FROM DUNES TO SHELF DEPOSITS:

A MULTIDISCIPLINARY INVESTIGATION OF COASTAL SAND MANAGEMENT IN NORTH CAROLINA

By

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May, 2019

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ABSTRACT

Coastlines around the world are environmentally and economically crucial to society but are being threatened by storms, sea-level rise and erosion. Beach nourishment is a widely used shoreline stabilization strategy that creates increased storm protection and other physical and economic benefits. This dissertation investigated multiple geologic and economic questions related to the management of sandy coastlines in North Carolina (NC), and work is separated into three chapters addressing different aspects. Using 22 months of terrestrial laser scanning, this research examined the evolution of a nourished, managed versus a non-managed beach-dune system and associated drivers of change. Largely due to anthropogenic factors (e.g., fencing and plantings) and increased sediment supply at the nourished site, the managed dunes accreted 1.7 times faster than the dunes in the unmanaged system. Observations showed storms are not just

erosional, but also can increase overall dune volumes during optimal wind conditions, despite scarping to the dune toe.

As erosion and sea-level rise persist, beach nourishment will continue, if not increase in the future. Because nearshore sand borrow sources may diminish, continental shelf resources may become necessary. This work examined the distribution of potential sand sources offshore southern NC. More than 300 nm (55 km) of sub-bottom, sidescan and core data showed the distribution of modern sand is complex and irregular. Some paleochannels contained viable sediment for beach nourishment, however, variable lithologies in others are not usable as a sand resource. Overall, geologic framework significantly influences the complex distribution of potential sand resources, hardbottom, and paleochannels. Reconnaissance data such as those produced for this study are critical to prevent multi-use conflicts on shelf areas under increasing demand (e.g,. wind, oil/gas).

Nourishment is costly due to comprehensive geologic surveying and engineering practices. The last chapter investigated several communities in northeast NC (Dare County) that have recently used local funding to pay for expensive projects through county-assessed occupancy taxes and municipal service tax districts. Oceanfront homeowners clearly receive the most benefits from nourishment, however this work examined the coastal housing market and homeowner’s responses to nourishment. Results showed inland and soundfront homeowners capitalized on the opportunity to rent due to increased amenity value from nourishment. Increased rentals generate more in occupancy taxes and should be considered by policymakers when developing funding structures and assessing the long-term sustainability of nourishment.

Overall, this research highlights the complexity of several integrated geologic, economic and policy issues on the coast. Coastal managers and planners should incorporate an understanding of these coupled natural and human responses to future management of sandy shorelines.

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A MULTIDISCIPLINARY INVESTIGATION OF COASTAL SAND MANAGEMENT IN NORTH CAROLINA

A Dissertation

Presented to the Faculty of the Department of Integrated Coastal Programs

East Carolina University

In Partial Fulfillment of the Requirements for the Degree

Coastal Resources Management

Primary Concentration in Coastal Geosciences

Secondary Concentration in Economics

By

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May, 2019

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ACKNOWLEDGEMENTS

I would like to thank many people who have helped with this dissertation. Foremost, I can't adequately express my gratitude for my advisors, JP Walsh and Reide Corbett. They each have immense charisma and unique strengths, are excellent scientists, provide many laughs, and ultimately make tedious work much more fun. It is no surprise that they are now in such important leadership roles. I can't thank them enough for providing me with this opportunity, for their patience, and for helping to guide me through.

I would also like to thank my committee. Kate Brodie is such a talented programmer and helped me over countless hours. Dave Mallinson is a fantastic geologist and assisted with the daunting task of seismic interpretation and enlightened me to many different geologic perspectives. Jake Hochard is an economic guru and was an enormous help in exposing me to another discipline that can be so closely tied to geology.

From CSI, I would like to thank Paul Paris, Keith Garmire, Brad Pickens, Trip Taylor, Liz Mason, Marie McGee, Kim Armstrong, Jeff Gottemeyer and Terry Kirby Hathaway. From ECU, thanks to the program director, Sid Mitra, and Dare Merritt, Shelia Ellis, Cindy Harper, John Woods, Jim Watson, Nate Wood and all my fellow CRMers. From the Field Research Facility, thanks to Chief Jeff Waters, and Judy Roughton, Nick Spore, Nick Cohn, Alex Renaud, Kent Hathaway, Pat Dickhudt, Spicer Bak and Heidi Wadman. Thank you to the Town of Nags Head for site use, and the Bureau of Ocean Energy Management (BOEM), the U.S. Army Engineer Research and Development Center (USACE-ERDC) and the Department of Coastal Studies for providing funding for this research.

Finally, none of this would be possible without my parents, John and Kathy, sister Kelly, and my wife, Beth. You are the person to always make me laugh and keep things positive. I have

endless admiration for your joyful and contagious spirit. Thanks for keeping me focused all these years and for making life such a great adventure.

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CHAPTER 1

Introduction

1.0 Research Significance

The coastal zone contains a multitude of resources, ecosystem services and recreational opportunities that are valuable to society. Drawn to economic and other opportunities at the land-sea interface, over half of the population of the United States is concentrated in coastal counties that represent only 17% of the total land area (Bourne, 2006). Developments are often in low elevation regions that are susceptible to the powerful forces of the ocean and storm-induced flooding. Despite a multitude of risks and hazards, coastal populations are drastically increasing and have doubled since 1960 (Bourne, 2006). As such, costly infrastructure has been constructed and a variety of stakeholders compete for limited resources (both physical and social) in the coastal zone, presenting potential multi-use conflicts and making management complex (Chalier and De Meyer, 1998). The human and natural systems are now highly coupled, and co-evolve at a range of spatial and temporal scales.

In the United States, beaches are the leading destination attracting an estimated 180 million visitors a year, which accounts for 85% of the tourism revenue in coastal states (Houston, 2008; U.S. Commission on Ocean Policy, 2004). Coastal tourism generates over $300 billion annually (Houston, 2008), but Leatherman (1989) estimates that 90% of the nation's sandy beaches are eroding, and annual property losses due to coastal erosion are estimated at $500 million (NRC, 2007). According to the U.S. Geological Survey, NC has the longest continuous stretches of erosion in the southeast and 70% of shoreline has been eroding at an average rate of ~0.7 m/yr. Erosion is likely exacerbated by accelerated rates of sea-level rise that are projected to produce up to a meter of rise by 2100 (IPCC, 2013). When coupled with predictions of increased storm intensity (Emmanuel, 2005; Mann et al., 2009; Knutson, 2010), there is increased risk of damage to the built environment in the coastal zone.

North Carolina aims to limit permanent stabilization structures, or “hardening” (Kittinger and Ayers, 2010). Therefore, beach nourishment has become a widely used “soft” coastal adaptation strategy to combat erosion. Large-scale beach nourishment projects involve the dredging of offshore sand borrow sources, or sometimes re-use of navigational channel dredged sediments, followed by pumping onshore. While beach nourishment is simple in theory, suitable sediment, i.e., material that is compatible with the native beach, is not ubiquitous offshore and has been poorly catalogued (Drucker et al., 2004). In addition, nourishment alters the sediment supply and possibly the sediment character, both of which significantly affect beach-dune dynamics, including dune growth and coastal storm impacts. Moreover, there is concern with ecosystem impacts (e.g., offshore benthic fauna and sea turtles).

The purpose of this research is to investigate several geologic and economic aspects and implications of nourishment along the State of NC, with the goal of having insights inform management decisions on a regional and global scale. Indeed, many coastal communities around the world are threatened with episodic and chronic long-term erosion. Because these issues are multi-faceted and interdisciplinary, this work takes an integrated approach, addressing both physical and socioeconomic perspectives. Much of the work can be linked back to beach sand as a resource that is highly influenced by coupled natural processes and human decisions. The linked research narrative begins with examining small-scale beach dune dynamics, moves to identifying offshore sand sources used to manage those dynamics, then finishes with evaluating some economic implications of funding costly offshore sand extraction and nourishment projects. This dissertation has three primary chapters; the specific objectives of which are to: 1) examine beach-dune dynamics of a managed, nourished segment and unmanaged, non-nourished segment under similar forcings, 2) evaluate the distribution of offshore nourishment sands and their relationship to geologic context in southern NC, and 3) examine available borrow sources relative to long-term erosion, the locally-based funding sustainability, and potential influences of nourishment on the housing market in Dare County, NC. Below is a brief description of the motivation and focus for each chapter of this dissertation.

2.0 Beach-Dune Dynamics

Along sandy coastlines, dunes are often the first line of defense for oceanside infrastructure during storms. Dunes continuously evolve in response to environmental forcings, and in some cases, can naturally recover following erosional events, making them particularly relevant to coastal resilience analyses (Claudino-Sales et al., 2008). While much research has focused on beach-dune dynamics in unmanaged areas, few studies have concentrated on the inter-annual evolution of human-altered systems, particularly those that have been nourished (Davison et al., 1992; Elko and Wang, 2007). Investigation is needed at meso-temporal (months, years) and multi- spatial (cm-km) scales because they align with management decisions (e.g., nourishment, dune and beach access design, plantings, fencing) (Elko et al., 2016). As a primary tool, the study used terrestrial lidar scanning (TLS). Repeat TLS has only recently been used to study beach-dune morphodynamics and can help resolve small- and large-scale dynamics, including storm response and recovery (e.g., Montreuil et al., 2013; Schubert et al., 2015; Fairley et al., 2016; Telling et al., 2017). This study employs TLS at high temporal resolution (~monthly) providing an unprecedented dataset of beach-dune dynamics.

3.0 Offshore Geology and Sand Resources

Highly dynamic beach-dune dynamics and the persistence of storms and chronic erosion has triggered an increased demand for diminishing sand resources in State waters (Drucker et al, 2004), making it necessary to start targeting Outer Continental Shelf (OCS) resources in federal waters. Following the detrimental impacts of Hurricane Sandy (2012) along the East Coast of the U.S., the Bureau of Ocean Energy Management (BOEM) recognized the importance in advancing the capacity of states to analyze and understand the distribution, geologic context and potential volumes of offshore sand resources (Walsh et al., 2016). Widespread surveying has been conducted in northern NC (e.g., Thieler et al., 2014; NCDCM, 2017), and prior work (seismic surveys and coring) has been conducted primarily in NC State waters (0-3 mi). There is a lack of data coverage on the OCS offshore southern NC. Sub-bottom and vibracores were collected in 2015 based on data coverage gaps, and the interpretations are the focus of this research. In addition to mapping sand resources, buried paleochannels provide an important preserved record of ancient environmental conditions and sea-level change. Furthermore, mapping hardbottom is critical as it represents potential habitat and provides insights into framework geology (Rutecki et al., 2018). As OCS use increases, mapping efforts and seabed characterization are crucial to inform potential use conflicts between different resource demands (e.g., wind farms, fishing, oil exploration).

4.0 Nourishment Economic Implications

Sand is a critical resource for beach nourishment, but offshore shelf extraction is costly, which has important economic ramifications for coastal communities. Having a known offshore supply of sand for nourishment may better facilitate cost estimates and potential use conflicts, especially as nearshore borrow sources diminish (National Research Council, 1995; Jones and

Mangun, 2001). Nourishment is a relatively new practice in the northern Outer Banks (2011), and the funding structure is unlike much of the State in that it relies completely on county and municipal funding through tax districts. However, these tax districts are somewhat arbitrary and not founded on formal economic analysis. While the storm protection benefits added to oceanfront properties through nourishment are clear (Pompe and Rinehart, 1995; Landry and Hindsley, 2011; Gopalakrishnan et al., 2011; Qiu and Gopalakrishnan, 2018), the spatial dynamics and heterogeneity in benefits to non-oceanfront owners is less understood and may have significant implications in determining funding structures. Using a difference-in-differences empirical strategy, this chapter aims to examine the response of homeowners to nourishment, rather than simply characterizing the benefits generated. With this approach, this work assesses whether rental behavior, which is being driven by changes in amenity value or changes in nourishment tax burden. The rental-behavior response of homeowners to nourished beaches and increased taxes has implications for the long-term sustainability of beach nourishment financing in coastal communities.

5.0 **Dissertation Overview**

With the exception of Chapters 1 and 5, the chapters in this thesis are written and formatted to achieve peer-reviewed publication. More specifically, this chapter (Chapter 1) provides important introductory and background material for context. Revisions are currently underway for Chapter 2 to be re-submitted to *Earth Surface Processes and Landforms*. It has been re-formatted to match the rest of this dissertation. Chapter 3 will be submitted to the *Journal of Coastal Research* as part of a special issue focusing on the regional BOEM cooperative work or to *Marine Geology*. Chapter 4 is being prepared for submission to *Marine Resource Economics*. Chapter 5 presents a brief summary and overarching conclusions.

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CHAPTER 2

Terrestrial Lidar Monitoring of Coastal Foredune Evolution in Managed and Unmanaged Systems

Abstract

Coastal dunes provide essential protection for infrastructure in developed regions, acting as the first line of defense against ocean-side flooding. Quantifying dune erosion, growth and recovery from storms is critical from management, resiliency and engineering with nature perspectives. This study utilizes 22 months of high-resolution terrestrial lidar (Riegl VZ-2000) observations to investigate the impact of management, anthropogenic modifications, and four named storms on dune morphological evolution along ~100 m of an open coast, recently nourished beach in Nags Head, NC. The influences of specific management strategies such as fencing and plantings were evaluated by comparing these to the morphologic response at an unmanaged control site at the USACE Field Research Facility (FRF) in Duck, NC (33 km to the north) which experienced similar environmental forcings. Various beach-dune morphological parameters were extracted (e.g., foredune volume) and compared with aeolian and hydrodynamic forcing metrics between each survey interval.

Results show that lidar is a useful tool for quantifying complex dune evolution over fine spatial and temporal scales. Under similar forcings, the managed dune grew 1.7 times faster than the unmanaged due to a larger sediment supply and enhanced capture through fencing, plantings and walkovers. These factors at the managed site contributed to the welding of the incipient dune to the primary foredune over a short period of less than a year, which has been observed to take up to decades in natural systems. Storm events caused alongshore variable dune erosion primarily to the incipient dune, yet also caused significant accretion, particularly along the crest at the managed site, resulting in net dune growth. Traditional empirical Bagnold equations correlated with observed trends of dune growth but overpredicted magnitudes. This is likely

because these formulations do not encompass supply limiting factors and erosional processes, which will be the focus of future work.

1.0 Introduction

Coastal regions across the globe contain a myriad of essential resources, and provide a broad range of economic, ecological and cultural value (Houston, 2008). Along sandy coastlines, dunes are often the primary line of defense for oceanside communities during storms, and are thus critical morphodynamic features to understand for management of sandy coastal systems. Dunes continuously evolve in response to environmental forcings, and in some cases, can naturally recover following erosional events, making them particularly relevant to coastal resilience analyses (Claudino-Sales et al., 2008). However, in order to properly quantify the amount of resiliency that dunes may add to a coastal system, research is needed to quantify rates of dune evolution relative to forcing conditions in both managed and unmanaged systems.

While much research has focused on beach-dune dynamics in unmanaged areas, few studies have concentrated on the inter-annual evolution of human-altered systems, particularly those that have been nourished (Davison et al., 1992; Elko and Wang, 2007). Also, limited research quantified the effects of fencing and plantings on dune evolution in developed systems (Anthony et al., 2006; Grafals-Soto, 2012; Jackson and Nordstrom; 2012). Fundamental knowledge is needed on both micro (centimeters) and mesoscale (meters) processes for coupled human and natural systems in order to inform management decisions (e.g., nourishment, dune and beach access design, plantings, fencing) (Elko et al., 2016).

Prior methodology to measure dune evolution includes quantifying dune geomorphic evolution using aerial imagery (van Puijenbroek et al., 2017), ground-based RTK-GPS surveys (Ruggiero et al., 2016), airborne lidar surveys (Darke et al., 2016), and more recently, terrestrial lidar scanning (Montreuil et al., 2013). Although these approaches may be sufficient to quantify some morphodynamic processes, low survey frequency (e.g., airborne lidar) and spatial resolution (e.g., GPS surveys) limits quantification of morphologic change at time-scales and spatial scales relevant to the forcing parameters. For example, Theuerkauf and Rodriguez (2012) demonstrated that coarsely separated cross-shore profiles do not sufficiently estimate subaerial beach volume change because they do not capture small-scale changes. Frequent terrestrial lidar scanning (TLS) has only recently been used to study beach-dune morphodynamics and can help resolve small- and large-scale dynamics, including storm response and recovery (e.g., Muileres 2013; Schubert et al., 2015; Fairley et al., 2016; Telling et al., 2017) but has rarely been used at high temporal resolution. Fabbri et al. (2017) provides the only example with frequent scanning (15 over two years).

Field data are needed to inform and advance beach, dune and nearshore process simulation efforts. Recent modeling studies have successfully simulated a variety of nearshore processes, and in terms of dunes, a primary focus has been erosion in response to storm wave collision/inundation (e.g. Palmsten and Holman, 2012; Ranasinghe et al., 2013; Roelvink et al., 2009; Splinter et al., 2018). Fewer efforts, however, have aimed to simulate dune growth (e.g., Coastal Dune Model, Duran and Moore, 2013; Aeolis, Hoonhout and de Vries; Windsurf, Cohn, 2018), which is particularly complex due to the plethora of aforementioned interrelated factors that are inherently difficult to measure (Delgado-Fernandez and Davidson-Arnott, 2011; Keijsers et al., 2014). Past research has used Bagnold-type transport formulations to calculate transport potential which can be compared to field-derived transport (Sherman et al., 2013), yet this is often challenging due to supply limiting factors and site-specific conditions.

The purpose of this study is to (1) evaluate the utility of high-resolution TLS for quantifying micro and meso-scale beach-dune dynamics and to (2) analyze spatio-temporal variability in beach-dune evolution relative to forcing conditions at managed and non-managed field sites with similar forcings. To accomplish these goals, two open-coast dune systems were surveyed 22 times using TLS for almost two years, providing relatively high-frequency TLS observations of dune evolution. Drivers and scales of change, including extratropical and tropical storms and anthropogenic factors, were assessed. Finally, simple aeolian transport models were evaluated to determine their ability to provide useful input into decision-making frameworks in coupled human and natural systems.

2.0 Background

2.1 Dune Dynamics

Coastal dunes exist in a variety of forms, and when left to evolve naturally, their changes are controlled primarily by wind, waves, ecomorphodynamic factors, and framework geology (Hesp, 2002; Cooper et al., 2018; Lentz and Hapke, 2011, Wernette et al., 2018). Generally, winds exceeding the sediment entrainment velocity threshold mobilize sand from the sub-aerial portion of the beach and deposit it when wind speeds are reduced around vegetation and topographic features, typically within the upper back beach and incipient dune (Hesp, 2002). Transport magnitudes are controlled by wind speed, duration and fetch (Anthony et al., 2006; Bauer et al., 2012; Davidson-Arnott et al., 2005; Delgado-Fernandez, 2011; Keijsers et al., 2014), vegetation (Bitton and Hesp, 2013; Charbonneau et al., 2017; Feagin, 2005), topographic slope breaks (Walker et al., 2006), as well as supply limiting factors including moisture content (Davidson-Arnott et al., 2005; Davidson-Arnott et al., 2008), beach width, sediment supply, and sediment characteristics (Bauer and Davidson-Arnott, 2003; Crapoulet et al., 2017; Poortinga et al, 2015). Dune growth, however, may be interrupted by hydrodynamic processes, especially during stormy periods when elevated water levels and runup may reach and erode the dune (Sallenger, 2000).

Although these same physical forces still exert dominant control on managed coastlines, when combined with anthropogenic, physical, environmental, and socio-economic factors, dune dynamics become even more complex (Arens and Wiersma, 1994). For example, the built environment (houses, roads, shore-protection structures) can reduce the space where dunes can form; sand-fencing, walkovers, and vegetation can alter sediment capture rates; and beach nourishments may at least temporarily increase the available sediment supply to dunes (Elko et al., 2016).

3.0 Field Sites

This study was conducted at two sites along the northwestern Atlantic Ocean coastline on the northern Outer Banks of North Carolina, USA (Fig 1). The long, narrow and linear structure of these barrier islands is typical of microtidal, wave-dominated systems (Hayes, 1979). Separated by only three inlets, the barriers are the eastern boundary of the Currituck, Albemarle and Pamlico Sounds, which comprise the second largest estuarine system in the U.S. Tides along the oceanfront in the region are semi-diurnal with a mean range of ~ 1 m, and mean annual significant wave height is 1.0 ± 0.6 m (Lee et al., 1998). The system is prone to high wave energy from both extratropical storms that typically occur in the winter and spring months, and tropical cyclones that can occur in the summer and fall. Extratropical storms, also known as "nor'easters," are the most frequent and longest in duration and thus control the net longshore transport from north to south, as evidenced by spit growth patterns at the capes and inlets (Dolan et al., 1988). Dunes in the region are typically in the collision regime during storms (Sallenger, 2000), with waves impacting the dune, and inundation is infrequent and localized. To protect the along-island roadway and reduce overwash, an artificial dune was constructed, fenced, and planted throughout the entire region in the 1930s and 1940s (Birkemeier et al., 1984).

The "undeveloped and unmanaged" site is located at the southern end of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) (Fig. 1A, B). The area of focus is approximately 350 m south of the FRF's 600-m long research pier and about 150 m north of the

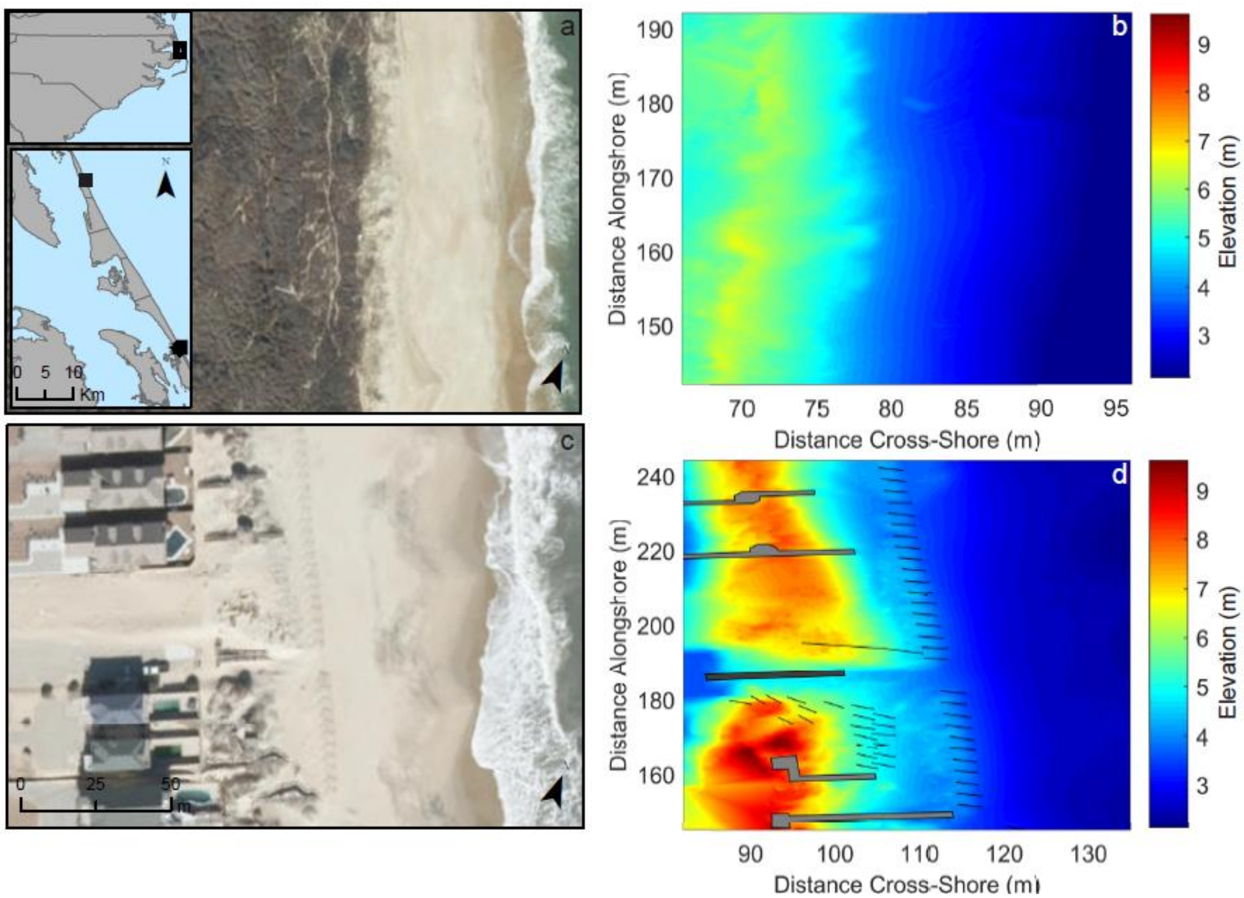

Fig 1. Field site location on the Outer Banks of NE North Carolina, USA (insets). ESRI basemap imagery and lidar-derived DEMs for the undeveloped dune system in Duck, NC (a and b) and the developed dune system in Nags Head, NC (c and d). The dark gray and light gray polygons in (d) indicate the beach access walk-through (y = 185) and walkovers, respectively. The black lines in (d) indicate fencing locations.

property border. Grainsize is bimodal and the main beach component mean is 0.25 mm (Stauble et al. 1992). The size of this site is 50 m in the alongshore direction and 30 m in the cross shore direction. The foredune is roughly 8-m wide and 6-m tall and densely vegetated with *Ammophila breviligulata* (American beachgrass), *Uniola paniculata* (Sea Oats) and *Iva imbricata* (dune marsh-elder). Landward of the site is a mature and static secondary dune ridge, which is also densely vegetated by similar species along with scrub shrub and woody material. Over the course of the study, this site was neither directly managed nor disturbed by human influences. From here on, this site will be referred to as "FRF."

The "developed and managed" site is located ~30 km south of the FRF in Nags Head, NC (Fig. 1C, D). Mean beach grainsize is 0.41 mm (Kaczkowski et al., 2018). The field site is 100 m in the alongshore direction (y) and 50 m in the cross shore direction (x). The northern dune ($190 < y < 240$ m) is characterized by a more uniform engineered profile (~17 wide and ~ 8 m tall), while the southern dune ($150 < y < 180$ m) is more irregular and hummocky (~15 m wide and ~9 m tall). The site was nourished in 2011, widening the beach by 35-40 m (relative to 0 m NAVD88 contour). Since the nourishment, the foredune system has grown more than 2 m vertically in 6 years likely due to the increased sediment supply provided by the nourishment (CSE, 2016). In addition, multiple rows of fencing have been added in conjunction with artificial plantings of *Ammophila breviligulata*, *Iva imbricate,* and *Hydrocotyle umbellate* (marsh pennywort) are present during the non-winter months. A walk-through has been maintained by periodic bulldozing and scraping in the center of the site (dark gray polygon, Fig. 1D). Several dune walk-overs also provide access for beachside homes (light gray polygons, Fig. 1D). Christmas trees were added in March 2016 along the most seaward portion of fencing. Herein, this site will be referred to as "Nags Head."

3.1 Environmental Conditions

Nor'easters are the most frequent weather events and typically occur in the winter months between December and April (Dolan et al., 1988) (Fig. 2). During the study period, the mean significant wave height was 1.0 m, and the mean wind speed was 5.9 m/s. However, multiple extratropical (Nor'easters) and several named tropical systems impacted both sites (Fig. 2). There were 15 events with wave heights exceeding 3 m in 17 m water depth (Fig. 2). A strong extratropical system (informally known as "Mars") in February 2016 had a maximum wave

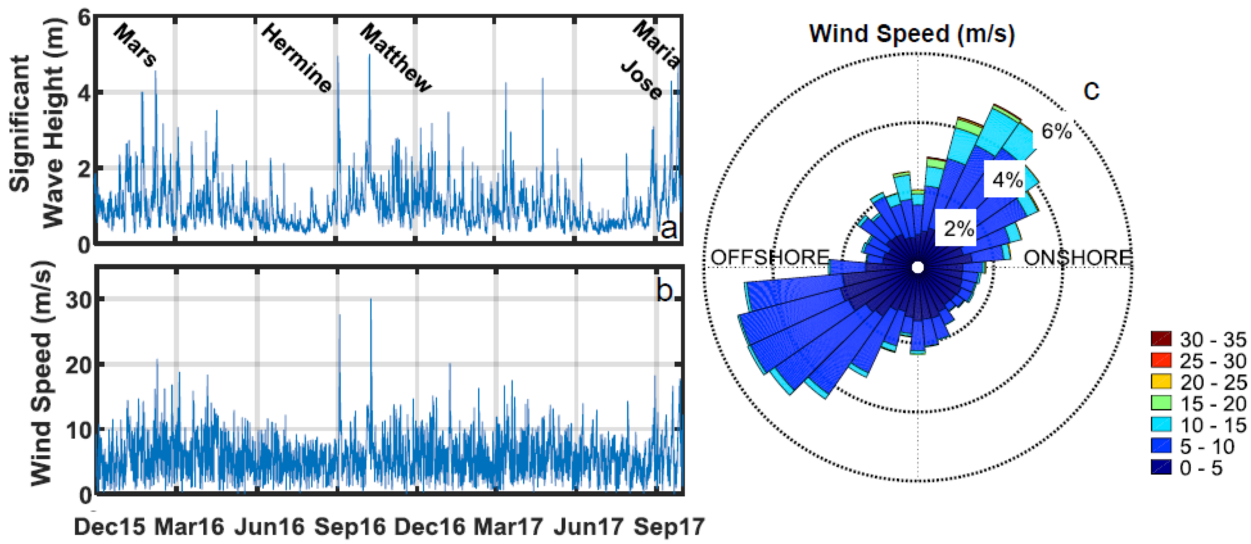

Fig. 2. Significant wave height (a) and wind speed (b) versus time, and wind rose (c) during the study period, with colors indicating wind velocity and dotted circles indicating percent occurrence. Data collected at the FRF in Duck, NC.

height of 4.5 m and maximum wind speed of 20.7 m/s. Hurricane Hermine in September 2016 had a peak wave height of 4.9 m and maximum wind speed of 27.5 m/s. Hurricane Matthew followed in October 2016 with peak wave height of nearly 5.0 m and maximum winds of 30.0 m/s. In September 2017, Hurricane Jose brought waves with a maximum height of 4.2 m and winds of 16.6 m/s, and Hurricane Maria followed in September with maximum waves of 4.8 m and winds of 17.7 m/s.

4.0 Methodology

4.1 Lidar Data Collection

Terrestrial lidar data was collected with a tripod-mounted Riegl VZ-2000 at roughly monthly intervals from December 2015 through September 2017 totaling 22 surveys. Surveys were conducted around low tide to ensure maximum subaerial beach exposure. To attain maximum spatial coverage and limit shadowing behind irregular surfaces, the tripod-mounted lidar was moved to two or three positions seaward of the dune, two within the dune and two landward of the dune for profile closure. Scanning from these multiple positions improved the ability to penetrate vegetation and other structures and measure the bare-earth surface. Horizontal and vertical angular resolution is fixed at 0.03 degrees for each position, providing a ground sampling distance of 1-2 cm throughout the site.

4.2 Rectification, Co-Registration and Filtering

Reflective cylinders were used for ground control and registration and were installed on at least five permanent steel poles. In addition, to achieve desired distribution of ground control throughout the study site, two portable bipods with reflective cylinders were placed toward the high water line during each survey. The centroids of each reflector were surveyed with an R10 Trimble RTK-GPS. After each 360-degree scan was completed, the reflectors visible from the scan position were re-scanned at a higher resolution (0.002 degrees) to ensure that the reflector center was clearly visible.

Reflector centroids were identified relative to the scanner's center in Riegl's processing software, RiScanPro, and then were used in conjunction with the known GPS-surveyed position of the reflector to identify a rigid transformation to convert the data into geo-rectified coordinates using a least-squares adjustment. This process was repeated for each scan position, and the rectification produced six overlapping positions all referenced to a unified coordinate system. At this stage, small rectification error (5 cm) was usually apparent where scans overlap.

To account for these minor offsets, the easternmost position was chosen as the baseline because it overlaps with data from all other scan positions. All scans were adjusted to this baseline position using RiScanPro's plane-matching coregistration algorithm following the methodology outlined by LeWinter (2014). The plane-matching algorithm was run iteratively, varying parameters, until the standard deviation in plane-matches fell below 0.01 m.

After the intra-site rectification and registration was completed for each survey date, each interval was rectified and coregistered relative to the initial survey for each site using static features (e.g. roof edges, chimneys, and other infrastructure) visible in the 360-degree scans. For consistency, polygons were utilized to run the intra-interval coregistration process only on these static features. This workflow of combined intra- and inter-site rectification and registration ensured low positional errors, thereby making the observation of small-scale morphological changes feasible.

Finally, ground cover including vegetation, structures, humans, and beach recreational supplies were filtered within RiscanPro software using the default vegetation filter settings (base grid size = 0.25 m, number of levels = 8, tolerance factor = 0.7, percentile = 1, max slope angle = 60 degrees, fine filter tolerance value = 0.1 m). The coverage from multiple angles for each scan position ensured sufficient laser penetration that aided in facilitating effective filtering. For each date, a bare-earth point cloud and filtered ground-cover point cloud was saved separately in order to also evaluate vegetation characteristics.

