2100. The projected positions of these margins—overlying aerial photographs of the locations—are included in figures 8*A–E*. As stated previously, these values should be interpreted cautiously, should be used only for assessing potential vulnerability, and should not be viewed as absolute positions because the rates are likely spatially and temporally variable. To put these erosion rates into a wider context, the rates were compared with those in corresponding zones in Jackson (2006). When compared to long-term retreat estimated by averaging the long-term erosion rates (about 132 years) of each zone reported in Jackson (2006), mean retreat in the Jackson study is quite similar to the results of this study, with a margin retreat of 15 m and 35 m, respectively, over the 37- and 87-year periods that correspond to 2050 and 2100, respectively. While the results of this study are in agreement with past observed retreat, the dynamics that are likely responsible and even discrete locations of erosion within these zones have likely shifted over time as promontories have eroded and energy has been shifted laterally across the margin face. Erosion rates measured in the present study are similar to those estimated over much longer time periods and may represent change during average and ongoing conditions.

Discussion

Based on the data recorded by the PEEPs, storm-driven erosion was the dominant factor of change for three out of the four instrumented sites at CUIS (with Raccoon Key [RK] being the exception). Relatively large-scale slumping resulting from storm events was estimated to account for 85 to greater than 95 percent of the observed erosion. The remainder of the erosion measured (5 to 15 percent) can be attributed to factors such as bioturbation, rain falling on the face of the margins, and (or) wind forces gradually removing the material. The margin of RK is the feature not showing indications of storm-driven erosion. The matrix at RK is composed of dense organic-rich sand and clay topped by peat and was observed to be much more resistant to punctuated erosion than the sand-dominated matrices of the three other locations. However, evidence for erosion was present, as collapsed peat blocks were routinely observed along the segment at RK where they remain largely intact for extended time periods along the strandplain after failure. These blocks appear to fail after gradually being undercut by the daily tidal cycle. The RK site has the lowest profile relative to incident tidal action, providing less of a physical barrier to wave action than the other sites.

Plum Orchard (PO) is higher in profile than RK but is considerably lower with respect to tidal interaction than the scarps at Dungeness Wharf (DW) and Brickhill Bluff (BB). The PO site also has a matrix composed of clay and organic material in addition to sands but does not resist large-scale perturbation over the time measurements made for this study. Some of this lack of resistance could be attributable to surficial runoff from the upland or possibly induced by boat wakes. Hydrophone data did not consistently indicate that erosion was occurring during periods when boat wakes were prevalent; however, periods of missing record do not preclude this happening during hydrophone malfunction. As previously described, the gully-like feature that began to form in the middle of the intensely studied portion of the erosional feature at the PO site was potentially related to upland runoff and not wave or tidal action. Because this study was not designed to address the possibility of upland sources of fluvial erosion, the origin of the gully was not examined. The position of the gully did correspond to some of the largest changes to the erosional scarps studied at PO.

A conceptual model showing a latitudinal cross section of erosion at work along an ocean-fronting margin is shown in figure 9 (modified for Riggs and Ames, 2003). This concept can be applied to a back barrier with the understanding that the strandplain feature and accompanying sediments that play a role on the ocean-fronting margin can be largely absent from the back barrier of a regressive barrier island that does not have a steady supply of material from estuarine sources. Survey measurements taken in this study indicate that the current high-tide shoreline is often at the base or higher than the base of the wave-cut scarp. The percentage of time that this occurred during the year of data collection is included in table 4. The DW and BB sites have low percentages of steady erosion (table 3) and also the least amount of time where tidal level is above the wave-cut scarp. Longer periods of inundation of the erosional scarp appear to coincide with more gradual but steady erosion. Increases in the duration of inundation (as presented in the projections of increases in relative sea level in table 4) could then be expected to further exacerbate the current non-storm related processes.

