Geomorphology 352 (2020) 106995

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

The effect of sand fencing on the morphology of natural dune systems

Michael Itzkin [a,*], Laura J. Moore [a], Peter Ruggiero [b], Sally D. Hacker [c]

[a] Department of Geological Sciences, University of North Carolina, 104 South Road, Mitchell Hall, Campus Box 3315, Chapel Hill, NC 27515, USA
[b] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, 104 CEOAS Administration Building, Corvallis, OR 97331, USA
[c] Department of Integrative Biology, Oregon State University, 3029 Cordley Hall, Corvallis, OR 97331, USA

ARTICLE INFO

Article history:
Received 16 August 2019
Received in revised form 6 December 2019
Accepted 10 December 2019
Available online 12 December 2019

Keywords:
Sand fences
Foredune morphology
Anthropogenic influence
Barrier island
Beach morphology
Coastal management

ABSTRACT

Sand fences are a frequently used management tool on developed coastlines because they are inexpensive and easy to install. While the geomorphic effect of sand fences has been investigated before, previous studies have been limited in both temporal and spatial domains. Here, we present the evolution of Bogue Banks, a developed barrier island along the Outer Banks of North Carolina, over a 20-year period from 1997 to 2016 where sand fences were emplaced along parts of the island in 2010. We use LiDAR-derived cross-shore transects (n = 38,454) to measure beach and foredune features along the extent (~40 km) of Bogue Banks for every available year of lidar data as well as the locations of sand fences, which we identify in 39% of the transects following fence construction. First, we found that vertical growth of the natural foredunes along Bogue Banks was slightly positive between 2010 and 2016 despite an increased amount of shoreline erosion. This pattern was coincident with a combination of sand fence installation and beach nourishment efforts, which were most heavily focused on the eastern end of the island. Second, we found that natural foredunes located behind fenced dunes are typically shorter, wider, and smaller in volume than natural foredunes in non-fenced and undeveloped areas. Although this may partly be due to a tendency for fences to be installed in front of more vulnerable dunes, our results suggest that, once emplaced, sand fences prevent growth of the landward foredune behind fenced dunes. These findings suggest that sand fences block sediment supply to landward dunes, leading to a shorter and wider complex foredune than would otherwise naturally occur.

1. Introduction

The prominent morphological feature on sandy coastlines is a continually evolving foredune (i.e., the seaward-most dune), which is built up over time through feedbacks between aeolian sediment transport and vegetation growth (e.g., Arens et al., 1995; Durán and Moore, 2013; Hesp, 2002) and eroded by wave runup during storms (Sallenger, 2000). As dune-building dune grasses grow (e.g., *Ammophila breviligulata* and *Uniola paniculata* on the US East Coast), they enhance sediment deposition by reducing shear stress below the critical threshold for sediment transport (e.g., Durán and Moore, 2013). As sediment is deposited, vegetation responds through vertical and lateral growth in a feedback that promotes further foredune growth (Baas and Nield, 2007; Biel et al., 2019; Godfrey, 1977; Hacker et al., 2012; Maun, 1998; Zarnetske et al., 2012, 2015).

Although some barrier islands remain in a somewhat natural state, developed barrier islands are home to upwards of 1.4 million people on the Atlantic and Gulf Coasts of the United States (Zhang and Leatherman, 2011), supporting a billion dollar tax base on barrier islands alone (FitzGerald et al., 2008) and a national coastal tourism economy which is valued at $124 billion (Administration, 2014). On developed barrier islands, natural dune-building processes are often modified by management activities designed to improve beach conditions and/or provide protection from storms. These management activities can include beach nourishment (e.g., Smith et al., 2009), beach grass planting (e.g., Hacker et al., 2019), sand fencing (e.g., Nordstrom and Mccluskey, 1985; Nordstrom et al., 2000; Miller et al., 2001; Anthony et al., 2007; Jackson and Nordstrom, 2011; Charbonneau and Wnek, 2016; Jackson and Nordstrom, 2018), and removal of beach wrack by raking (e.g., Nordstrom et al., 2012). Such management efforts are typically designed to increase beach width and build tall frontal dunes that reduce the probability of overwash (i.e., wave overtopping of the foredune), though sometimes there is a preference for narrower beaches and shorter dunes to preserve ocean views (Nordstrom et al., 2000). Because overwash facilitates island rollover, management efforts resulting in tall dunes may inhibit an island's ability to persist under conditions of rising sea level (Magliocca et al., 2011; Rogers et al., 2015).

Beach nourishment efforts produce rapid seaward beach growth (i.e., artificial progradation), which increases the distance between the shoreline and the cross-shore position where dune-building vegetation becomes established (i.e., the vegetation limit), leading to the formation

* Corresponding author.
E-mail address: mitzkin@unc.edu (M. Itzkin).

https://doi.org/10.1016/j.geomorph.2019.106995
0169-555X/

of larger dunes (Durán and Moore, 2013). In a study of dunes on the Danish coast, van Puijenbroek et al. (2017) found that embryo dune growth was greater in nourished locations compared to non-nourished locations. Beach nourishment also decreases the beach slope, which makes the dunes less likely to be eroded during a storm because more wave energy is attenuated before reaching the dune (Cohn et al., 2019; Ruggiero et al., 2001).

Sand fences are commonly used to enhance dune building, and thus to provide coastal protection, because they are inexpensive and easily constructed by property owners (Jackson and Nordstrom, 2011). The formation of a foredune by a sand fence is controlled by interactions between aeolian processes and the fence (Fig. 1). The decrease in wind velocity across a sand fence is controlled by the porosity of the sand fence and will lead to a minimized velocity at a distance landward of the fence (e.g., Cornelis and Gabriels, 2005; Li and Sherman, 2015; Gillies et al., 2017). This decrease in velocity through the fence leads to a decrease in the shear stress acting on the bed, a gradient in aeolian sediment transport, and hence, deposition, which occurs mostly in the lee of the fence (with a small amount of deposition seaward of the fence) (e.g., Nordstrom and Mccluskey, 1985; Cornelis and Gabriels, 2005; Lima et al., 2018). While the porosity of a fence controls its sand trapping efficiency, the height of the fence controls how tall the fenced foredune can grow (Alhajraf, 2004). Once the height of the fence above the bed is less than the elevation of the saltation layer, the fence ceases to have an effect on transport and deposition (Li and Sherman, 2015).

Sand fences are often emplaced seaward of the existing (or previously existing) natural foredune, typically in response to an erosional event (Charbonneau and Wnek, 2016), to initiate the formation of a new foredune seaward of the natural foredune (Fig. 1), making them effective for post-storm dune recovery (Charbonneau and Wnek, 2016) and erosion control (Anthony et al., 2007). Previous studies on the use of sand fences have focused on the construction and aerodynamic properties of sand fences (e.g., Cornelis and Gabriels, 2005; Li and Sherman, 2015; Gillies et al., 2017; Lima et al., 2017) and their monthly to annual impacts on foredune morphology (e.g., Mendelssohn et al., 1991; Miller et al., 2001; Anthony et al., 2007; Charbonneau and Wnek, 2016; Jackson and Nordstrom, 2018). However, it is unclear how the emplacement of sand fences seaward of a pre-existing natural foredune influences the morphology of the natural foredune itself after sand fence emplacement.

Here, we use observational data to understand how sand fences influence natural foredune morphology by comparing areas with and without sand fences. We also consider the influence of beach nourishment on natural and fenced dune growth. We hypothesize that following emplacement of sand fences, formation of a fenced foredune inhibits sediment transport and prevents the growth of the landward naturally

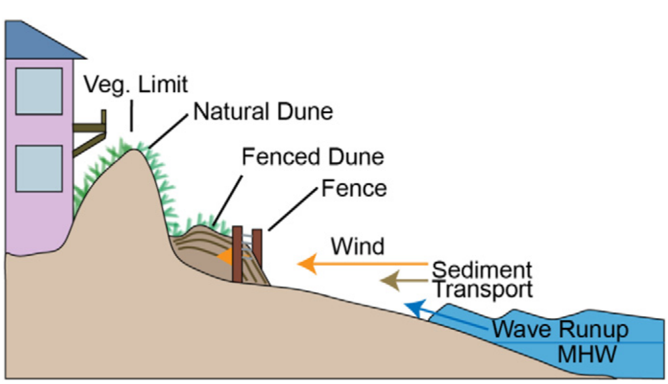

Fig. 1. Conceptual model of the processes involved in the formation of a fenced dune seaward of a pre-existing natural dune. Wind velocity is reduced at the fence, which promotes deposition of sediment around the fence location. While the vegetation limit, and thus the natural dune location, is a function of wave runup and saltwater inundation (Hesp, 2002), the fenced dune can form wherever the fence is located as long as there is sufficient sand flux.

occurring foredune. We further hypothesize that because of this effect, foredunes in natural areas without sand fences will be taller and experience greater magnitudes of morphologic change than foredunes behind fenced dunes.

2. Study area

2.1. Bogue Banks

Bogue Banks, North Carolina, is an approximately 40 km-long east-west oriented barrier island located southward and westward of Cape Lookout National Seashore (CALO) (Fig. 2A). The island is bounded to the east by Beaufort Inlet, to the west by Bogue Inlet, and separated from the mainland by Bogue Sound. Bogue Banks is a developed barrier island with an estimated 2017 population of 6500 people (U.S. Census Bureau, 2018) within the communities of Emerald Isle (pop. 3683), Indian Beach (pop. 112), Pine Knoll Shores (pop. 1332), and Atlantic Beach (pop. 1494) and a tourism industry that generates over $350 million in annual revenue (Carteret County Economic Development, 2018). The eastern ~2 km of the island is the site of Fort Macon State Park, a Civil War era fort where the beach has been relatively undeveloped compared to the rest of the island. Although Fort Macon's beach has undergone numerous episodes of beach nourishment (Carteret County Shore Protection Office, 2017), there are no sand fences within the park's boundaries.

Sand fences on Bogue Banks tend to be constructed by individual property owners. For this reason, records of the timing and location of sand fence construction do not exist (Rudolph, 2016; Sanderson, 2016). Historical satellite imagery from Digital Globe using Google Earth shows sand fences appearing on the island in 2010, however it is likely that older rows of fences exist and have been covered by sand over time. Sand fences are common across the entire length of Bogue Banks although they become significantly denser (contained in 50–100% of profiles) eastward in the communities of Pine Knoll Shores and Atlantic Beach (Fig. 2B).