4.3 DEM Generation

Bare-earth point clouds from each survey interval were exported to QT Modeler from RiScanPro. Point clouds were checked for erroneous or non-filtered points and manually cleaned when necessary as a final quality control of the data. DEMs were generated using 10-cm grid cells. In the rare case of missing points due to shadowing, gaps were interpolated using adaptive triangulation. The DEMs were clipped to uniform study bounds. Finally, to make analysis more efficient, the DEMs were rotated into shore-normal local coordinate systems for each site. The cross-shore and alongshore dimensions are referred to herein as x and y, respectively.

4.4 Morphometric Change Calculations

A number of morphology metrics were identified and calculated for each alongshore grid location at each site: dune crest position (D_{high}), dune toe (D_{low}), dune volume (V_d), dune slope (β_d), beach width, and beach volume (V_b). The dune crest position (D_{high}) was defined as the highest bare-earth elevation for each alongshore grid location. A number of approaches for morphologically defining the dune toe (D_{low}) were evaluated (e.g., Houser, 2013). In many cases morphological definitions of the dune toe based on slope breaks were easily influenced by scarping lower down on the beach face. Instead, the cross-shore location of the 3-m contour was found to provide the most robust metric to evaluate progradation or recession of the dune base. V_d was calculated between D_{high} and D_{low} from the first survey by calculating the area under the profile using trapezoidal numerical integration and multiplying by the cell width for each alongshore grid location. Due to the maintenance and clearing of the walkover and absence of a dune feature, the alongshore bounds from 175 to 195 at the Nags Head site were omitted from dune volume change calculations (Fig. 1). Each of the morphology metrics were analyzed to quantify spatial variability within each site, as well as averaged in the alongshore to provide characteristic profile morphology metrics for each site to quantify inter-site differences. V_d was also summed in the alongshore direction to calculate total volume at each site. Mean interval dune profile volume in m^3/m is indicated herein by $\overline{V}_I$. Change rates through time were normalized by the time between surveys (roughly monthly). Normalized foredune volume changes in $m^3/m/month$ are indicated herein by ΔV_N. Non-normalized interval foredune volume changes in m^3/m are indicated herein by ΔV_I . At Nags Head, volume changes were also analyzed by zone, where a fence zone was delineated using a 1 m buffer around the seaward most fencing, a vegetated swale zone was extended landward from the fencing zone boundary midway up the foredune slope, and the crest zone extended from the swale zone boundary landward to the backslope break. In addition, the percentage ground cover (i.e., vegetation and structures presence in grid cell) and vegetation height were calculated for each interval. Vegetation height was calculated by differencing a surface generated from only vegetation data and the bare-earth DEM.

4.5 Hydrodynamic Forcing

Wave data including significant wave height (H_s), peak direction and mean period (T) were collected from a directional waverider buoy in 17-m water depth offshore of the FRF field site (https://chlthredds.erdc.dren.mil). In cases where this data was unavailable due to technical issues or maintenance, data from an 11-m AWAC (acoustic wave and current) was used. To quantify hydrodynamic forcing during the study, H_s and T were used to compute total wave power (kW/m) for each survey interval (P_I) with the following equation:

$$\boldsymbol{P = 0.5 * H_s^2 * T} \tag{1}$$

4.6 Aeolian Forcing

Time-series data of wind direction and speed were collected from an array of RM Young serial output marine anemometers located at 18.84 m NAVD88 at the end of the FRF pier (500 m northeast of the FRF site). Wind data were sampled at 1 Hz, and statistics were computed in 10-minute intervals. Winds were rotated from their original true north orientation into the local coordinate systems for the FRF and Nags Head. A number of aeolian transport equations exist in the literature (see Sherman et al., 2013). We followed the work conducted by Keijsers et al. (2014) and Delgado-Fernandez and Davidson-Arnott (2011) because of the extensive experience of these authors and it is recent, simple and applicable. To encompass transport of fine sediment, we first conducted the following calculations using a threshold wind speed of 6 m/s, consistent with Delgado-Fernandez and Davidson-Arnott (2011) and did not account for wind direction. Next, we used threshold velocities based on grainsize differences between sites and accounted for wind direction, including the removal of any offshore wind events.The following workflow was conducted in Matlab.

First, wind speeds were converted to shear velocities using the Law of the Wall:

$$\boldsymbol{u_z = \frac{u_*}{k} \ln \frac{z}{z_0}} \tag{2}$$

where u_Z is the wind speed (m/s) at elevation z (18.8 m) above the bed (~3 m); u_* is the critical shear velocity (m/s); k the von Karman constant (0.4), and z_0 the roughness length (0.001 m).

Second, threshold shear velocity for transport was calculated by:

$$\boldsymbol{u_{*t}} = \boldsymbol{A}\sqrt{\boldsymbol{gd}\left(\frac{\boldsymbol{\rho_s - \rho}}{\boldsymbol{\rho}}\right)} \qquad (3)$$

where u_{*t} is the threshold shear velocity; A is a dimensionless constant (0.1 for the impact threshold); g is the gravitational acceleration (m/s^2); d is mean grain size (FRF = 0.25 mm; Nags Head = 0.41 mm); r_s is the density of common sand (2650 kg/m^3), and r is the density of air (kg/m^3).

Next, hourly transport potential (q) was calculated when the threshold shear velocity was met or exceeded for at least two consecutive hours:

$$\boldsymbol{q} = \boldsymbol{3600C}\sqrt{\frac{\boldsymbol{d}}{\boldsymbol{D}}}\,\frac{\boldsymbol{\rho}}{\boldsymbol{g}}\,\boldsymbol{u_*^3} \qquad (4)$$

where C is a dimensionless empirical constant (solved for), and D the grain diameter of a standard sand (0.25 mm).

Lastly, to obtain transport magnitudes based on the potential of wind to deliver sediment towards the foredune, for each wind measurement classified as an event, wind directions were incorporated using:

$$\boldsymbol{q_n} = \boldsymbol{q} * \mathbf{cos} \propto \qquad (5)$$

where q_n represents the potential transport into the foredune per unit alongshore distance (kg m^{-1} s^{-1}) and ∝ represents the angle of incidence of the wind.

Hourly transport was summed over each event and mean event speed and direction through vector averaging were also calculated. Finally, events were summed over each survey interval (q and q_n), and potential aeolian transport, Q_I, was converted from kg/m to m^3/m using the average bulk density of sand 1590 kg/m^3 (Keijsers et al., 2014).

5.0 Results

5.1 Net Geomorphic Change

Currently, the Nags Head dune system has nearly four times the gross volume of the FRF dune system (Table 1). This is primarily due to differences in the cross-shore dimension (x); the Nags Head dune system is ~ 30 m wide compared to the ~15 m wide dune at the FRF. The engineered system has been widened to include a developing incipient dune along a sand fence line. The Nags Head and FRF dune volumes increased by 8.9 and 5.0 m^3/m, respectively, over the 21 months of this study.

The FRF site showed net accretion throughout the foredune region over the course of the study (Fig. 3A). Accretion was mostly uniform along the study site, with two discrete cross-shore zones. The seaward-most half of the dune ($80 < x < 90$ m) accreted <0.5 m whereas the landward half ($70 < x < 80$ m) showed net change of ~ 0.75 m in the vertical. Examining the behavior of representative profiles shows several trends (Fig. 3C). In general, the entire dune face aggraded with time, coincident with the seaward migration of the dune crest and toe. In the initial profile, the upper beach and dune face had a similar shape without a prominent slope break. Episodic aggradation was focused on the upper slope and crest, causing the dune face to steepen and become more convex with a pronounced slope break between the lower and upper foredune by the end of the study.

Table 1. Summary of geomorphic parameters over the study period.

	Mean	Min	Max	σ
Nags Head V_{TOT} (m^3)	128,571.5	114,766.1	124,454.6	2,711.6
FRF V_{TOT} (m^3)	35,032.6	33,433.1	36,656.2	803.5
Nags Head mean D_{high} elevation (m)	7.8	7.6	7.9	0.1
FRF mean D_{high} elevation (m)	6.2	6.0	6.3	0.1
Nags Head mean β_d (m/m)	-0.19	-0.21	-0.18	0.01
FRF mean β_d (m/m)	-0.27	-0.29	-0.24	0.01
Nags Head mean monthly W_b (m)	23.0	13.9	39.4	6.0
FRF mean monthly W_b (m)	14.8	9.4	18.0	2.4

Profiles at Nags Head evolved less uniformly over the study interval (Fig. 3B, D, E). Accretion was concentrated in the vegetated swale just landward of the seaward-most fencing (105 m < x < 110 m). Vertical growth in this region exceeded 1.5 m in many areas (e.g., 200 m < y < 225 m) over the course of the study, as the dune transitioned from a foredune/incipient dune system into a single dune system (Figure 3D, compare dark blue and red lines). The area of fencing (110 m < x < 120 m) also predominantly accreted in a rhythmic, hummocky pattern (Figure 3B & E), however, in some locations the seaward portion of the fencing was eroded by several storm events resulting in less net growth. Accretion on the order of 0.5 m also occurred on the upper slope and crest portions of the dune in many locations. Some crest locations, such as near the walk-through (180 m < y < 190 m) and along the southern portion of the site (150 m < y 153 m; 170 m < y < 173 m) in the vicinity of a hummocky and less continuous dunes,

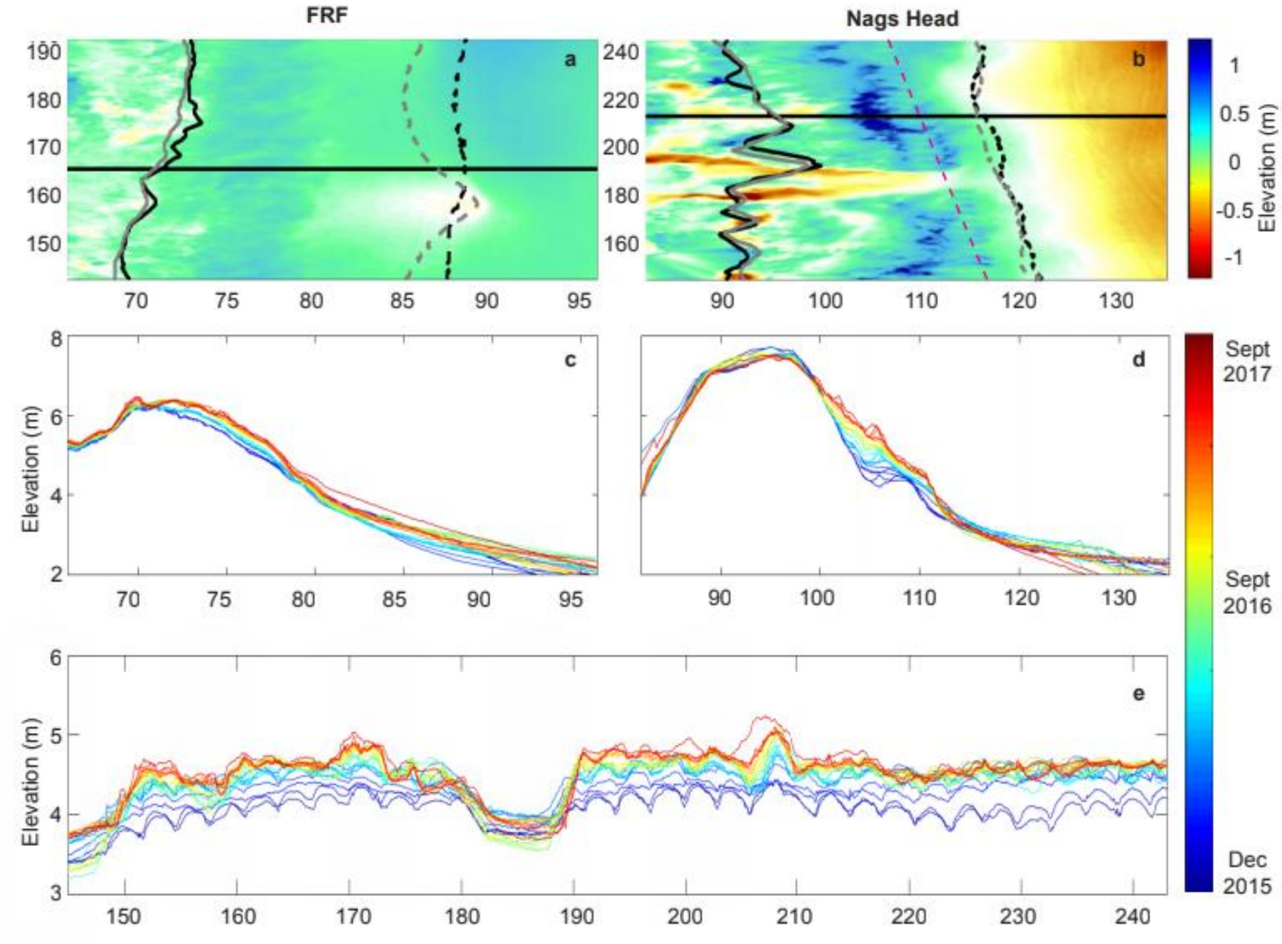

Fig. 3. Net elevation change (colors) between the first and last survey at the (a) FRF and (b) Nags Head field sites. Solid and dashed lines represent the dune crest and dune toe position for the first (gray) and last (black) surveys. Elevation versus cross-shore position for all surveys (colors represent increasing time from blue to red) for (c) FRF and (d) Nags Head sites at y = 166 and y = 214, respectively (see solid cross-shore black line in (a) and (b)). Elevation versus alongshore position (colors represent increasing time from blue to red) for the Nags Head site along the magenta dashed line in (b).

experienced net erosion (red colors in Figure 3B). At these locations, slumping was common, particularly along the lateral edge of the walk-through, and root integrity of the dune vegetation was diminished (visual observations; not shown).

The dune crest at Nags Head had higher elevations than at FRF (Table 1). Standard deviation in the monthly crest elevation was small at both sites (0.1 m). The cross-shore position of the FRF crest moved between 1 and 2 meters seaward from the first to the last interval, while the Nags Head initial and final crest positions were essentially unchanged (compare gray and black solid lines in Fig. 3A & B). The cross-shore position of the dune toe migrated ~3 m seaward at the FRF whereas the cross-shore position of the dune toe remained fairly constant at the Nags Head site (compare gray and black dashed lines in Fig. 3A & B).

5.2 Vegetation Characteristics

Vegetation characteristics varied within and between the sites and over the course of the study (Fig. 4). In winter months, the vegetation at Nags Head was especially sparse and was concentrated on the seaward-facing dune face (Fig. 4A). In these locations, vegetation heights rarely exceeded 0.2 m. In contrast, the landward half of the FRF foredune was densely vegetated with stalks up to 0.6 m tall (Fig. 4B). As expected, vegetation increased in spatial coverage and grew taller in summer months at both sites (Fig. 4). Minimums in foredune vegetation coverage of 12 and 29% were observed at Nags Head and the FRF in December 2015 and February 2017, respectively. In the summer, Nags Head showed an increase of 0.3 m in height of vegetation, predominantly in the swale and fencing zone, and a maximum foredune coverage of 40% was observed (Fig. 4). At the FRF, maximum foredune coverage was 75% in August 2016, and the height difference between winter and summer was on the order of +0.5 m. With the exception of

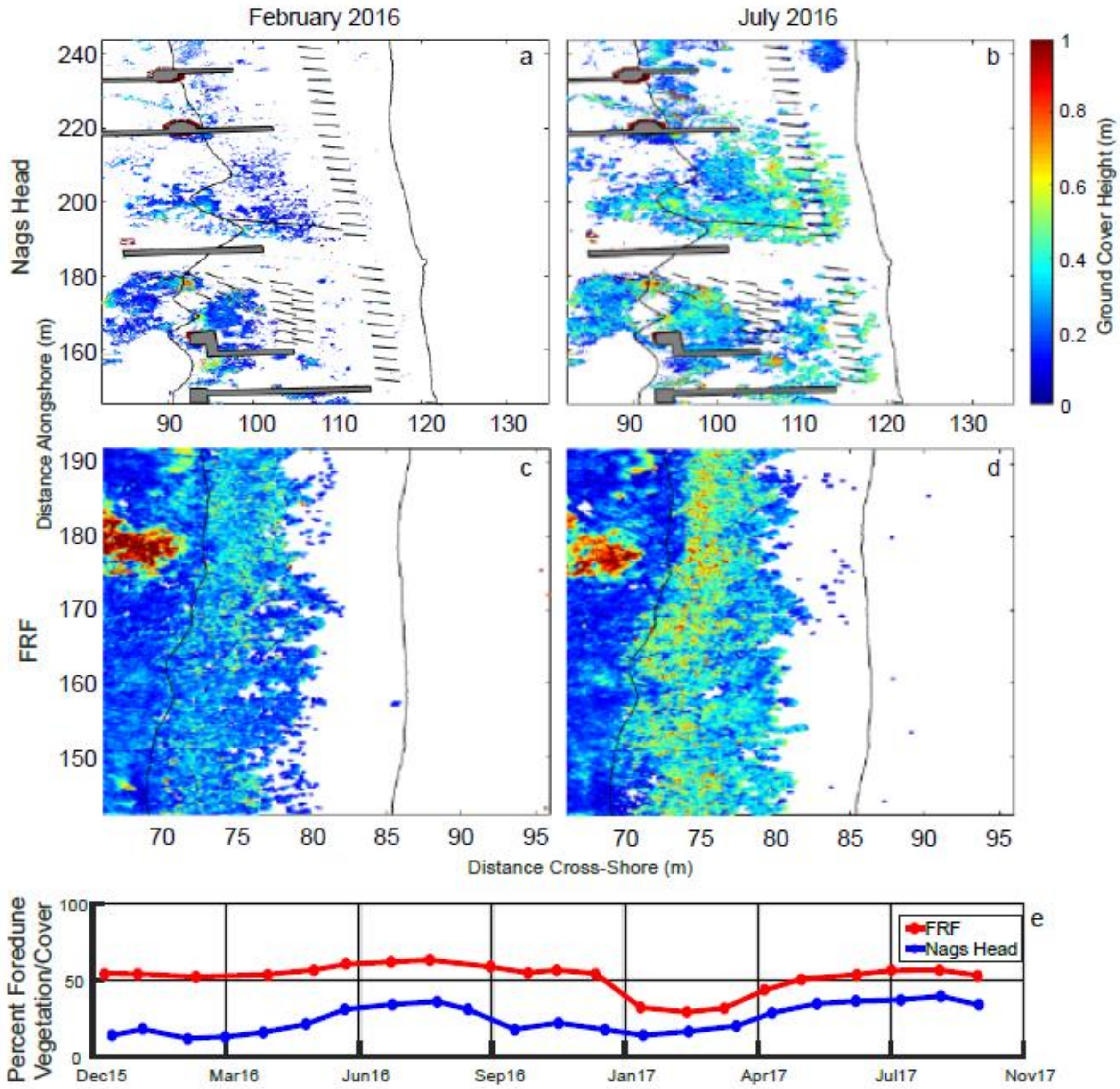

Fig. 4. Vegetation presence and height (colors) over two survey intervals (Feb 2016 and July 2016) at Nags Head (a, b, respectively) and FRF (c, d, respectively) derived from point cloud filtering. e) Vegetation coverage (percent) through time at Nags Head (blue) and FRF (red).

Winter 2017, vegetation coverage remained relatively constant at the FRF during the whole study. Generally, intra-annual vegetation coverage varied significantly more at Nags Head.

5.3 Spatial and Temporal Geomorphic Variability

Both dune systems grew in total volume over the study (Fig. 5). Overall, the FRF and Nags Head sites accreted at average rates of 0.22 and 0.37 m^3/m/month, though some intervals contained significantly higher growth rates, as well as erosion, and the responses did not always align between sites (Fig. 5). To understand processes driving changes, temporal variations in site responses were quantified by comparing the per-transect foredune volumetric change, ΔV_I, across each site for each time interval (Fig. 6A & B) with wind and wave forcings (Figure 6C & D), beach geomorphology (Fig. 6E) and vegetation coverage (Fig. 4E). Spatial variability within each time interval was examined by analyzing distributions in dune response along each site (shaded colors, Fig. 6A & B) and through surface difference maps for each interval (e.g., Fig. 7).

Generally, during an average net accretional month at the FRF, all or the majority of transects along each site were accretional, and the same trend applied with erosional months (Fig. 6B). This differed from Nags Head where many months contained distributions with a high percentage of both accretional and erosional transects, resulting in a higher standard deviation (Fig. 6A, e.g., September 2016 and September 2017). At Nags Head, the average foredune volumetric response was erosional in only three out of 21 intervals (January 2016, October 2016, June 2017; Fig. 6A). In contrast, the average FRF foredune response was erosional during six intervals (February 2016, June 2016, September 2016, January 2017, June 2017, August 2017;

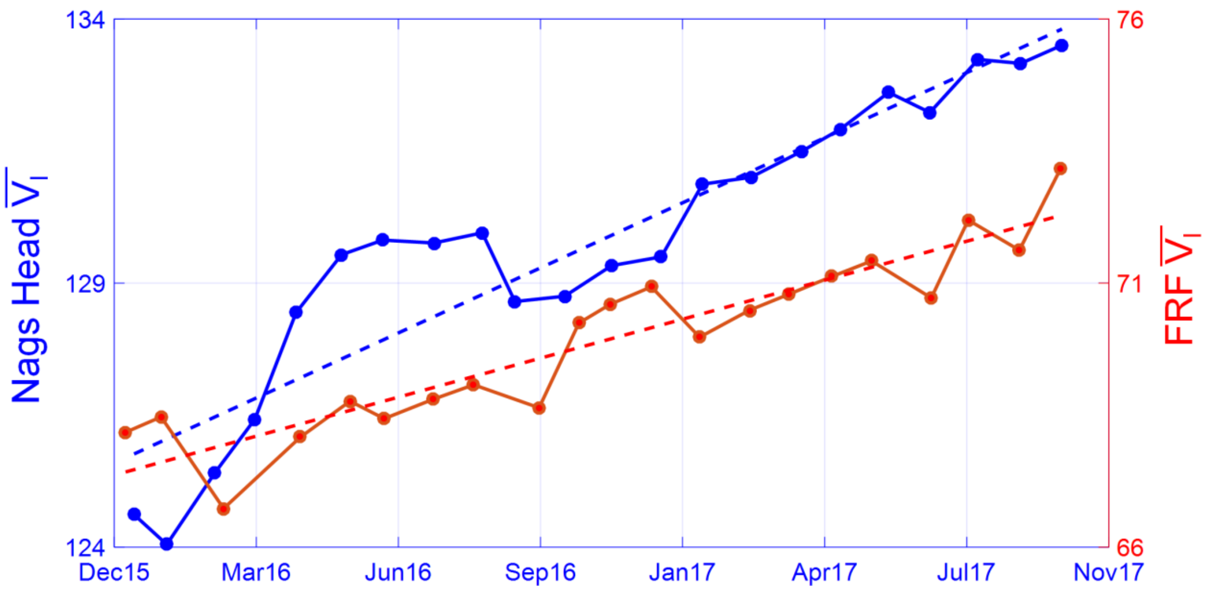

Fig. 5. Interval total dune volume through time for Nags Head (blue) and FRF (red).

Fig. 6A & B). The largest mean erosional response was measured at the FRF (- 1.7 m^3/m) in February 2016, which far exceeded the largest mean erosional response in Nags Head (-0.8 m^3/m), though some profiles within the Nags Head site occasionally saw erosion rates reaching -3 to 6 m^3/m (January 2016, October 2016, June 2017; Figure 6A).

On average, the Nags Head beach width was 27% wider than the FRF and its variability during the course of the study was roughly twice that of the FRF (compare standard deviation in beach width, Table 1; red and blue lines, Fig. 6E). The maximum observed beach width at Nags Head was nearly double that of the FRF (39 versus 22 m). With the exception of Summer 2016, the Nags Head beach was always wider than the FRF beach.

Numerous extratropical and named tropical storms impacted both sites over the study interval. In February 2016, winter storm Mars brought elevated winds and wave energy (Fig. 2, Fig. 6C & D). Interval wave power was computed at 2.2e+4 kW/m, the second greatest in the study period. Wind speeds reached 22 m/s and were sustained above 6 m/s out of the NNE for 55 hours (Fig. 7A). Drastically different foredune responses were observed between the two sites (Fig. 6A & B; Fig. 6C & E). On average, the Nags Head foredune accreted (1.5 m^3/m), whereas the FRF suffered its highest erosion (- 1.7 m^3/m). The Nags Head beach width prior to the storm was over 10 m greater than the FRF (Fig. 6E), and the foredune was not impacted by wave runup, unlike the foredune at the FRF (red colors extend landward of the pre-storm dune base (grey dashed line), Fig. 7C). The extent of wave collision at the FRF resulted in a scarp developing on the seaward dune face (Fig. 7C). A large proportion of erosion appears to have also resulted from the migration of cusp features that had welded to the upper beach and incipient dune (alongshore alternating red & blue patterns, Fig. 7C). At Nags Head, the dune toe position moved 1-2 m seaward across the entire site (compare grey and black dashed line, Fig. 7E). Nearly all of the accretion occurred on the upper beach, dune toe and just landward of the fencing. Infilling of the vegetated swale exceeded 0.5 m for the majority of the site. Little change was observed on the dune slope and crest, with the exception of localized areas of accretion near walkovers on the dune crest (black box, Fig. 7E & G).

Hurricane Hermine in September 2016 was the first tropical system to impact the sites. Similar erosional responses were captured at each site. Nags Head experienced its highest erosion over the interval (Nags Head = -0.75 m^3/m), FRF had erosion of - 0.4 m^3/m (Fig. 6A & B). Hermine occurred during the 3-month period when the Nags Head beach width was narrow (~15 m), and this was the only time that the FRF beach width was greater (~ 20 m)(Fig. 6E). Erosion at Nags Head was focused on the incipient dune, which experienced wave collision. Along the sand fencing region, recently deposited sand at the base of the fencing was scarped and scour occurred in the fencing deflation gaps (data not shown). Volumetric loss of the upper beach was significant with a continuous ~ 10 m wide portion eroding > 0.5 m. The dune toe at

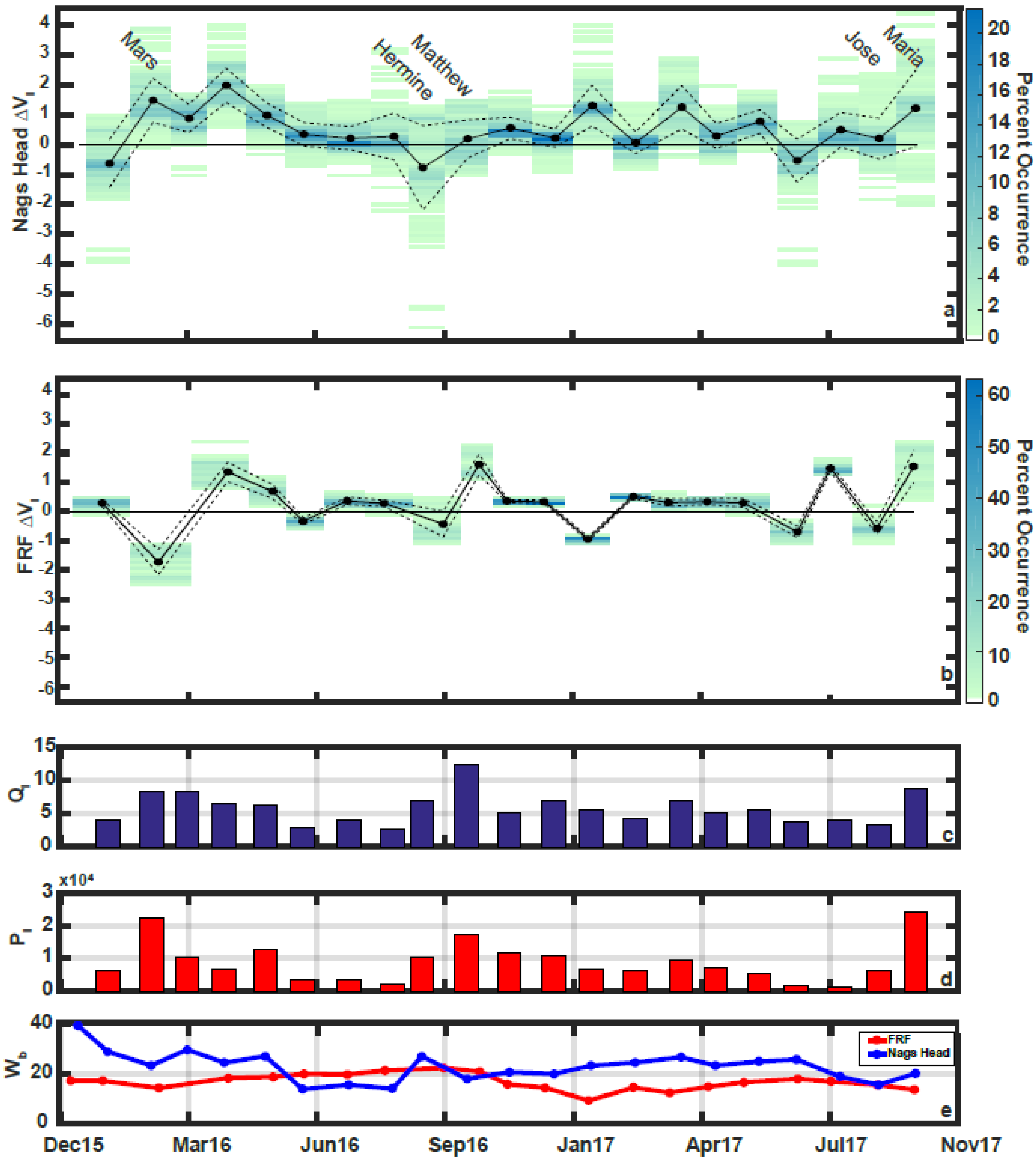

Fig. 6. Distribution (colors), mean (solid black circles), and standard deviation (black dashed lines) in transect foredune volume change (ΔV_I) versus time for each Nags Head (a) and FRF (b) survey interval. Aeolian transport potential (Q) and wave power (P_I) (c, d, respectively) summed for each interval and beach width (W_b) from the 1.5 m contour to the dune toe (e) versus time.

Nags Head retreated ~ 5 m across the whole site, while the FRF toe only retreated ~ 1 m along most of the site. An exception to this occurred near a beach cusp horn (147 m < x < 155 m), where the dune toe retreated ~ 3 m.The FRF experienced minor erosion (~ 0.1 - 0.2 m) across the dune slope, while the crest accreted by a similar magnitude during the storm.

Hurricane Matthew occurred the following month in October 2016, and this interval had the third highest wave power (1.7e+4 kW/m) of the study. Interestingly, this event contributed to the second highest accretion interval at the FRF (1.6 m^3/m). Wave runup again did not appear to impact the foredune (Fig. 6B, Fig. 7D). Instead the dune toe moved ~ 3 m seaward, and accretion of more than 0.5 m was observed along some sections of the crest (Fig. 7D). Nearly the entire foredune accreted on the order of 0.1 - 0.2 m. During the same time period, average accretion at Nags Head was only 0.2 m^3/m, and severe upper shoreface and incipient dune erosion resulted from wave collision (Fig. 7F). Scarping of the incipient dune dislodged some Christmas trees within the fenced zone. In addition, overwash appears to have penetrated the walk-through access point, removing >0.5 m of sediment from the southern swale zone (Fig. 7F; 165 < x < 185). While the dune toe position did not shift considerably in the southern portion of the site, the dune toe in the northern half moved landward >3 m (Fig. 7F). Despite these losses to the incipient dune and upper beach, a positive net change across the dune was calculated due to accretion landward of the fencing (Fig 7F). Homogenous vertical growth of 0.1 - 0.3 m was measured throughout the swale and parts of the dune slope, with the highest vertical growth of more than 0.5 m at localized portions along the crest (Fig. 7F & H). In addition, significant infilling of the northern part of the walkway was also observed (blue colors, 180 < y < 200, Fig. 7F), likely due to strong oblique winds and slumping.