Figure 8. Shoreline position in 2013 and projected erosional margins for years 2050 and 2100 along the *A*, Cumberland Wharf (CW) study segment; *B*, Brickhill Bluff (BB) study segment; *C*, Plum Orchard (PO) study segment; *D*, Dungeness Wharf (DW) study segment; and *E*, Raccoon Key (RK) study segment, Cumberland Island National Seashore. Positions were based on rates of change determined in this study; the 2013 survey is the beginning position. Hardened or armored structures currently in place were not taken into account in these estimations. See figure 1 for locations.

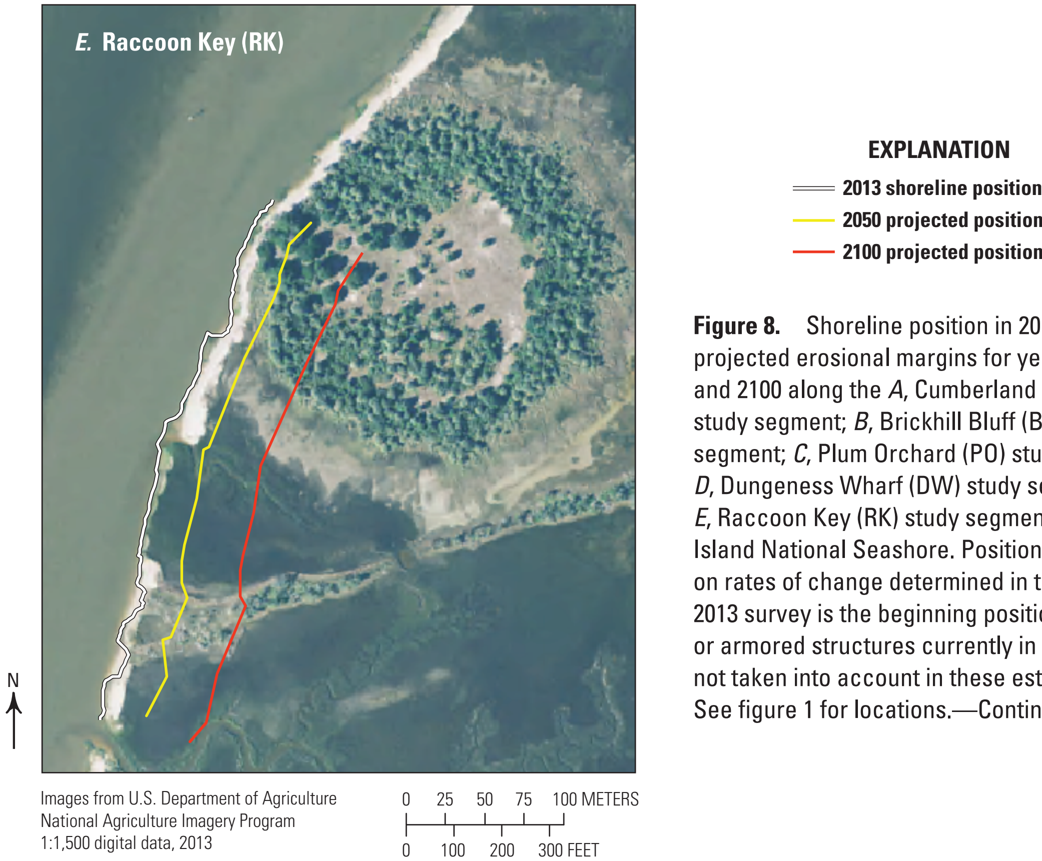

Figure 8. Shoreline position in 2013 and projected erosional margins for years 2050 and 2100 along the *A*, Cumberland Wharf (CW) study segment; *B*, Brickhill Bluff (BB) study segment; *C*, Plum Orchard (PO) study segment; *D*, Dungeness Wharf (DW) study segment; and *E*, Raccoon Key (RK) study segment, Cumberland Island National Seashore. Positions were based on rates of change determined in this study; the 2013 survey is the beginning position. Hardened or armored structures currently in place were not taken into account in these estimations. See figure 1 for locations.—Continued