2.2. Environmental conditions

Based on available data from 2008 to 2016, Bogue Banks experienced mean wind velocities of 5.7 m/s with measured wind speeds up to 31.7 m/s. Winds (NDBC wind gage CLKN7) were primarily out of the southwest although the strongest winds were from the northeast (Fig. 3A). The strongest recorded winds during this time (31.7 m/s, associated with 2.64 m waves) occurred on July 4, 2014 with the landfall of Hurricane Arthur over Shackleford Banks, adjacent to Bogue Banks. Over the same time period, the tidal range in the Bogue Banks/CALO region was 2.45 m (NOAA tide gage 8656483) and the mean significant wave height was 0.89 m, with wave heights ranging from 0.02 m to 4.46 m (Waverider buoy 41110, 17 m depth). Waves were primarily out of the southeast (Fig. 3B) with the largest waves (4.46 m, associated with 19.20 m/s winds) occurring on September 6, 2008, associated with the landfall of Hurricane Hanna south of Bogue Banks near Wilmington, NC.

Between 1997 and 2016, twenty-nine tropical storms and cyclones impacted Bogue Banks (Fig. 4), most of which were tropical storms ($n = 20$) and the strongest ($n = 5$) were Category 2 hurricanes (Sefcovic, 2016). Of the twenty-nine storms during this time, six made landfall in or near Carteret County including Tropical Storm Dennis (1999), Hurricane Isabel (2003), Tropical Storms Barry and Gabriel (2007), Hurricane Irene (2011), and Hurricane Arthur (2014).

2.3. Beach nourishment history

A series of beach nourishment projects were completed on Bogue Banks between 1997 and 2016. Fort Macon was nourished in 2002,

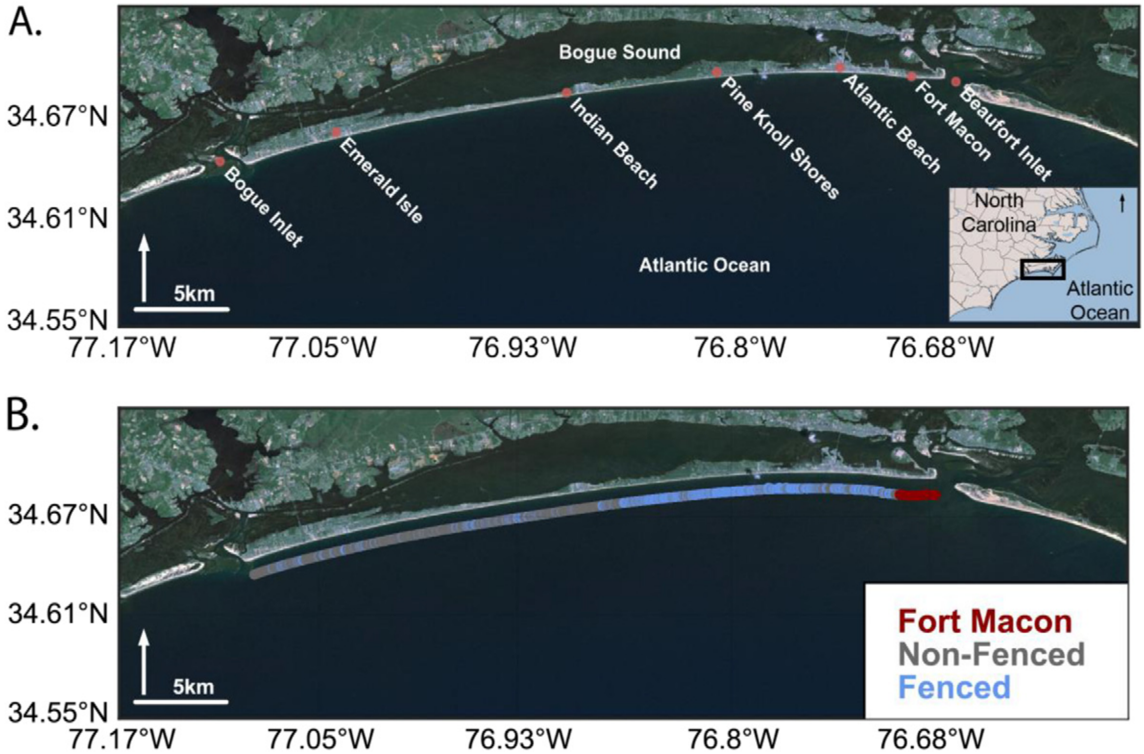

Fig. 2. A. Map of Bogue Banks and its position along the coast of North Carolina (inset), showing town locations and location of Fort Macon State Park. B. Bogue Banks showing Lidar profile locations color coded according to the presence or absence of sand fences. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

2005, 2007, 2011, 2014, and 2015 with dredged sediment from Beaufort Inlet whereas the western end of Emerald Isle near Bogue Inlet was nourished in 1997, 1999, 2000, 2003, 2006, 2010, and 2013 with sediment from the Intracoastal Waterway (Carteret County Shore Protection Office, 2017). Portions of the rest of the island have also been nourished as part of recovery efforts following Hurricanes Isabel (2004), Ophelia (2007), and Irene (2013) (Carteret County Shore Protection Office, 2017). The 2004 nourishment was located along a ~11 km stretch of Emerald Island and Indian Beach. The 2007 nourishment was located along a ~5 km stretch of Emerald Isle and a ~15 km stretch that includes Emerald Isle, Indian Beach, and Pine Knoll shores. The 2013 nourishment, which occurred during the post-fencing period, was contained to a ~2 km and ~5 km alongshore stretch along Emerald Isle and a ~5 km stretch near Pine Knoll Shores. The island also experienced beach nourishments as part of a three-phase restoration effort in 2002 (phase 1, Pine Knoll Shores and Indian Beach), 2003 (phase 2, central and eastern parts of Emerald Isle), and 2005 (Emerald Isle).

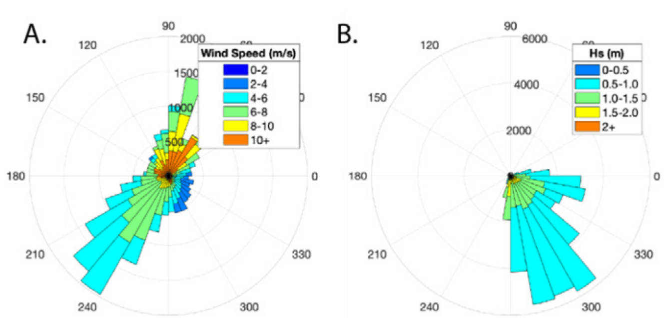

Fig. 3. Wind (left) and wave (right) roses for Bogue Banks, North Carolina, from 2008 to 2016. Measured from NDBC wind gage CLKN7, Waverider buoy 41110, and NOAA tide gage 8656483.

3. Methods

3.1. Lidar

We use lidar-derived topography from 1997 to 2016 to sample 1 m alongshore-spaced transects along the length of Bogue Banks (Table 1, Fig. 2B). A total of 38,454 profiles were extracted for all years of available lidar topography, each extended from seaward of the mean high water (MHW) contour to landward of the natural dune line. The eastern and westernmost ends of the island near Bogue and Beaufort Inlets were not included to avoid the effects of inlet dynamics, which are not relevant to this study. The western limit of the study area is defined as the location where the dune line begins in Emerald Isle and the eastern limit is defined as the location where the dunes along Fort Macon become highly recurved leading toward Beaufort Inlet (Fig. 2B).

3.2. Sand fences

Sand fences along Bogue Banks can easily be identified using Google Earth satellite imagery where they appear as dark, typically shore-oblique, lines along the beach near the dune line. To incorporate sand fences into the analysis, all fences along Bogue Banks were marked in Google Earth as a path. The paths were then overlain on the lidar DEMs and profile transects using QT Modeller software (Fig. 2B). The locations of intersections between the transects and fences were marked and stored to match each profile with a fence to the correct cross-shore location of the fence during profile analysis.

To analyze how the presence of sand fences affects the morphology of the natural dune behind the dune that arises from the fence itself, we classify each transect into one of three categories: fences present, fences absent, or located within Fort Macon State Park. Of the 38,454 sampled transects, 2229 (5.8% of all transects) are located in Fort Macon (Fig. 2B). The remaining transects are located along developed portions of Bogue Banks. Among transects in developed locations, we classify 14,830

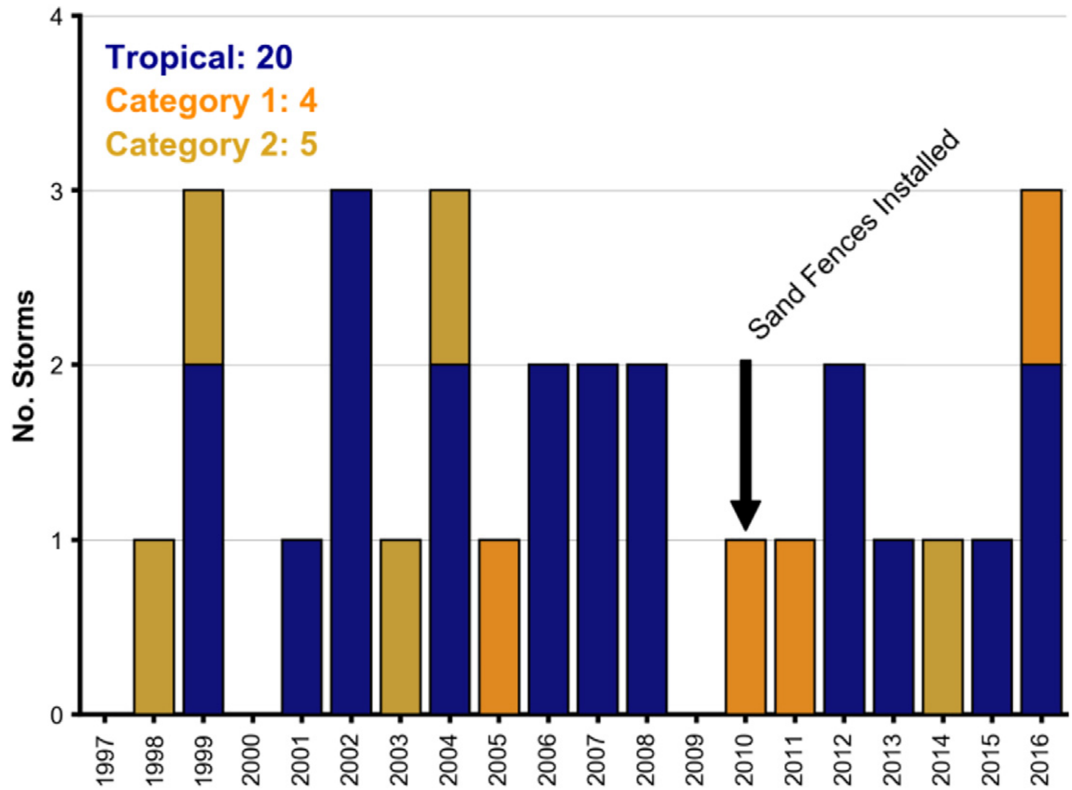

Fig. 4. Timeline of tropical storms and cyclones that have impacted Carteret County (location of Bogue Banks, NC), and the adjacent counties to the north (Dare), and south (Onslow) between 1997 and 2016 (Sefcovic, 2016).