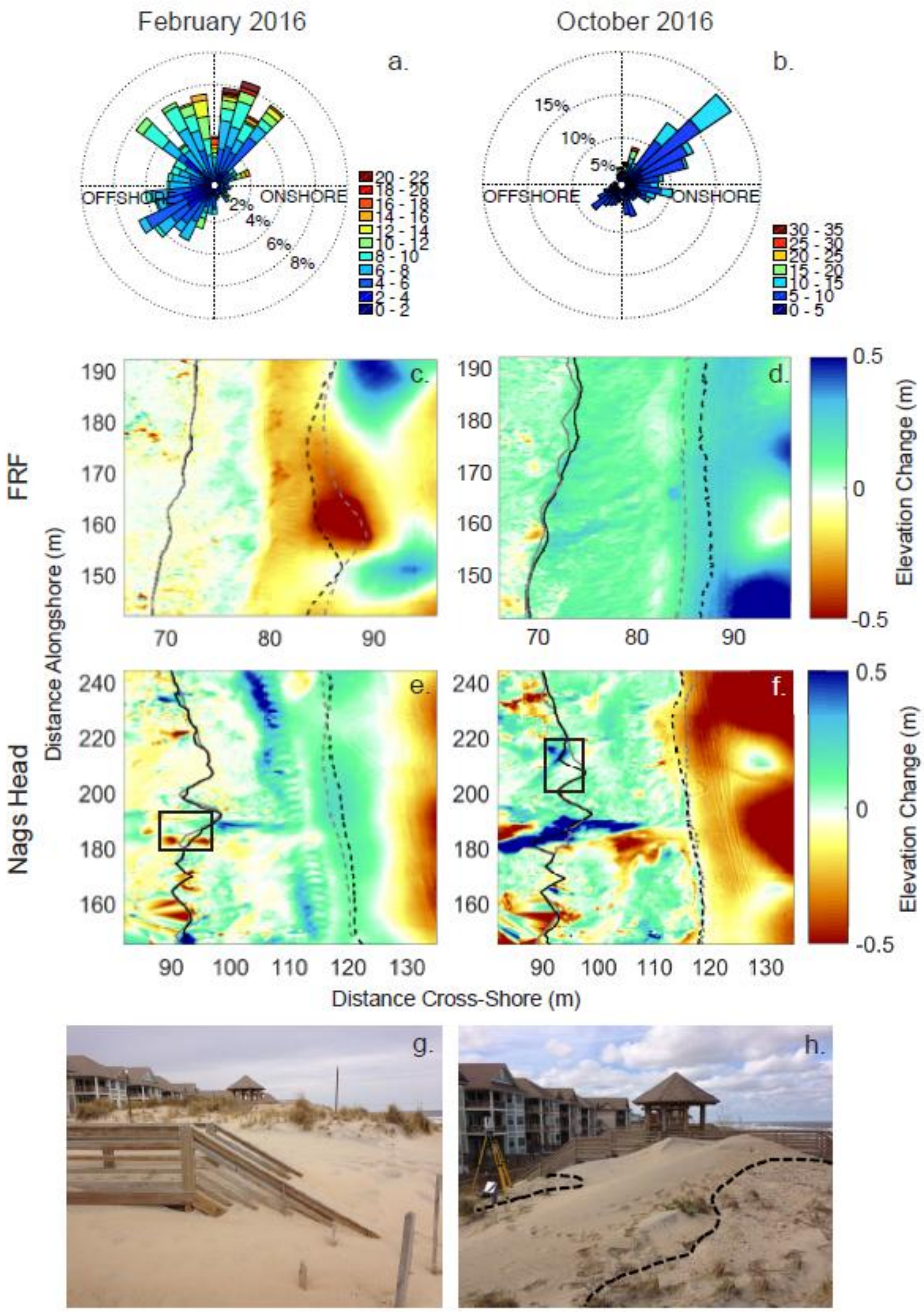

Fig. 7. Wind roses from Winter Storm Mars (Feb 2016) and Hurricane Matthew (Oct 2016) (A, B). Elevation changes at the FRF (c, d) and Nags Head (e, f) sites for each storm (Winter Storm Mars, left panels; Hurricane Matthew, right panels). Pre (black) and post (gray) dune crest position (solid lines) and dune toe position (dashed lines) are overlain. Black boxes in (e) and (f) show location of Nags Head post-storm photos (g, h) for winter storm Mars and Hurricane Matthew, respectively. Dashed lines in (h) indicate the base of new deposition on dune crest.

6.0 Discussion

6.1 TLS Efficacy

TLS has rarely been utilized to examine beach-dune dynamics (Fairley et al., 2016), especially at the temporal frequency of this study. In this study, the usefulness of TLS is demonstrated by observing the complex spatial and temporal eco-morphodynamic evolution of two dune systems. Each TLS survey took roughly 2.5 hrs to complete and were successfully collected 22 times at both sites over the course of nearly 2 years, and enabled the generation of high-spatial resolution (0.1 m) digital elevation models (DEM) (Fig. 3). The high-resolution DEMs were co-registered and supported quantification of cm-scale changes to the topographic surface (Fig. 3). In Nags Head, foredune evolution varied significantly in the alongshore (Fig. 3B & E) and through time (Fig. 6A), and the 3D lidar data efficiently quantified this evolution, demonstrating the utility of TLS over traditional GPS profiling. While the use of unmanned aerial systems (UASs) and structure-from-motion photogrammetry may provide similar high-resolution datasets and have become increasingly popular due to advantages in cost, accessibility, and improvements in automated processing software (Mancini et al., 2013; Puijenbroek et al., 2017), multi-view TLS enables simultaneous creation of a robust bare-earth topographic surface in most dune environments (as vegetation can be more effectively penetrated and filtered) as well as quantification of the spatial coverage and height of vegetation. For example, TLS was used here to quantify the differences between the more mature and dense vegetation at the FRF compared to the Nags Head site (Fig. 4). The following sections further demonstrate how TLS was utilized to elucidate morphodynamic processes controlling foredune evolution at these two sites.

6.2 Dune System Evolution

Despite multiple named tropical and extratropical storms impacting both sites, both dune systems grew over the course of the study (Fig. 5). The accretion rates of 6.0 $m^3m^{-1}year^{-1}$ at Nags Head and 2.7 $m^3m^{-1}year^{-1}$ at the FRF are similar to rates observed at other mid-latitude beaches around the globe (Davidson-Arnott and Law, 1996; Van der Wal, 2004). Examining the foredune accretion rates shows that Nags Head is accreting 1.7 times faster than the FRF site under similar forcing conditions (Fig. 5). Nags Head displayed a much higher range of accretion rates compared to the FRF (Fig. 6) which is hypothesized to be attributable to differences in sediment supply, beach width, and enhanced capture mechanisms at Nags Head (e.g., fencing, plantings, Christmas trees, walkovers).

Multiple researchers have observed a positive correlation between beach width and embryo/foredune development (Anthony, 2013; Keijsers et al., 2014; Puijenbroek et al., 2017). The nourishment at Nags Head created a beach that was on average 27% wider than the FRF over the course of the study. Large differences in width translate to variability in wave attenuation (Ruggiero et al., 2001; Puijenbroek et al., 2017), sediment supply, and available fetch over the dry beach. The critical fetch for maximum aeolian transport at similar sandy sites has been measured in past work to be between 10 and 50 m (Dong et al., 2004; Delgado-Fernandez, 2010). Both sites met this critical fetch criteria over the study period, although the FRF was typically in a lower range of 10-20 m, versus 20-30 m at Nags Head, representing potentially significant differences in available fetch. Ultimately, this was hypothesized to impact sediment flux to the dune.

The mechanisms of sand capture and topographic variability also differed between the managed and non-managed site. At the FRF, accretion was focused on the heavily vegetated portion of the dune (72 m < x < 80 m), suggesting that trapping by vegetation was the primary capture mechanism. In contrast, at Nags Head, the major accretion in the first four months of monitoring occurred along the upper beach and within the fence zone (red and blue lines, Fig. 8) in accordance with Grafals-Soto and Nordstrom (2009) and Anthony et al. (2006). During this period, the fence and swale zone growth were synchronous (Fig. 8). Despite no seaward migration of the incipient dune beyond the fencing, the fencing served its primary purpose of initiating the succession of a wider, more robust dune complex for shore protection. Lack of seaward expansion is likely due to the non-natural cross-shore positioning of fencing that created the new incipient dune at an elevation not in equilibrium with the hydrodynamic forcing – i.e., sand fencing positioned the incipient dune toe at too low of an elevation, such that it was frequently impacted by waves during storms, which prevented seaward expansion of the dune complex (Nordstrom, 1994).

The fenced areas at Nags Head filled vertically with distinct hummocks after 5-6 months (Fig. 3E). Spectral analysis of the alongshore profile through the fencing region in Figure 3, shows alongshore hummocks with a peak wavelength at fence spacing (3 m) during the initial 5-6 surveys within the fenced region (blue lines, Fig. 9). Once fence areas were filled, the peak wavelength increased to roughly 10 m (red lines, Fig. 9), as the dune became more spatially uniform, similar to the alongshore-homogenous dune morphology at the FRF site (Fig. 1). Following the fence filling, accumulation was focused in the swale zone, and the correlation in the swale zone allowed the incipient dune to weld onto the primary dune slope, toward the center of the primary foredune volume mass (e.g. Fig. 3D). Relative to other regions globally, the welding and transition of the embryo dune and swale morphologic units to the established foredune at Nags Head was rapid, on the order of months to years, compared to years to decades

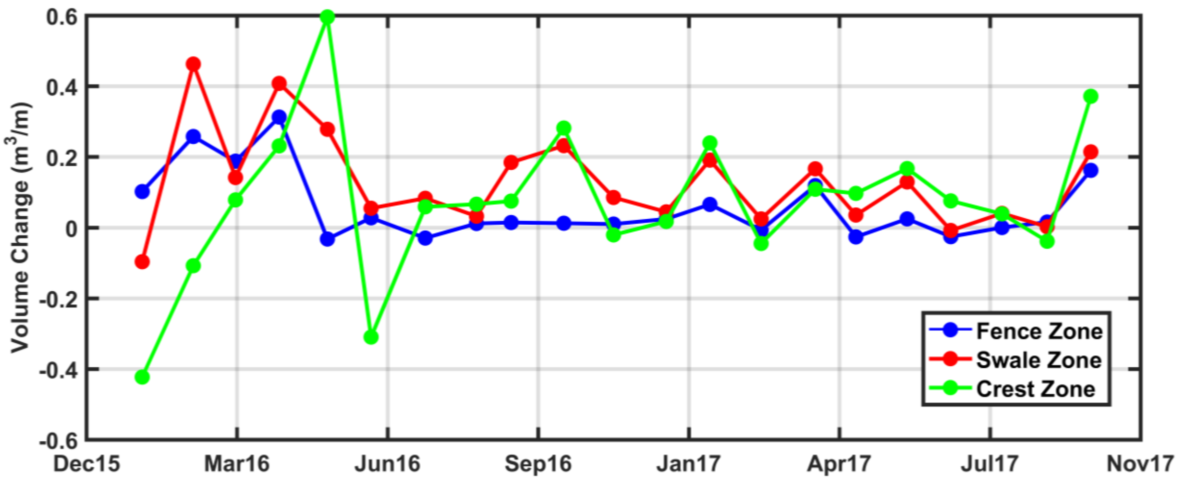

Fig. 8. Volume change in the sand fence (blue), swale (red), and dune crest (green) zones verses time for the Nags Head study site.

as reported in other regions (Carter and Wilson, 1990; McLean and Shen, 2006; Mathew et al., 2010; Montreuil et al., 2013).

The majority of human-constructed structures were observed to increase accretion of the dune. Christmas trees triggered rapid accretion along the embryo fringe by increasing backshore storage capacity (e.g., Fig. 6A, April 2016), acting similarly to woody debris observed by Eamer and Walker (2010). Walkovers acted to capture sediment and speed the coalescence of the embryo dune to the primary foredune volume (Fig. 3B). For example, the lee of the northernmost walkover recorded some of the highest crest accretion rates in the study (>0.5 m in single intervals) (e.g., Fig. 7F). However, the walk-through, where pedestrians access the beach, generated an erosional feedback (Fig. 3B). When the walkway was cleared, including the sandy southern portion also used by foot traffic, the lateral dune slopes became too steep, and slumping to the upper reach of the adjacent crest portions (Fig. 3E; 180 m < x < 192 m) was triggered,

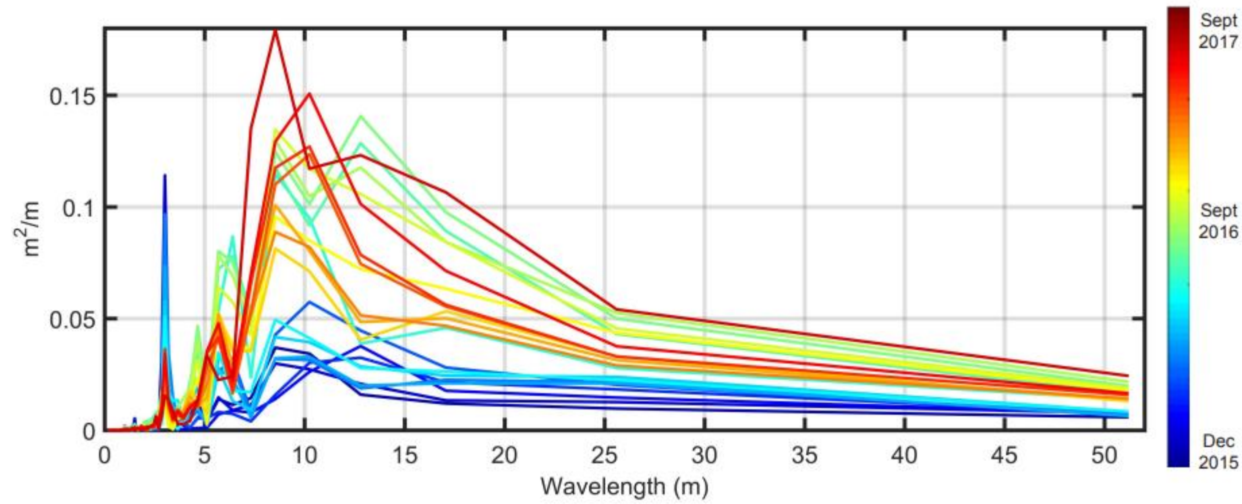

Fig. 9. Power spectral density verses alongshore wavelength through time (colors show increasing time, blue to red) for the alongshore transect through the fencing indicated by the dashed pink line in Fig. 3b.

widening the gap between the dunes and increasing vulnerability to high water levels through the walk-through, similar to observations of Houser (2013) in a natural system.

6.3 Storm Response and Recovery

Storms caused variable impacts at both sites. The Nags Head system's embryo dunes were scarped during Hurricanes Hermine and Matthew (Sep and Oct 2016) leading to significant erosion along some transects (up to -6 m^3/m), and the highest vegetation loss at the site during the study interval (5 and 13%, respectively, Fig. 4). At the FRF, the embryo dune was severely scarped during Hermine and in February 2016, yet vegetation coverage persisted and showed little change in density (Fig. 4). The differing vegetation responses are likely attributable to non-natural positioning of plantings at lower elevations at Nags Head (Nordstrom, 1994) and the greater ecological maturity at the FRF.

Overall, both systems can be considered resilient to impacts from named and un-named storms over the study period, as any erosional month at both Nags Head and the FRF was always followed by an accretional month (Fig. 6A & B). For example, the volume of sediment lost from the dune system during large events like Hurricane Matthew was substantial ($-6 < \Delta V < 2$ m^3/m) along some transects, yet these locations entirely recovered in a matter of a few months (Figs. 6 & 7). These growth rates ($1 < \Delta V < 2$ m^3/m) are similar to the observed rates of embryo dune growth following storms in France (Suanez et al., 2012), but significantly larger than those observed on Texas and Florida coasts (0.2 – 0.4 m/yr), which followed more substantial storm impacts (Morton and Paine, 1994; Houser et al., 2015). No storm overtopped the dunes at either site and complete erosion of the incipient dune would likely require a far longer recovery time (Claudino-Sales et al., 2008). Consistent with this study, over a longer timescale, Puijenbroek et al. (2017) found low-intensity storms had no net effect on embryo dune development because of the rapid aeolian-driven recovery.

Storms are most often considered erosional events to dunes, but results here show that in some locations, strong winds during storms actually lead to significant dune growth. For example, the strong extratropical event in February 2016 triggered one of the largest growth intervals at Nags Head (Fig. 7E). Similarly, the April 2016 nor'easter and Hurricane Maria in September 2017 resulted in rapid accretion at both sites (Fig. 6). While Hurricane Hermine was a net erosional event, Hurricane Matthew resulted in rapid growth at the FRF as well as upper dune growth in Nags Head (e.g., 0.5 m dune crest accretion, Fig. 7H). In addition to flow reduction at the walkover, sediment was deposited at the crest regions of the dune through the process of jettation, defined as jet-like flow over steep dune face slopes and deposition where turbulence is reduced at the crest slope break (Arens, 1996). These observations suggest that, in sufficiently wide beach areas with ample sediment capture mechanisms, large coastal storms may actually drive inter-annual accumulation to the dune. As such, both the unmanaged and managed sites observed here did not adhere to the common observation of seasonal cyclicity of erosion of foredune systems in the winter during the stormy months and accretion during quiescent summer months (e.g., Carter et al., 1990; Ruz and Meur-Ferec, 2004; Montreuil et al., 2013).

6.4 Aeolian Transport Potential

To better evaluate environmental forcing factors responsible for the dune growth observed at both sites, we calculated the potential sediment flux to the dune, Q, based on the aeolian forcing following the work of Keijsers et al., (2014) who computed sediment fluxes for a similar system on the Dutch Coast using a Bagnold-type relationship (designed for simplified equilibrium transport conditions), and solved for the dimensionless constant C that best fit our observations for each site. Observed dune volume change during accretive months was positively correlated to Q (not accounting for wind direction) at both the FRF and Nags Head (Figure 10; R^2 = 0.69 and 0.44, p-value<<0.05, respectively), however, the best-fit dimensionless constant, (C), varied between sites (FRF = 0.12; Nags Head = 0.35). The correlation is stronger at the FRF compared to Nags Head, which may be attributable to the complex interaction of structures as well as a less-uniform cross-shore profile and vegetation density at Nags Head. Recent work at the same Nags Head site (Kaczkowski et al., 2018), used a literature-derived value of C = 1.8 (Masselink and Hughes 2003) to find good agreement in the predicted volumes of sediment flux to the dune and observed dune growth rates during the first 3 years after the nourishment completion. Kaczkowski et al. (2018) concluded that during the initial phases of

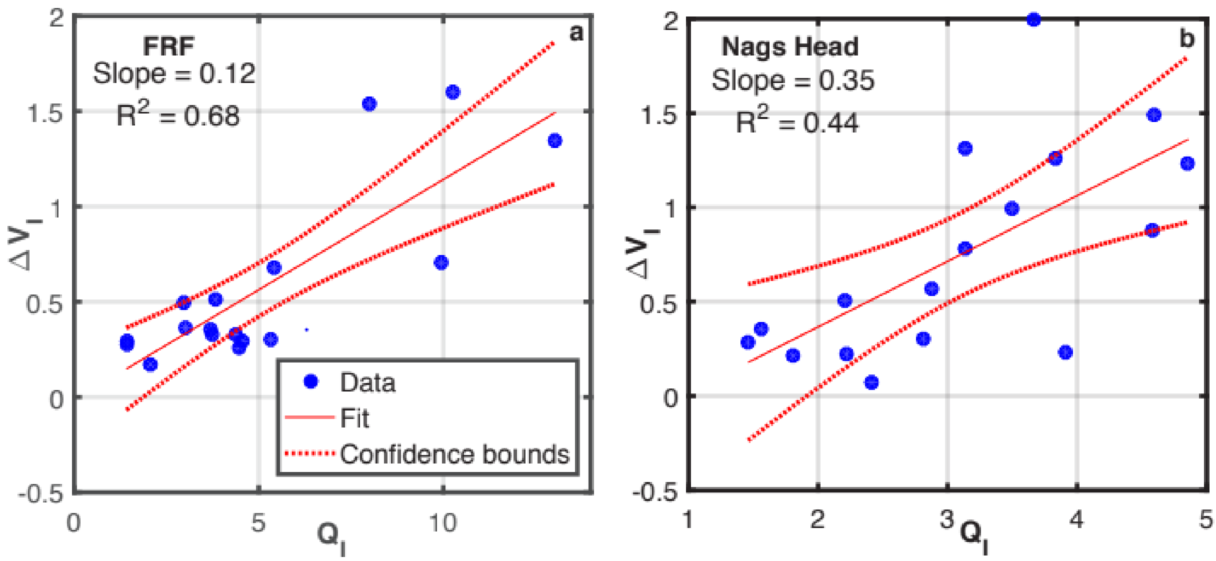

Fig. 10. Linear regression models of observed foredune volume change and interval Q sum for the FRF and Nags Head using 6 m/s threshold velocity and not accounting for wind direction.

beach nourishment equilibration, supply was rarely limited and equilibrium transport rates were frequently reached.

In contrast, this study found that the magnitude of transport (Q) was overpredicted using these methods relative to the actual volume gain, similar to other findings (e.g. Keijsers et al., 2014; Sherman et al., 2013), requiring a small, site-specific, dimensionless constant, C, to scale results (see slope of best-fit linear trend, Figure 10). Since it had been 5 years since the beach nourishment when our study began and the beach width is now significantly less than following placement (~30 m vs. 60 m), supply limiting factors may now be of higher importance. While there was a significant positive correlation between observed volume change and calibrated, predicted Q at both sites and in prior work, the calibration coefficient needed to be changed temporally and spatially. As a result, without temporally and spatially specific calibration data, these simplified relationships may not provide useful input into decision-making frameworks that aim to predict dune evolution on management relevant timescales (years to decades), particularly in coupled human and natural systems where management actions alter capture mechanisms.

When incorporating wind directions to examine transport directed to the dune, the predicted magnitudes of transport were lowered, yet storms were still over predicted, and the relationship to the observed changes was not as strong (Fig. 11; FRF R^2 = 0.38 and Nags Head R^2 = - 0.02). As other researchers have noted (e.g., Walker et al., 2006; Brodie et al., 2019), transport to dunes is complex and has been observed from alongshore wind directions. Furthermore, topographic steering may even contribute to transport to the dune from offshore wind directions, making predictions challenging.

Others have also suggested scaling issues that occur when linking micro-scale transport processes to meso-scale dune evolution (Davidson-Arnott and Law, 1996; Fabbri et al., 2017). For example, high-winds often accompany high waves and water levels and increased precipitation, which reduce fetch and increase the surface moisture on the beach, reducing transport—processes that are unaccounted for in these simplified transport models (e.g. Sherman et al. 2013). Since transport potential scales with U^3, high velocity wind events, such as those that accompany coastal storms, lead to significant over-estimates of Q. Multiple researchers have identified that temporal variability in foredune volume change has a stronger link to storm erosional processes (i.e., waves) than to aeolian transport potential (Keijsers et al., 2014; de Vries et al, 2016; and Fabbri et al., 2017). The use of the von Karman constant (0.4) in the derivation of shear velocity, as opposed to the apparent von Karman parameter that is transport-rate dependent, may also lead to increases in the magnitude of Q (Sherman et al., 2013). In addition, the simplified Bagnold-type equations do not simulate a plethora of important physical

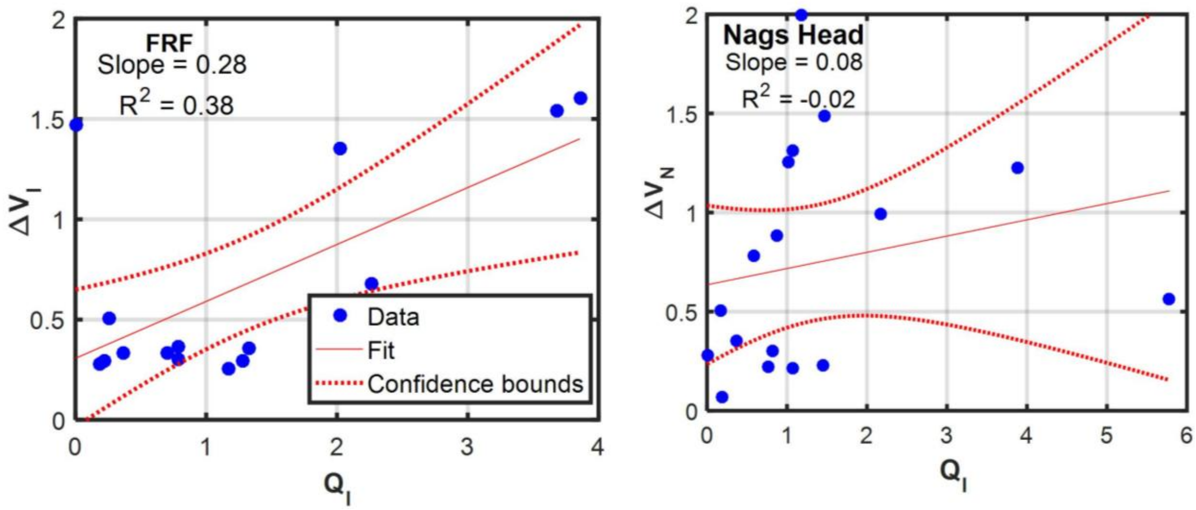

Fig. 11. Linear regression models of observed foredune volume change and interval Q sum for the FRF and Nags Head using wind directions and threshold velocities based on grainsize differences.

processes affecting saltation and sediment supply (de Vries et al., 2016). Moreover, using a mean grainsize is problematic because it is not reflective of the whole grainsize distribution. Once fine sands are winnowed, the sediment availability and transport capacity may be affected and diminished as different wind velocity thresholds are required to mobilize a coarser fraction (i.e. armoring).

In this case, the TLS data provided a useful tool to calibrate the simplified model, however, these data would rarely be available in practical applications. Ultimately, as suggested by Delgado-Fernandez and Davidson-Arnott (2011), deterministic equations may be insufficient for exact transport conditions but can help elucidate the most likely scenarios for high transport. In contrast, a better approach may be to utilize Aeolis, a process-based model which accounts for spatial and temporal variations in sediment availability (Hoonhut and de Vries, 2016) to estimate potential sediment fluxes into the dune, in combination with hydrodynamic and dune growth models such as in the Windsurf modeling suite, (Cohn, 2018), to properly account for the natural processes affecting dune evolution. In managed systems, it would be important to also incorporate the effects of management actions, such as fencing, plantings, and excavation activities to properly simulate dune evolution.

7.0 Conclusions

A combined analysis of high resolution TLS monitoring, meteorological forcings, and dune management actions provided multiple insights into dune morphodynamic evolution at managed and unmanaged systems. This study was unique due to the high frequency of TLS use, and shows TLS is a useful tool for measuring complex dune evolution over fine spatial (cm-m) and temporal (monthly) scales.

The managed dune system was observed to accrete 1.7 times faster than the unmanaged dune system under similar forcings. This is due to multiple factors including the wider beach and higher sediment supply (from nourishment) and enhanced capture mechanisms (i.e. fencing, plantings, walkovers). Anthropogenic features such as sand fencing, Christmas trees, plantings, and walk-overs were effective in promoting dune growth, while the walk-through caused erosion and slumping. TLS can effectively provide vegetation metrics such as height and density and showed that the unmanaged dune system contained denser, taller and more stable vegetation compared to the managed system. Accretion at the unmanaged site was consequently focused within the vegetated zone.

When compared to other natural dunes in the literature, the managed dune displayed much more rapid welding of the incipient dune to the primary foredune mass. This transition was accelerated by effective capture along the seaward fencing and accommodation space within the vegetated swale.

Extra-tropical and tropical storm events are often viewed as erosional, but results from this study show that storm events can actually be net accretional. At the managed dune system, the erosion on the dune toe was sometimes offset by high amounts of accretion in the vegetated swale and on the crest of the dunes. At the unmanaged site, accretion was more spatially uniform along the foredune face and crest.

Traditional empirical Bagnold equations not accounting for wind direction aligned with observed trends of aeolian transport but overpredicted magnitudes and required site specific calibration. Unless adequate data is available for proper calibration and supply limiting factors are not important at the site of interest, these equations will not provide useful input into decision-making frameworks in managed systems. This is likely because these formulations do not encompass supply limiting factors and erosional processes, which will be the focus of future work.

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CHAPTER 3

Marine Geology and Sand Resources of the Southern North Carolina Inner Shelf: Insights from a Sediment Starved Continental Margin

Abstract

Beach nourishment is a popular engineering-with-nature (EWN) strategy used globally for shoreline stabilization and coastal storm damage reduction. Large-scale projects require dredging from offshore sand borrow sources. However, suitable sands for nourishment are not ubiquitous offshore, especially in sediment-starved southern NC. In 2015, >300 nautical miles (555 km) of sub-bottom, sidescan, bathymetry and 38 cores/grabs were collected in data gaps offshore southern NC and interpreted for geologic horizons and potential nourishment-compatible sand thickness. In addition, hundreds of paleochannels were mapped and evaluated for fill patterns and resource potential. Various forms of hardbottom were delineated, sometimes in close proximity to sand resources. Results show high spatial variability in the distribution of beach-compatible sands across the southern NC shelf, where only a thin sand veneer is observed in many locations, although some regions contained continuous deposits exceeding 3 m. The thickest shoal deposits (>5 m) were observed offshore New Hanover County Region. Underlying strata and bathymetry appear to affect channel shape and distribution. Channels with acoustically transparent fill may be suitable as nourishment sources, yet many channels show complex and variable fill suggestive of tidal and estuarine environments. Seafloor reconnaissance data are valuable in preventing multi-use conflicts on the shelf as shelf areas are increasingly being explored for other functions (e.g , wind farms, oil/gas, fish habitat). These findings provide a useful starting point for coastal managers seeking sufficient offshore sediment resources for nourishment in response to future storm events and sea-level rise.

1.0 Introduction

Like many areas around the world, the North Carolina ocean coast is experiencing widespread erosion as a result of reoccurring storm events. The shelf geomorphology and geology play a key role in shoreline changes, and also hold sand resources to mitigate against erosion. Beach nourishment is used worldwide as a strategy to combat erosion of sandy coasts. Often described as a "soft-engineering" strategy, nourishment is designed to dissipate wave energy and minimize storm surge to protect infrastructure and to sustain recreational beaches that are economically essential in tourism-driven areas. Along some sections of the U.S. Mid-Atlantic Coast nourishment occurs every few years. For example, since 1939, nearly $850 million has been spent in North Carolina (NC) on nourishment of > 250 projects and > 250 miles of coastline (PSDS, 2018).

Beach nourishment is typically a multi-pronged process involving multiple stakeholders, permitting steps and geologic reconnaissance, surveys, and engineering (ASBPA, 2007). In the case of dune maintenance and small-scale beach projects (e.g., <50,000 cubic yards), trucked sand is often economically effective (Dobkowski, 1998). However, large-scale beach nourishment projects, typically involve the dredging of sand and pumping it from offshore borrow sites (i.e., with a hydraulic dredging system). While beach nourishment is simple in theory, suitable sediment, i.e., material that is compatible with the natural beach, is not ubiquitous offshore. Thus, project costs fluctuate with distance to the borrow area. Costs are also dependent on the geological nature of the borrow source and the efforts needed to extract the beach quality sand (Leatherman, 1989, Dobkowski, 1998). Regional sediment management (RSM) is a strategy highlighted by the U.S. Army Corps of Engineers, and in keeping with this management philosophy, use of navigational dredged material is considered when possible. But, the persistence of storms and chronic erosion has triggered an increased demand for diminishing sand resources in State waters (Drucker et al, 2004), making it necessary to target material from the Outer Continental Shelf (OCS) under federal jurisdiction.

Following the detrimental impacts of Hurricane Sandy (2012) along the east coast of the U.S., the Bureau of Ocean Energy Management (BOEM) recognized that establishing a central hub for existing geologic knowledge relevant to potential borrow sources would increase response efficiency and provide a better understanding of the distribution, character and volume estimate of known suitable sands (Walsh et al., 2016a). In response, research was funded in thirteen states to collect and synthesize data on marine sand resources. Based on this and earlier research here and elsewhere around the world, it is understood that offshore sand bodies persist in a variety of morphosedimentary forms depending on varied complex geologic history, and often require multiple survey and sediment sampling techniques (e.g., sub-bottom profiling, vibracoring) to sufficiently map and characterize them.

Widespread surveying has been conducted in northern NC (e.g., Thieler et al., 2014; NCDCM, 2016), but there was a lack of broad-scale data coverage in the southern NC OCS as work has been conducted primarily in NC State waters (0-3 mi). To address this deficiency, reconnaissance sub-bottom geophysical data and vibracores were collected in 2015 based on data coverage gaps, as part of the Atlantic Sand Assessment Project, a post-Sandy BOEM-funded sand resource assessment effort (Walsh et al., 2016a). The work herein stems from this project, and specific objectives are to: 1) examine the geomorphology and geology of the southern NC shelf, 2) evaluate the distribution of sand resources offshore southern NC and its relationship to geologic context, and 3) assess the variability in form and classification of paleochannels and hardbottom.

2.0 Study Region

The underlying geologic framework varies significantly along NC and has a strong control on the modern configuration of the coastline (Riggs et al., 1995, Zaremba et al., 2017). The northern part of the State is characterized by long, narrow barrier islands with few inlets and large estuaries, whereas the southern portion has shorter barrier islands, more inlets and smaller estuaries (Riggs et al., 1995) (Fig. 1). Differences in tectonics, sea-level rise and sediment supply influenced the long-term basin evolution. As sea-level rose following the Last Glacial Maximum and into the Holocene, shorelines retreated and transgressive ravinement by wave action eroded and exposed subsurface sedimentary strata consisting of shelf, coastal, and fluvial lithofacies (e.g., relict barrier complexes, tidal deltas and fluvial deposits) (Rutecki et al., 2014). The northern coastal zone contains a thick wedge (up to 90 m) of Quaternary strata that has been reworked during sea-level change (Mallinson et al., 2010; Thieler et al., 2014). Offshore sand bodies, which can serve as potential borrow areas, are present but localized (Swift, 1976; McBride and Moslow, 1991; Snedden and Dalrymple, 1999; Walsh et al., 2016b). Southern NC, however, is characterized by even more limited sand bodies (i.e., "sediment-starved") along with exposed Cretaceous through Pliocene rocks along much of the seafloor (Meisburger, 1979; Snyder et al., 1994; Riggs et al., 1995). Ultimately, with chronic shoreline erosion rates (often less than -1 m/yr), sand resource demands may pose problems along many parts of the NC coast, but considering the geological setting, a number of communities are facing long-term challenges.