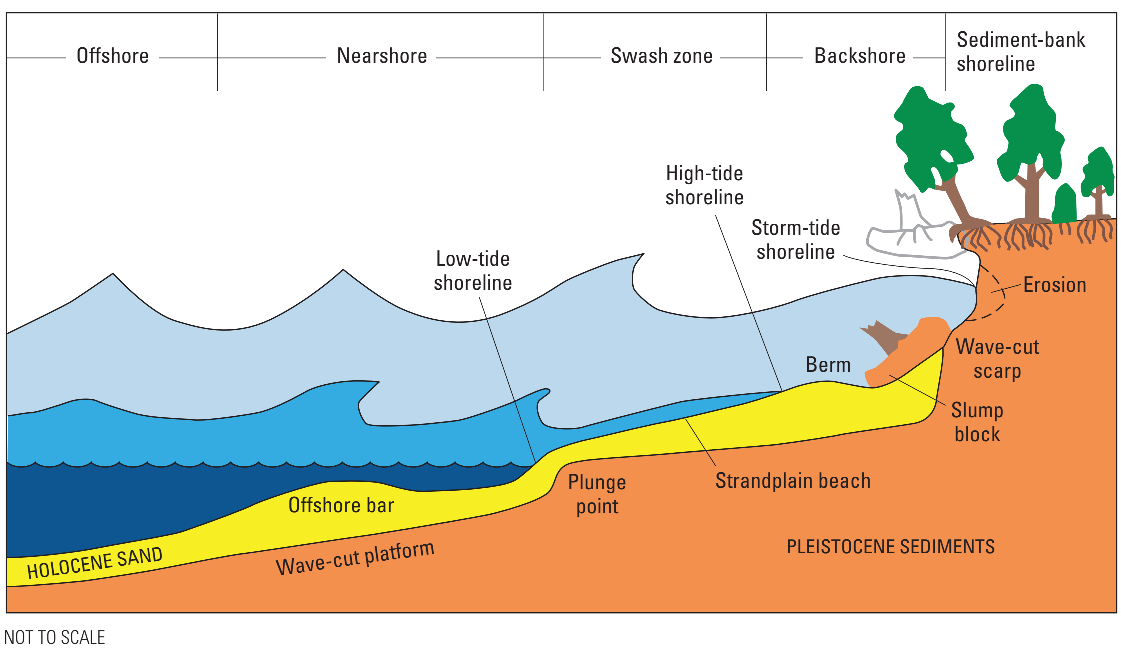

Figure 9. Conceptual diagram of shoreline erosion of a wave-cut scarp (modified from Riggs and Ames, 2003).

Cumberland Wharf (CW) does have an extensive strandplain feature, as is shown in figure 8*A*. The material that forms the strandplain appears to be delivered, at least in part, from the extensive bluff slumping that was observed there. Storm tides appear to be reaching the base of the margin at CW, undercutting the bluff, and leading to further slumping. Continuous measurements were not collected at the CW site, as has been noted above, preventing any attribution of the timing of the change. However, the average annual rate of retreat of the top of the margin (table 2) is close to that measured at DW, which was most similar among the study sites—in both matrix material and profile—to CW.

Given that the application of the data collected in this study to future projections of SLR lacks any process-driven mechanisms, it can be expected that erosional scarps in these locations and at their current positions will experience greater physical forces than they did during this study. A recent study by Tebaldi and others (2012) used data from the Fernandina, Florida, tide gage—among many other gages along the shores of the United States—and projections of SLR to predict that the Georgia coast will be subject to annual storm tides by 2050 that equal what in the past were seen only once per century. As appears to be the case in the current study, a large part of the observed erosion is occurring during the times of tidal surges associated with storm events.