(38.6% of all transects) as fenced and 21,395 (55.6% of all profiles) as non-fenced. Most transects that cross sand fences are situated in the area between Pine Knoll Shores and Atlantic Beach (Fig. 2B). Profiles that do not intersect a sand fence but are within 5 m of a profile that does contain a sand fence are classified as fenced to account for likely influences from the nearby fence.

3.3. Topographic analysis

To quantify changes in morphology over time along Bogue Banks, we developed an automated method, hereafter referred to as Automorph, to systematically identify natural and anthropogenically-influenced dune morphometrics from the lidar-derived profiles (Fig. 5). Existing methods for identifying natural dune features (e.g., Elko et al., 2002; Hardin et al., 2012; Mull and Ruggiero, 2014; Wernette et al., 2016) are effective where there is a singular dune of interest, however, Automorph expands upon these methods by including the ability to identify a secondary seaward dune (i.e., the fenced dune) on the profile based on the presence and cross-shore location of a sand fence.

Automorph begins by identifying all features associated with a natural dune and beach profile, including the toe, crest, heel, and mean high water (MHW) contour regardless of whether or not sand fences are present (see Fig. 5 for locations and abbreviations). MHW is identified as the most seaward point on the profile that crosses the pre-defined MHW elevation contour of 0.34 m (NOAA Station 8,656,502). The natural dune crest (D_{high}) is selected as the seaward most peak in the profile that contains a backshore drop of at least 0.6 m (Mull and Ruggiero, 2014) and exceeds a 3 m threshold elevation in order to avoid misidentifying berms as the dune. The natural dune toe (D_{low}) is identified using a simplified version of the elastic sheet method outlined in Mitasova et al. (2011) wherein a straight line is drawn from D_{high} to MHW and the point on the profile farthest from that line is identified as D_{low}. At this point, the dune slope from D_{high} to D_{low} is calculated to ensure it does not exceed 35° and is not misidentified as a building (Stockdon et al., 2009). If the dune slope threshold is not exceeded, then Automorph continues; if it is exceeded, a new dune crest (and toe) is identified using a more seaward peak in the profile. The natural dune heel (D_{heel}) is identified as a low point in the profile landward of D_{high}, identified by the first point landward of D_{high} that satisfies the

Table 1
Summary of Lidar data used in this study with survey dates and spatial accuracy.

	Name	Begin date	End date	Vertical accuracy (m)	Horizontal accuracy (m)
1997	Fall East Coast Lidar (SC to DE)	9/15	10/2	0.15	0.80
1998	Fall East Coast Lidar (SC to VA)	9/1	9/7	0.15	0.80
1999	Post-Floyd Lidar (NC, SC, VA)	9/18	9/18	0.15	0.80
2000	Summer East Coast Lidar (GA, NC, SC)	8/2	8/7	0.15	0.80
2004	USACE NCMP Topobathy Lidar: Gulf (AL, FL, MS) & Atlantic Coast (NC)	4/1	9/25	0.15	0.80
2005	USACE NCMP Topobathy Lidar: Atlantic Coast (NY to VA)	8/24	11/26	0.20	0.75
2010	USACE NCMP Topobathy Lidar: Atlantic Coast (FL to NC)	5/4	6/16	0.15	0.75
2011	NOAA NGS Lidar: Post-Irene	8/28	8/29	0.15	1.00
2014	NOAA NGS Topobathy Lidar: Post-Sandy (SC to NY)	1/8	7/27	0.06	1.00
2016	USACE Post-Matthew Topobathy Lidar: Southeast Coast (VA, NC, SC, GA, FL)	10/1	12/31	0.19	1.00

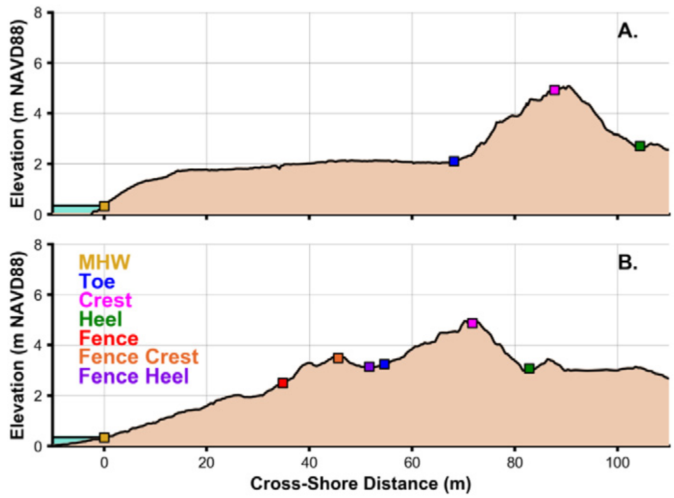

Fig. 5. Examples of *Automorph* output. A) Profile from Fort Macon where sand fences are not present. B) Profile that includes a sand fence (red marker) and a fenced dune located seaward of the natural foredune. MHW = Mean High Water (0.34 m NAVD88), D_{low} = natural dune toe, D_{high} = natural dune crest, D_{heel} = natural dune heel, F_{crest} = fenced dune crest, F_{heel} = fenced dune heel.

0.6 m backshore drop and then continuing landward from this point to a local minima. We measure the natural dune volume for each profile by integrating over the portion of the profile located between D_{low} and D_{heel} and above the lower of D_{low} or D_{heel}.

The marks identifying sand fence locations on the profiles (Section 3.2) are used to determine whether or not the current profile being analyzed contains a sand fence. If a profile is flagged as having a fence then the location of the fence, as well as a fenced dune crest (F_{crest}) and fenced dune heel (F_{heel}), are identified (See caption for Fig. 5). The cross-shore location of the fence on the profile is used to identify where the fence is located on the profile. The crest of the fenced dune, F_{high}, is then identified as a peak seaward of D_{high} but landward of the fence. Once F_{high} is located, F_{heel} is identified as the first local minima landward of F_{high}. We measure beach width for each profile as the cross-shore distance between the MHW contour and D_{low}.

3.4. Uncertainty and statistical analysis

We calculated the uncertainty in the rate of change in shoreline position using the approach of Hapke et al. (2011) for calculating the regionally averaged rate uncertainty:

$$\overline{U}_{Rq^*} = \frac{1}{\sqrt{n^*}}\overline{U}_R$$

where n^* is the effective sample size determined using an autocorrelation (i.e., the number of statistically independent samples) and $\overline{U}_R$ is the average rate uncertainty, which is calculated as the quadrature sum of positional uncertainties over the time between measurements. The positional uncertainty is calculated for each profile based on the spatial error associated with the lidar data and the slope of the profile at the shoreline. We calculate a rate uncertainty (U_R) for each profile by taking the quadrature sum of the positional uncertainties for each profile at $time_0$ and $time_1$ and dividing by $time_1 - time_0$. Finally, we find the average rate uncertainty ($\overline{U}_R$) and multiply by $1/\sqrt{n^*}$ to account for uncertainties in neighboring profiles cancelling each other out. We calculated the uncertainty in the mean beach width change rate, and mean D_{high} elevation change rates using the 95% confidence interval. We also calculated the uncertainty in the mean natural dune height, mean natural dune width, mean natural dune volume, and mean beach width for individual years during the post-fencing period using the 95% confidence interval.

Statistical analysis was performed using methods from SciPy's (Jones et al., 2001) statistics module. To test for the statistical significance of differences in dune and beach morphology at the decadal scale (1997–2016), we performed a Kolmogorov-Smirnov test ($\alpha = 0.05$) to compare the pre-fencing and post-fencing change in shoreline position, beach width, and D_{high} elevation. We then performed a series of Mann-Whitney *U* tests ($\alpha = 0.05$) to test for statistical significance in changes for Fort Macon, non-fenced areas, and fenced areas for the pre-fencing time period (1997–2010), post-fencing time period (2010–2016), and all study years. Island-scale results are presented as raw data with a trend overlain that was created using the Savitzky-Golay filter included in SciPy's (Jones et al., 2001) signal processing module (Figs. 6–8), a smoothing filter applies a polynomial fit (here a 3rd order polynomial) over a moving filter window (here set to 5001 profiles).

To test for statistically significant differences in natural dune morphology (height, width, volume) and beach width between Fort Macon, non-fenced areas, and fenced areas between 2010 and 2016 we performed a series of Kruskal-Wallis H-tests ($\alpha = 0.05$), using Mann-Whitney U tests ($\alpha' = 0.017$) as a post-hoc test. The Kruskal-Wallis H-test is a non-parametric version of ANOVA which tests if multiple groups are from the same populations, and the Mann-Whitney U test is used to test if two groups are equal to each other.

4. Results

4.1. Island-scale morphology of the beach and natural dunes

4.1.1. Shoreline change

From 1997 to 2016 the average shoreline change rate along Bogue Banks was 1.22 ± 0.30 m/yr, indicating progradation. Comparing the pre-fencing and post-fencing periods, the average shoreline change rate increased from 1.17 ± 0.41 m/yr to 1.32 ± 1.17 m/yr. During the post-fencing period, the shoreline along Fort Macon prograded by an average rate of 8.34 ± 2.92 m/yr compared to a mean rate of 0.89 ± 1.05 m/yr for the rest of the island. Further, fewer profiles experienced shoreline accretion during the post-fencing period (67.5%) than during the pre-fencing period (87.4%), demonstrating that the increased rate of island-averaged shoreline progradation during the post-fencing period is due to disproportionately larger increases in shoreline progradation along Fort Macon (due to beach nourishment) during the post-fencing time period (Fig. 6).

Rates of shoreline change were substantially larger along Fort Macon compared to the rest of this island while rates of shoreline change along fenced and non-fenced areas were similar during the pre- and post-fencing periods. During the pre-fencing period, the shoreline along Fort Macon eroded by an average of −1.31 ± 1.44 m/yr, with 85.2% of the transects in Fort Macon undergoing shoreline erosion. During the post-fencing period, the shoreline prograded along Fort Macon by an average of 8.34 ± 2.92 m/yr, with 100% of the transects within the park's boundaries undergoing shoreline progradation. Non-fenced locations experienced an average shoreline progradation rate of 1.39 ± 0.37 m/yr during the pre-fencing period and an average shoreline progradation rate of 0.78 ± 0.92 m/yr during the post-fencing period. Fenced locations experienced an average shoreline progradation of 1.22 ± 0.34 m/yr during the pre-fencing period and an average of 1.05 ± 1.25 m/yr during the post-fencing period.

