Project Title: Using Lidar to Assess Impacts of Dune Restoration on Coastal Resilience in North Carolina

· PI Name: Lagomasino, David

· PI Affiliation: Integrated Coastal Programs, East Carolina University

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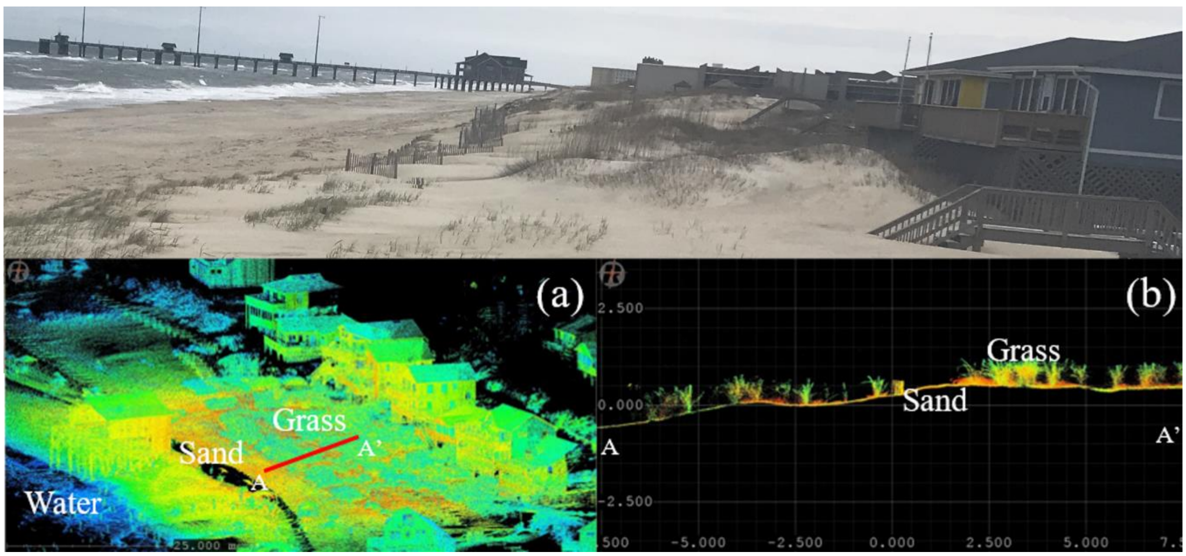

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Abstract

Coastal beaches and dunes are very dynamic landscapes due to changes of ocean waves, tides, wind, and human activities. The average shoreline erosion rate from 1949 to 2016 in Nags Head was -0.9 m yr^{-1} with a maximum value of 2.5 m yr^{-1}. To prevent erosion, beach nourishments, vegetation planting, sand fences have been built along the coastal line of Nags Head. However, very few studies have quantified detailed sediment responses after restoration. In the project, we used a coastal lidar scanner system to quantify sediment budgets, foredune dynamics 10 dune restoration sites in Nags Head, NC. We assessed how various dune restoration activities impact coastal resilience along the North Carolina coast. We collected lidar data over these sites in December 2022 and March 2023. Elevation profiles and Difference of DEMs show all beaches were eroded after three months. The volume changes of foredunes show stable or little accretion of sand due to fencing and planting. The project provides preliminary data, a monitoring framework, and initial results from which to understand larger beach and dune systems across the OBXs.

1. Introduction

Coastal beaches and dunes are natural barriers at low-lying coastal margins that can reduce storm surge, and in turn, protect inland communities and infrastructure from coastal flooding (Barbier et al., 2011). In the Outer Banks of North Carolina (OBX), these ecosystems also support millions of annual visitors and a 2.3-billion-dollar tourism industry (Economic Development Partnership of NC, 2020). But beaches and dunes are often subjected to acute and chronic erosion as a result of climate change and sea level rise as well as increases in coastal development, population, and tourism (Brown and McLachlan, 2002). Beach renourishment projects and dune stabilization initiatives are underway to build more resilient coastlines by local communities and homeowners to enjoy into the future.