Regardless of the change in relative sea level, future erosion of the back barrier of a complex barrier island will continue to be dependent on multiple factors, including the balance in natural accretive processes. A balance between accretion and erosion would mean no further net erosion, which has been predicted to be possible in some locations under current rates of SLR where storm-supplied material is transferred across a barrier island to fortify its back barrier or where estuarine sources of material are sufficient to balance rates of SLR (FitzGerald and others, 2008). Were erosion rates to become higher, accretive capacity, where this exists, could not be expected to withstand increases in erosive forces. Some areas of long-term accretion to the back barrier of Cumberland Island (CUIS) were noted in the Jackson (2006) study where adjacent estuarine wetlands may be providing both the buffer from erosive elements and material to maintain elevation and vegetative growth and stabilization. Similar findings related to short-term accretion to marsh surfaces have been shown for the southwestern portion of CUIS—coincident with the RK site (Cofer-Shabica and Nakashima, 1992). Hurricane overwash on the south end of CUIS could potentially offset these gains (or magnify them) based on the narrowness of the island at this point and its relatively low elevation, thus leading to inlet formation on the western margin and subsequent geomorphic alteration (Stockdon and others, 2007).

Summary

The five erosional margins selected for the Cumberland Island National Seashore (CUIS) study were found to be undergoing a continual retreat during the period of study. Comparison with data from previous studies suggests that this process has been ongoing for much of the 20th century to present. The annual rate of erosion is coincident with earlier findings that used other less precise techniques to determine long-term changes to the back barrier and ranged from no observed erosion up to 2.5 meters of measured margin retreat. Three of the four sites where continuous measurements were made exhibited large loss of material during short periods of time whereas the fourth, southernmost site, was characterized as having slower but steady erosion during the majority of the study period. High tides and storm-driven tidal surge among other climatic factors are resulting in the punctuated material loss tempered only by the site characteristics, matrix composition, and temporary buffering by collapsed material, falling trees, and peat blocks. The matrix material composing each site as well as the relative height of the margin above the high-tide level appeared to be strong determinants in the erosion that was measured during the study. Results from acoustic monitoring indicated differences in vessel (boat) traffic among the study sites, although attempts to ascribe relative contribution of vessel traffic to rates of erosion were not accomplished. It can be assumed, however, that vessel traffic during periods of high tide increases wave frequency and wave height, exacerbating ongoing erosion, especially at the two sites that were most frequently inundated by tidal sequences.

Under a range of estimates of the position of the relative mean sea level for the remainder of the 21st century, it was projected that the current margin base at the four sites where continuous measurements were made will be inundated by daily high tides from approximately 20 to 90 percent of the time, which would be equivalent to an increase from between 2 and 45 times the duration of current conditions. Using average rates of erosion that were measured during this study, it was estimated that the position of the erosional margin across these locations on CUIS will be approximately 37 meters inland from their current position by the end of the 21st century. These values should be interpreted cautiously, should be used only for assessing potential vulnerability, and should not be viewed as absolute positions because actual erosion rates are likely to vary both spatially and temporally. The challenges of dealing with erosion to the back barriers of islands such as CUIS can be expected to continue into the future and potentially worsen if current rates of sea-level rise increase.

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Appendix 1. Field Calibration Information From In Situ Photo-Electronic Erosion Pins (PEEP)

Table 1–1. Field calibration information from in situ Photo-Electronic Erosion Pins (PEEP) including regression offset (*c*), slope (*d*), and calibration coefficients (r^2), Cumberland Island National Seashore, May 20, 2012.