4.1.2. Beach width

The island-scale average rate of change in beach width for the entire study period was 0.55 ± 0.02 m/yr (Fig. 7). The average pre-fencing rate of change in beach width was 0.41 ± 0.03 m/yr and the average post-fencing beach width change rate was 0.85 ± 0.07 m/yr.

A comparison of beach width change for Fort Macon, non-fenced areas, and fenced areas shows that the greatest rates of change

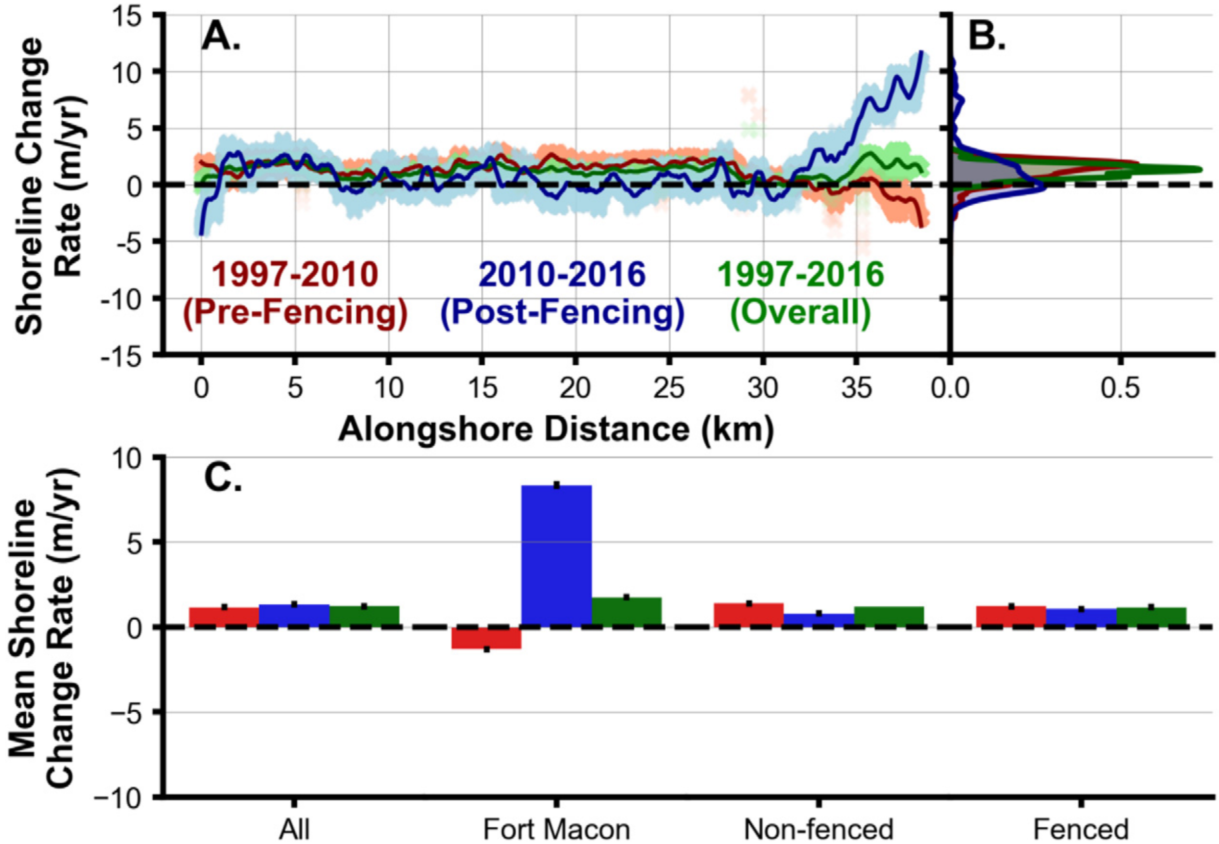

Fig. 6. A) Alongshore variability of shoreline change for Bogue Banks, NC, for 1997–2016 (green), 1997–2010 (red), and 2010–2016 (blue). B) Density distributions of shoreline change for Bogue Banks for 1997–2016, 1997–2010, and 2010–2016. Positive values indicate progradation, negative values indicate erosion. C) Mean shoreline change for the entire island, Fort Macon, non-fenced areas, and fenced areas colored by time period (with 95% confidence intervals).

occurred in Fort Macon followed by non-fenced and fenced areas. During the pre-fencing period, the beach width along Fort Macon changed by an average of -1.55 ± 0.12 m/yr before widening by an average of 7.05 ± 0.17 m/yr during the post-fencing period. The pre-fencing average change in beach width in fenced areas was the lowest of the three areas at 0.11 ± 0.06 m/yr compared to a post-fencing average change of 0.82 ± 0.11 m/yr. In non-fenced areas, the beach widened by an average of 0.83 ± 0.04 m/yr during the pre-fencing period and 0.22 ± 0.08 m/yr during the post-fencing period. (Table 2).

4.1.3. D_{high} elevation change

The average change in D_{high} elevation for the full study period is -0.01 ± 0.00 m/yr representing an overall slight loss in natural dune elevation since the beginning of the study period (Fig. 8, Table 2). During the pre-fencing period, D_{high} elevation changed by an average of -0.03 ± 0.00 m/yr before increasing during the post-fencing period at an average of 0.03 ± 0.00 m.

Unlike non-fenced and fenced areas, Fort Macon experienced increases in natural dune D_{high} elevation during both the pre- (0.04 ± 0.01 m/yr) and post-fencing (0.09 ± 0.01 m/yr) periods. Non-fenced and fenced areas both experienced elevation loss during the pre-fencing period. During the pre-fencing period, fenced and non-fenced areas experienced an average D_{high} change of -0.03 ± 0.00 m/yr. These areas (non-fenced and fenced) both became less vertically erosive during the post-fencing period when non-fenced areas experienced an average D_{high} elevation change of 0.00 ± 0.01 m/yr while fenced areas experienced an average D_{high} change of 0.05 ± 0.01 m.

4.2. The influence of sand fences on natural dune morphology of Bogue Banks

4.2.1. Natural dune height

The tallest natural dunes were located in Fort Macon with an average elevation of 5.3 ± 0.03 m, followed by natural dunes in non-fenced areas (4.5 ± 0.04 m), and natural dunes in fenced areas (4.3 ± 0.06 m) (Fig. 9A).

Average natural dune height through time varied among Fort Macon, non-fenced areas, and fenced areas (Fig. 10A). Average dune elevations along Fort Macon decreased between 2010 (5.2 ± 0.06 m) and 2011 (5.0 ± 0.07 m) and then grew to an average elevation of 5.8 ± 0.06 m by 2016. Natural dune elevation in non-fenced areas steadily increased every year from an average of 4.2 ± 0.08 m in 2010 to an average of 4.7 ± 0.06 m in 2016 (Table 3). The average height of the natural dune in fenced areas was lower than in Fort Macon and non-fenced areas for all years following the emplacement of sand fences in 2010. The natural dunes in fenced areas grew from 2010 (4.1 ± 0.12 m) to 2011 (4.4 ± 0.08 m), were eroded in 2014 (4.2 ± 0.10 m) and then maintained their elevation from 2014 to 2016 (4.3 ± 0.10 m).

4.2.2. Natural dune width

Natural dune widths varied across Bogue Banks with the narrowest natural dunes (mean, $\mu = 19.8 \pm 0.56$ m) located in fenced areas and the widest natural dunes ($\mu = 21.3 \pm 0.34$ m) located in non-fenced areas (Fig. 9B).

Temporal variation in natural dune widths between 2010 and 2016 were minimal, with natural dunes in non-fenced and fenced areas narrowing slightly over time and natural dunes along Fort

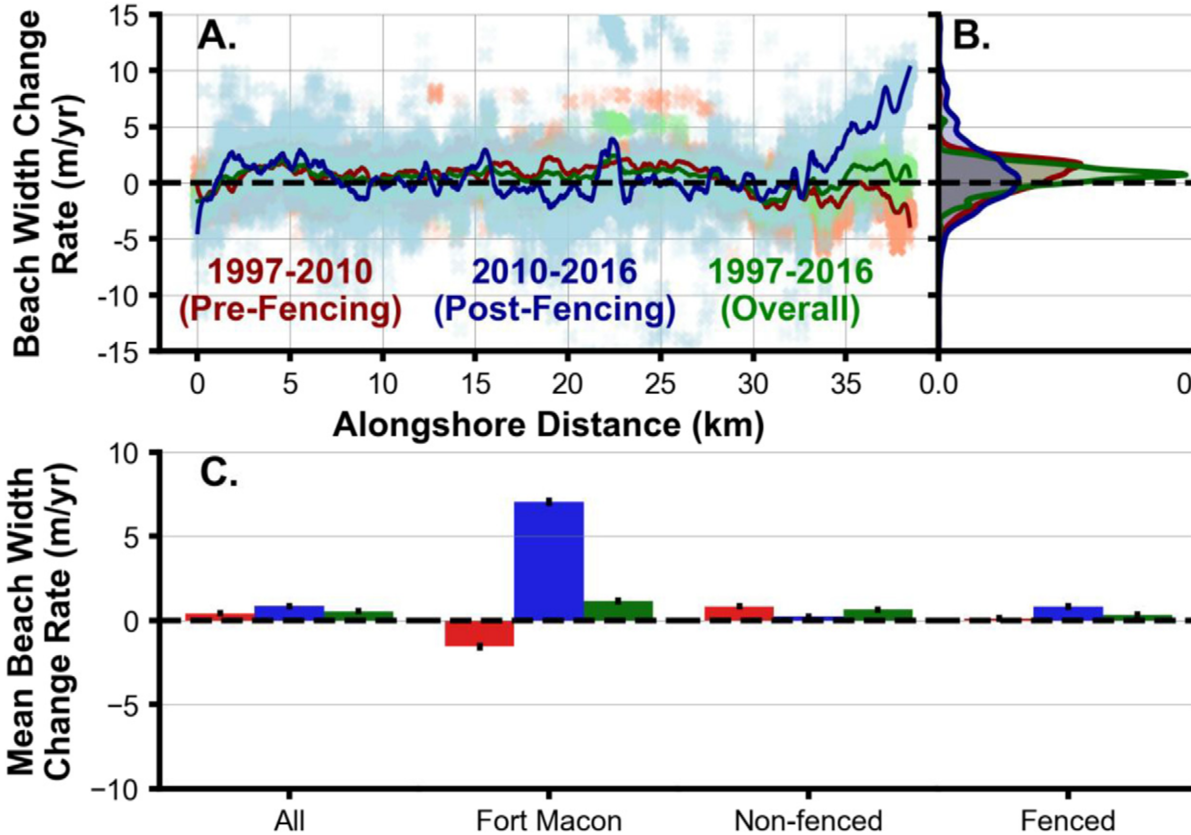

Fig. 7. A) Alongshore variability of beach width change for Bogue Banks, NC, for 1997–2016 (green), 1997–2010 (red), and 2010–2016 (blue). B) Density distributions of beach width change for Bogue Banks for 1997–2016, 1997–2010, and 2010–2016. Positive values indicate progradation, negative values indicate erosion. C) Mean beach width change for the entire island, Fort Macon, non-fenced areas, and fenced areas colored by time period (with 95% confidence intervals).