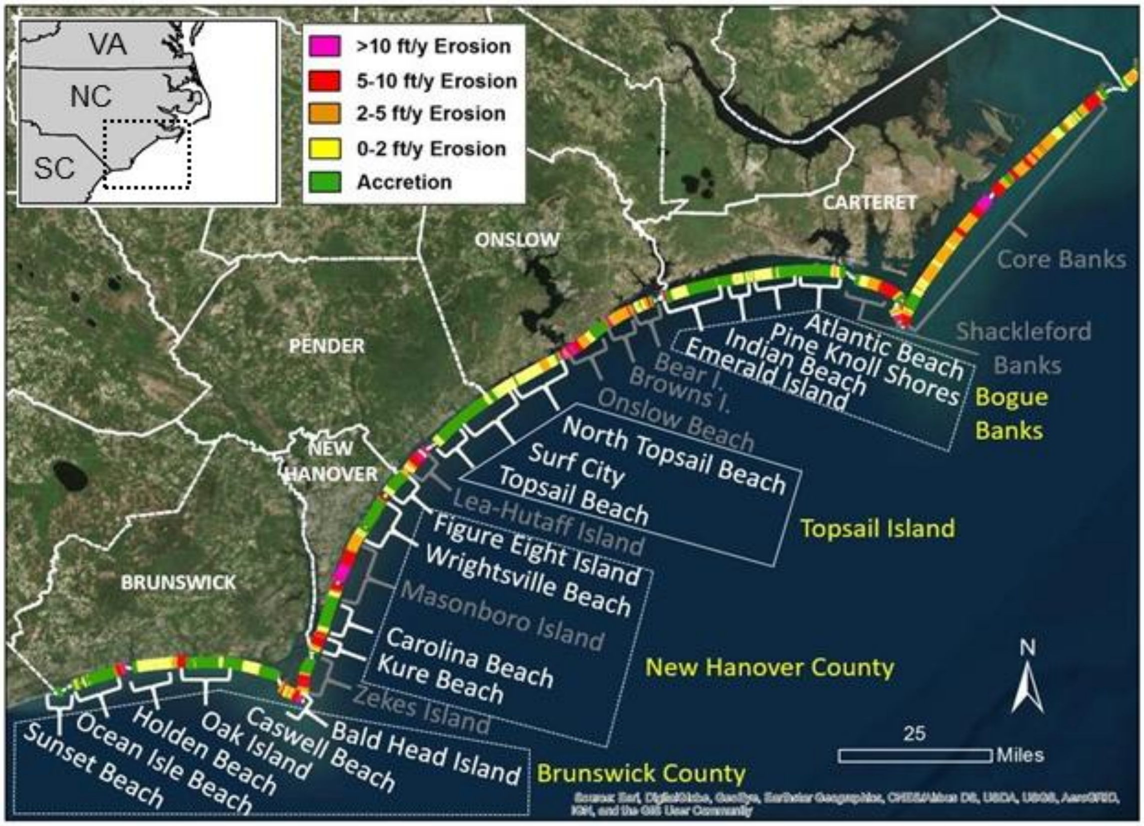

Fig. 2. Site map of southern North Carolina and focus areas (labelled yellow). White labels indicate incorporated towns that are managed with beach nourishment. Gray labels signify undeveloped zones that include state and federal lands which are unlikely to be nourished. Long-term DCM (2017) shoreline change rates are shown by colors (see legend) and show the variability of erosion along the state.

3.0 Background

3.1 Shoal and Sediment Sources

Sand resources exist in a variety of geologic forms, ages and locations. In North Carolina, moderate volumes are extracted at several localities from navigational channels for "beneficial reuse" in nourishment projects (NCDCM, 2017). The work presented here, however, focuses on the shelf, where sand bodies are in the geomorphic form of ridges, rippled scour depressions, shoals/sediment banks, channel fill and shoal complexes and fields. Shoals are generally divided into relict shoals (e.g., Oregon Shoals; Thieler et al., 2014), cape-associated shoals (e.g., Frying

Pan Shoals) and sorted bedforms (e.g., Wrightsville Beach; Thieler et al., 2001). In northern NC, the ample Quaternary sand supply has led to the formation of shoal fields that are kilometers wide with relief up to 10 meters (e.g., Oregon Shoals; Swift, 1976; Snedden and Dalrymple, 1999; Thieler et al., 2014). In contrast, in southern NC unconsolidated sediment has been reported to be less abundant on the shelf (Riggs et al., 1995), and sources are typically small-scale sorted bedforms or thin modern veneers (Hine and Snyder, 1985; Gutierrez et al., 2005; Thieler et al., 2001).

3.2 Paleochannel Background

Buried paleochannels also may contain sand fill useful for nourishment. Fluvial and tidal processes are the primary channel-carving mechanisms (Gutierrez et al., 2003). Major paleo-river systems on the U.S. East Coast that have been extensively surveyed include the Hudson (Carey et al., 1998), the Delaware (Fletcher et al., 1992), the Susquehanna/Potomac (Coleman et al., 1990), the Pee Dee/Waccamaw (Baldwin et al., 2006) and the Roanoke/Albemarle Rivers (Riggs et al., 1995; Boss et al., 2002; Mallinson et al., 2005). Commonly referred to as incised valleys, these systems generally exhibit dendritic drainage patterns with a large trunk channel. The preservation potential of a paleo-channel is contingent upon the initial channel morphology, tidal enhancement, depth of wave ravinement and burial (Belknap and Kraft, 1981). The best preservation potential for channel morphology has been suggested to occur in outer shelf areas of rapid transgression during the late Pleistocene/early Holocene, as shown by seismic data collected along the paleo-Delaware River (Belknap and Kraft, 1981). As such, the rate of sea-level rise is believed to be critical to the depth of ravinement and channel preservation (Belknap and Kraft, 1981).

3.3 Shelf Habitat

Sediment bodies and hardbottom also may serve as critical habitat for fish and other benthic organisms in addition to being sources for beach nourishment (NCDEQ, 2016; Rutecki et al., 2014). In order to best manage multi-use conflicts, an understanding of the effects of dredging on habitat is crucial. For shelf mineral resource extraction, projects must comply with NOAA fisheries and the U.S. Fish and Wildlife Service guidelines as outlined in the Endangered Species Act (ESA) and Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). Ridge and swale and cape-associated shoal complexes have been defined as essential fish habitat by NOAA Fisheries (NOAA, 2014). Sand dredging has been shown to have several short- and long-term physical and biological impacts affecting habitats (Rutecki et al., 2014). Physical effects include alteration of sediment grainsize and transport, wave and current patterns and turbidity, which in turn have a biological influence (Drucker et al. 2004, Hayes and Nairn 2004). Direct biological impacts include alteration or removal of benthic epifaunal and infaunal communities that are linked to higher trophic levels (Drucker et al. 2004, Hayes and Nairn 2004). Spatially compiling all knowledge on potential borrow areas is important to determining habitat effects and for long-term, sustainable management of multi-use shelf resources.

3.4 NC Nourishment History

Wrightsville Beach, in the southern part of the State, conducted the first beach nourishment in NC in 1939 (NCDCM, 2016) (Fig. 1). Since then, dozens of nourishment and renourishment projects have taken place in NC (Table 1), totaling over $800 million (Program for the Study of Developed Shorelines, 2018). Today, beach nourishment is being considered for about 75% (120 of 160 miles) of the developed NC oceanfront shoreline (NCDCM, 2016).

In the Bogue Banks region (Atlantic Beach to Emerald Isle; Fig. 1), the process of implementing a federally sponsored 50-yr Coastal Storm Damage Reduction (CSDR) project began in 1989 and was authorized in 2016. In addition, Carteret County adopted the Bogue Banks Beach Master Nourishment Plan in 2010 because future federal funding is not certain (BBMNP, 2017). Atlantic Beach was recently nourished in 2017 with >650,000 cy of sand. In 2019, three areas of Bogue Banks (Emerald Isle, Indian Beach and Salter Path) will be nourished with 945,446 cy using sediment from the Offshore Dredged Material Disposal Site (ODMS) as part of the Post-Florence Renourishment Project (BBFRP, 2019).

In the Topsail Region (Fig. 1), a CSDR was authorized in 1992, but it did not proceed. Because federal projects were not ensuing, the North Topsail Beach Shoreline Protection Plan (2009) and Town of Topsail Beach 30-Year Beach Management Plans were developed. The most recent project in 2015 used 860,000 cy from inlet and other federal navigation channel sources.

In the New Hanover County Region, Wrightsville Beach was authorized for a CSDR in 1965 and was most recently nourished in 2014 and 2018 using sediments primarily from Masonboro Inlet (USACE, 2015). Carolina Beach was authorized for CSDR in 1962, one of the first in the U.S., and was most recently nourished in 2016 (890,000 cy) using the Carolina Beach Inlet (USACE, 2010b). Kure Beach also was authorized for CSDR in 1965 and was most recently nourished in 2016 (655,000 cy) using an offshore borrow source.

Table 1. Beach nourishment data from the Beach and Inlet Management Plan (NCDENR, 2016).

Location	First year of Record	Number of Times Nourished	Total Volume Nourished (cy)
Atlantic Beach/Ft. Macon	1958	14	17,525,228
Bald Head Island	1991	12	11,186,190
Cape Hatteras	1966	3	1,812,000
Cape Lookout	2006	1	75,700
Carolina Beach	1955	36	19,803,048
Caswell Beach	2001	2	256,600
Emerald Isle	1984	19	4,571,214
Figure Eight Island	1977	26	6,113,852
Hatteras Island	1974	7	887,801
Holden Beach	1971	49	4,661,045
Indian Beach/Salter Path	2002	3	1,385,692
Kill Devil Hills	2004	1	38,016
Kitty Hawk	2004	1	143,000
Kure Beach	1998	6	5,964,932
Masonboro Island	1986	6	3,234,686
Nags Head	2001	3	4,800,000
Oak Island	1986	9	6,545,287
Ocean Isle Beach	1974	18	4,479,790
Ocracoke Island	1986	5	516,062
Onslow Beach	1990	4	405,829
Pea Island	1990	20	9,673,228
Pine Knoll Shores	2002	6	2,969,185
Rodanthe	2014	1	1,618,083
Topsail Island	1982	20	5,394,479
Wrightsville Beach	1939	26	14,709,157

In the Brunswick County Region, a CSDR was approved for Ocean Isle Beach in 2001 for a 3-year maintenance cycle that was most recently conducted in 2017 (270,000 cy) using sediment from Shallotte Inlet. Holden Beach was most recently nourished in 2017 (1,800,000 cy) using an offshore borrow site. Oak Island was nourished in 2015 (227,315 cy) using Eastern Channel sediments and again in 2018. Caswell Beach was nourished in 2018 using dredged sediments from the Wilmington Harbor entrance channel. Finally, the Village of Bald Head Island was nourished in 2015 (1,850,000 cy) from the Wilmington Harbor entrance channel.

3.5 Existing Data

Many different entities have conducted seafloor mapping and geological research offshore NC over the last half century. As a result, a wide variety of sediment, seismic, and bathymetric data are available; recent reports review available information (NCDCM, 2017; Walsh et al., 2016a) (Fig. 2). The largest data collections (many with large spatial coverage) are available from federal agencies, including the National Oceanic and Atmospheric Administration (e.g., the National Centers for Environmental Information, formerly the National Geophysical Data Center at https://www.ngdc.noaa.gov/), the U.S. Army Corps of Engineers and the U.S. Geological Survey (http://walrus.wr.usgs.gov), including information in usSEABED and from a large cooperative study conducted in the 2000s (Reid et al., 2005). Other data sources include information from academic, private, state and other federal efforts.

4. 0 Methods

4.1 Priority Target Areas and Data Collection

As a result of a large USGS cooperative project (OFR 2011-1015) and earlier work, a relatively extensive amount of geophysical and core data, and thus geological knowledge, exist in northern NC (Thieler et al., 2013; 2014). In early 2015 with input from NC scientists, managers, and private consultants, it was agreed that reconnaissance data collection would occur in southern NC for the BOEM-funded Atlantic Sand Assessment Project (ASAP), where there was sparse data on the OCS (Fig. 2). These data are the foundation of the research herein. CBI (currently APTIM) collected 317 nautical miles of sub-bottom data (EdgeTech Chirp 512i), interferometric sidescan sonar data (EdgeTech 6205), swath bathymetry data (EdgeTech 6205), magnetometer (Geometrics G-882) along with 24 vibracores and 14 surface sample grabs (Fig. 2).

4.2 Core Logging and ^{14}C Dating

Cores were logged on the CBI vessel, and subsequently, logs were refined and verified by a team from East Carolina University. Cores were subsampled at lithologic boundaries, or at a minimum of 30 cm intervals. For grain-size analysis, a Rotap system was used with 12 sieves at 0.5 phi intervals from -2.25 to 4.0 phi. While relogging the cores, 29 *in situ* shells or shell fragments were extracted for ^{14}C analysis (Table 2). Samples were sent to the Center for Applied Isotope Studies, Univ. of Georgia for dating. The open source software Calib (Stuiver et al., 2018) was used to calibrate age ranges using the radiocarbon age, standard deviation in age, and MARINE13 curve. Two sigma values are reported in years before present (Cal y BP).

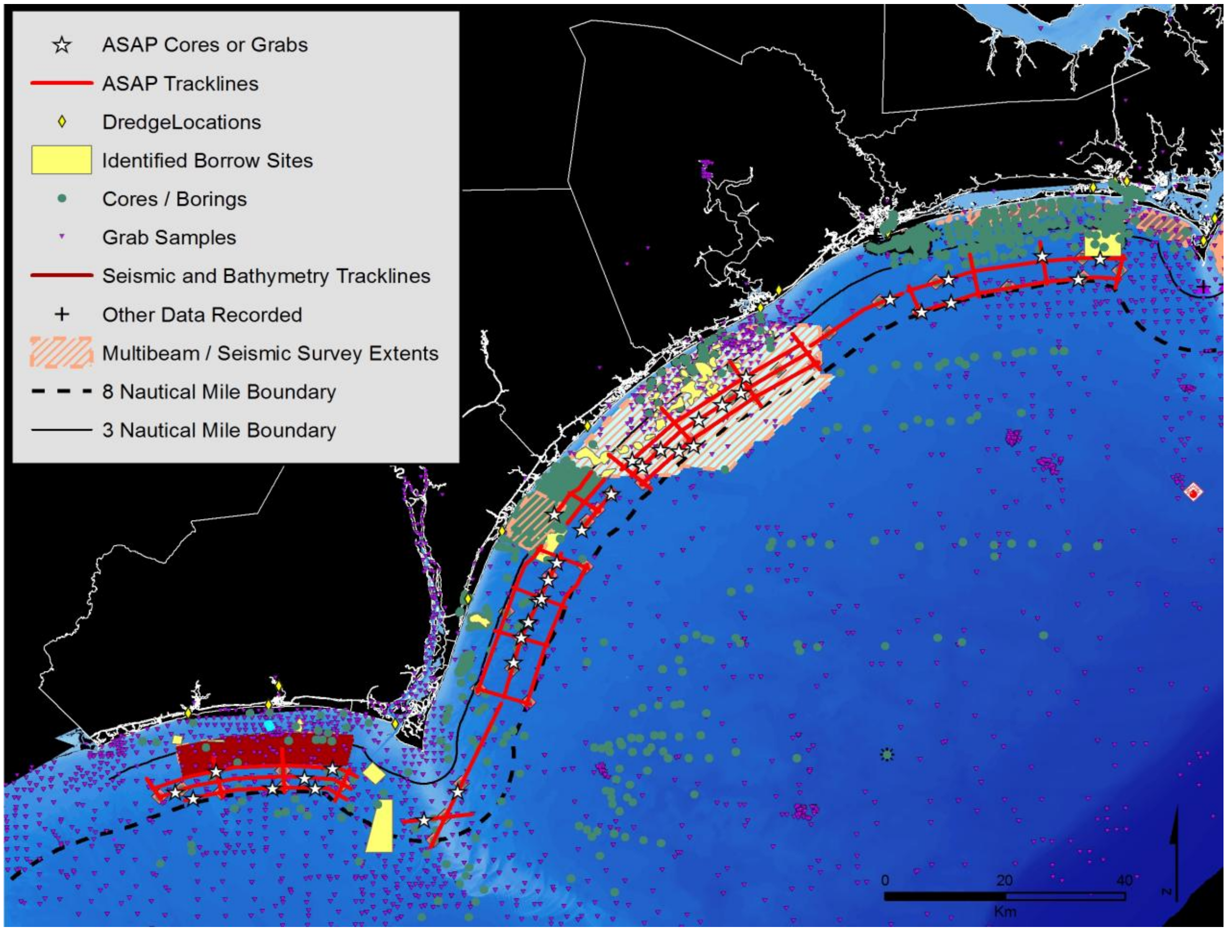

Fig. 2. Survey lines (red lines) and core locations (stars) analyzed in this study. The ASAP data collection in 2015 targeted the Outer Continental Shelf offshore NC (3-8 nautical miles) and was strategically planned to fill gaps in available federal, state and private datasets (shown; Walsh et al., 2016a).

Table 2. Calibrated ^{14}C ages and associated cores and depths. All analysis used shells or shell fragments.

Sample ID	**Depth in Core (cm)**	**cal y BP (2σ)**
VC03	183	6661 – 6831
VC08	93	36346 - 37361
VC08	319	44568 - 45679
VC09	144	969 – 1134
VC09	292	8025 – 8196
VC09	436	44979 – 46075
VC09	495	38745 – 39663
VC09	523	33583 – 34001
VC13	140	7833 – 7978
VC15	201	42253 – 42892
VC17	46	5315 – 5519
VC17	61	2980 – 3177
VC17	373	7980 – 8143
VC18	497	10540 – 10735
VC19	124	8185 – 8338
VC23	67	42119 – 42755
VC23	183	45030 – 46134
VC24	30	1529 – 1677
VC24	241	8531 – 8744
VC25	21	4580 – 4795
VC25	247	4415 – 4598
VC25	328	4769 – 4892
VC27	26	20866 – 21268
VC31	26	1710 – 1858
VC31	43	9875 – 10133
VC31	86	9917 – 10156
VC31	122	10500 – 10683
VC31	170	34435 – 34952
VC32	23	32415 – 33268
VC32	27	42274 – 42933
VC32	61	45083 – 46351
VC33	30	563 – 668
VC33	117	9078 – 9313
VC33	197	48446 - [50000]
VC34	140	45407 – 46737

4.3 Sand Thickness Analysis

Chesapeake Technologies Sonarwiz software (Version 6.04) was used for sub-bottom processing and sand thickness calculations. SEG-Y Chirp files were imported and smoothed using the swell filter function. Vibracores and grab samples were added based on coordinate positions within seismic lines. The seafloor reflector was created using the automated bottom-tracker. For the purpose of this work, the interpreted base of reworked Holocene sand (H), the Quaternary Transgression surface (QT), the base of Quaternary channels (QC), and hardbottom (R) were interpreted and digitized. These reflectors are common in the study region. After digitization, the reflector thickness calculator was used to estimate sand thicknesses between the relevant reflectors and the seafloor (by subtracting elevation values). These thicknesses were exported as XYZ text files and imported to ArcGIS as points for analysis of the spatial distribution of the reflectors and related sand thicknesses.

5.0 Results

5.1 ASAP Results and Interpretations

This study focused on mapping key reflectors in the region that define important stratigraphic units. Properties of these reflectors and the units they define are presented in Figure 3. Based on the core and seismic observations, units H and QT are the most likely sources for unconsolidated sands with potential for beach nourishment. Specific examples are provided below.

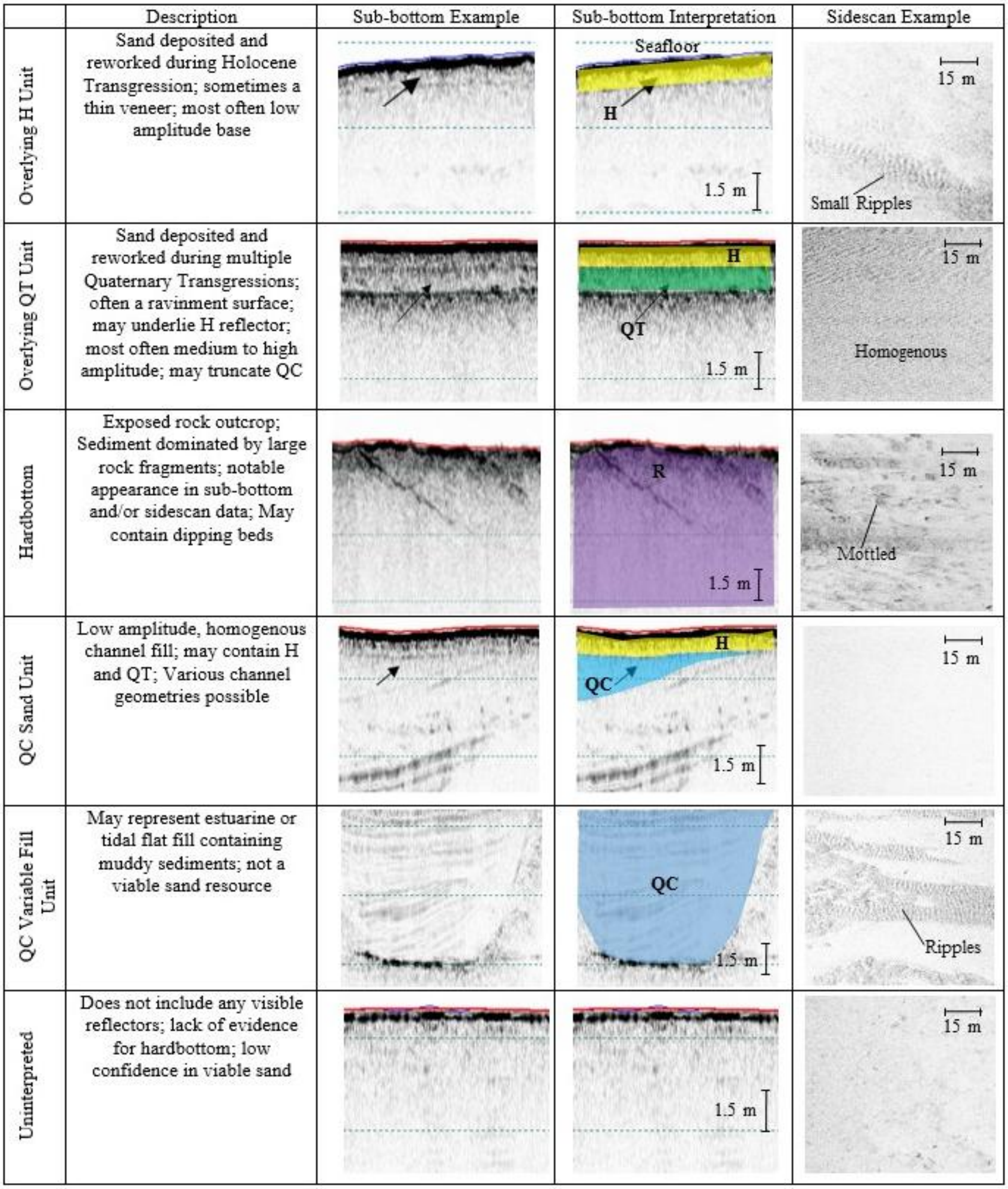

Fig. 3. Interpretation guide depicting various seismic unit examples, descriptions and associated appearances in sub-bottom and sidescan data. Note, this is not all-inclusive and these lithologic units have a variety of geophysical signatures.

5.2 Bogue Banks Region

The Bogue Banks region of Carteret County (Fig. 4) shoreline is oriented predominantly E-W and is bordered by Cape Lookout to the east. The survey lines are relatively shore parallel, contain four north-south shore-perpendicular crossing lines, and are between 7.4 and 15.0 km offshore (Fig. 4). Water depths range from 15.0 m (closest to shore) to 19.0 m at the seaward edge of the survey area. Seafloor gradients vary in the region, and slopes of 0.2 m/km occur to the east (seaward of the 17 m isobath). The steepest slopes of 2.5 m/km occur toward the center of the region (seaward of the 18 m isobath). The seafloor is generally low relief, and the highest relief of up to 1.5 m occurs at a ridge and depression in the SE quadrant. The eastern half of the region contains three small-scale, shore-detached ridges that extend NW-SE and are ~1 m high, ~0.5 km wide, range in length from 2.0 to 3.4 km and have little to no asymmetry.

The ASAP Bogue Region contains an extensive modern sand layer (Unit H) mapped in 49% of the total survey distance with unit thicknesses reaching up to 3.59 m in the northern and southeastern portions (mean = 1.06 m)(Fig. 4). These observations are consistent with Hine and Snyder (1985) who also note the patchy presence of a 1-2 m thick Holocene veneer on the inner shelf. Extensive Holocene deposits are thought to be absent due to wave ravinement which removed much of the sedimentary record in Onslow Bay. Consequently, Tertiary rocks and sediments outcrop at the seafloor in many locations (Hine and Snyder, 1985; Geodynamics, 2012).

The deeper QT reflector is visible in the eastern third of this region (20% of the mapped linear distance) and the overlying unit contains thicker sands up to 4.7 m (mean = 2.5 m)(e.g., Fig. 5). Paleochannels and hardbottom are frequently observed in the central region (Fig. 4), and are present in 31% and 23%, respectively, of the total mapped distance. When ASAP

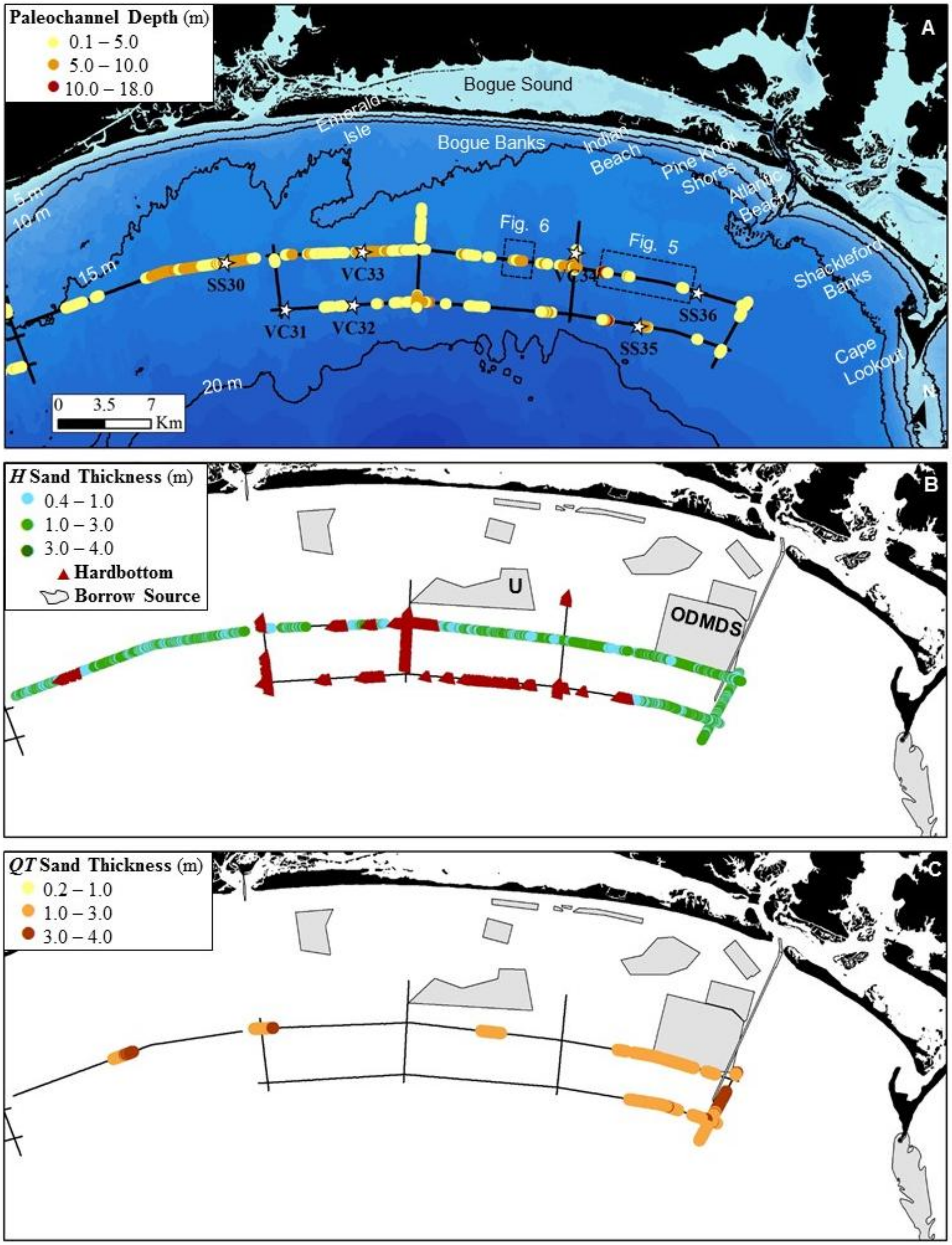

Fig. 4. Bogue Banks Region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources; those labelled U and ODMS are discussed in text.

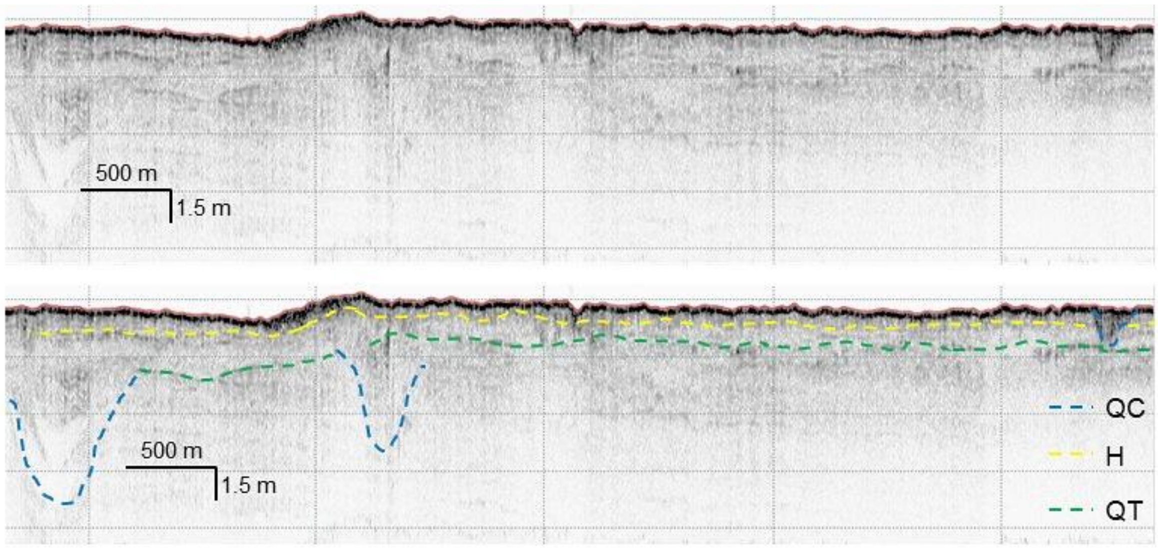

Fig. 5. Example seismic line and interpretations from Bogue Region. Location indicated by black dashed box in Fig. 4.

interpretations are overlain on Hine and Snyder (1985), numerous areas of mapped paleochannels align that are interpreted as relict tidal inlets/lower coastal plain streams that can be identified by truncation in the Tertiary seismic stratigraphy (Fig. 6). ^{14}C ages from four cores within channels show two channels contain surficial Holocene sand and variable Pleistocene fill below (VC31 and VC33; Table 2; Fig. 4 and 7), whereas the other two channels are filled with Pleistocene or reworked sediments (0.3 - 1.5 m depth) (VC32 and VC34; Table 2, Fig. 4 and 7). The infilling of the paleochannels is variable and complex, and mostly appears to be representative of estuarine and fluvial fill (i.e., sands interbedded with muds and clay and gravel base) (Hine and Snyder, 1985). While some buried channels may contain sands suitable for nourishment as shown by core and seismic appearance, more core validation is needed. Hine and Snyder (1985) show areas of especially thick (10 - 20m) quaternary sediments within channels that are corroborated by ASAP data (see black box focus area in Fig. 7).