[RK, Raccoon Key; DW, Dungeness Wharf; PO, Plum Orchard; BB, Brickhill Bluff; S, south installation; N, north installation]

PEEP	Serial number	Offset (*c*)	Slope (*d*)	r^2
RK.N	278	–87.154	3.099	0.983
RK.S	274	–69.664	2.930	0.985
DW.N	269	–4.336	2.289	0.997
DW.S	275	5.062	2.211	0.996
PO.N	273	26.334	2.322	0.999
PO.S	272	20.107	2.148	0.997
BB.N	276	–3.253	2.359	0.999
BB.S	270	23.592	2.164	0.999

Appendix 2. Campbell Scientific Program Used for In Situ Monitoring Instruments During the Back-Barrier Erosion Project at Cumberland Island National Seashore

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'CR800 Series Datalogger
'Program To measure 2 Photo-Electronic Erosion Pin (PEEP) sensor
'Based on program provided by Jason Ritter at Campbell Scientific from
'June 2002
'modified by Jason Ritter CSI 2/22/12; modified by dcalhoun 3/2012 for
'2 min data, 1 hour table2

'Multiplexer wiring (AM16/32B in 4x16 mode)
'12V To 12V
'GND To G
'RES To C1
'CLK To C2

'COM ODD H To SE1
'COM ODD L to SE2
'COM EVEN H To SE3
'COM EVEN L To SE4
'COM Gnd To G

'PEEP200 sensor To AM16/32
'AM16/32 channels 1-4
'Diode 1 Yellow To H1
'Diode 1 Blue To SHIELD
'Diode 2-19 Red To L1
'Diode 2-19 Black To SHIELD
'Diode 20 Green To H2
'Diode 20 White To SHIELD

'Note that each SHIELD channel will have three wires going to it

'PEEP200 sensor To AM16/32
'AM16/32 channels 5-9
'Thermistor TH1 Brown To H1
'Thermistor TH1 Violet To L2

'Thermistor TH2 Orange To H2
'Thermistor TH2 Grey To L2

'Two half bridge circuits are employed, both use E1 on the datalogger
'AND single ended channels 1 AND 3.
'VX1 (EX1) 1kOhm resistor to 1H (SE 1)
'VX1 (EX1) 1kOhm resistor to 2H (SE 3)

'Declare Public Variables
Public PTemp, batt_volt
Public volt(6)
Public Tvolt(4)
Public R(4)
Public temp(4)
Public CS450Data(2)
Const A = 0.00112797
Const B = 0.000234313
```

```
Const C = 8.69838*10^-8
Dim i
Alias CS450Data(1)=Lvl_ft
Alias CS450Data(2)=Temp_C
Units Lvl_ft=feet
Alias volt(1)=PEEP1_1
Alias volt(2)=PEEP1_2_19
Alias volt(3)=PEEP1_20
Alias volt(4)=PEEP2_1
Alias volt(5)=PEEP2_2_19
Alias volt(6)=PEEP2_20
Alias temp(1)=PEEP1_TH1
Alias temp(2)=PEEP1_TH2
Alias temp(3)=PEEP2_TH1
Alias temp(4)=PEEP2_TH2

'Define Data Tables
DataTable (Table1,True,-1)
  DataInterval (0,2,min,3)
  Average (4,temp(),IEEE4,False)
  Average (6,volt(),IEEE4,False)
  Sample(1,Lvl_ft,FP2)
  Minimum(1,Lvl_ft,FP2,False,False)
  Maximum(1,Lvl_ft,FP2,False,False)
  StdDev(1,Lvl_ft,FP2,False)
EndTable

DataTable (Table2,True,-1)
  DataInterval (0,1,Hr,1)
  Minimum (1,batt_volt,FP2,0,False)
EndTable

'Main Program
BeginProg
  Scan (10,Sec,0,0)
    PanelTemp (PTemp,250)
    Battery (batt_volt)
    'Measure, in loop, 2 PEEP photocell lengths with single voltages
via
    'multiplexer.  each probe has 3 voltage measurements
    PortSet(2,1) 'turn on AM16/32
    i = 1
    SubScan (0,uSec,2) 'Loop to measure 2 PEEPs
      PulsePort(1,10000) 'Advance to next multiplexer channel
      VoltSe (volt(i),3,mV250,1,True,0,250,1.0,0)
      i = i + 3
    NextSubScan
    'Measure, in loop, 2 PEEP thermistor pairs
    i = 1
    SubScan (0,uSec,2) 'Loop to measure 2 PEEP thermistor pairs
      PulsePort(1,10000) 'Advance to next multiplexer channel
      'Measure thermistor voltage in half bridge
```