Macon widening slightly over time (Fig. 10B). The mean natural dune width in Fort Macon increased from 15.0 ± 0.48 m in 2010 to 20.3 ± 0.66 m in 2014 before narrowing to a mean width of 18.4 ± 0.48 m in 2016 (Table 3). Natural dunes in non-fenced areas widened from a mean width of 21.4 ± 0.66 m in 2010 to 23.0 ± 0.77 m in 2011. The natural dunes in non-fenced areas narrowed to a mean width of 19.8 ± 0.60 m in 2014 before widening to a mean width of 21.0 ± 0.68 m in 2016. Natural dunes in fenced areas maintained their width between 2010 and 2011 ($p = 0.36$) before narrowing to a mean width of 16.9 ± 0.92 m in 2014 and widening to a mean width of 19.4 ± 0.98 m in 2016. The natural dune widths in 2010 in both fenced and non-fenced areas were statistically similar to each other ($p = 0.53$), before the natural dunes in fenced areas narrowed the subsequent years. Although the natural dune widths are of similar magnitude across the island, the overall foredune system in fenced areas – which includes the fenced dune – is, by nature of the fenced dune existing, nearly double the width of the non-fenced areas and Fort Macon (Fig. 11).

4.2.3. Natural dune volume

Natural dune volume varies among Fort Macon ($\mu = 27.2 \pm 0.61$ m^3/m), non-fenced areas ($\mu = 25.4 \pm 0.65$ m^3/m), and fenced areas ($\mu = 20.0 \pm 0.89$ m^3/m) (Fig. 10C), and through time (Fig. 10C). Mean natural dune volumes in Fort Macon increased every year except 2011 (Table 3). The mean natural dune volume in non-fenced areas varied within uncertainty between 2010 and 2014 before increasing to 27.6 ± 1.32 m^3/m in 2016 (Table 3). The mean natural dune volume in fenced areas did not vary significantly between 2010 and 2011 ($p = 0.72$) before decreasing in 2014 (15.8 ± 1.30 m^3/m) and increasing in 2016 (20.4 ± 1.54 m^3/m).

4.2.4. Fenced dune height

Fenced dunes elevations increased by 0.5 ± 0.04 m between 2010 and 2016, with a mean value of 3.6 ± 0.01 m over the entire post-fencing period (Table 3). Mean fenced dune height increased by 0.2 ± 0.05 m from 2010 (3.4 ± 0.02 m) to 2011 (3.6 ± 0.03 m) and 0.3 ± 0.04 m from 2014 (3.6 ± 0.02 m) to 2016 (3.9 ± 0.02 m). Fenced dune heights were maintained between 2011 and 2014 (0.00 ± 0.01 m). For all years between 2010 and 2016, the fenced dunes were lower in elevation than natural dunes anywhere on the island (Fig. 12), as expected given that the natural dunes have existed longer than the fenced dunes).

4.3. Interannual (2010–2016) variations in beach width

The beach width was widest along Fort Macon ($\mu = 47.8 \pm 0.95$ m) and narrowest in fenced areas ($\mu = 34.8 \pm 1.29$ m) (Fig. 13A). The mean beach width in non-fenced areas was 45.9 ± 0.71 m. Distributions of beach width are bimodal (Fig. 13A), due to occasionally large changes in beach widths between lidar surveys (Fig. 13B, C, D) associated with nourishment events.

The mean beach width along Fort Macon (Fig. 13B) was 19.0 ± 0.68 m in 2010, the narrowest of any location at any time. The mean beach width along Fort Macon increased between every survey, with the largest increases being concurrent with the timing of beach nourishments (Carteret County Shore Protection Office, 2017; Table 3). The mean beach width in non-fenced areas decreased every year from 2010 (50.5 ± 1.42 m) to 2014 (39.0 ± 1.46 m), and then increased to 48.1 ± 1.24 m in 2016 (Fig. 13C, Table 3). The mean beach width in fenced areas steadily increased each year from 2010 (28.3 ± 2.50 m) to 2016 (42.5 ± 0.68 m) (Fig. 13D). With the exception of 2010, the

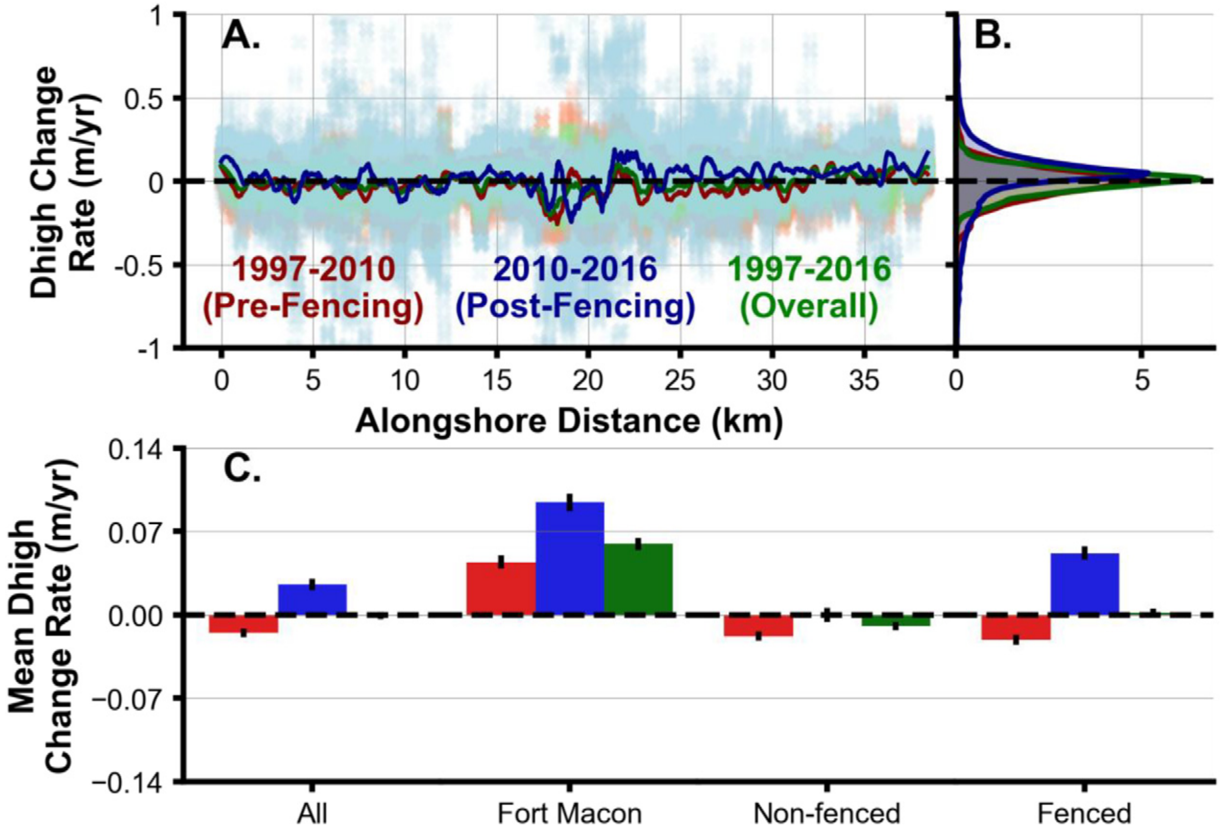

Fig. 8. A) Alongshore variability of dune growth and erosion for Bogue Banks for 1997–2016 (green), 1997–2010 (red), and 2010–2016 (blue). B) Density distributions of vertical dune growth for Bogue Banks for 1997–2016, 1997–2010, and 2010–2016. Positive values indicate vertical dune growth, negative values indicate vertical dune erosion. C) Mean D_{high} elevation change for the entire island, Fort Macon, non-fenced areas, and fenced areas colored by time period (with 95% confidence intervals).

beach was consistently narrower in fenced areas than along Fort Macon (where nourishment occurred) and non-fenced areas.

5. Discussion

We observed that, following the emplacement of sand fences, a new foredune was created seaward of the original dune and just behind the sand fence (Fig. 5). Similar to the schematization by Nordstrom and Mccluskey (1985), the fenced dunes on Bogue Banks form with a slight landward offset from the fence position where the wind velocity reduction is maximized (e.g., Li and Sherman, 2015). Upon formation of the fenced dune, we observe that the landward natural dune which had been growing vertically eventually ceased its growth concurrent with vertical accretion of the fenced dune (Fig. 12). During the post-fencing period (2010 to 2016) the beach width steadily increased in fenced areas (Fig. 13D), however this was not matched with an increase in natural dune elevation suggesting that the fenced dune cut off sediment flux to the natural dune preventing its vertical growth.

Natural dune building processes involved in the formation of a new foredune are dependent upon the ability of pioneering vegetation to survive seaward of the previous vegetation limit in the face of wave runup and salt spray (e.g., Davidson-Arnott et al., 2012; Durán and Moore, 2013; Hesp, 2002; Maun, 1998; Stallins, 2001). In contrast, the formation of a foredune in the presence of a sand fence merely requires sediment sly

Table 2
Island-scale changes in shoreline position, beach width, and D_{high} elevation during the pre-fencing (1997–2010), post-fencing (2010–2016), and overall (1997–2016) periods.