Several previously identified potential borrow sources are identified in the vicinity of ASAP data. For example, the USACE (2014) indicate the “U” borrow source contains an estimated 8.9 million cubic yards (mcy) or million cubic yards (6.8 million m^3) of beach compatible sand (Fig. 4). The Offshore Dredged Minerals Disposal Site (ODMDS),where Bogue Inlet channel sands have been dumped since 1987, is estimated to contain 28.3 mcy (21.6 million m^3) (Fig 4). At the ODMS site, dredge spoil sand (up to 4.9 m thick) overlies fine and silty sand that is stratified as much as 9.2 m below the seafloor, although its base is not continuous throughout the Bogue region (Freeman et al., 2012).

ASAP reconnaissance data provide several potential high volume areas of beach compatible sand that represent a complex geologic history and are in reasonable proximity to a series of towns with a history of nourishment (Table 1). Based on future demand of sand for continued replenishment projects (NCDCM, 2017) these are viable options, if the need for additional resources arises.

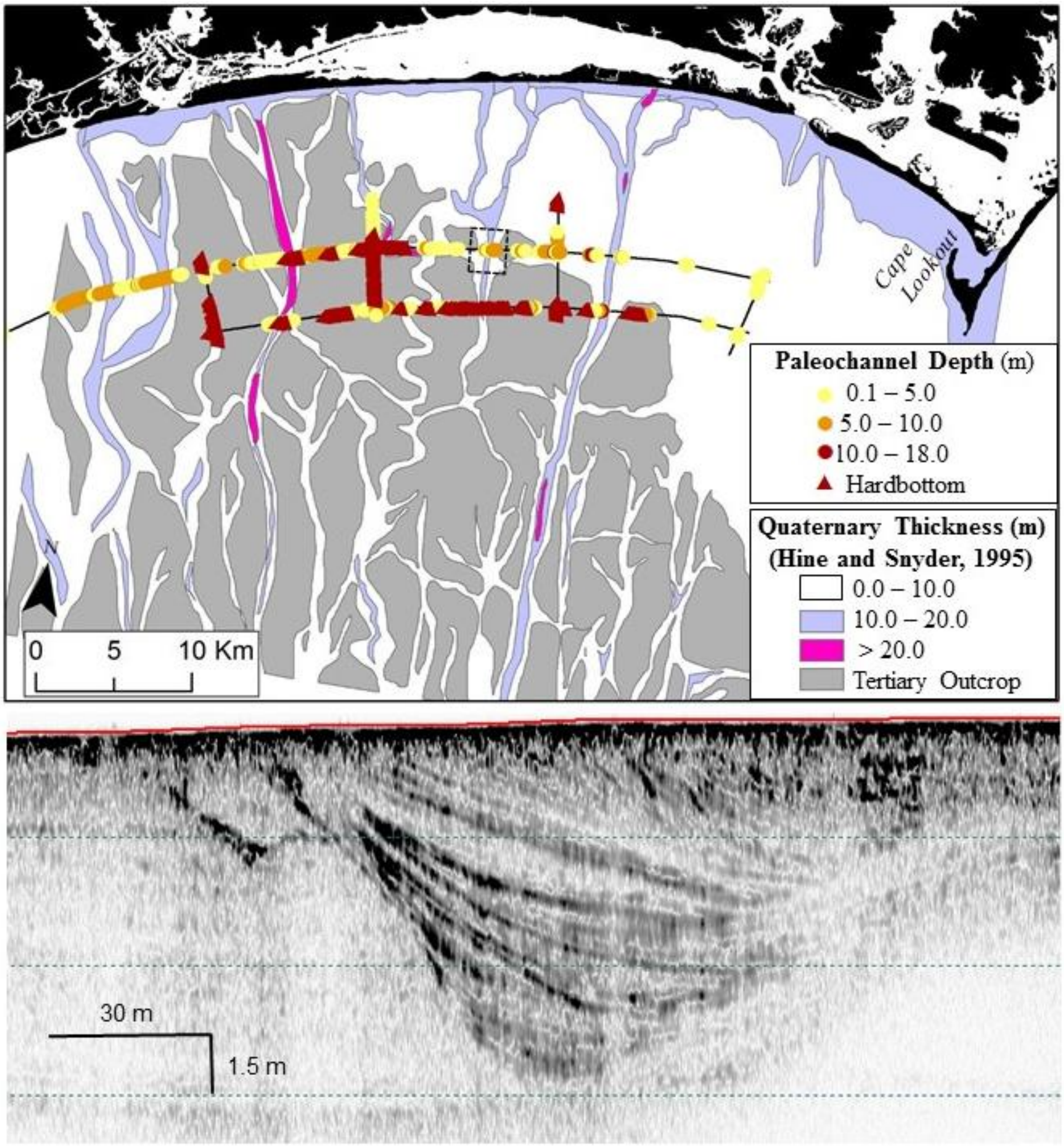

Fig. 6. ASAP results draped over geo-rectified interpretations from Hine and Snyder (1985). Areas of thick Quaternary sediments and hardbottom as interpreted by Hine and Snyder (1985) often are corroborated by ASAP results. A channel example is shown (location is indicated black dashed box in top panel) where Hine and Snyder mapped particularly thick (10-20 m) Quaternary sediments.

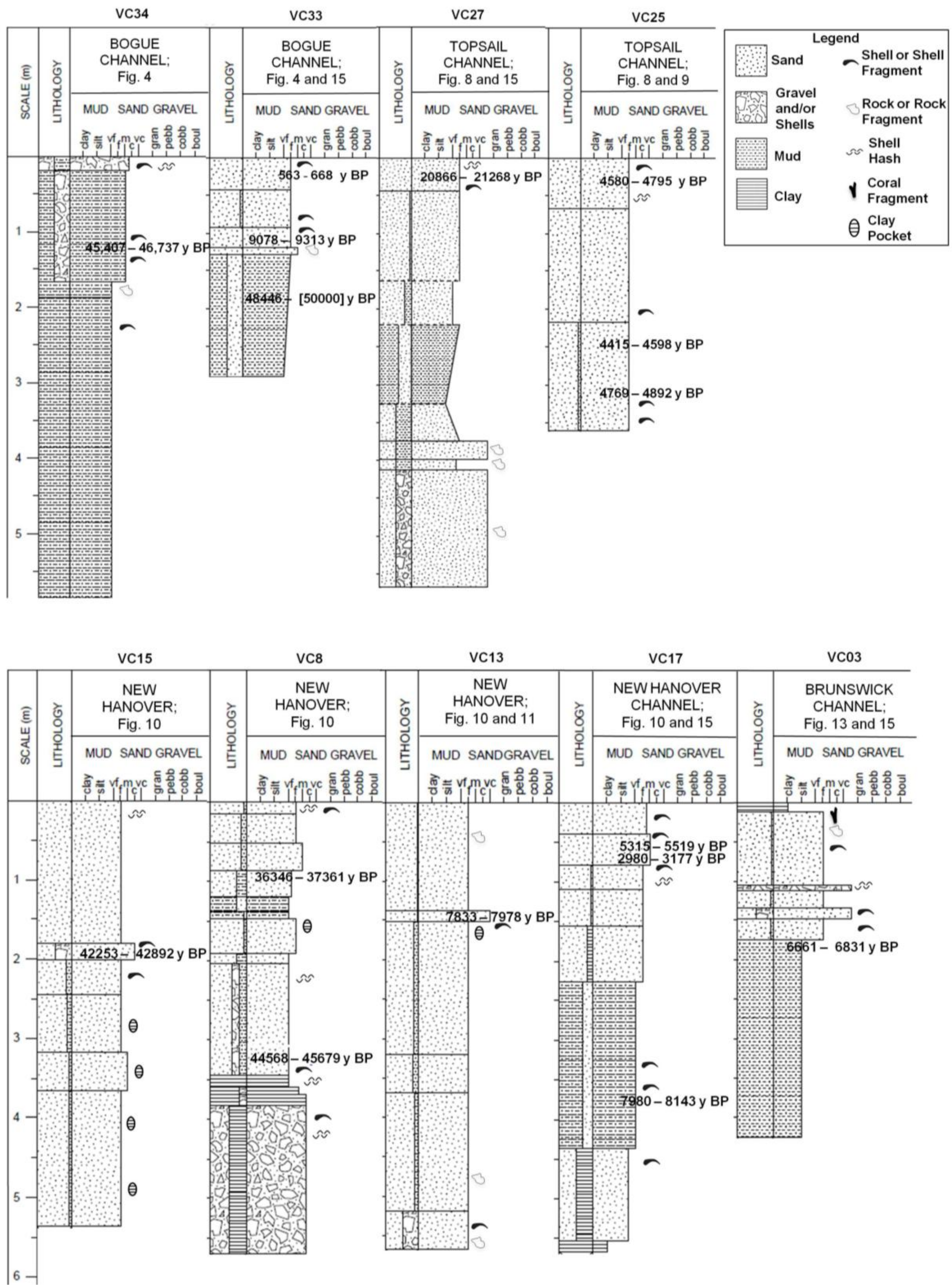

Fig. 7. Core logs and associated ^{14}C age estimates at depth (calibrated years before present). Note, lithology column reflects relative percentages. Cores are in the order in which they are discussed in the text.

5.3 Topsail Island Region

The shoreline in the Topsail Island region is oriented NE-SW. Three survey lines are shore-parallel, along with five shore-perpendicular crossing lines (Fig. 8). Water depths range from 13 m closest to shore (5.4 km offshore) to 17 m at the seaward edge of the survey area (14.8 km offshore). The NE half exhibits a gently dipping seafloor (0.45 m/ km slope) seaward of the 13 m isobath. The southern half of the region contains a valley-like feature with sidewalls up to 4 m/km in slope defined by the 20 m contour in Fig. 8. The southern section of the region is characterized by a bathymetric fabric produced by a series of shore-detached, shore-oblique small scale ridges ~1 m high, ~1 km wide and ranging in length from 3.8 to 4.4 km. The highest local relief is 2.2 m. These ridge features become more pronounced seaward of the survey lines at the 15 m isobath.

Most of the Topsail region contains a lense of sand unit (mean thickness = 1.0 m) reaching up to 2 m thick and visible in 73% of the total mapped linear distance (Figs. 8 and 9) . However, this modern sand unit is discontinuous and quite thin in most areas, making resource extraction by dredging unlikely. OSI (2004) and Snyder et al. (1988) indicated much of the region landward of the survey area is characterized by low relief Oligocene limestone and siltstone hardbottom overlain by a thin, patchy veneer of Quaternary sands and gravels and numerous Quaternary channel-fill sequences. The QT reflector is interpreted in 29% of the total linear survey distance (mean unit thickness above QT= 2.6 m, range 0.2 to 6.4 m), and the unit above appears to be thicker in the central section where many areas exceed 4 m (e.g., Fig. 8 and 9).

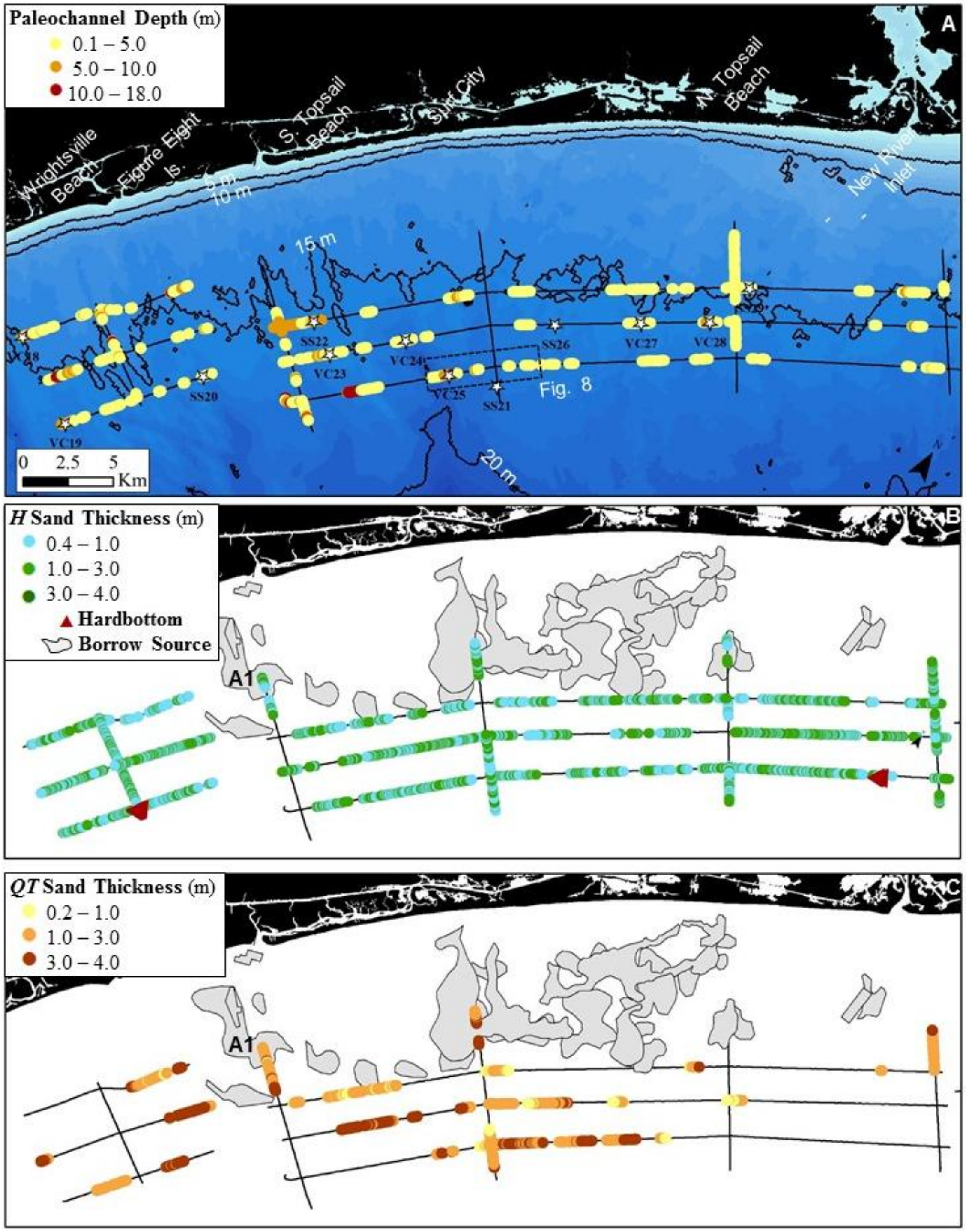

Fig. 8. Topsail Island region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data.Polygons are previously identified borrow sources; A1 is discussed in the text.

Paleochannels also are widespread (31% of mapped distance) and are most common in the central areas (Fig. 8). ASAP core data indicate some channels may contain usable sand (e.g., Fig. 7), yet others are more heterogeneous and indicative of variable estuarine fill (i.e., silts and clays), also noted by OSI (2004). ^{14}C ages from cores within four separate channels indicate two channels (VC23 and VC27; Fig. 7 and 8; Table 2) are filled with shallow (< 2 m) Pleistocene (or reworked) sediments, whereas the other two channels are filled with Holocene sediments overlying the interpreted QT reflector (VC24 and VC25; Fig. 7 and 8; Table 2). The Holocene channel fill is composed of a homogenous fine sand, while the Pleistocene channel fill consisted of variable estuarine lithofacies. .

Mapped hardbottom is minimal in this region (1%) (Fig. 8). Extensive low to high-relief hard bottom outcrops have been mapped nearshore of Surf City and New River Inlet, although a thin layer of sand covers much of the low relief hardbottom (Crowson, 1980). Using sidescan, multibeam, and diver-collected ground truth data, HDR (2003) reported an irregular exposure pattern of hardbottom in this region extending from the 9.1 m contour to 8 km offshore. Much of the complexity of the exposure is likely due to the irregular burial of low relief hardbottom areas by sands.

An adjacent previously identified borrow source was recently examined by Coastal Planning and Engineering, Inc., (CPE) for Topsail beach projects. CPE conducted design-level surveys in the USACE-identified A1 potential borrow site, yet data collection stopped at 3 nm (i.e., State water boundary) (Fig. 8). A1 contains an estimated 0.9 km^2 (214 acres) and 1.45 million m^3 (1.99 mcy) of potential beach compatible sand, although the town opted for a closer, less-expensive inlet-derived borrow source. The ASAP data reveal the extent of this potential borrow area into federal waters.

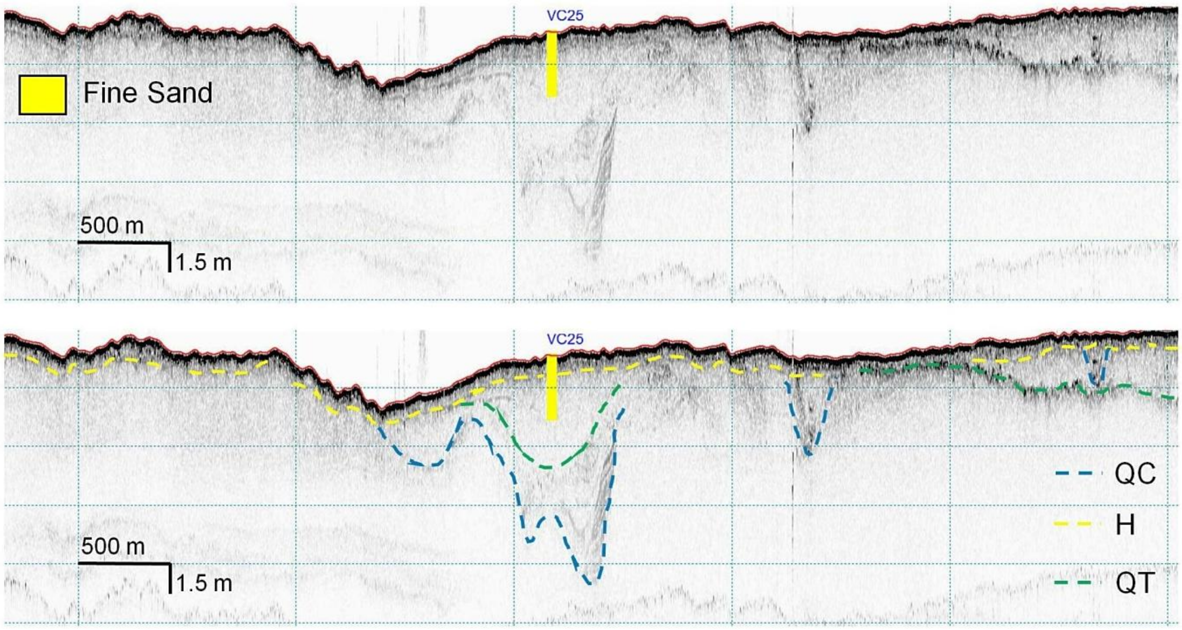

Fig. 9. Example seismic line and interpretations from the Topsail region. Location indicated by black dashed box in Fig. 8.

5.4 New Hanover County Region

The New Hanover County region shoreline is oriented N/NE-S/SW. The survey lines are located between 5.6 and 15.8 km offshore and are near shore-parallel with four shore-perpendicular crossing lines. Water depths range from 8 m around Frying Pan Shoals (southern extent) to 18 m at the seaward survey extent. This region exhibits the most complex bathymetry of all the regions. Ridges with up to 1.9 m relief and moderate asymmetry are observed around Frying Pan Shoals. Multiple well-developed, shore-attached ridges are evident landward of the survey region. Most of the survey coverage is seaward of the 14 m isobath where ridges appear to be shore-detached with a relief of mostly ~ 1-2 m in relief. These wide ridges have slopes up to 10 m/km, are up to 4 km long and ~1 km wide. Localized shoals in the central and north sections have relief up to 3.1 m in relief and hardbottom outcrop with relief up to 2.2 m is present in the southern extent.

The modern sand unit in this region has a mean thickness of 1.0 m with thicknesses up to 3.6 m (Fig. 10). The H reflector is extensive in the region and visible in 71% of total mapped distance (Fig. 10). ^{14}C ages from two cores verify Holocene ages of the surficial modern sand (VC13 and VC17) (Fig. 7 and 10; Table 2). Compared to other regions, this region has the most mapped QT reflector (61%) with an overlying mean unit thickness of 1.7 m and reaching up to 5.3 m in thickness (Fig. 10). The QT unit generally appears to thicken to the north. A ^{14}C age from a shell just below the QT reflector has a Pleistocene age (42,253 - 42,892 cal y BP; Table 2) (VC15; Fig. 7 and 10). Core VC8 contains Pleistocene-aged surficial (~1 m depth) sand based on a shell fragment (36346 – 37361 cal y BP; Table 2; Fig. 7). The New Hanover County region region contains a lesser distribution of paleochannels (25%) and hardbottom (15%) than most of

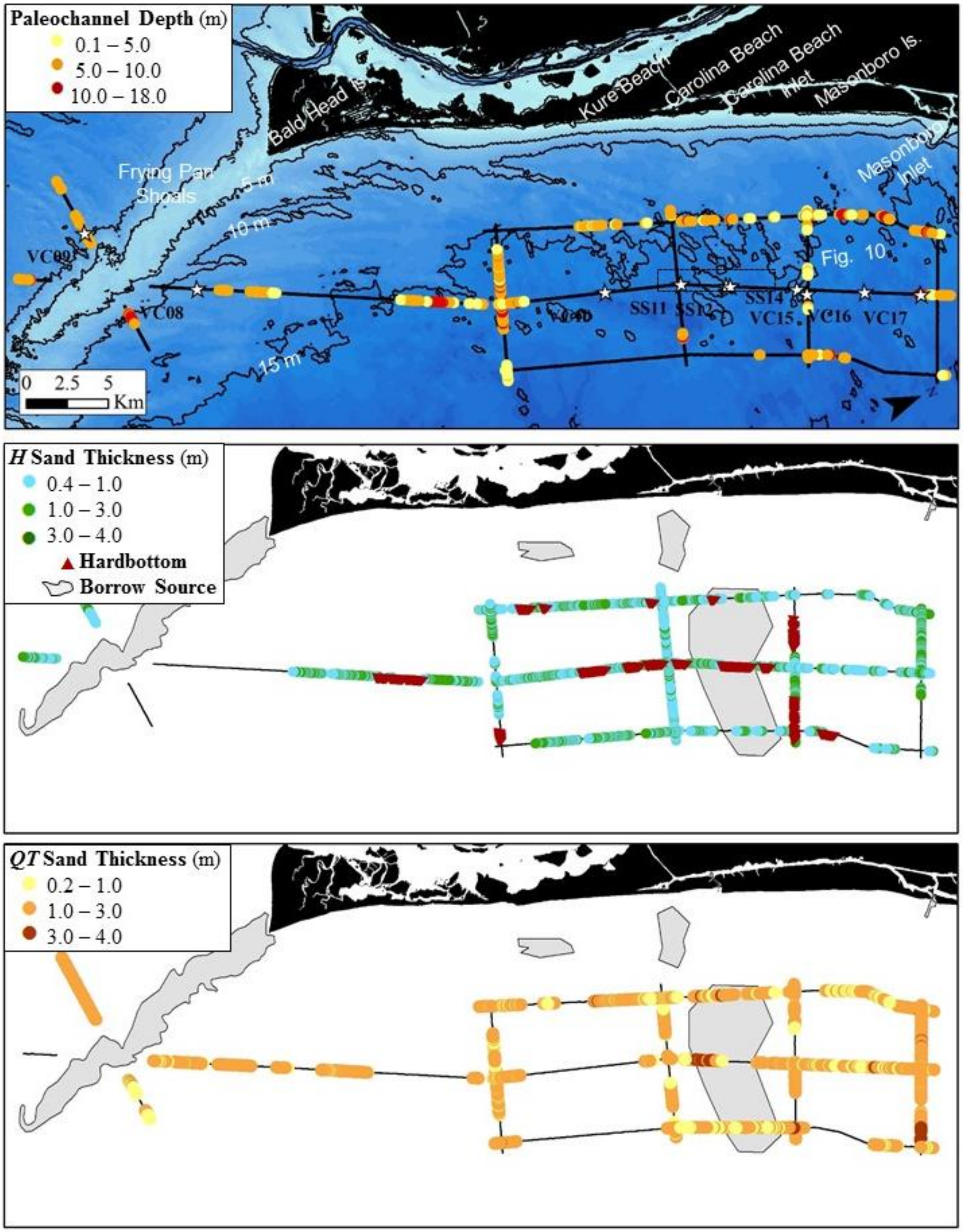

Fig. 10. New Hanover Region ASAP interpretations. Irregular black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources.

the other regions (Fig. 10). A channel sampled by core VC09 estimated a shell fragment dated to the Pleistocene (44979 – 46075 cal y BP; Table 2; Fig. 10). Another channel (VC17) contained a shell fragment dated to the Holocene (5315 – 5519 cal y BP; Table 2; Fig. 7 and 10).

According to the BIMP (2011), few offshore sand sources have been identified in this region, and most replenishment projects have used nearby inlets. However, the USGS seabed database indicates a region of possible beach compatible sand (Fig. 10; large polygon intersecting with ASAP lines), although it is poorly characterized. ASAP data help to corroborate this possibility, showing extensive high relief shoal features with thicknesses exceeding 3 m in some areas (Fig. 10 & 11). The shoals contain both the H and QT reflectors and are often laterally bound by hardbottom outcrop (Fig. 10 & 11).

The New Hanover County region borders work conducted by several researchers (i.e., Meisburger, 1979; Hoffman et al., 1991; Zarra, 1991) and several areas of ASAP sands intersect the lithosomes interpreted by Snyder et al. (1994) as lower shoreface lithosome (LSL), the Inner Shelf Sand Shoal (ISSS), and Linear Shoreface Attached Shoal (LSAS), in addition to the Plio-Pleistocene Valley Fill and Sequence Orb-A (Fig. 12). These lithosomes represent a variety of depositional settings including barrier, backbarrier, estuarine and fluvial environments that are now subject to erosion at the seafloor (Wren and Leonard, 2005). Prior work, consistent with ASAP observations, has noted the presence of linear shoal features that are over a kilometer in length, hundreds of meters wide, and up to 5 m in relief that are likely "erosional remnants of partially preserved Pleistocene sections deposited during successive Quaternary sea-level fluctuations" (Snyder et al., 1994).

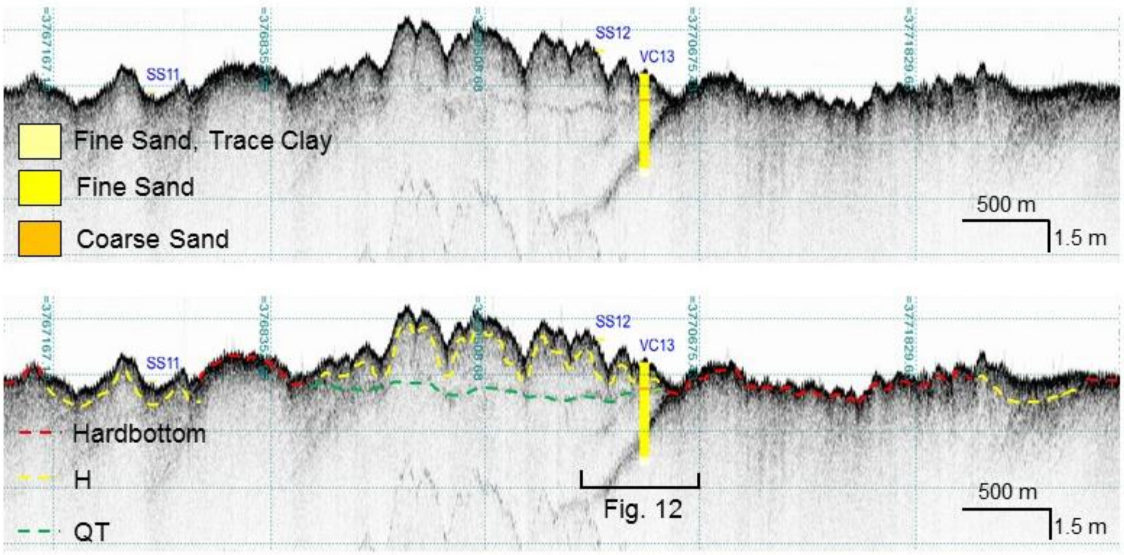

Fig. 11. Example seismic line and interpretations from New Hanover Region. Location indicated by black dashed box on Fig. 9.

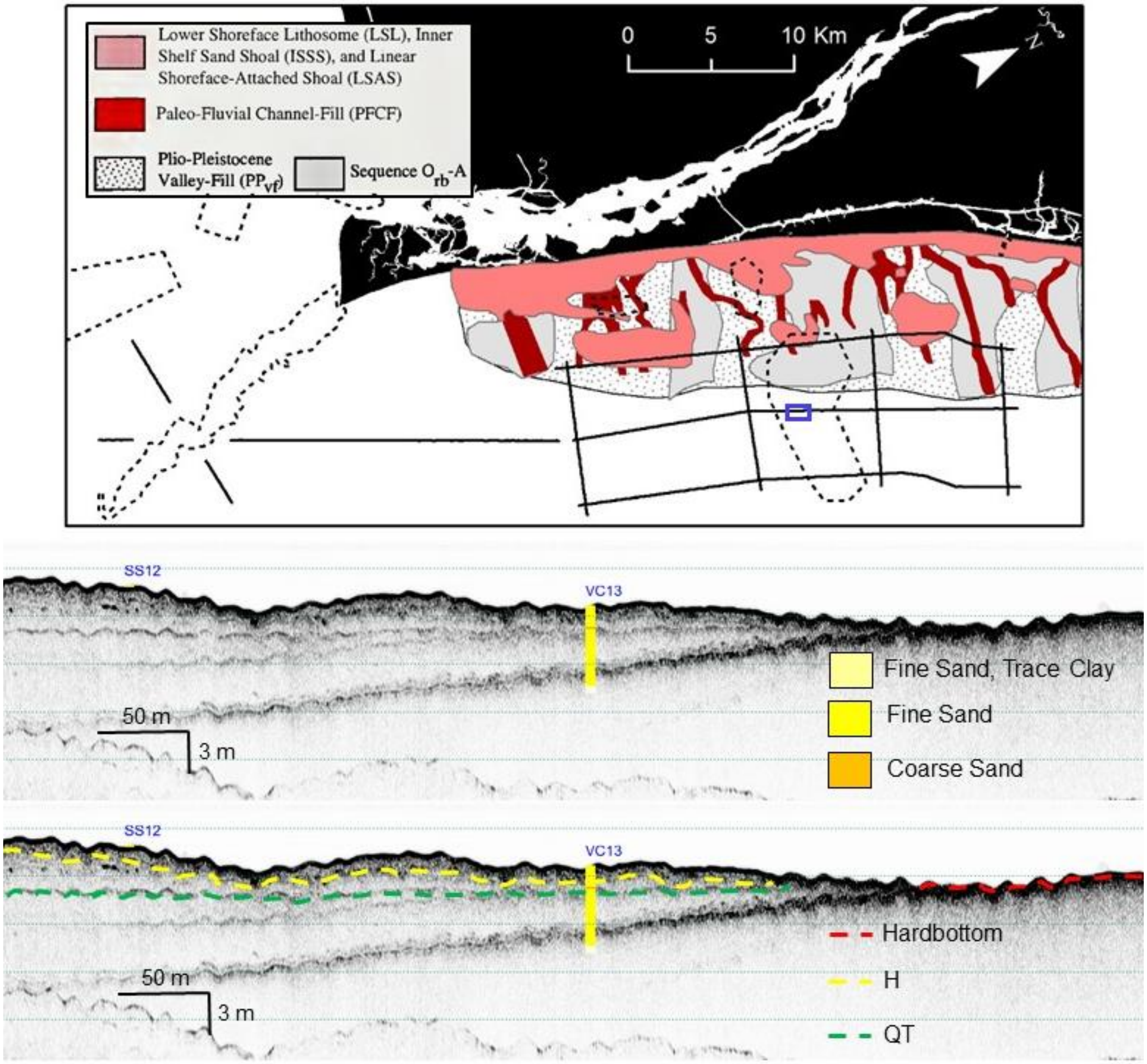

Fig. 12. New Hanover Region ASAP interpretations relative to geo-rectified facies from Snyder et al. (1994). The extent of the seismic line is indicated by the blue box and is also noted in Fig. 10. Note, this area lies within a formerly identified potential borrow source and contains thick shoal deposits.

5.5 Brunswick County Region

The Brunswick County Region shoreline is E-W oriented and bound by Cape Fear and Frying Pan Shoals at its eastern boundary. Survey lines run shore-parallel with four shore-perpendicular crossing lines (Fig. 13). The water depths range from 12 m (7.8 km offshore) to 16 m (15.8 km offshore). The shelf in this region exhibits low-relief, gently seaward dipping seafloor (0.5 m/1 km slope) with the most uniform bathymetry of all the regions (i.e. aligned isobaths). The eastern portion contains the highest relief with ridges up to 1.4 m relief showing little to no asymmetry.