```
      BrHalf (Tvolt(i),2,mV2500,1,Vx1,1,2500,True ,0,250,2500,0)
      i = i + 2
    NextSubScan
    PortSet(2,0) 'turn AM16/32 off
    'Calculate R and temperature
    For i = 1 To 4
      R(i)=1000*Tvolt(i)/(2500-Tvolt(i))
      temp(i)= 1/(C*(LN(R(i)))^3 +B*LN(R(i))+A)-273.15
    Next i
    'CS450/CS455 Pressure Transducer measurements Lvl_ft and Temp_C
    SDI12Recorder(Lvl_ft,3,"0","M1!",1,0)
    Lvl_ft=Lvl_ft*2.30666

    CallTable (Table1)
    CallTable (Table2)

  NextScan
EndProg
```

Appendix 3. Campbell Scientific Wiring Diagram Used During the Back-Barrier Erosion Project at Cumberland Island National Seashore

Table 3–1. Campbell Scientific wiring diagram for Photo-Electronic Erosion Pins (PEEP) used in the back-barrier erosion study, Cumberland Island National Seashore. Wiring for CS455 transducer, CR850 datalogger, AM16/32B multiplexer, and two PEEP-3T sensors.

[C, communication; CLK, clock; Ex, excitation channel; Gnd, ground; H, high; L, low; SE, single ended; TH, Thermistor; V, voltage]

Resistor bridge	CS455 transducer	CR850 datalogger	AM16/32B multiplexer	Multiplexer jumper color or PEEP wire color	PEEP-3T wire function	Connects to CR850 channel number
		1H	COM ODD L	White		
		1L	COM EVEN H	Blue		
		Gnd	COM ODD H	Yellow		
		2H	COM EVEN L	Green		
		Gnd	COM Ground	Brown		
		Gnd	GND	Black		
		12V	12V	Red		
		C1	CLK	White		
		C2	RES	Green		
	Red	12V				
	Black	G				
	White	C3				
	Blue, yellow, and clear	Gnd				
1kOhm #1		VX1 (EX1)	1H	Diode 1 Blue	Ground	Gnd
1kOhm #1		1H (SE1)	1L	Diode 1 Yellow	Signal	1H (SE1)
			Gnd		Shield	Gnd
1kOhm #2		VX1 (EX2)	1H	Diode 2-19 Black	Ground	Gnd
1kOhm #2		1L (SE2)	2H	Diode 2-19 Red	Signal	1L (SE2)
			Gnd		Shield	Gnd
			1H	Diode 20 White	Ground	Gnd
			2L	Diode 20 Green	Signal	2H (SE3)
			Gnd		Shield	Gnd
			3H	Diode 1 Blue	Ground	Gnd
			3L	Diode 1 Yellow	Signal	1H (SE1)
			Gnd		Shield	Gnd
			3H	Diode 2-19 Black	Ground	Gnd
			4H	Diode 2-19 Red	Signal	1L (SE2)
			Gnd		Shield	Gnd
			3H	Diode 20 White	Ground	Gnd
			4L	Diode 20 Green	Signal	2H (SE3)
			Gnd		Shield	Gnd
			5H	Thermistor TH1 Violet	Ground	Gnd
			5L	Thermistor TH1 Brown	Signal	1H (SE1)
			Gnd			
			5H	Thermistor TH2 Gray	Ground	Gnd
			6H	Thermistor TH2 Orange	Signal	1L (SE2)
			6L			
			Gnd			
			7H	Thermistor TH1 Violet	Ground	Gnd
			7L	Thermistor TH1 Brown	Signal	1H (SE1)
			Gnd			
			7H	Thermistor TH2 Gray	Ground	Gnd
			8H	Thermistor TH2 Orange	Signal	1L (SE2)
			8L			
			Gnd			

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