	All (n = 38,454)		Fort Macon (n = 2229)		Non-fenced (n = 21,395)		Fenced (n = 14,830)	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Shoreline change rate (m/yr)								
1997–2010 (pre-fencing)	1.17 ± 0.02	1.02	−1.31 ± 0.02	0.88	1.39 ± 0.02	0.74	1.22 ± 0.02	0.90
2010–2016 (post-fencing)	1.32 ± 0.05	2.45	8.34 ± 0.05	1.34	0.78 ± 0.05	1.55	1.05 ± 0.05	1.97
1997–2016 (overall)	1.22 ± 0.01	0.60	1.74 ± 0.01	0.53	1.20 ± 0.01	0.55	1.17 ± 0.01	0.65
Beach width change rate (m/yr)								
1997–2010 (pre-fencing)	0.41 ± 0.03	1.68	−1.55 ± 0.12	1.45	0.83 ± 0.04	1.45	0.11 ± 0.06	1.76
2010–2016 (post-fencing)	0.85 ± 0.07	3.45	7.05 ± 0.17	2.03	0.22 ± 0.08	2.88	0.82 ± 0.11	3.44
1997–2016 (overall)	0.55 ± 0.02	1.22	1.17 ± 0.08	1.00	0.63 ± 0.03	1.15	0.34 ± 0.04	1.30
Dhigh elevation change rate (m/yr)								
1997–2010 (pre-fencing)	−0.03 ± 0.00	0.12	0.04 ± 0.01	0.08	−0.03 ± 0.00	0.13	−0.03 ± 0.00	0.11
2010–2016 (post-fencing)	0.03 ± 0.00	0.22	0.09 ± 0.01	0.11	0.00 ± 0.01	0.24	0.05 ± 0.01	0.20
1997–2016 (overall)	−0.01 ± 0.00	0.09	0.06 ± 0.00	0.06	−0.02 ± 0.00	0.09	0.00 ± 00	0.08

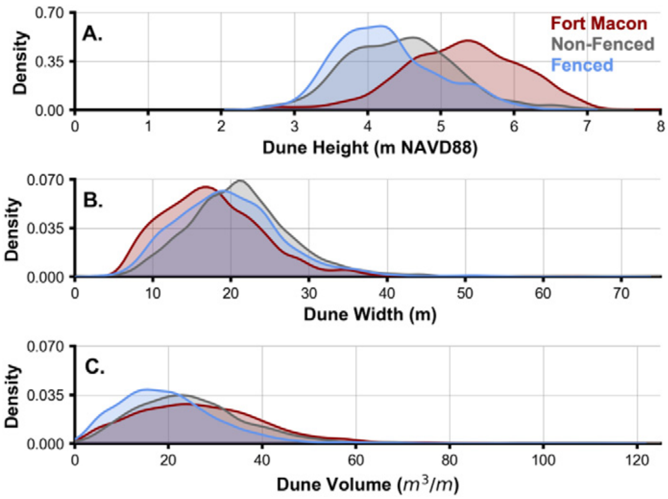

Fig. 9. Density distribution plots of A) natural dune height, B) widths, and C) volumes for all years 2010–2016 combined and color coded by the location of the transects in either Fort Macon, non-fenced areas, or fenced areas on Bogue Banks, NC. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)

as the fence can persist unless it is destroyed by a storm or removed. This means that while a new seaward natural foredune would not typically form unless the shoreline was prograding, fenced dunes can form and persist on a transgressive barrier island, such as we see on Bogue Banks (Timmons et al., 2010). A majority of the sand fences on Bogue Banks are located in Atlantic Beach and Pine Knoll shores (Fig. 2), which are adjacent to Fort Macon State Park. Although Atlantic Beach and Pine Knoll shores were not directly nourished post-2010 (Carteret County Shore Protection Office, 2017), westward directed alongshore drift (Roessler and Wells, 2001) allows nourishment sand to be transported into these locations, leading to increases in shoreline progradation (Fig. 6) and beach widths (Figs. 7 and 13) in the densely fenced areas adjacent to Fort Macon. This additional sediment available for transport to the dune following a nearby nourishment event may have facilitated fenced dune growth that occurred between 2010–2011 and 2014–2016 (Table 3), concurrent with nourishment events that impacted Atlantic Beach where most of the fenced dunes are located. However, we note that we do not observe noticeable changes in natural dune morphology that may be attributable to these nourishments.

Compared to natural dunes along Fort Macon, the natural dunes in non-fenced and fenced areas experienced the greatest rates of elevation

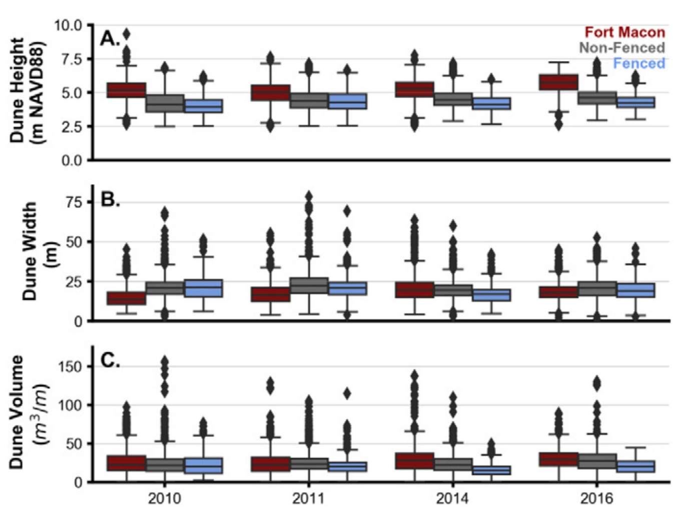

Fig. 10. Temporal variation of natural A) dune height, B) dune width, and C) dune volume for natural dunes in Fort Macon, non-fenced areas, and fenced areas on Bogue Banks, NC.

loss prior to 2010 (Fig. 8, Table 2), perhaps partially explaining the decision to emplace fences in these areas. Following the emplacement of sand fences, the natural dunes in fenced areas generally stopped losing elevation and demonstrated an initial trend toward slight accretion (Table 3, Fig. 10). During the post-fencing time period, the mean natural dune height in fenced areas increased by 0.2 ± 0.22 m, compared to an increase of 0.5 ± 0.14 m in non-fenced areas and 0.6 ± 0.12 m in Fort Macon. Not only did the natural dunes in fenced areas experience the smallest amount of vertical growth during the post-fencing period, but most of the vertical growth during this time occurred between 2010 and 2011 after which time the mean natural dune elevations in fenced areas varied by only ± 0.1 m. Further, the natural dune elevations in fenced areas experienced no significant change between 2014 and 2016 ($p = 0.15$) whereas the natural dune elevations in non-fenced areas and Fort Macon increased between every survey from 2011 to 2018 (Table 3). Given the timing of the installation of sand fences in 2010, it appears likely that the natural dunes in fenced areas were able to grow vertically only until the fenced dune became established, at which time the fenced dune appears to have prevented the landward natural dune from receiving additional sediment which would have otherwise led to increases in D_{high} elevation.

Observing the trends in both natural and fenced dune elevations during the period 2010–2016 (Fig. 12) further supports the hypothesis that fenced dune formation prevents vertical growth of the landward natural dune. From 2011 to 2014, the natural dunes in fenced areas are the only dune "type" to lose elevation. Natural dunes in fenced areas decreased in elevation while the elevation of the fenced dunes in front of them did not change over this period. The observed lack of elevation change in the fenced dunes, while the natural dunes behind them were eroded, can likely be explained by faster recovery after storms of the fenced foredunes and the inhibition of recovery of the natural dunes behind them. From 2014 to 2016, the fenced dunes experience a level of vertical growth surpassed only by the natural dunes along Fort Macon while the natural dunes in fenced areas do not change significantly in elevation ($p = 0.015$). While greater temporal resolution may be required to more clearly analyze changes between 2011 and 2014, changes in natural dune elevations between 2014 and 2016 demonstrate that vertical growth of the fenced dunes came at the cost of insignificant growth of the natural dunes behind fenced dunes.

Comparison of the variations in beach width over time in fenced areas (Fig. 13D) and the variations in natural dune heights in fenced areas over time (Fig. 10A) further supports the hypothesis that natural dune growth is limited in areas where sand fences are present. The mean beach width in fenced areas increased steadily, by a total of 14.2 $\pm$ 3.18 m from 2010 to 2016 while the mean natural dune height increased by only 0.2 ± 0.22 m during that same period (Fig. 10A). The steadily increasing beach widths would typically allow for a greater flux of sediment to the dune and thus an increase in elevation. Rather, what we observe is a trend of increasingly stable natural dune elevations in fenced areas from 2010 to 2016; the changes in mean elevation become progressively smaller between surveys (0.3 m, −0.2 m, 0.1 m) until they are no longer statistically significant. During the same period the fenced dunes grew in height by 0.6 ± 0.04 m with the majority of this increase occurring from 2014 to 2016 (0.3 ± 0.04 m), during which time the natural dunes landward of the fenced dunes did not grow vertically.

In addition to differences in the way natural dunes grow in areas where sand fences are present compared to where they are absent, we observe differences in the height, width, and volume of natural dunes in fenced areas on Bogue Banks versus those in non-fenced areas and Fort Macon. For much of the study period, the natural dunes in fenced areas are lower, wider, and lesser in volume than in Fort Macon. Natural dunes are also shorter and lower in volume than those in non-fenced areas but are not as wide. Toward the end of the study period, the width of the natural dunes in fenced areas appears to decrease, however, this is likely due to the fenced dune forcing the natural dune

Table 3
Interannual variations in natural dune height, natural dune width, natural dune volume, and beach width during the post-fencing period. The overall values represent the mean and standard deviation for the entire post-fencing period. Natural dunes in fenced areas and fenced dunes have the same beach width.

		Dhigh (m)		Dune width (m)		Volume (m^3/m)		Beach width (m)	
		Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Fort Macon	2010	5.2 ± 0.06	0.8	15.0 ± 0.48	5.8	26.1 ± 1.26	15.2	19.0 ± 0.68	7.7
(n = 2229)	2011	5.0 ± 0.07	0.8	17.3 ± 0.52	6.2	24.3 ± 1.11	13.4	47.1 ± 0.87	10.0
	2014	5.2 ± 0.07	0.8	20.3 ± 0.66	7.9	28.9 ± 1.35	16.2	62.2 ± 1.64	18.7
	2016	5.8 ± 0.06	0.7	18.4 ± 0.48	5.7	29.5 ± 1.11	13.4	62.9 ± 0.98	11.2
	Overall	5.3 ± 0.03	0.8	17.8 ± 0.28	6.8	27.2 ± 0.61	14.7	47.8 ± 0.95	21.8
Non-Fenced	2010	4.2 ± 1.20	0.8	21.4 ± 0.66	6.9	24.0 ± 1.45	15.0	50.5 ± 1.42	15.2
(n = 21,395)	2011	4.4 ± 0.08	0.8	23.0 ± 0.77	7.9	25.5 ± 1.25	12.9	46.3 ± 1.29	13.8
	2014	4.5 ± 0.07	0.7	19.8 ± 0.60	6.1	24.3 ± 1.18	12.2	39.0 ± 1.46	15.6
	2016	4.7 ± 0.06	0.7	21.0 ± 0.68	7.0	27.6 ± 1.32	13.6	48.1 ± 1.24	13.2
	Overall	4.5 ± 0.04	0.8	21.3 ± 0.34	7.1	25.4 ± 0.65	13.5	45.9 ± 0.71	15.1
Fenced	2010	4.1 ± 0.12	0.7	21.7 ± 1.20	7.4	22.6 ± 2.19	13.6	28.3 ± 2.50	10.0
(n = 14,830)	2011	4.4 ± 0.12	0.7	21.3 ± 1.21	7.5	21.4 ± 1.79	11.1	32.7 ± 1.92	7.7
	2014	4.2 ± 0.10	0.6	16.9 ± 0.92	5.7	15.8 ± 1.30	8	35.8 ± 3.11	12.5
	2016	4.3 ± 0.10	0.6	19.4 ± 0.98	6.1	20.4 ± 1.54	9.6	42.5 ± 0.68	2.7
	Overall	4.3 ± 0.06	0.7	19.8 ± 0.56	7.0	20.0 ± 0.89	11.1	34.8 ± 1.29	10.4
Fenced dunes	2010	3.4 ± 0.02	0.5	16.7 ± 0.37	7.8	15.6 ± 0.63	13.4		
(n = VARIES)	2011	3.6 ± 0.03	0.6	18.4 ± 0.38	7.1	18.4 ± 0.56	10.8		
	2014	3.6 ± 0.02	0.5	14.1 ± 0.22	5	13.2 ± 0.39	9.1		
	2016	3.9 ± 0.02	0.4	14.4 ± 0.32	6.9	13.3 ± 0.60	13.1		
	Overall	3.6 ± 0.01	0.5	15.6 ± 0.16	6.9	15.1 ± 0.28	11.7		