Half (50%) of the Brunswick region has a visible H reflector, which is most frequently mapped in the eastern section (Fig. 13). H unit thickness also averages 1.0 m, but the range is smaller than other regions (0.2 to 1.8 m) (Fig. 13). The QT reflector is not noted in the area likely because of the thinness of Unit H, making it difficult to resolve two reflectors. Hardbottom is widespread (39%) in the western area and is interwoven with paleochannels (20%) (Fig. 13). Core and sub-bottom data suggest the presence of sand in the surficial layers of many paleochannel features, although the fill is variable. Figure 14 displays a good representation of the paleochannel and modern sand appearance. A core sample (VC03) at ~2m depth and below the H reflector shows a C14 age of cal BP 6661 – 6831 (Fig. 7 and 13), yet this age may not be representative of all channels in the region. Extensive hardbottom interpreted in the ASAP data is consistent with NCDEQ (2016).

The ASAP data are somewhat adjacent (~1 km) to an estimated 5.3 mcy (4.1 million m^3) of sand source areas (ATM, 2010). ATM (2010) reports four sites (Fig 13; 1-4 borrow source labels) that range in sand veneer thickness from 0.3 to 1.8 m. These additional sand sources identified in the ASAP data may be a viable and necessary resource option for coastal communities.

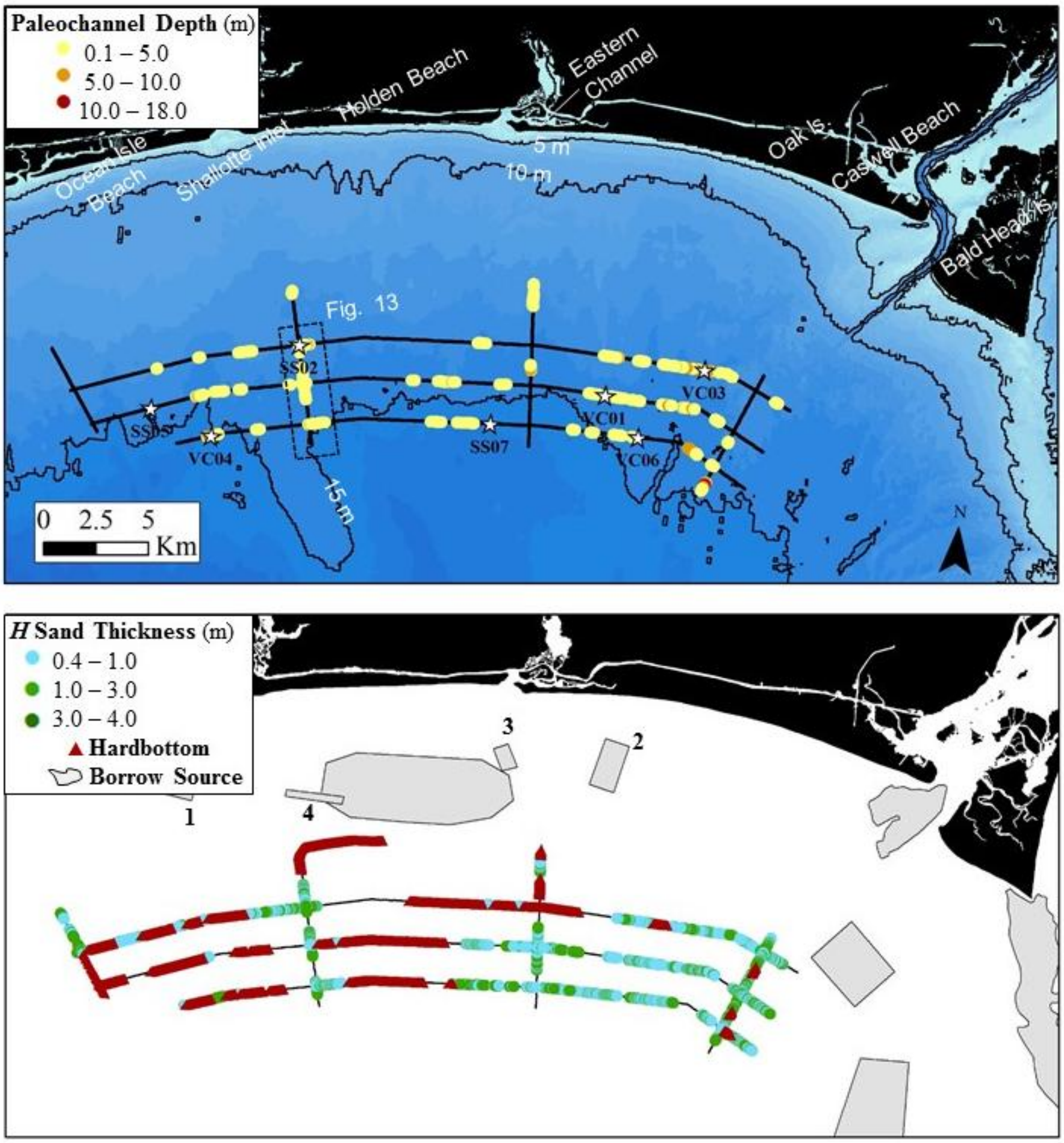

Fig. 13. Brunswick County ASAP interpretations. Solid black lines in top panel represent 5 m isobaths. Vibracores (VC) and surface samples (SS) are represented by stars. Colors represent depth below seafloor of channels identified in Chirp data. Polygons are previously identified borrow sources; areas 1-4 are discussed in text.

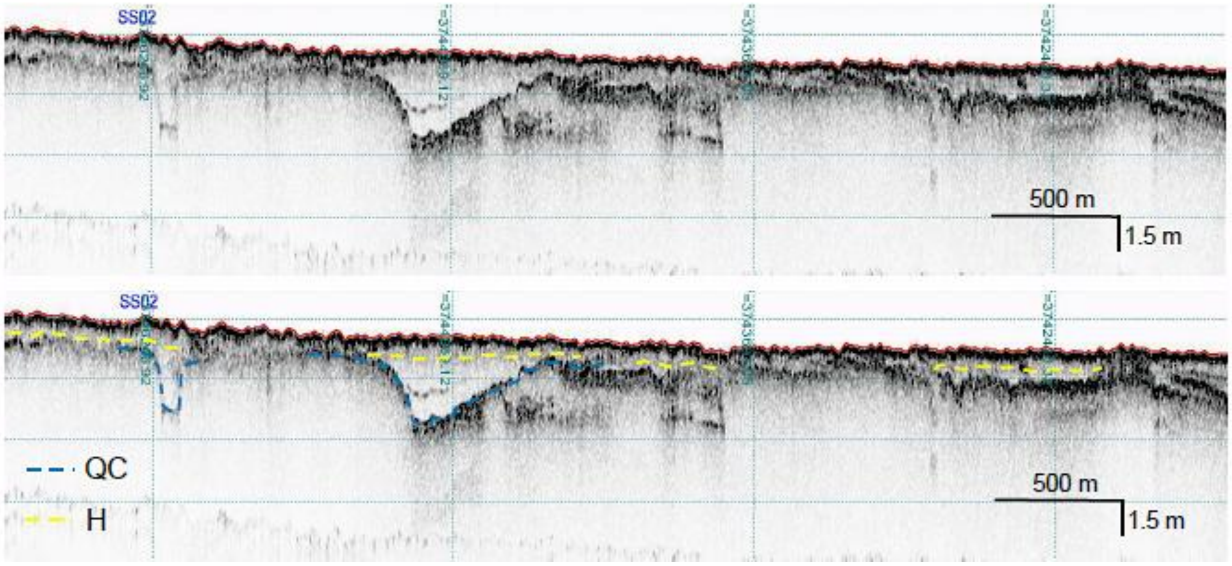

Fig. 14. Example seismic line and interpretations from Brunswick Region. Location indicated by black dashed box on Fig. 12.

6.0 Discussion

6.1 Variability in Channel Distribution and Architecture

Buried channels on the NC continental shelf represent important preserved environmental conditions and reflect a complex variety of transgressive and regressive physical processes (Oertel et al., 1991). Due to the lack of fluvial sedimentation coupled with deep shoreface wave scour during transgression, preserved channels are anticipated to be the only depositional record of transgression in the region (Kraft et al., 1987; Oertel et al., 1991). Because inlet channels are prone to erosion by wave ravinement during transgression in the wave-dominated system, most large, buried channels found within this region are hypothesized to be paleostream valleys (Hine and Snyder, 1985; Oertel et al., 1991), similar to the inner shelf adjacent to the Cape Henlopen headland of Delaware (Belknap and Kraft, 1981). In other tide-dominated (as opposed to wave-dominated) shelf regions such as South Carolina, Georgia and Virginia, buried channels may be more reflective of lagoonal and inlet drainage patterns, in addition to paleostream valleys (Henry et al., 1981; Oertel et al., 1991). Tidal-inlet channels are typically discontinuous and have rounded bases (Belknap and Kraft, 1981; Oertel et al., 1991; Riggs et al., 1995). According to Harris et al. (2005), however, tidal channels incising into less-resistant Holocene and Pleistocene sediments exhibit more angular bottom shapes with low width-to-depth ratios. On the contrary, U-like shaped channels with flat bottoms and high width-to-depth ratios are characteristic of channels and valleys in Tertiary strata or compacted Pleistocene muds (Harris et al. 2005).

Hundreds of channels were delineated across the ASAP regions with high variability in form and fill. While characterizing each individual channel is beyond the scope of this work, Figs. 14 and 15 (VC33, VC27, VC03) provide examples of channels characteristic of each region, and highlights the varied form and fill of the preserved paleochannels. The Bogue Banks

Region contains extensive mapped buried channels that may be associated with the paleo-New River Valley (Cleary et al., 1996). The deepest channels are concentrated to the west and may be related to the antecedent bathymetric depressions extending from the highly irregular 15 m isobath. The prevalence of hardbottom in the central region (Fig. 4) appears to influence channel shape (i.e., more flat bottom forms evident) and limit channel distribution, as noted by (Hine and Snyder, 1985). Figure 15a shows an example of a Bogue channel with an asymmetrical rounded bottom, and complex fill, representing multiple episodes of cut and fill implying tidal influence. Below a ~1.25 m thick sand layer, the heterolithic fill as indicated by the core would not be ideal for beach nourishment (Fig. 7; VC33). The western portion of the channel contains the highest amplitude reflections suggestive of lateral infill and reworking (Oertel et al., 1991). Toward the eastern edge, there is acoustically transparent fill and low amplitude reflections that show bedding planes of upbuilding and constricting strata from flow inhibition (Oertel et al., 1991). A Holocene sand cap, as seen in many studies (e.g., Nordfjord et al., 2006), is verified by a ^{14}C date (Table 1; Fig. 15a). Many channels in the region are similar in incision depth (6 to 10 m) to the Folly and Kiawah rivers in SC (Harris et al., 2005).

The Topsail Region contains numerous mapped buried channels (Fig. 7) that may also be associated with a paleo-pathway of the New River Valley (Cleary et al., 1996). To the west, the channels are deepest (> 5 m), with low width-to-depth ratios, and exhibit angular bottoms (Fig. 8). The western-central area of the subregion also exhibits a deep incisional channel network possibly related to the valley-like feature apparent in the bathymetry to the south (Figs. 8 and 9). Toward the east, the channels are generally shallower and wider suggesting incision into more resistant strata. High amplitude channel bases are also evident toward the east possibly indicating

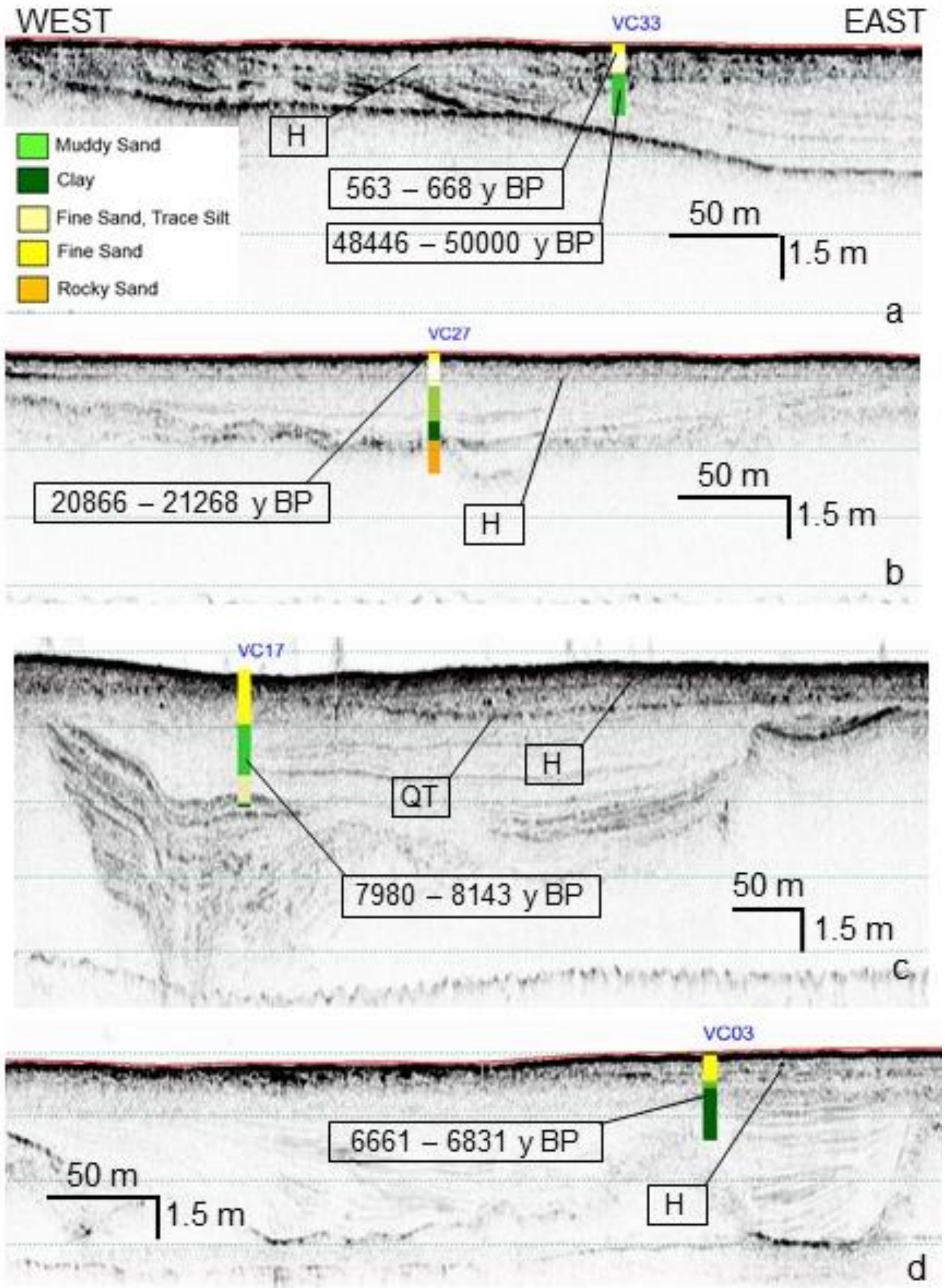

Fig. 15. Channel examples, core logs and associated ^{14}C ages. Panel A is from Bogue Banks Region; B is from Topsail Island Region; C is from New Hanover Region, and D is from Brunswick Focus Region. Dimensions, fill architecture and geometry are highly variable and described in the text.

a coarse fluvial lag (Chaumillion et al., 2007). Sediment facies in VC27, VC33 and VC03 from the region are indicative of estuarine fill and are not ideal for nourishment (Fig. 7 and 15b).

The New Hanover region contains the least amount of channels, yet they are among the deepest in all of the regions (>10 m) (Fig. 10). Fewer mapped channels in the subregion are likely attributable to the absence of a major river system in the area - the Cape Fear River flows to the west (Cleary et al., 1996). Maximum channel depth below the seafloor locally is 18 m deep, similar to the incision of the Stono (15 m) and North Edisto (20 m) paleochannels observed in SC (Harris et al., 2005). Thieler et al. (2001) also observed “Quaternary fluvial channels” up to 18 m in the vicinity (offshore Wrightsville Beach). The central and seaward-most lines contain few to no channels which may be related to the bathymetry and hardbottom distribution. Some channels in the central region are topped by shoals above the QT reflector, suggesting the channel network provided a source for modern sediments (Fig 15c).

The Brunswick County region contains a number of shallow (< 5 m) channels as highlighted in Figs. 12 and 13. Most channels are mapped on the eastern portion of the region and are likely related to the Cape Fear Valley (Cleary et al., 1996). These channels are predominantly constrained to areas where there is also a thin modern sand veneer. To the west, more hardbottom is visible, corresponding to a lack of buried paleochannels. Of all the regions, Brunswick likely was subject to the lowest amount of wave scour during transgression, and consequently, the numerous shallow channels (< 5 m) are indicative of tidal influence. Similar shallow channels have been mapped in tidally-dominated Georgia (Oertel et al., 1991). Additionally, shallow channel incision in this region may be attributable to the differences in shelf slope and more uniform bathymetry (i.e. steeper slopes may have caused incision of deeper channels). The Brunswick channels also differ from the other ASAP regions and areas such as the New Jersey Outer Continental Shelf (Nordfjord et al., 2006), in that they are less likely to be truncated by a transgressive ravinement surface.

In general, the channel observations across the SE NC shelf reflect tidal vs. fluvial development (i.e., the distribution of different channel sizes) as well as the underlying geology into which the channels are incised. The shape of the channels is hypothesized to be governed by the geologic strata of Onslow Bay (Hine and Snyder, 1985). However, the fill and preservation is hypothesized to reflect the relationship between fluvial transport capacity, sea-level rise and local geomorphic changes (which are no longer visible due to wave ravinement). These data show that channel-limited areas tend to be hardbottom-rich and the distribution and depth of large channels is related to paleovalley locations (e.g., Fig. 7 and 8). It is reemphasized that channels may contain some sand suitable for beach nourishment where acoustically transparent fill and/or the surficial modern sand (H unit) is observed and validated by core data. However, many channels are complex indicating multiple incisions/processes, and are interbedded with heterolithic fill (i.e., shelly and muddy fluvial and estuarine) making its use impractical.

6.2 Hardbottom Variability

Hardbottom areas are widely viewed as key habitat, thus accurate maps of their distribution are important. However, determining their distribution is somewhat subjective and dependent on the method used and the interpretation of the data. Hardbottom may be indicated by the inability to acquire grab samples or the presence of large gravel. Alternatively, the geologic context in seismic or sidescan data may define areas without sediment cover. To divers, the actual presence of a rock outcrop may evidence a hardbottom area. Thus, the definition and classification of hardbottom varies and is inconsistent when synthesizing academic, government and private work (Riggs et al., 1996). *Hardbottom* has been defined by Riggs et al., (1996) as "a descriptive term for an indurated surface on the seafloor with no implications of synsedimentary cementation or growth of reef-building organisms; the term refers to all hardgrounds, reefs, and rock outcroppings on the seafloor" (Riggs et al., 1996). If the hardbottom serves as a persistent habitat it is often referred to as *live-bottom (*Riggs et al., 1996). More recently, Street et al. (2005) gave a more encompassing hardbottom description, "exposed areas of rock or consolidated sediments, distinguished from surrounding unconsolidated sediments, which may or may not be characterized by a thin veneer of live or dead biota, generally located in the ocean rather than in the estuarine system." Hardbottom may also be called *live rock* with colonization of algae, sponges, corals and invertebrates (NCDEQ, 2016). According to studies from North Carolina to Florida, hardbottom types include " 1) emergent hard bottom dominated by sponges and gorgonian corals; 2) sand bottom underlain by hard substrate dominated by anthozoans, sponges and polychaetes, with hydroids, bryozoans, and ascidians frequently observed; and 3) softer bottom areas not underlain with hard" (SAFMC 2008a).

Several other terms are often used interchangeably with hardbottom and these may produce confusion. *Hardground* includes rock surfaces that "show unmistakeable evidence (borings, encrustations, marine cementation) of synsedimentary lithification..." (Bromley, 1975), although these are also hypothesized to not outcrop in Onslow Bay (Riggs et al., 1996). This study has mapped hardbottom primarily using seismic and sidescan interpretation. While this is good for identifying larger areas of no or low sediment cover, resolution and positioning have their limits.

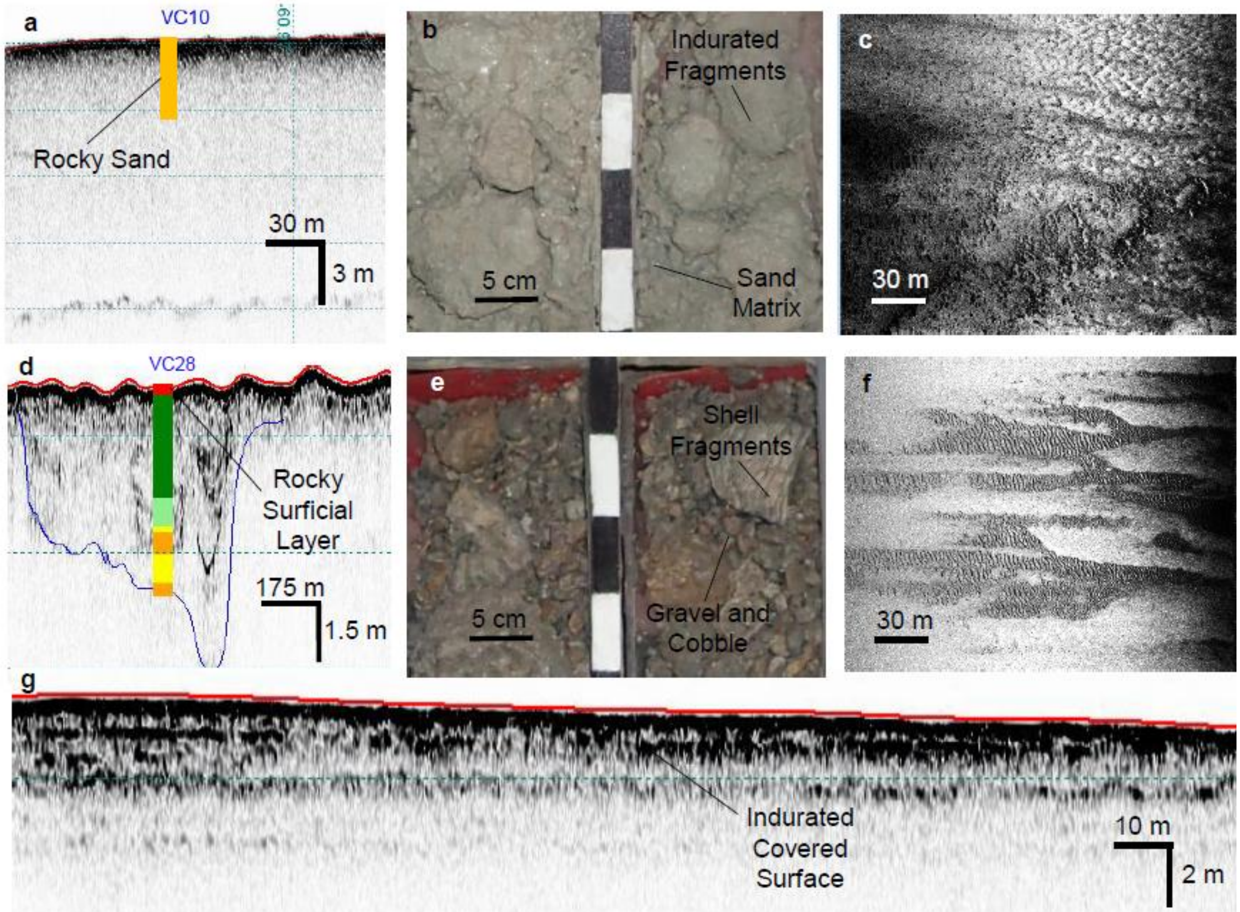

Fig. 16. Seafloor examples of New Hanover region hardbottom (a-c) and Topsail Island region non-hardbottom (d-f) areas. Hardbottom interpreted in seismic data from New Hanover and Topsail Island, a and d respectively, with corresponding cores (b,e) and in sidescan data (c,f). Panel G shows the seismic appearance of a hardbottom buried by <1 m of sand, commonly observed in Brunswick County.

The interpretations of ASAP data here thus apply a more broad classification of hardbottom (essentially following the definition of Street et al., 2005). This is useful from a habitat and sand resource perspective as it indicates where all forms of hardbottom are likely creating key habitat and dredging is not viable. Figs. 3 and 16 show some of the variety of forms of hardbottom and non-hardbottom within the ASAP data. In Fig. 16b, hardbottom is mapped based on the presence of large indurated fragments, although the matrix is sand. Distinguishing this hardbottom based solely on the acoustic signature is less evident, showing that a combination of geophysical and core data is needed to accurately classify the seabed and map benthic habitat (Harris and Baker, 2012). Fig. 16e shows seafloor with a mixture of surficial gravel, cobble and large shell fragments, which would be classified by Riggs et al. (1996) as a *lag pavement*. Although not technically a hardbottom, from a habitat standpoint it is hypothesized that it would be similar to the seabed shown in Fig. 16b. In this light, hardbottom classifications might require new considerations that clarify the geological nature of the substrate (e.g., rock vs. unconsolidated coarse sediments).

According to Snyder et al. (1994) and Riggs et al. (1996), hardbottom character and distribution in Onslow Bay is determined by the outcropping of SE-dipping Tertiary indurated sedimentary strata. The morphology of hardbottoms is quite variable as a result. Past research has shown that hardbottom varies in relief with outcrops up to 10 m in vertical relief (farther offshore) to areas that are relatively flat (Riggs et al., 1996; NCDEQ, 2016). The majority of the ASAP-mapped hardbottom is low-relief and shallow-sloped. Outcrops with vertical relief up to 3 meters were mapped mostly in the New Hanover region, which is consistent with past studies (e.g., NCDEQ, 2016). Most of the ASAP hardbottom likely falls under the Riggs et al. (1996) classification of *flat hardbottoms* that are “smooth to slightly irregular, semi-indurated to indurated surfaces of great extent that form the upper, lower, and in some places middle bounding surfaces of low-relief and high-relief scarped harbottoms." In Onslow Bay, *flat hardbottoms* are generally composed of semi-indurated Tertiary muds to muddy sands, and are covered by a thin layer of mobile or permanent Holocene surficial sand that are difficult to map through remote sensing (Riggs et al., 1996; Schmid, 1996).

The distribution of hardbottom is widespread on the southern NC shelf as highlighted by past research and this study, although it is subject to challenges relating to interpretation and definitions described above. From Cape Hatteras to Cape Fear, it is estimated that hardbottom represents 14% (or 500,000 acres) of the seabed between 27 and 101 m water depth (Parker et al. 1983). However, due to the discontinuous and patchy nature of hardbottom, as well as the vastness of the outer continental shelf, more recent efforts have refrained from estimating the overall distribution of hardbottom in NC (Rutecki et al., 2014). Hardbottom distribution is critical to better understand not just from ecological habitat and sand resource perspectives, but because they are an extensive part of the stratigraphic and paleoceanographic record on the Atlantic Shelf (Riggs et al., 1996; Riggs et al., 1998). The data from this work suggests hardbottom represents 23% of the seabed in the Bogue region, <1% in the Topsail region, 15% in the Hanover region and 39% in the Brunswick region, respectively.

Several factors make the delineation of hardbottom in the ASAP dataset challenging. Firstly, these areas contain a variety of hardbottom forms (Figs. 3 and 16). Next, in some areas it is difficult to distinguish hardbottom using geophysical signatures alone (i.e. seismic, sidescan) and the sparseness of cores and samples prohibits validation in many cases. Finally, low relief hardbottom areas are subject to ephemeral burial and exposure by moving sand bodies (Cleary et al., 1996; Riggs et al., 1996). This is notable in the ASAP data, as evidenced primarily by sidescan (e.g., Fig. 16f). Because the sand veneer covering hardbottom is often thin, the exposure of hardbottom fluctuates as sediments are transported and mobilized during storm events. Ultimately, these data and past research have shown that hardbottom definition, form and distribution is complex and variable on the NC OCS. Because of the described dynamics and interpretation challenges, it is our recommendation that a combination of geophysical and sampling is used to define hardbottom zones, and that a broad, inclusive definition be used.

6.3 Influence of Geologic Framework and Management Implications

Due to the drastic differences in framework geology across NC, each region is unique in terms of the characteristics of potential and historically used borrow sources. The northeast NC shelf has thick sand deposits, as shown by a host of researchers (e.g., Boss and Hoffman, 2001; Thieler et al., 2014). As such, ASAP collection efforts were focused on the southern half of the state, where data are more sparse and there is much more nourishment demand (NCDCM, 2017).

A primary control on the distribution of interpreted sand resources is the underlying geologic framework and consequent lack of sediment input to the region. As many researchers have emphasized, like other high-energy shelves on passive continental margins, the southern NC shelf and Onslow Bay are considered sediment-starved due to either lack of fluvial input, entrapment of sediment within estuaries or transport to slope environments, i.e., sediment bypassing (Emery, 1968; Cleary et al., 1996; Riggs et al., 1996; Riggs et al., 1998). Consequently, Onslow Bay is dominated by hardbottoms (Mearns et al., 1988; Cleary et al., 1996; Riggs et al., 1996). Modern sands are limited to a discontinuous veneer as shown by the data in the ASAP regions (Cleary et al., 1996; Riggs et al., 1996; Riggs et al., 1998). Similarities are noted on the SC shelf, where the modern sediment layer is patchy and thin due to lack of fluvial input and reworking over an irregular transgressive erosional surface, allowing for underlying strata to crop out at the seafloor (Gayes et al., 2003, Baldwin et al., 2007; Denny et al., 2013). Physical and bioerosion processes are hypothesized to be responsible for creating much of the modern sands in Onslow Bay and SC that reflect the composition of underlying Tertiary and Pleistocene hardbottom being eroded (Cleary et al., 1996; Riggs et al., 1998; Gayes et al., 2003; Putney et al., 2004; Baldwin et al., 2007). While the majority of ASAP-delineated sand can be considered a *veneer*, in multiple areas two or more deeper reflectors (i.e., H and QT) are visible that represent thicker sand deposits. In addition, this ASAP effort has mapped numerous channels that may be a viable source of offshore sand in sediment-starved areas.

This new reconnaissance effort provides a broad starting point to search for offshore sand resources. As sand resources may diminish with increased demand (Jones and Mangun, 2001), these data are critical for effective coastal management in response to storm events. Moreover, they provide some framework for advanced planning and/or long term RSM, as well as economic evaluations to help constrain costs relative to known volumes.

7.0 Conclusions

In sediment-starved southern NC, the distribution of potential beach-compatible sand is irregular and complex. Some areas contain especially thick (> 5 m) sand deposits (e.g., New Hanover), while others contain thinner (< 1 m) modern sand deposits impractical for dredging. Buried paleochannels provide important preserved records into past environmental conditions and hardbottom represents potential critical habitat. Paleochannels may also be viable sand sources when fill is acoustically transparent or validated by cores, but many locations show complex fill not useful for beach nourishment. Ultimately, design-scale surveys and sampling are needed to refine sand volume estimates when being considered as nourishment sources.

Reconnaissance data for seabed geology, habitat potential and resource evaluation is quite valuable not only in NC but also globally, as many sandy coastlines throughout the world experience similar erosion issues. Moreover, continental shelf areas are increasingly being used or considered for other resources and functions including wind farms, aquatic habitat, commercial/recreational fishing, hydrocarbon exploration/extraction, marine sanctuaries, etc. Because these OCS resources may overlap (in both space and time), multi-use conflicts may arise and protocol is still poorly developed to handle federal continental shelf rights (Jones and Mangun, 2001; National Research Council, 1995). Therefore, data collection and interpretation efforts like this work are important to ensure shelf value can be assessed before the areas are exploited for resources. Prioritization of vital habitats and/or potential sand borrow sources is essential, especially in regions where there is a high demand for nourishment but a shortage of shelf sand availability.

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CHAPTER 4

Identifying Borrow Source Supply and Amenity and Financial Drivers of Rental-Market Responses to Beach Nourishment, Outer Banks, NC

Abstract

Beach nourishment is used widely in NC and globally to stabilize eroding shorelines. Large-scale beach nourishment projects involve the dredging of offshore sand borrow sources followed by pumping onshore. Sediment that is compatible with the native beach, is not ubiquitous offshore and has been poorly catalogued. Long-term linear erosion rates (>60 years) were compiled and used to estimate eroded volumes by municipality in the northern Outer Banks, NC. These volumes were then compared with potential offshore sand borrow source volumes in the county to assess long-term supply based on erosion rates and current nourishment frequency. Because nourishment is costly, the unique locally-derived funding structures of Dare County were evaluated. A difference-in-differences empirical strategy and natural experiment were used to examine homeowner responses to a nourishment in 2011. Results showed heterogeneity in rental behavior following nourishment that significantly affected the coastal housing market. Specifically, inland and soundfront homeowners capitalized on the amenity value increase following nourishment and converted homes to rentals. The demand-side driver that caused increases in the amount of rentals may also cause a rise in rental rates, which together add to the tax base used to fund nourishment. Based on this work, planners and mangers should consider the additional occupancy tax revenue when developing long-term nourishment financing structures and reevaluate highly disproportionate tax districts used to fund nourishment projects.

1.0 Introduction

Beach nourishment is a strategy used globally to manage eroding sandy shorelines. The pumping of offshore sand to widen beaches creates increased storm protection for valuable coastal infrastructure and adds recreational and amenity value (Gopalakrishnan et al., 2017; Gopalakrishnan et al. 2011; Landry et al. 2003). In areas that have experienced high rates of erosion, such as the U.S. Atlantic Coast, nourishment has become an essential coastal adaptation practice in maintaining the shoreline. In NC, the coast generates enormous tourism revenues for state and local economies. As storms and erosion persist, nourishment will continue, and nearshore sand resources may diminish, making it crucial to assess long-term needs and the availability of offshore sand borrow sources (Drucker et al., 2004). Also, where federal funding is lacking, local support is critical. The propensity for coastal communities to fund increasingly expensive beach nourishment projects remains poorly understood. The ability for some affected homeowners to offset costs by converting their residences to rental properties may be essential.

Because of the multi-faceted engineering process involving geophysical research, geological sampling and the mobilization of large dredges offshore, nourishment is costly. A variety of federal, state and local funding has been employed by communities to support different projects. Northeast NC's Outer Banks are unique in that large nourishments have become more widespread recently (e.g., following Hurricane Isabel, 2003) and have relied on a combination of county and municipality funds. In the locally-funded Nags Head nourishment in 2011, oceanfront properties paid a disproportionate cost through tax increases relative to non-oceanfront properties. Because these practices are new to this region, there is a unique opportunity to evaluate the effect of different financing strategies and inform policy design for future nourishment events.

Past literature has recognized that beach nourishment creates substantial amenity and storm protection benefits (Pompe and Rinehart, 1999; Landry and Hindsley, 2011; Gopalakrishnan et al., 2011; Qiu and Gopalakrishnan, 2018). For example, Qiu and Gopalakrishnan (2018) used a series of triple-difference models to examine the amenity and risk-reduction effect of beach nourishment, specifically Hurricane Sandy (2012) served as a natural experiment to estimate the perceived risk-reduction capitalized in housing values. Rather than characterizing the benefits, the research herein aims to examine the response of homeowners to nourishment. In the situation of local funding, beach nourishment creates an increased cost through a local tax burden, and previous work has not considered the effect of increased taxes on the propensity of homeowners to rent. The difference-in-differences empirical strategy presented here leverages beach nourishment activity and thresholds in coastal community tax rates as a natural experiment. Specifically, it compares households that experience similar changes in their property's amenity/storm protection value from nourished beaches but substantial differences in tax rates to fund nourishment projects. With this approach, we assess whether rental behavior, which to date has not been examined, is being driven by changes in amenity value or changes in nourishment tax burden. The rental-behavior response of homeowners to nourished beaches and increased taxes has implications for the long-term sustainability of beach nourishment financing in coastal communities. Specifically, this work seeks to understand the extent to which coastal tourism communities threatened by eroding shorelines and sea-level rise can leverage their real estate rental options to finance increasingly expensive, community-level adaptation to climate-change strategies.

It is well understood that amenity and storm protection benefits from nourishment accrue disproportionately to oceanfront homeowners (Qiu and Gopalakrishnan, 2018). Yet, unlike the home sales market, storm protection presumably has no effect on the rental market, but amenity value does (i.e., would-be renters enjoy larger beaches but likely do not care about future hurricane destruction). In fact, both the homeowner's marginal amenity value and the renter's marginal amenity value increase with beach nourishment. Consequently, homeowners are willing to fund beach nourishment regardless of if they rent their homes. But, if would-be renters get more amenity value from nourishment than the homeowners, or homeowners simply cannot afford to remain in the home without renting (i.e., their budget constraint is not satisfied), it is logical for the homeowner to rent the home. As such, there are distributional consequences of beach nourishment that need further investigation.

Nourishment-driven tax structures ought to recognize the disproportionate benefits from nourishment (and many have). But, if the nourishment tax is too large, it might cause a shift to even more home rentals, which may create a negative externality on non-oceanfront homeowners. In such a case, when beachfront homeowners face excessively disproportionately high taxes to fund nourishment (e.g., Qiu and Gopalakrishnan, 2018), it may be rational for non-oceanfront homeowners to "subsidize" beach nourishment efforts – i.e., contribute to the nourishment fund beyond their "fair share" of the tax, which would otherwise be based on amenity/storm protections generated. The intuition is that barrier island residents who are inland might prefer avoiding expanding the rental community and would rather be taxed to support beach nourishment efforts to maintain the community's oceanfront permanent residents, (who have a high rental option value). However, an opposite scenario may be more common; inland residents might prefer to pay less and have the beach-proximal rental properties carry more burden. Either behavior would be particularly relevant to local managers and policymakers that determine beach nourishment funding structures and mediate the level of tourist presence within these communities.

The purpose of this study in Dare County, NC is to: 1) analyze the sand volume need based on historic erosion rates and relate those sand requirements to future expected costs, 2) assess potential offshore borrow sources for long-term nourishment demand, 3) evaluate the funding structure of recent nourishments in Dare County, NC, and 4) use panel parcel data and a difference-in-differences regression approach to determine the link between local beach nourishment and homeowners' rental behavior.

2.0 Background

The first beach nourishment in NC was conducted in 1939 at Wrightsville Beach, in the southern part of the State (NCDCM, 2016). Since then, dozens of nourishment and renourishment projects have taken place in the State, totaling over $800 million (Program for the Study of Developed Shorelines, 2019). Today, beach nourishment is being considered for about 75% (120 of 160 miles) of the developed NC oceanfront shoreline (NC DCM, 2016). Offshore borrow sites are dredged for sand which is pumped onshore for large nourishment projects. As expected, project costs rise as the distance to the offshore borrow site increases and also fluctuate depending on the amount of processing required to achieve beach quality sand (e.g., removal of fine sediment) (Dobkowski, 1998; Leatherman, 1989). In some locations, instead of offshore borrow sites, the most efficient regional sediment management strategy may be reusing navigational dredged sediment.

2.1 Nags Head Nourishment Funding

For the $36 million dollar 2011 nourishment project, the Town of Nags Head received half of the funding from the Dare County Beach Nourishment Fund, which is composed of funds generated through occupancy taxes (note, two percent of all occupancy tax goes toward beach projects). The other half of the project ($18 million) was funded by a bond through a combination of sources. Of that $18 million bond, about $10 million was paid back over six years with proceeds from a one percent increase to the occupancy tax. The remaining $8 million of the bond was covered by an increase in taxes through municipal service districts (MSDs). Two MSDs were developed, one where oceanside homeowners paid an additional $0.16 per $100 assessed value (MSD A), and another for the rest of Nags Head in which property owners paid an additional $0.02 per $100 assessed value (MSD B). Finally, a remainder of $1 million was contributed from the Town's general fund for engineering costs.

2.2 Natural Capital

Natural resources have been viewed as natural capital for over 200 years (Gaffney, 2008). More recently, researchers have attempted to undertake the challenging task of measuring the value of ecosystem service flows from natural resources, although in many cases, "nature is capital" is largely still metaphorical (Fennichel and Abbot, 2014). Natural capital valuation is complex and interdisciplinary. Fennichel and Abbott (2014) highlight, "Understanding the feedback between the state of natural capital and human behavior — mediated by markets, regulations, social norms, and other institutions that mold this behavior— is imperative to valuation."Beaches are especially complex because they are a public resource, and have a "stock" that is difficult to measure. Also, they are engineered beyond their natural state through replenishment projects. Ultimately, it is critical to consider the many different value flows that beaches provide including tourism, recreation, storm damage reduction, and ecological, cultural, historical, and existence value.

3.0 Study Region

Dare County extends from Duck (near the Virginia border) to Hatteras (Fig. 1). The adjacent vast sounds and pristine beaches, some of which belong to the Cape Hatteras National Seashore, are well-known for a plethora of activities such as surfing, fishing and boating. These outdoor recreational activities along with cultural landmarks including the Wright Brothers Memorial, Fort Raleigh National Park, and the Cape Hatteras Lighthouse combine to attract millions of tourists annually. Dare County is a critical economic asset, being the third largest NC county in terms of tourism expenditures, having surpassed the $1 billion mark in 2014 (Economic Development Partnership of NC, 2016).

The frequent nor'easters of the winter months and hurricane strikes during the summer and fall are key drivers of the erosion measured in Dare County (Fig. 1). In addition to storms, Dare County is also experiencing a high rate of relative sea-level rise (NC Sea-level Rise Assessment, Report, 2015). The USACE FRF in Duck, NC, has measured water levels since 1978. This long-term record is a key component of the NC Sea Level Rise Report (2015) and documents the fastest rise rate in the State at 0.18 ± 0.03 inches/yr over the past 36 years. To the south, the tide gauge at Oregon Inlet Marina has shown a rise of 0.14 ± 0.05 inches/yr. Both of these rates are hypothesized to increase in the future (NC Sea Level Rise Report, 2010).

Part of the aesthetic charm of the Outer Banks is its beautiful, uninterrupted beaches. This is due in large part to the lack of shoreline hardening, which is prohibited by the State (with

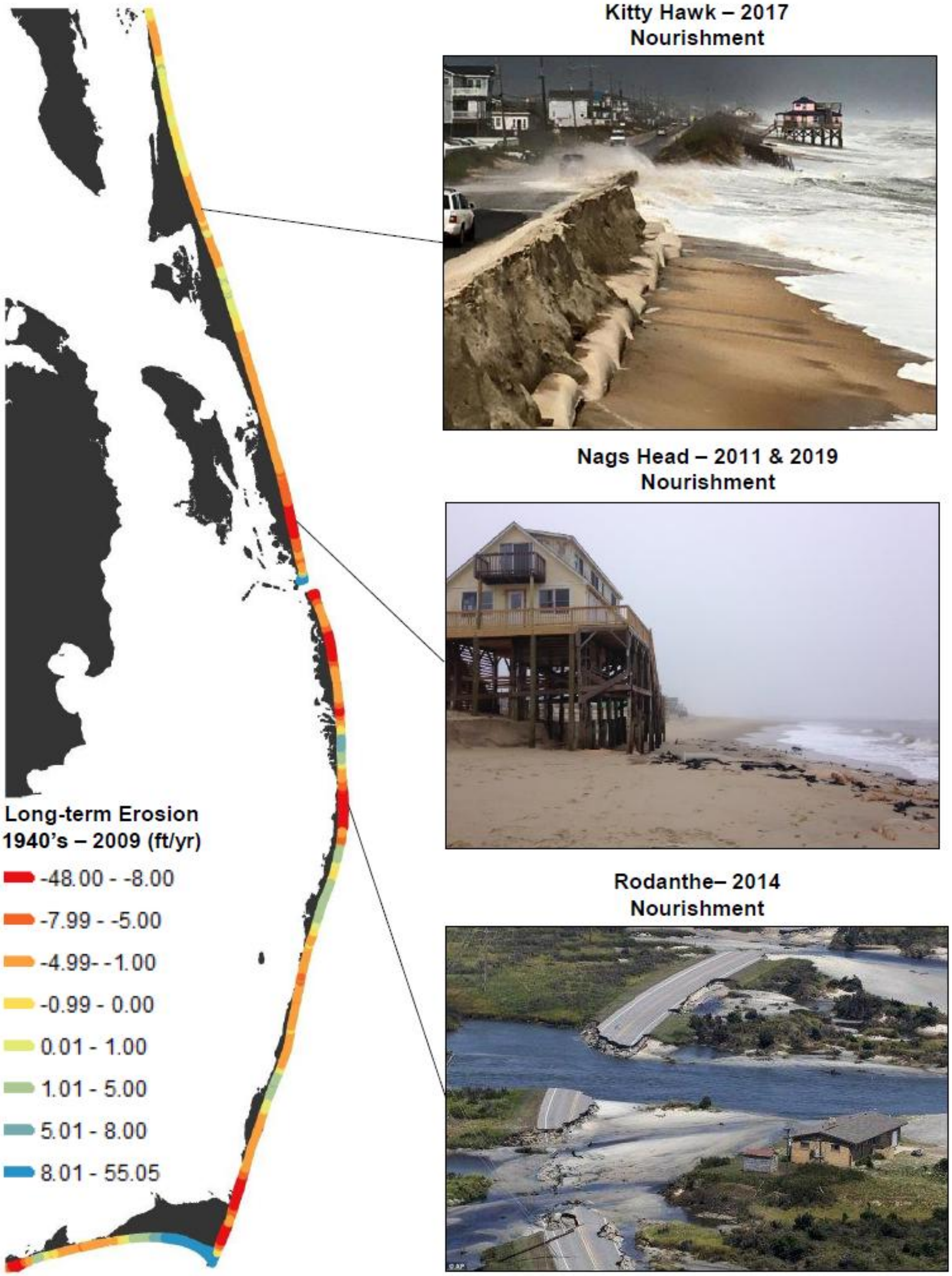

Fig. 3. Long-term ocean erosion rates for Dare County from the NC Division of Coastal Management (2012). Note the erosional hotspots (photos) at Kitty Hawk, South Nags Head and Rodanthe are the sites of past/future nourishment efforts. Modified from Walsh et al., 2016.

a few exceptions) (Kittenger and Ayers, 2010). Because of the legal restrictions on hardened structures, beach nourishment has been and will continue to be a widely used strategy to combat erosion.

3.1 Dare County Offshore Borrow Sources

Based on a combination of reports (e.g., BIMP, USGS, CPE and NC DOT), 27 potential offshore sand borrow sources are identified near Dare County, with some that are overlapping (Fig. 2; Walsh et al., 2016); most of the larger zones are associated with sand ridges or shoal complexes. Design-scale seismic-reflection data and cores are needed in most areas to assess if these potential areas contain sufficiently thick and compatible sand, but existing data suggest most are good possible sources. Note that the phrasing "sediment volume" is used here deliberately as the percentage of sand is not known in most of these locations.

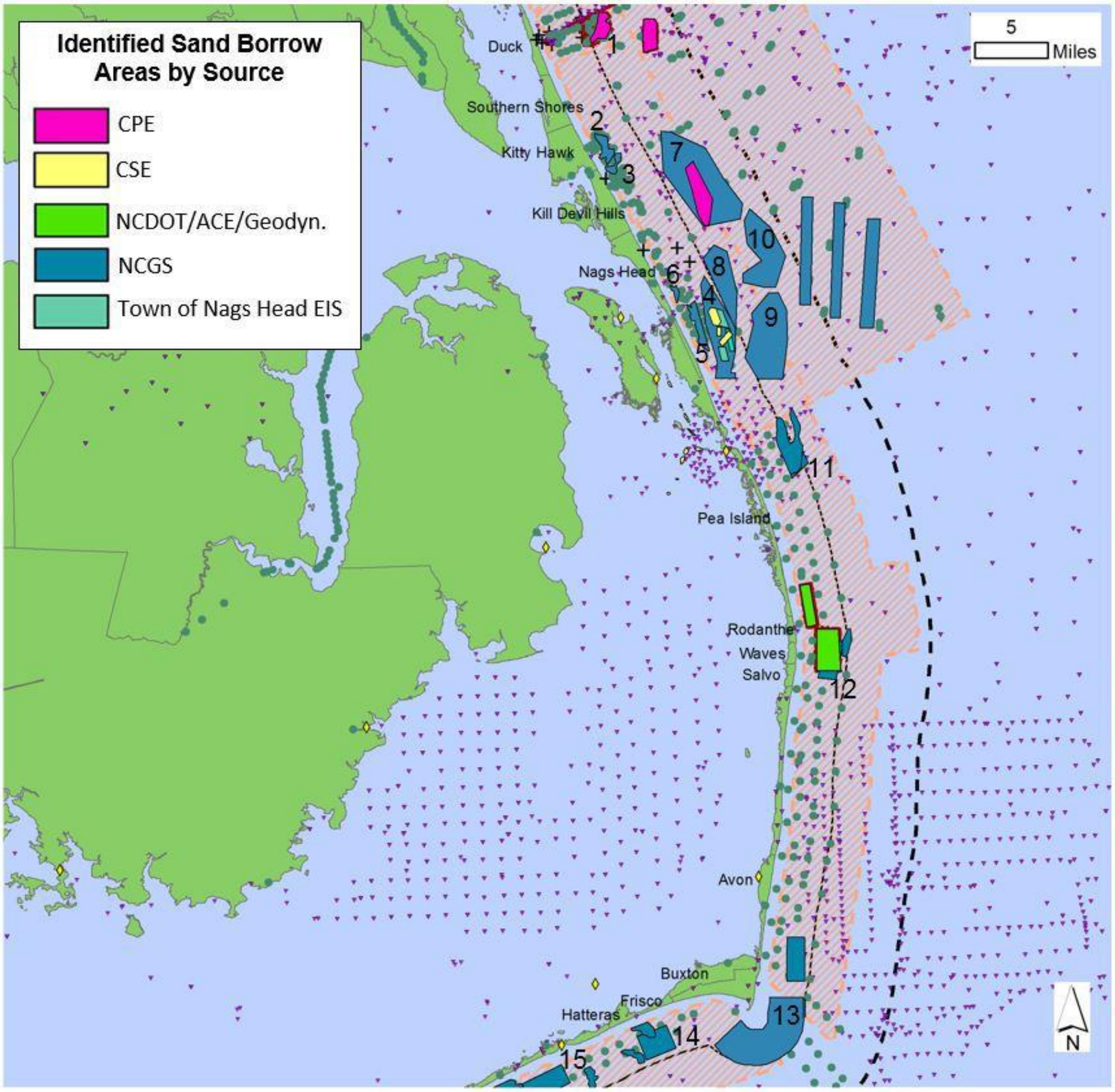

Fig. 2. Identified potential borrow areas in Dare County. Color coding indicates identifying source. From Walsh et al., 2016.

Table 1. Identified potential borrow areas in Dare County. Color coding indicates identifying source.

ID# (Fig. 2)	Borrow Area Name	Sediment Volume (millions in yd^3)	Reference for Volume Estimate
1	Area C Duck	2.7	CPE, 2014
2	N1	5.2	USACE, 2000
3	N2	2.4	USACE, 2000
4	S1	104.5	USACE, 2000
5	S2	7.2	USACE, 2000
6	S3	1.4	USACE, 2000
7	OCS1	173.5	Boss and Hoffman, 2001
8	OCS2	44.9	Boss and Hoffman, 2001
9	OCS3	64.7	Boss and Hoffman, 2001
10	OCS4	23.2	Boss and Hoffman, 2001
11	N. Pea Is.	68.5	Boss and Hoffman, 2000
12	S. Pea Is.	55.9	Boss and Hoffman, 2000
13	Diamond Shoals*	1660	Boss and Hoffman, 2000
14	Hatteras Village	28.5	Boss and Hoffman, 2000
15	Ocracoke	70.1	Boss and Hoffman, 2000
Total	-	2312.7	

4.0 Methods

4.1 Erosion Calculations

The erosion assessment reported here was initially conducted as part of a BOEM study (Walsh et al., 2016); it is important to framing the physical problem (erosion vs sand availability) to add context to the economic evaluation. Shoreline change data was obtained for a ≥60-year period (~1940s to 2009) from the NC Division of Coastal Management (NC DCM); these data were calculated from georeferenced historical aerial photos using the end-point method and the Digital Shoreline Analysis System (NC DCM, 2012). To better understand the magnitude of sand loss, total subaerial and subaqueous eroded sediment volume was calculated for the specified period using the average long-term erosion rate (from 2,754 NC DCM transects), the transect spacing and a volume estimator (16.4 yd^3/yd). The available aerial photography governed the initial year of the analysis period (1940 to 1949). The volume estimation parameter (16.4 yd^3/yd) is described in Inman and Dolan (1989) and is based on the equilibrium profile concept. While this method has limitations due to the alongshore morphological variability in profiles, it is anticipated to be reasonably accurate for the purposes of this work over a large temporal and spatial scale. These erosion data are used below to compare with borrow area estimates.

4.2 Geospatial Processing and Data

To evaluate rental behavior, parcel data from 2007-2017 was obtained from the Dare County Tax Office. These data are summarized in Table 2 by town and year and a shapefile containing the spatial coordinates as pin numbers was obtained from the Dare County GIS office. The ArcGIS join function was used to merge the parcel data with its corresponding location (99.8% or 39,831 of 39,892 records were matched).

Table 2. Number of parcels by town per year included in econometric analysis.

	Nags Head	**Kill Devil Hills**	**Kitty Hawk**	**Duck**
2007	4112	5296	2248	2217
2008	4143	5335	2261	2223
2009	4159	5372	2276	2226
2010	4178	5407	2287	2232
2011	4194	5434	2293	2236
2012	4213	5452	2295	2243
2013	4236	5482	2318	2242
2014	4269	5520	2346	2245
2015	4295	5563	2363	2253
2016	4324	5606	2387	2261
2017	4346	5662	2410	2271

The MSD extents were digitized and used to identify homes in MSDs A and B (Fig. 3). A small zone in north Nags Head that was not nourished was delineated and coded as non-nourished (Fig. 3). A distance-to-ocean shoreline variable was created in ArcGIS using the Near tool with the parcels and the 2009 ocean shoreline. Similarly, a distance-to-water variable that captured soundside and oceanside shorelines (i.e., whatever nearest to parcel) was created using a merged estuarine and ocean shoreline (NCDCM, 2016) (See Fig. 3 for shorelines). A Python programming language script was employed to create a panel dataset by stacking matching parcel numbers through time (N = 156,731) for the towns of Nags Head, Kill Devil Hills, Kitty Hawk, and Duck.

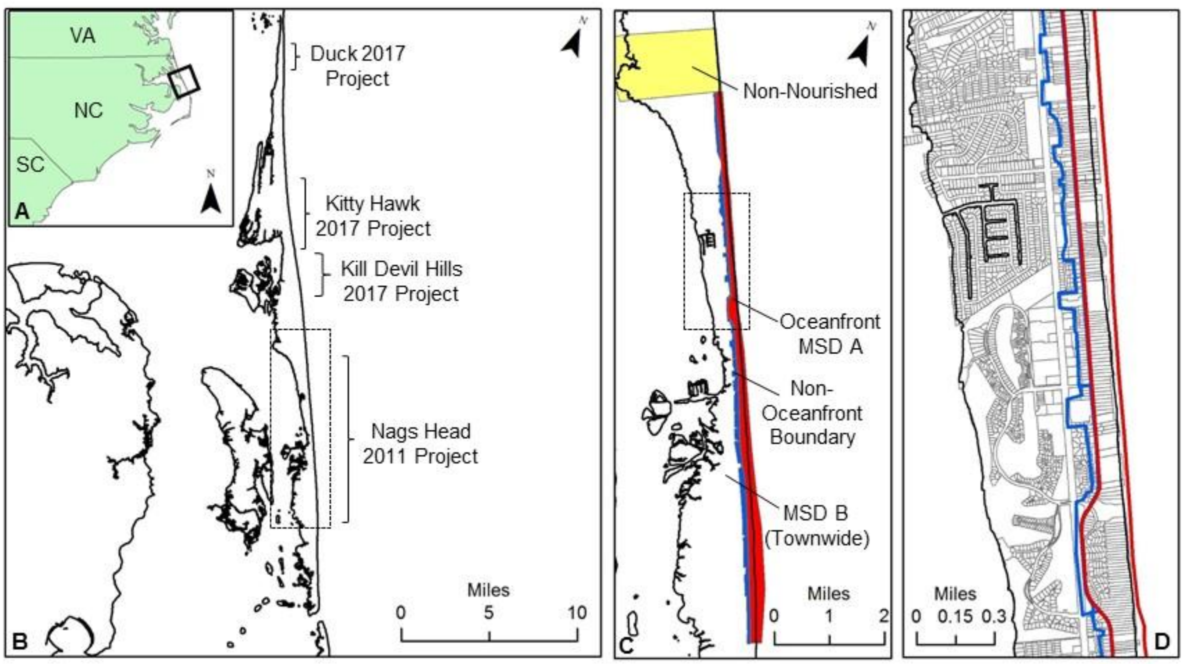

Fig. 3. Analysis areas in Dare County in this study. Location of study region in Dare County, NC is in panel A (black box). Northern Outer Banks beach nourishment project extents (panel B, location shown by black box in panel A). Panel C shows 2011 Nags Head beach nourishment project area, MSD A (oceanfront parcels), the boundary parcels just outside MSD A (blue) and MSD B (townwide). Panel C location is indicated by dashed box in panel B. Panel D shows parcels within MSD A (red) and in along the boundary (blue) which serve as the natural experiment. Panel D zoomed location is marked by a dashed box in panel C.

Several variables were extracted from the parcel data (Table 3). A binary indicator, R, was used to set "1" for a rental property and "0" for primary home classification of parcel *i* in year *t*, based on county records (Table 3). *N* is a binary nourishment indicator equal to "1" for all parcels in the nourished Nags Head zone and "0" otherwise based on town construction maps (Table 3). P is a binary outcome variable representing post-2011 observations – i.e., following

Table 3. Summary statistics for regressions.

Variable	Description	Observations	Mean	St. Dev.	Min	Max
R_i	Rental home	156,731	0.345	0.475	0	1
$N_{i,t}$	Nourished zone	156,731	0.242	0.428	0	1
$P_{i,t}$	Post-2011	156,731	0.643	0.479	0	1
$N_{i,t}P_{i,t}$	Interaction variable	156,731	0.155	0.362	0	1

the Nags Head renourishment project (Table 3). *NP* is a binary representation of homes in the nourished area following 2011 (Fig. 3; Table 3). Using the distance-to-oceanfront variable for each parcel, six distance quantiles were created in Stata (Table 4). Similarly, using the distance-to-coastline variable, six distance quantiles were created representing the nearest coastline (i.e. sound or ocean) (Table 4).

Table 4. Average rental rates across six distance quantiles.

	Distance to oceanfront (ft.)			**Distance to coastline (ft.)**		
Quantile	Distance Min.	Distance Max.	Average rental rate	Distance Min.	Distance Max.	Average rental rate
1	0	418.948	0.690	0	156.992	0.503
2	419.049	822.096	0.566	157.156	489.486	0.450
3	822.153	1488.059	0.423	489.521	764.465	0.4551
4	1488.097	2279.032	0.233	764.480	1134.265	0.362
5	2279.304	3295.819	0.122	1134.814	1702.714	0.246
6	3296.657	14985.64	0.037	1703.439	3980.046	0.059

4.3 Econometric Estimation

The primary estimating equation following the difference-in-difference specification is the following:

$$R_{i,t} = \beta_0 + \beta_1 N_{i,t} + \beta_2 P_{i,t} + \beta_3 N_{i,t} P_{i,t} + \epsilon_{i,t} \quad (1)$$

where R is a binary indicator equal to "1" for a rental property and "0" for primary home classification of parcel *i* in year *t*. *N* is a binary nourishment indicator equal to "1" for all parcels in the nourished Nags Head zone and "0" otherwise. The coefficient, β_1, represents the baseline difference in rental rates among homes in the nourished area relative to homes in the unnourished area. P is a binary outcome variable representing post-2011 observations – i.e., following the Nags Head renourishment project. Here, β_2, captures the baseline difference in rental rates following 2011 that is common to the entire study region. For example, using all the parcels outside the nourishment region as control, β_2 sweeps out the effects of extraneous factors such as the overall economic climate (i.e., recession following 2008) and the rise of other rental mechanisms (e.g., AirBnB), thereby isolating the effect of nourishment itself. In addition to controlling for time trends in rental rates that may have coincided with Nags Head nourishment, β_2 will also capture "spillover" effects in the case where Nags Head nourishment increased amenity value in neighboring communities that may have influenced the propensity of homeowners to rent. Together, the interaction NP is a binary representation of homes in nourished area following 2011. The coefficient of interest in this specification, β_3, captures the treatment effect of beach nourishment on a homeowner's propensity to rent. The vertical intercept, representing the average rental rate across our sample, is β_0 and $\epsilon_{i,t}$ is an error term. Equation 1 was estimated using a Probit regression to best fit the binary outcome variable: rental status (*R*).

To examine heterogeneity in rental outcomes across distances to the oceanfront and shorelines, samples were stratified across the six distance quantiles for shoreline and oceanfront.

4.4 MSD Natural Experiment

A natural experiment was setup using the border along the oceanside MSD (A) and the first row of parcels in the non-oceanside MSD (B)(Fig. 3). A cost shock was included and the amenity value kept constant. This exploits the fact that homeowners along the MSD A and MSD B border experience the same amenity shock but different cost shocks. The following regression was run using robust standard errors:

$$R_{i,t} \ = \ \beta_0 + \beta_1 A_{i,t} + \beta_2 P_{i,t} \ + \ \ \beta_3 P_{i,t} A_{i,t} \text{ if } A > 0 \qquad (4)$$

where R is a binary indicator equal to “1” for a rental property and “0” for primary home classification of parcel *i* in year *t*. P is a binary outcome variable representing post-2011 observations. Here, β_3, captures the baseline difference in rental rates following 2011 between MSD *A* and the boundary row, where there is a binary indicator equal to “1” for MSD *A* and “0” for the boundary (see Fig. 3 for zones).

5.0 Results

5.1 Erosion and Related Economic Considerations of Dare County

As noted above, much of the Dare County ocean shoreline has experienced long-term erosion (Fig. 1). Rates of change vary from localized accretion, such as along the northern shoreline of Oregon Inlet to substantial loss, e.g., >8 ft/y in several locations (Fig. 1). The variable erosion rates across the county are impacted by the underlying geologic framework and transport processes (Riggs et al., 1995; McNinch et al., 2004; Miselis and McNinch, 2006; Thieler et al., 2014). Specific areas of high erosion, often called "erosion hotspots", are found in Duck, Kitty Hawk, northern Kill Devil Hills, southern Nags Head, Rodanthe, and Buxton (Fig. 1). Erosion data for the towns are in Table 3. A volumetric analysis of sand loss due to erosion is employed here to place nourishment efforts in a broader perspective. Based on the long-term average erosion rates, Dare County has lost roughly 100 million yd^3 in volume over the 60+ year period (i.e., from the exposed and submerged beach). This amounts to 1.6 million yd^3 annually. Duck, Kitty Hawk, Kill Devil Hills and Nags Head have lost an estimated 2,012,934 yd^3, 4,394,700 yd^3, 1,296,047 yd^3, and 19,124,091 yd^3 over the 60+ year period, respectively (Table 3). Indeed, much of these losses are in concentrated areas, and it must be highlighted that the beaches are typically managed to consider the "system" as a whole, considering both the updrift and downdrift areas. A major concern about beach erosion, and thus an argument in support of beach nourishment, is the potential loss in economic revenue.

Table 5. Erosion information for Dare County towns involved in beach nourishment. Time interval for erosion assessment was 60+ years. See text for details.

Town	Avg. Shoreline Change Rate (ft/y)	Max Shoreline Change Rate (ft/y)	Total Sand Volume Lost (yd^3)	Avg. Annual Sand Volume Lost (yd^3)
Duck	-0.5	-2.4	2,012,934	29,175
Kitty Hawk	-1.9	-3	4,394,700	63,694
Kill Devil Hills	-0.4	-4	1,296,047	18,788
Nags Head	-3.4	-10.9	19,124,091	314,231
Dare County	-1.9	-10.9	99,897,609	1,591,003

Dare County is an important economic engine, generating over a billion dollars in tourism annually (Economic Development Partnership of NC, 2016). For example, according to data from the Outer Banks Visitors Bureau, Dare County accumulated over $414 million in occupancy receipts in 2014. From this revenue, the State of NC receives 6.75% in sales tax (~$28 million in 2014), and the county receives a 6% occupancy tax (~$25 million in 2014). Of the 6% collected by the County, one third (i.e., 2% or ~$8 million in 2014) is added to a shoreline management fund for potential beach nourishment, vegetation planting, sand fencing and dune building projects and related planning. Additional tourism value related to beaches includes tourism expenditures including shopping and services; data are not available for all of these revenues. However, meal receipts in 2014 totaled $225 million in the County. So of this, the State received 6.75% in sales tax ($15 million), and the Dare County Tourism Board received 1% ($2.25 million) primarily to promote tourism and administration. Beaches are undoubtedly an important draw for visitors, and they drive revenue and rentals.

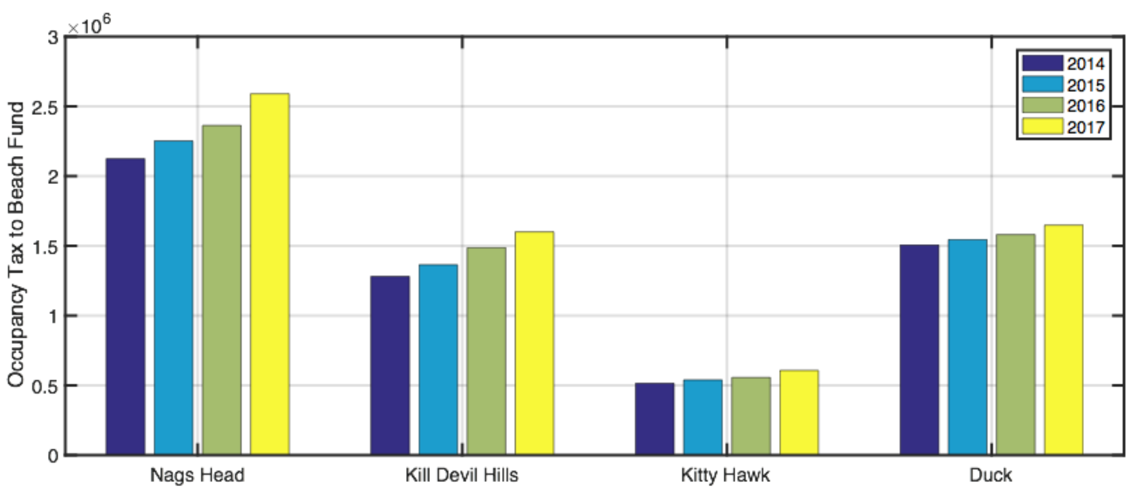

Fig. 4. Occupancy taxes in dollars contributed to nourishment and beach projects by year. Data acquired from Outer Banks Tourism Bureau.