toe landward. Despite this narrowing of the natural dune in fenced areas over time, the overall morphology of the dune system—which consists of a natural dune in combination with a fenced dune—differs greatly from that of the non-fenced areas and Fort Macon. In areas with sand fences, the dune system, although not as tall, is substantially wider than in Fort Macon and non-fenced areas (Fig. 11). While a taller dune is considered to offer more protection against storm induced erosion (i.e., Sallenger, 2000), the lower but wider dune system observed in fenced areas may be more resistant to volumetric dune erosion during longer duration storms or storms in which the dune is impacted but water levels are not sufficient to cause overwash to occur.

6. Conclusions

The emplacement of sand fences on Bogue Banks, NC has led to the formation of fenced dunes that have prevented the natural dunes behind them from growing vertically. At least partly as a result of this effect, the overall dune system (natural foredune + fenced dune) is lower and wider in fenced areas, making them more vulnerable to overwash (Sallenger, 2000) but more resistant to scarping and lateral erosion, than taller, narrower dunes.

Our analysis of the multi-decadal morphology of Bogue Banks shows that there has been a statistically significant difference in the pre- (1997–2010) and post-fencing (2010–2016) morphology of Bogue Banks wherein the shoreline has become less progradational overall with a greater number of profiles experiencing erosion ($p < 0.001$), the beach has narrowed slightly ($p < 0.001$), and the natural dunes have stopped losing elevation ($p < 0.001$). Frequent nourishments have caused localized areas of shoreline progradation (such as along Fort Macon) and therefore beach widening, which have likely allowed the dunes in these locations to grow taller than they would have if nourishment had not occurred. Natural dune elevations along Bogue Banks have been slightly accretional, compared to their erosional pre-fencing condition (when averaged over the entire time period since fences were installed). We find that natural dunes in fenced areas are shorter,

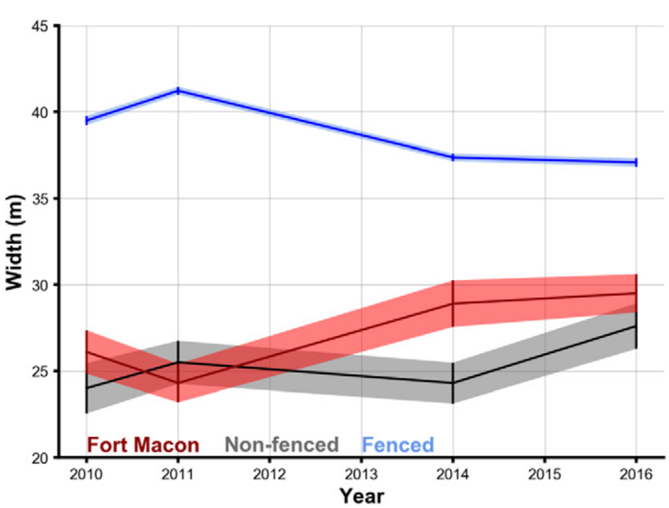

Fig. 11. Temporal evolution of the width of the overall dune system along Bogue Banks, NC, during the post-fencing period (2010–2016). The dune system for Fort Macon and non-fenced areas consists of a single natural dune, while in fenced areas it consists of a natural dune fronted by a fenced dune. The shaded areas represent the 95% confidence interval.

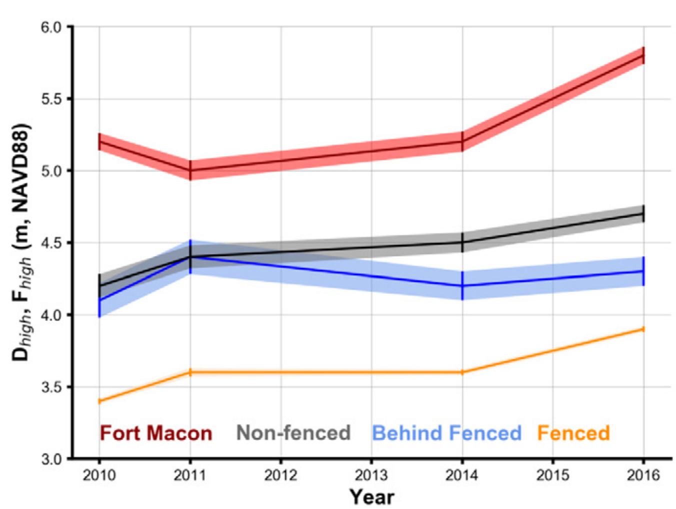

Fig. 12. Evolution of mean natural (D_{high}) and fenced (F_{high}) dune elevations along Bogue Banks, NC, during the post-fencing period (2010–2016). The shaded area represents the 95% confidence interval.

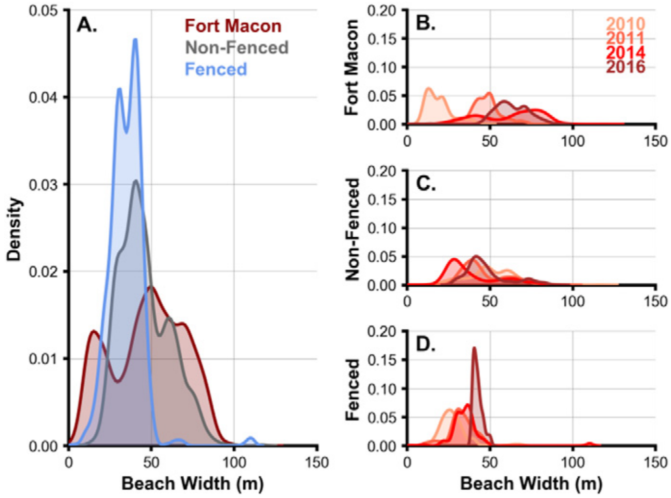

Fig. 13. Distribution of beach widths on Bogue Banks, NC. A) Overall beach widths for Fort Macon, non-fenced areas, and fenced areas. B) Beach width variations in Fort Macon colored by year. C) Beach width variations in non-fenced locations colored by year. D) Beach width variations in fenced locations colored by year.

wider, and lower in volume than natural dunes in non-fenced areas and Fort Macon, although the difference in width between the natural dune fenced and non-fenced areas is marginal and may explain the selection of locations for sand fence installation. Differences in measured width and volume may also arise due to a landward shift in toe position of the natural dune, which occurs as the fenced dune grows.

Overall, the effect of sand fencing on Bogue Banks has been to: (1) prevent loss of natural dune height through lateral erosion in fenced areas despite a greater number of profiles experiencing shoreline erosion and a decrease in shoreline progradation outside of Fort Macon, and (2) prevent vertical growth of the natural dunes behind the sand fences as the fenced dunes form by blocking sand flux to the natural dune. Taken together, the fenced and natural foredune (i.e., the modified foredune system) in fenced areas is shorter than the single natural foredune in non-fenced areas, however it is also much wider due to the combined width of the fenced and natural dune. The lower and wider dune system has implications for how storms may impact areas with sand fences—while the relatively lower elevation makes the dunes more susceptible to overwash, the increased width may be more effective at preventing volumetric loss due to erosion in the more prevalent collision regime (i.e., Brodie et al., 2019; Stockdon et al., 2007) by increasing the lateral distance of the dune that can be eroded through before the dune system is breached.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgements

This work was funded by the US National Oceanic and Atmospheric Association (NOAA) via the NOS/NCCOS/CRP Ecological Effects of Sea-Level Rise Program (grant no. NA15NOS4780172) to P.R., S.D.H., and L.J.M. The authors declare no competing interests. The authors thank the two anonymous reviewers for their comments, which helped to improve this manuscript.

References

Alhajraf, S., 2004. Computational fluid dynamic modeling of drifting particles at porous fences. Environ. Model. Softw. 19, 163–170. https://doi.org/10.1016/S1364-8152(03)00118-X.
Anthony, E.J., Vanhee, S., Ruz, M.H., 2007. An assessment of the impact of experimental brushwood fences on foredune sand accumulation based on digital elelvation models. Ecol. Eng. 31, 41–46. https://doi.org/10.1016/j.ecoleng.2007.05.005.
Arens, S.M., Van Kaam Peters, H.M.E., Van Boxel, J.H., 1995. Air flow over foredunes and implications for sand transport. Earth Surf. Process. Landforms 20, 315–332. https://doi.org/10.1002/esp.3290200403.
Baas, A.C.W., Nield, J.M., 2007. Modelling vegetated dune landscapes. Geophys. Res. Lett. 34, 1–5. https://doi.org/10.1029/2006GL029152.
Biel, R.G., Hacker, S.D., Ruggiero, P., 2019. Elucidating coastal foredune ecomorphodynamics in the US Pacific Northwest via Bayesian networks. J. Geophys. Res. Earth Surf. https://doi.org/10.1029/2018JF004758.
Brodie, K., Conery, I., Cohn, N., Spore, N., Palmsten, M., 2019. Spatial variability of coastal foredune evolution, part a: timescales of months to years. J. Mar. Sci. Eng. 7, 1–28. https://doi.org/10.3390/jmse7050124.
Carteret County Shore Protection Office, 2017. Beach Preservation Plan: Nourishment Chronology & Geographic Extents [WWW Document]. http://www.carteretcountync.gov/DocumentCenter/View/2788/Beach-Nourishment-History-Figure-2017_FINAL?bidId.
Charbonneau, B.R., Wnek, J.P., 2016. Reactionary fence installation for post-Superstorm Sandy dune recovery. Shore and Beach 84, 42–48.
Cohn, N., Ruggiero, P., García-Medina, G., Anderson, D., Serafin, K.A., Biel, R., 2019. Environmental and morphologic controls on wave-induced dune response. Geomorphology. https://doi.org/10.1016/j.geomorph.2018.12.023.
Cornelis, W.M., Gabriels, D., 2005. Optimal windbreak design for wind-erosion control. J. Arid Environ. 61, 315–332. https://doi.org/10.1016/j.jaridenv.2004.10.005.
Davidson-Arnott, R.G.D., Bauer, B.O., Walker, I.J., Hesp, P.A., Ollerhead, J., Chapman, C., 2012. High-frequency sediment transport responses on a vegetated foredune. Earth Surf. Process. Landforms 37, 1227–1241. https://doi.org/10.1002/esp.3275.
Development, C.C.E, 2018. Crystal Coast Tourism & Attractions|Carteret EDC [WWW Document].
Division, U.S.C.B.P, 2018. Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2017 [WWW Document].
Durán, O., Moore, L.J., 2013. Vegetation controls on the maximum size of coastal dunes. Proc. Natl. Acad. Sci. 110, 17217–17222. https://doi.org/10.1073/pnas.1307580110.
Elko, N.A., Sallenger Jr., A.H., Guy, K., Stockdon, H.F., Morgan, K.L.M., 2002. Barrier Island Elevations Relevant to Potential Storm Impacts: 1 (Techniques).
FitzGerald, D.M., Fenster, M.S., Argow, B.A., Buynevich, I.V., 2008. Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet. Sci. 36, 601–647. https://doi.org/10.1146/annurev.earth.35.031306.140139.
Gillies, J.A., Etyemezian, V., Nikolich, G., Glick, R., Rowland, P., Pesce, T., Skinner, M., 2017. Effectiveness of an array of porous fences to reduce sand flux: Oceano Dunes, Oceano CA. J. Wind Eng. Ind. Aerodyn. 168, 247–259. https://doi.org/10.1016/j.jweia.2017.06.015.
Godfrey, P.J., 1977. Climate, plant response and development of dunes on barrier beaches along the U.S. east coast. Int. J. Biometeorol. 21, 203–215. https://doi.org/10.1007/BF01552874.
Hacker, S.D., Zarnetske, P., Seabloom, E., Ruggiero, P., Mull, J., Gerrity, S., Jones, C., 2012. Subtle differences in two non-native congeneric beach grasses significantly affect their colonization, spread, and impact. Oikos 121, 138–148. https://doi.org/10.1111/j.1600-0706.2011.18887.x.
Hacker, S.D., Jay, K.R., Cohn, N., Goldstein, E.B., Hovenga, P.A., Itzkin, M., Moore, L.J., Mostow, R.S., Mullins, E.V., Ruggiero, P., 2019. Species-specific functional morphology of four US Atlantic coast dune grasses: biogeographic Implications for Dune Shape and Coastal Protection. Diversity 11, 1–16. https://doi.org/10.3390/d11050082.
Hapke, C.J., Himmelstoss, E., Kratzmann, M., List, J.H., Thieler, E.R., 2011. National Assessment of Shoreline Change: Historical Shoreline Change along the New England and Mid-Atlantic Coasts. Geological Survey Open-File Report, U.S. https://doi.org/10.1393/ncc/i2007-10271-5.
Hardin, E., Kurum, M.O., Mitasova, H., Overton, M.F., 2012. Least cost path extraction of topographic features for storm impact scale mapping. J. Coast. Res. 28, 970–978. https://doi.org/10.2112/Jcoastres-D-11-00126.1.
Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48, 245–268. https://doi.org/10.1016/S0169-555X(02)00184-8.
Jackson, N.L., Nordstrom, K.F., 2011. Aeolian sediment transport and landforms in managed coastal systems: a review. Aeolian Res. 3, 181–196. https://doi.org/10.1016/j.aeolia.2011.03.011.
Jackson, N.L., Nordstrom, K.F., 2018. Aeolian sediment transport on a recovering storm-eroded foredune with sand fences. Earth Surf. Process. Landforms 43, 1310–1320. https://doi.org/10.1002/esp.4315.
Jones, E., Oliphant, T., Peterson, P., 2001. SciPy: Open Source Scientific Tools for Python.
Li, B., Sherman, D.J., 2015. Aerodynamics and morphodynamics of sand fences: a review. Aeolian Res. 17, 33–48. https://doi.org/10.1016/j.aeolia.2014.11.005.
Lima, I.A., Araújo, A.D., Parteli, E.J.R., Andrade, J.S., Herrmann, H.J., 2017. Optimal array of sand fences. Sci. Rep. 7, 45148. https://doi.org/10.1038/srep45148.
Lima, I.A., Parteli, E.J.R., Shao, Y., Andrade, J.S., Herrmann, H.J., Araújo, A.D., 2018. CFD simulation of the wind field over a terrain with sand fences: critical spacing for the protected soil area. (arXiv:1808.08945v1 [physics.flu-dyn]). ArXiv 1–30.
Magliocca, N.R., McNamara, D.E., Murray, A.B., 2011. Long-term, large-scale morphodynamic effects of artificial dune construction along a barrier island coastline. J. Coast. Res. 276, 918–930. https://doi.org/10.2112/JCOASTRES-D-10-00088.1.
Maun, M.A., 1998. Adaptations of plants to burial in coastal sand dunes. Can. J. Bot. 76, 713–738. https://doi.org/10.1139/b98-058.
Mendelssohn, I.A., Hester, M.W., Monteferrante, F.J., Journal, S., Winter, N., Mendelssohn, I.A., Hester, M.W., Monteferrantet, F.J., Talbot, F., 1991. Experimental dune building and vegetative stabilization in a sand-deficient barrier island setting on the Louisiana Coast, USA. J. Coast. Res. 7, 137–149.

Miller, D.L., Thetford, M., Yager, L., 2001. Evaluation of sand fence and vegetation for dune building following overwash by Hurricane Opal on Santa Rosa Island, Florida. J. Coast. Res. 17, 936–948.
Mitasova, H., Hardin, E., Starek, M.J., Harmon, R.S., Overton, M.F., 2011. Landscape dynamics from LiDAR data time series. Geomorphometry.org 1–4.
Mull, J., Ruggiero, P., 2014. Estimating storm-induced dune erosion and overtopping along U.S. west coast beaches. J. Coast. Res. 30, 1173–1187. https://doi.org/10.2112/JCOASTRES-D-13-00178.1.
NOAA, 2014. Total Economy of Coastal Areas Data.
Nordstrom, K.F., Mccluskey, J.M., 1985. The effects of houses and sand fences on the eolian sediment budget at Fire Island, New York. J. Coast. Res. 1, 39–46.
Nordstrom, K.F., Lampe, R., Vandemark, L.M., 2000. Reestablishing naturally functioning dunes on developed coasts. Environ. Manag. 25, 37–51. https://doi.org/10.1007/s002679910004.
Nordstrom, K.F., Jackson, N.L., Freestone, A.L., Korotky, K.H., Puleo, J.A., 2012. Effects of beach raking and sand fences on dune dimensions and morphology. Geomorphology 179, 106–115. https://doi.org/10.1016/j.geomorph.2012.07.032.
van Puijenbroek, M.E.B., Limpens, J., de Groot, A.V., Riksen, M.J.P.M., Gleichman, M., Slim, P.A., van Dobben, H.F., Berendse, F., 2017. Embryo dune development drivers: beach morphology, growing season precipitation, and storms. Earth Surf. Process. Landforms 42, 1733–1744. https://doi.org/10.1002/esp.4144.
Roessler, T.S., Wells, J.T., 2001. Beach changes along Eastern Bogue Banks, North Carolina, resulting from the 1996 hurricane season. J. Coast. Conserv. 17, 964–975.
Rogers, L.J., Moore, L.J., Goldstein, E.B., Hein, C.J., Lorenzo-Trueba, J., Ashton, A.D., 2015. Anthropogenic controls on overwash deposition: evidence and consequences. J. Geophys. Res. Earth Surf. 120, 2609–2624. https://doi.org/10.1002/2015JF003634.
Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., Bach, R., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. J. Coast. Res. 17, 407–419. https://doi.org/10.2307/4300192.
Sallenger, A.H., 2000. Storm impact scale for barrier islands. J. Coast. Res. 16, 890–895. https://doi.org/10.2307/4300099.
Sefcovic, Z.P., 2016. Climatology of Tropical Cyclones in Eastern North Carolina [WWW Document]. URL. https://www.weather.gov/mhx/TropicalClimatology.
Smith, M.D., Slott, J.M., McNamara, D., Brad Murray, A., 2009. Beach nourishment as a dynamic capital accumulation problem. J. Environ. Econ. Manage. 58, 58–71. https://doi.org/10.1016/j.jeem.2008.07.011.
Stallins, J.A., 2001. Soil and vegetation patterns in barriers-island dune environments. Phys. Geogr. 22, 79–98.
Stockdon, H.F., Sallenger, A.H., Holman, R.A., Howd, P.A., 2007. A simple model for the spatially-variable coastal response to hurricanes. Mar. Geol. 238, 1–20. https://doi.org/10.1016/j.margeo.2006.11.004.
Stockdon, H.F., Doran, K.S., Sallenger, A.H., 2009. Extraction of Lidar-based dune-crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. J. Coast. Res. 53, 59–65. https://doi.org/10.2112/SI53-007.1.
Timmons, E.A., Rodriguez, A.B., Mattheus, C.R., DeWitt, R., 2010. Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA. Mar. Geol. 278 (1–4), 100–114. https://doi.org/10.1016/j.margeo.2010.09.006. https://www.sciencedirect.com/science/article/abs/pii/S0025322710002549?via%3Dihub.
Wernette, P., Houser, C., Bishop, M.P., 2016. An automated approach for extracting barrier island morphology from digital elevation models. Geomorphology 262, 1–7. https://doi.org/10.1016/j.geomorph.2016.02.024.
Zarnetske, P.L., Hacker, S.D., Seabloom, E.W., Ruggiero, P., Killian, J.R., Maddux, T.B., Cox, D., 2012. Biophysical feedback mediates effects of invasive grasses on coastal dune shape. Ecology 93, 1439–1450. https://doi.org/10.1890/11-1112.1.
Zarnetske, P.L., Ruggiero, P., Seabloom, E.W., Hacker, S.D., 2015. Coastal foredune evolution: the relative influence of vegetation and sand supply in the US Pacific Northwest. J. R. Soc. Interface 12. https://doi.org/10.1098/rsif.2015.0017.
Zhang, K., Leatherman, S., 2011. Barrier Island population along the U.S. Atlantic and Gulf Coasts. J. Coast. Res. 27, 356–363. https://doi.org/10.2112/JCOASTRES-D-10-00126.1.