5.2 Econometric Baseline Specification

Occupancy taxes are a major source of revenue to planners, policymakers and the public on the intensive – i.e., the average rental rate – and extensive – i.e., the total number of rentals – margins. The econometric findings outline the influence of nourishment on the coastal housing and propensity to rent, which presents an approach to understanding rental activity on the extensive margin that may have an important, albeit often overlooked, influence on local tax revenue.

The results from the baseline linear regression specification (Equation 1), estimated using ordinary least squares, reveals that rental rates were on average 1.8% lower following beach nourishment in 2011 and that the nourished zone contained, on average, 18.2% more rentals than the unnourished zone. Specifically, there was an 18% higher rental rate for oceanside rentals in Nags Head as compared to the other municipalities that make up the control group. The interaction coefficient of interest suggests that beach nourishment itself did not differentially affect rental rates in the nourished zones with a statistically insignificant and economically-unmeaningful magnitude near zero. One potential explanation for this null result is that nourishment activities create heterogeneous treatment effects on rental rates.

Table 6. Results of baseline regression (Equation 1). See methods text for variable descriptions.

Variable	*R*
N	0.182***
	(0.00485)
P	-0.0179***
	(0.00279)
NP	0.00226
	(0.00604)
Constant	0.313***
	(0.00225)
Observations	156,731
R-squared	0.028

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

A probit estimation was employed to examine the rental behavior before and after nourishment, by quantiles of distance to the oceanfront, and reveal a heterogeneous relationship. These findings are summarized in Figure 5 and Table 7. The first band of homeowners lived an average of 137 ft. from the shoreline and nourishment caused an increase in rental rate from 68.9% to 70.1%, which is a 1.6% increase (Fig. 5). The second distance band is an average of 592 ft. from the ocean shoreline, and rentals increased from 56.6 to 57.5% (3.0% increase) (Fig. 5). At 1,084 ft. from the ocean shoreline, the third band reduced rentals from 42.3 to 40.9%, a 3.3% reduction (Fig. 5). Next, the fourth band at 1,878 ft. from the ocean shoreline, reduced the rental rate from 23.0 to 20.8%, a 11.1% reduction following nourishment (Fig. 5). The fifth distance band at 2,741 average distance from shoreline revealed a rental reduction from 12.2 to 11.3% (7.7%) (Fig. 5). Finally, the sixth distance band of parcels at an average of 5,453 ft. from the shoreline experienced the largest increase in rentals from 3.7 to 6.9%, which was an increase of 84.1% following nourishment (Fig. 5). All rental rate treatment effects, except for the fifth band, were statistically discernible from zero.

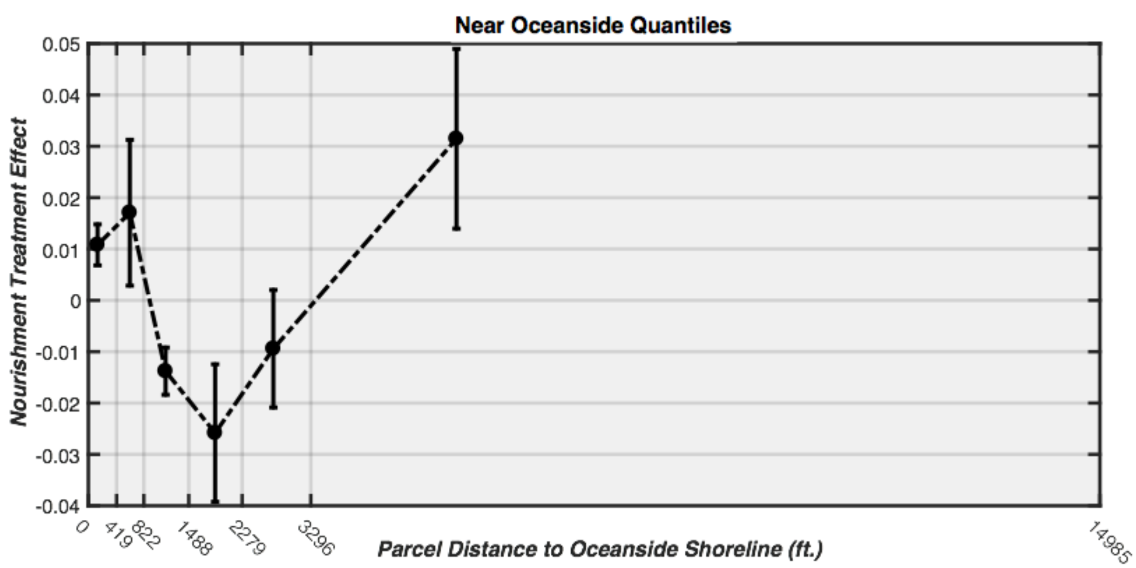

Fig. 5. Combined results of probit regressions for the six distance quantiles to the ocean shoreline. Error bars represent 95% confidence interval. The points are plotted at the mean

distance of each distance quantile. See methods text for regression setup and variable descriptions.

Here, homeowners near and far (quantiles 1, 2 and 6) from the oceanside appear to convert their property to a rental following nourishment while those mid-distance from the oceanside (quantiles 3, 4 and 5) appear to convert their home to a primary residence. This distributional finding is peculiar because amenity values generated from nourishment are likely to accrue among oceanside residences, yet, distant homeowners appear to be capitalizing on a nourishment-generated rental opportunity.

Table 7. Combined results of probit regressions for the six distance quantiles to the ocean shoreline (Equation 2). See methods text for regression setup and variable descriptions.

	Quantile					
Variable	1	2	3	4	5	6
N	0.210**	0.278**	-0.191	0.0381	0.455*	0.235
	(0.0870)	(0.130)	(0.224)	(0.479)	(0.270)	(0.181)
Marginal Effects	0.0737**	0.108**	-0.0747	0.0117	0.0905***	0.0189**
	(0.0322)	(0.0512)	(0.0897)	(0.144)	(0.0300)	(0.00895)
P	0.00335	-0.0696***	-0.0779***	-0.0404**	-0.0727***	-0.0537***
	(0.00524)	(0.0184)	(0.00526)	(0.0173)	(0.0173)	(0.00670)
Marginal Effects	0.00117	-0.0271***	-0.0304***	-0.0124*	-0.0145***	-0.00433***
	(0.00181)	(0.00727)	(0.00160)	(0.00697)	(0.00126)	(0.000901)
NP	0.0308***	0.0438**	-0.0354***	-0.0844***	-0.0473***	0.390***
	(0.00524)	(0.0184)	(0.00526)	(0.0173)	(0.0173)	(0.00670)
Marginal Effects	0.0108***	0.0171**	-0.0138***	-0.0258***	-0.00942	0.0315***
	(0.00206)	(0.00723)	(0.00236)	(0.00683)	(0.00584)	(0.00893)
Constant	0.403***	0.0953	-0.113	-0.696	-1.211***	-1.790***
	(0.0870)	(0.130)	(0.224)	(0.479)	(0.270)	(0.181)
Observations	26,128	26,121	26,126	26,121	26,120	26,115

Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

The drastic increase of rentals following nourishment in the last distance band to the ocean shoreline prompted investigation of the distance quantiles to both the soundside and oceanfront shorelines. These quantiles will be referred to as “distance-to-coastline” herein, meaning the closest distance to the sound or oceanfront shoreline. Results are summarized in Fig.

6 and Table 8. The first distance band, an average of 19 ft. from water, showed a reduction in rentals following nourishment from 50.3 to 49.6%, a 1.4% decrease (Fig. 6). The second band, at an average distance of 339 feet from water, showed an increase in rentals from 45.0 to 47.1% (4.6% increase) (Fig. 6). At 625 ft. from water, the third band rental rate increased from 45.0 to 46.3%, a 2.8% increase (Fig. 6). The fourth distance quantile, showed a reduction in rentals from 36.2 to to 34.9% (5.8% reduction) (Fig. 6). Next, at 1383 ft. from water, the fifth distance quantile showed a reduction in rental rates from 24.6 to 21.9% (11.1% decrease) (Fig. 6). Lastly, the sixth distance band, at an average of 2,457 ft. from water showed an increase in rentals from 5.9 to 6.7% (13.5% increase) (Fig. 6).

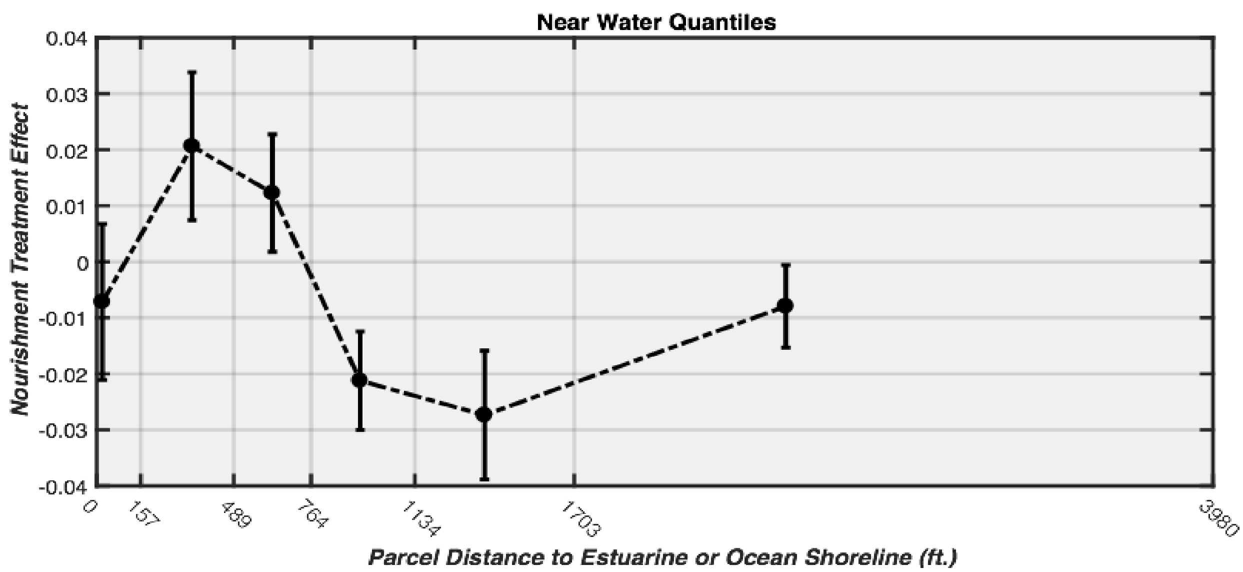

Fig. 6. Combined results of probit regressions for the six distance quantiles to the ocean or sound shoreline (nearest). Error bars represent 95% confidence interval. The points are plotted at the mean distance of each distance quantile. See methods text for regression setup and variable descriptions.

Fig. 6, relative to Fig. 5, shows a more intuitive monotonic decrease in the treatment effect of nourishment on rental rates. The exception case is near-ocean residents that do not reveal a statistically distinguishable change in their rental rates. This result is likely explained by the already-existing high rental rates among this quantile whereas those homeowners living a modest distance from the coastline – i.e., quantiles 2-3 – still reserve the option to begin renting their property. The differences in Fig. 5 and Fig. 6 also suggest that homeowners living on the soundfront can capitalize on the amenity value generated by nourishment on the oceanside. Such a finding is consistent with a demand-side rental market effect where potential renters are attracted by nourished beaches and seek out waterfront, but not necessarily oceanfront, rentals.

Table 8. Combined results of probit regressions for the six distance quantiles nearest to the ocean or sound shoreline (Equation 3). See methods text for regression setup and variable descriptions.

	Quantile					
Variable	1	2	3	4	5	6
N	0.308	0.227	0.334	0.133	0.205	0.0235
	(0.274)	(0.240)	(0.283)	(0.299)	(0.337)	(0.0264)
Marginal Effects	0.122	0.0892	0.131	0.0499	0.0646	0.00277
	(0.106)	(0.0914)	(0.104)	(0.107)	(0.0927)	(0.00303)
P	0.0199	-0.0608***	-0.0646***	-0.0614***	-0.0795***	-0.0538*
	(0.0177)	(0.0171)	(0.0145)	(0.00704)	(0.00519)	(0.0310)
Marginal Effects	0.00787	-0.0239***	-0.0252***	-0.0230***	-0.0250***	-0.00633*
	(0.00712)	(0.00673)	(0.00507)	(0.00111)	(0.00529)	(0.00357)
NP	-0.0182	0.0525***	0.0314**	-0.0567***	-0.0871***	-0.0676**
	(0.0177)	(0.0171)	(0.0145)	(0.00704)	(0.00519)	(0.0310)
Marginal Effects	-0.00717	0.0206***	0.0122**	-0.0212***	-0.0274***	-0.00795**
	(0.00711)	(0.00672)	(0.00534)	(0.00449)	(0.00586)	(0.00376)
Constant	-0.131	-0.173	-0.196	-0.331	-0.656*	-1.527***
	(0.274)	(0.240)	(0.283)	(0.299)	(0.337)	(0.0264)
Observations	26,122	26,131	26,113	26,127	26,127	26,111

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1.

The mechanism driving the rental behavior documented in Fig. 6 could be explained by two scenarios. First, near-waterfront homeowners may be converting their primary residences to a rental property to fund the beach nourishment tax they incur from living in a municipal service district. Second, near-waterfront homeowners may be converting their primary residences to a rental property because wider beaches attract new renters that desire these properties. The former scenario is a supply-side shock that would lower property rental rates as the supply of potential rentals increases. The latter scenario is a demand-side shock that would increase property rental rates as the demand for potential rentals increases.

While both outcomes result in observed increases in the number of rental properties – i.e., an increased equilibrium number of rentals, distinguishing between these two scenarios is important to local managers and planners. The demand-side story is consistent with an increase in the number of rentals (increase in extensive margin) and the rate received on those rentals (increase in intensive margin), which together will increase the tax base to fund beach nourishment activity. However, a supply-side story is consistent with an increase in the number of rentals (increase in extensive margin) but a decrease in the rental rate (decrease in the intensive margin). In such a scenario, local tax revenue might decrease depending on how elastic rental rates are relative to the supply shock.

5.3 MSD Natural Experiment

A natural experiment is exploited in the boundaries of municipal service districts to determine whether the observed rental effects are being driven by demand-side (amenity) or supply-side (tax financing) forces. Equation 1 is re-estimated on a sample that includes only those homes on each side of the MSD A boundary. The ocean side of this boundary contains homes that are taxed at the highest rate following nourishment while those neighboring homes on the other side of this boundary experience a similar shock to amenity value from nourishment but do not receive the same tax burden. Tailoring the sample in this way eliminates rental demand-side forces by focusing only on homes with similar amenity value shocks. Results from this estimation fail to detect any meaningful treatment effect of beach nourishment on rental rates within the MSD A boundary (Table 11). This finding suggests that cost of nourishment, operating through MSD implementation, is not the driving force behind rental property decisions, and homeowners are unlikely renting to finance beach nourishment activity. Rather, heterogenous rental rates responses to nourishment are likely to be driven by the creation of on-beach amenity value and renter preferences to secure a waterfront, but not necessarily oceanfront, rental property. This finding suggests that property owners may indeed be able to and be keen to finance future, albeit more expensive, nourishments that source sand farther offshore.

Table 11. Results from the MSD boundary regression (Equation 4).

Variable	*R*
MSDa	0.0998***
	(0.0127)
P	0.00448
	(0.0134)
PMSDa	0.00456
	(0.0159)
Constant	0.633***
	(0.0107)
Observations	17,226
R-squared	0.011

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.0 Discussion

6.1 Erosion and Sand Demand vs. Source Volume for Beach Nourishment

Erosion along the northern Outer Banks has been ongoing at high rates (>5 ft/yr) in many areas for decades (Fig. 1); the average erosion rate for Dare County is estimated to be 1.9 ft/yr (Table 5). With strong storms and sea-level rise anticipated to continue (and potentially intensify according to some predictions; IPCC, 2014), continued landward translation of the beach and shoreface is expected in the future. Because of erosion, there is a clear need for sand to enable nourishments. Although localized, the amount of sand potentially available offshore is sizable. Based on rough estimates of 15 of the potential source areas, 2.3 billion cubic yards are present (Table 1). Using this information and assuming a need to nourish every five years at a similar volume of recent planned projects (~13 million cubic yards), there is theoretically enough volume to last ~900 years. Instead, if we calculate need based on the annualized eroded volume, there is potentially enough offshore to last ~1500 years. However, as outlined above, there are variables still poorly understood with these potential borrow areas such as the quality of material, non-beach-quality overburden and accurate spatial extents. All these factors are critical to consider, especially from a cost perspective. Sand shortages in some areas are inevitable because of the inhomogenous distribution of sand offshore, and sand needs will probably increase with time because of continued sea-level rise, storms, and development. As demands increase, the closest and most affordable borrow sources may be exhausted requiring the use of sources farther from the project site or more offshore.

6.2 Economic Considerations of Beach Nourishment

This discussion section is not meant to provide a complete account of the many economic considerations of coastal community revenues and the financial specifics of beach nourishment. But, some general data are provided here to help provide a fiscal perspective on the matter of erosion, including the mitigation of erosion and the overarching economic impacts where beach tourism plays a major role in revenue generation. In total, a combination of Dare County and municipal funding has been used to cover ~$100 million dollars of beach nourishment from 2011-2017 in Nags Head, Duck, Kitty Hawk, Kill Devil Hills and Buxton (north to south, Fig.

2). The projected “lifespan” of these projects, based on numerical engineering models, have different estimates ranging from 5-10 years. However, it should be noted that these models typically assume time-average erosion rates and have limited accuracy predicting the lifecycle of an engineered beach due to the impossibility of knowing the future occurrence of powerful hurricane and nor’easter storms. Assuming these project investments last ten years, this cost represents a minute (~1%) portion of the billion-dollar tourism industry (per year) for Dare County over a 10-year period, and the success of this industry hinges on robust beaches. Moreover, the County has taken a responsible, proactive approach by implementing tax districts to cover nourishment costs as federal dollars for beach projects have dwindled. Over a 10-year period, occupancy tax revenue (based on 2014 data) for beach projects is estimated to be ~$83 million dollars. This estimated revenue is comparable to the recent expenditures (i.e., $100 million).

However, we can expect the cost of beach nourishment in the future to increase based on shoreline erosion trends and sea-level rise requiring more frequent nourishment cycles and projects in new areas, in addition to the need to use borrow sources farther from shore as nearshore sources are diminished. Consequently, additional funding sources will likely be required, local tax streams may need altered, and other extensive margins revenues generated through nourishment (e.g., increased home rentals increasing occupancy tax) will need assessed.

6.3 Econometric Policy Implications

Beach nourishment has become a popular strategy for shoreline erosion management and while the engineering processes are similar (i.e., dredges), funding strategies remain quite diverse. Multiple researchers have highlighted equity and social justice issues regarding who should pay for beach nourishment projects (Cooper and McKenna 2008; Landry, 2011). The funding structures of the Outer Banks are unique in that they are completely locally-derived through the combination of a county fund and the implementation of MSDs. However, there is a slight exception, in that Nags Head will receive partial FEMA funding for 2019 renourishment as result of losses from Hurricane Matthew (2016).

The results of this work show that there are implications from the heterogeneity in rental responses to beach nourishment. It is clear that nourishment and increases in beach width disproportionately benefit oceanfront and nearshore homeowners by increasing storm protection and property value (Pompe and Rinehart, 1999; Landry and Hindsley, 2011; Gopalakrishnan et al., 2011; Qiu and Gopalakrishnan, 2018), but the current MSDs may not be proportioned to fully represent the benefits to non-oceanfront homeowners by making the rental option more appealing. Although their homes do not receive the physical benefits of nourished beaches (e.g. protection against storm surge), nourished beaches attract tourists, who end up renting their soundside and non-oceanfront homes, as shown by Figs. 5-6 and the example parcels in quantiles two and three in Fig. 7. Evidence suggests that as oceanfront/oceanside rentals increase rates or become limited in quantity, people may opt for lower rate soundside/non-oceanfront rentals instead as they are able to enjoy a waterfront rental and still capture amenity value from beach nourishment. Past work has noted positive spillover effects of nourishment through increased sediment transport/accretion at oceanfront areas outside replenishment project boundaries (Slott, Smith, and Murray 2008). This work, however, shows positive spillover effects of nourishment extending beyond the beachfront itself.

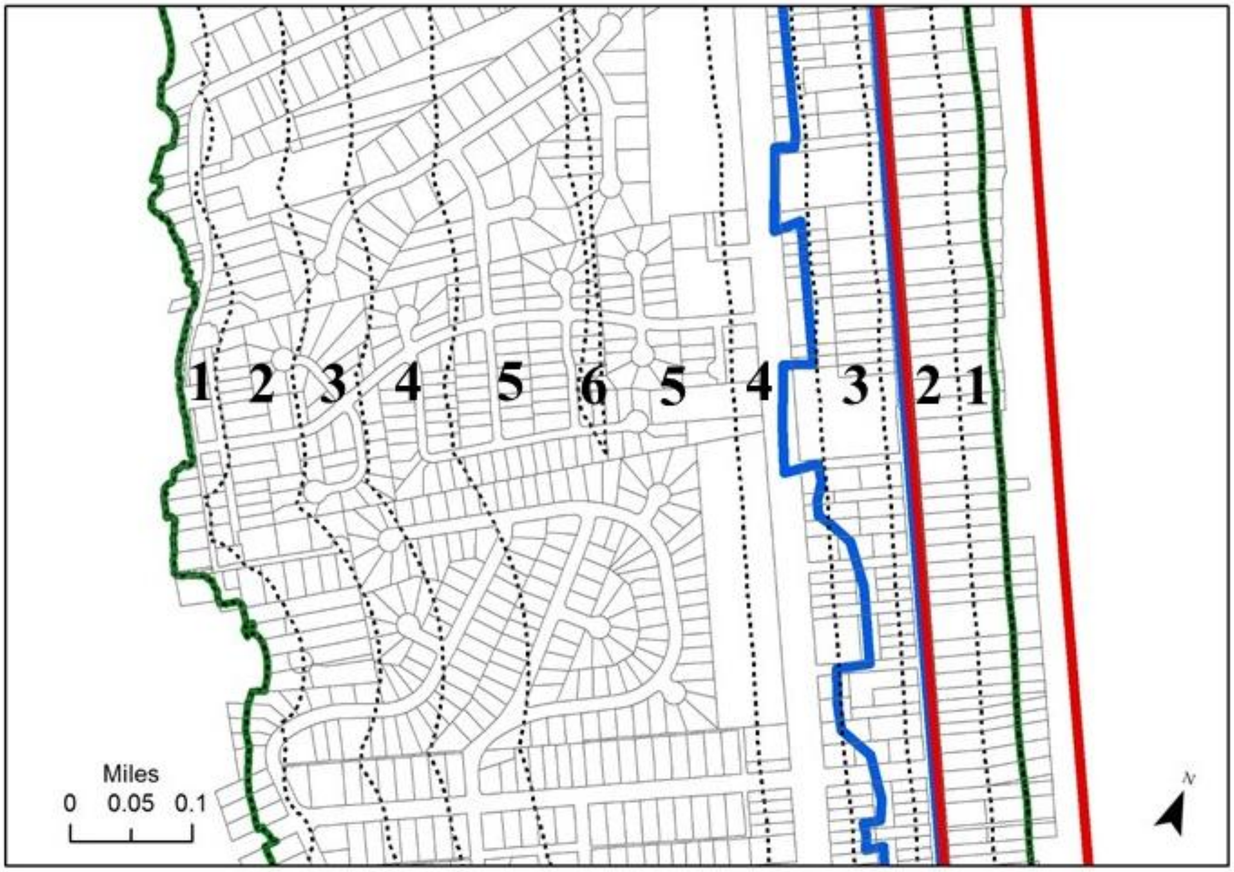

Fig. 7. Example of parcels (gray) in Nags Head with coastline distance quantiles (dashed, numbered). Green indicates shoreline. Red represents parcels within oceanfront MSD A and blue represents parcels along the natural experiment boundary in MSD B.

With nourishment, amenity values are increased for oceanfront homeowners through increased storm protection and wider beaches (Landry and Hindsley, 2011; Qiu and Gopalakrishnan, 2018), potentially making the rental option more desirable. In addition, the rental option may also become more desirable with increased costs of ownership (i.e., nourishment MSD tax). Increases in rentals in some areas as shown by this study following nourishment reveals that there is an indirect revenue of beach nourishment from the extensive margins perspective – i.e., increase in the total number of rentals (demand-side) that generates additional occupancy tax, also noted by Landry (2011). A demand-side driver (amenity) may also synchronously cause an increase in property rental rates (intensive margin). Together, the increases to both the extensive and intensive margins will increase the taxes generated to fund nourishment, which is information critical to planners and managers. Ultimately, when developing funding structures, policymakers need to consider not just the MSD revenue, but also the increased occupancy tax income, especially as nourishment costs rise due to diminishing nearshore borrow sources and the need for more frequent renourishments because of exacerbated erosion from storms/sea-level rise.

This work uses primary and secondary home classification from parcel data as a proxy for rental behavior, which is imperfect. Rental numbers are likely an underestimate because we presume some homeowners do not update the town when switching to a rental, or when deciding to begin renting out a room or split level of their home. As such, future work will begin to examine rental mechanisms such as Vacation Rental by Owner (VRBO) and Airbnb. Furthermore, future work will also attempt to quantify the amount of actual dollars added to the occupancy tax base as governed by changes in rental behavior.

6.4 Regional Nourishment Funding Examples and Implications

Nags Head was the first town in the northern Outer Banks to nourish in 2011, but towns to the north, Kill Devil Hills, Kitty Hawk and Duck (Fig. 2), followed suit in the summer of 2017, also implementing locally-based funding. While these towns to the north also received money from the County's fund generated through the occupancy tax, the MSDs differed. As previously mentioned, because nourishment is new to this area and dependent on local funds, there is no standardized funding structure, as shown by the variability in the MSDs. Kill Devil Hills employed a single MSD where homes paid a rate of $0.33 per $100 of valued property and a townwide tax of $0.03 per $100 of property. Kitty Hawk also had a single MSD consisting of parcels primarily east of US 158 (i.e., “beach road”) where owners paid \$0.16 per \$100 of property and the remainder of the town paid \$0.04 per \$100. The most northern town of Duck is the most dissimilar of the neighboring towns and incorporated a “20-40-40” plan where 20% is paid by the town’s general fund, and 40% is paid by each MSD. Specifically, the oceanside MSD paid \$0.315 and the non-oceanside MSD pays \$0.148 per \$100 of assessed property. In addition, oceanfront homeowners pay a combined rate of both MSDs for \$0.463 per \$100.

To put these MSD rates in context, an owner of a non-oceanside home valued at \$300,000 would owe \$60 annually in Nags Head, \$90 in Kill Devil Hills, \$120 in Kitty Hawk and \$444 in Duck. In contrast, an owner of an oceanfront home valued at \$1,000,000 would owe \$1,600 in Nags Head, \$3,300 in Kill Devil Hills, \$1,600 in Kitty Hawk, and \$4,630 in Duck. Results showed that cost of nourishment through MSD taxes in Nags Head does not appear to be a driving force behind rental property decisions, which is not surprising based on the actual effective cost to these homeowners. And ultimately, these homeowner costs for nourishment both inside and outside the MSD’s are relatively insignificant compared to the added amenity value of a wider beach with enhanced storm protection.

Differences in the local funding of the Dare County projects point to the challenge in understanding the heterogeneity of amenity value gained from nourishment across space. Each Outer Banks town has structured the funding based on the notion that the majority of benefits from nourishment are to oceanfront homeowners. In a press article Kitty Hawk Mayor said, “These properties in the MSD are the ones directly affected by the project,” and continued, “The rest of the town is taxed to a lesser extent because they are indirectly affected (Wagner, 2015)”. A different local funding approach was taken by New Hanover County in NC who have been under a longer term, partial federally-sponsored nourishment program. Instead of MSD’s, a uniform property tax is used ranging from $0.13 to $0.26 per $100 of assessed property, thus non-oceanfront homeowners help to bear much more of the cost of the renourishments, which may also be viewed as subsidizing maintenance for beachfront properties (Qiu and Gopalakrishnan, 2018). These examples speak to the complexity of equitable funding across towns. Moreover, the setup of the MSD frameworks is complicated because of the challenges in the valuation of the added benefits, service and amenity flows influenced by nourishment. Data from this work show how non-oceanfront areas are also benefitting from added amenity value from nourishment through rental opportunities (e.g., Figs. 5, 6 and 7). And while it is beyond the scope of this work to recommend an exact localized funding structure, we recommend the high discrepancy of ocean versus other townwide MSD taxes, like in Nags Head, be re-evaluated to better reflect comprehensive benefits from nourishment. A more balanced financing plan, like the structure implemented by Duck, better reflects the heterogeneous distribution of amenity value added from nourishment.

7.0 Conclusions

A simplified erosional model was used to relate long-term sediment losses to known available sand for nourishment in Dare County, and shows the region contains plentiful resources sufficient to last hundreds of years. However, nearshore sources may be depleted as nourishment demands increase. Currently, the approach of funding nourishments through county occupancy taxes and town tax districts is keeping pace with costs, but as project costs rise (with more frequent projects and/or farther borrow sources), more funding streams may need considered.

As far as additional funding mechanisms, the empirical analysis in this work suggests non-oceanfront homeowners are benefiting and capitalizing on the amenity value added by nourishment and renting more homes (extensive margins). The demand-side driver may also potentially increase rental rates (intensive margins). Disentangling the supply-side vs. demand-side amenity drivers is crucial for policy design. Planners and managers should consider the additional occupancy tax revenue when developing long-term nourishment financing structures. Moreover, the distributional effects and heterogeneity in rental behavior also shows the highly disproportionate tax districts needs thorough reconsideration.

These findings show nourishment significantly affects the coastal housing market and homeowner behavior. Observations reveal that nourishment causes increases in amenity value and spillover effects not just on the oceanfront, but on the soundfront and inland. Ultimately, this suggests that property owners would be willing to finance future, more expensive nourishments, which is critical information for policymakers and promising for the long-term sustainability of coastal regions.

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CHAPTER 5

Summary and Conclusions

Sandy coastlines throughout the world contain a host of resources tremendously valuable to society, yet many are faced with significant erosion. To stabilize the shoreline and add storm protection, beach nourishment has been widely employed. This dissertation investigated how nourishment and other anthropogenic factors influence beach-dune dynamics, how nourishments can be sourced with offshore sand deposits, and the economic implications stemming from costly nourishment projects.

While most past work has focused on beach-dune erosion, these findings showed storms can actually accrete dunes, when there is ample sediment supply and properly implemented capture mechanisms (i.e., fencing and plantings). Understanding vegetation distribution and dune growth rates in non-managed vs. managed systems is critical for model development, and to coastal managers and engineers who are seeking to design beach-dune projects and add resilience to the coastline.

Dunes are critical protection features to maintain on developed shorelines, but as storms and sea-level-rise continue to erode the coast, nourishments will persist. Since beach compatible sand is a limited resource, and nearshore sources will diminish with increased demands, offshore sand borrow sources may be needed, especially in the long-term. This work targeted data gaps in southern NC, where there was a major lack of geologic knowledge regarding potential sands for resource extraction. The investigation highlighted multiple areas of thick sand deposits viable for nourishment. In addition, the effort mapped the distribution of paleochannels, which provide an important preserved record of ancient environmental conditions and showed some contained fill practical for nourishment extraction. Hardbottom was also delineated and represents critical marine habitat, but potential challenges to dredging. Overall, observations show how geologic framework significantly affects the distribution of modern sands, paleochannels and hardbottom on the southern NC shelf.

Nourishments are tremendously costly yet vital for tourism-driven coastal communities. This work investigated borrow source volumes related to erosional demands and locally-derived funding structures to help assess the long-term sustainability of nourishment. Dare County contains ample borrow sources when compared to current nourishment frequency and erosion rates. While the benefits to oceanfront homeowners are clear, this work was unique in that it examined the influence of nourishment on the coastal housing market and homeowner behavior. Findings showed positive spillover effects from nourishment extending beyond the beachfront itself, where inland and soundfront homeowners capitalized on rental opportunities following nourishment, despite paying less tax than oceanfront homeowners. More rentals add occupancy tax revenue and should be factored in by policymakers and planners when designing the funding structure for projects.

Ultimately, this work focused on coastal management related to sand as critical resource. The findings are particularly important for coastal modelers, planners, engineers and policymakers for maintaining long-term resilient coastlines.