Nags Head is a town in the OBX and sits on a barrier island system that stretches 17 miles separating the sounds from the Atlantic Ocean (Fig. 1a). The town has the largest sand dune system along the US east coast (Mitasova et al., 2005) but has sustained significant erosion over the past 50 years leading to economic damage (Kaczkowski et al., 2018). For example, Hurricane Dorian in 2019 caused nearly $15 million in damages to Dare County with the town of Nags Head suffering nearly half a million USD ($457,041) in damages. Similarly, Hurricane Michael in 2018 caused $7 million in damages and caused life-threatening flooding in Kill Devil Hills, Manteo, and Nags Head (https://www.darenc.com/). Therefore, efforts to address beach erosion and overwash flooding are a critical need for coastal communities.

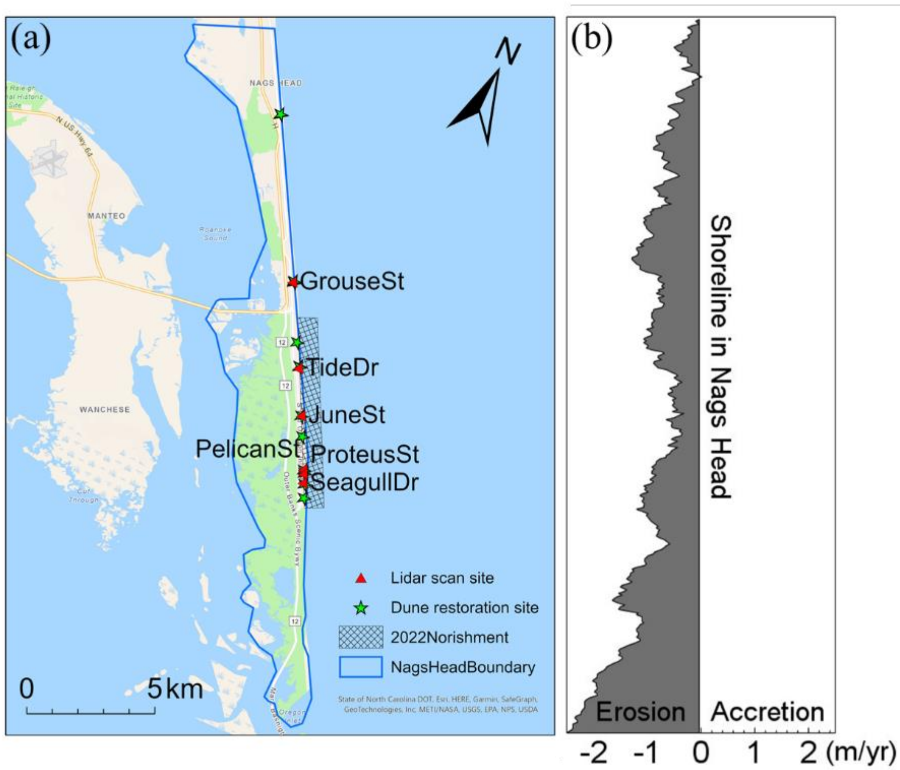

Figure 1 (a) Dune restoration sites before 2021 and lidar scanned sites in 2021. (b) Shoreline erosion rate from 1949 to 2016 at Nags Head, NC.

The average shoreline erosion rate from 1949 to 2016 in Nags Head was -0.9 m yr-1 with a maximum value of 2.5 m yr-1 (Fig. 1b) (NC Division of Coastal Management, 2019). Because of these high rates of erosion, Nags Head and other municipalities in the Outer Banks conduct beach renourishment projects, which are some of the largest locally funded projects in the United States. Current renourishment projects in 2022 are underway and will add sand to approximately 4.45 miles of shoreline in Nags Head at the cost ~$14 million (Fig. 1a). The dynamic changes after dune restoration are important indicators of coastal resilience. An important way to repair the dunes is by planting vegetation to help their formation and stabilization (Gracia et al., 2018). Better Beaches OBX (BBOBX), a grassroots organization supported by local volunteers and private homeowners, have planted beach grass and placed recycled Christmas trees along the dune line to help reinforce and build dunes in Nags Head, Kitty Hawk, and Southern Shores for the past several years. However, there are no measures of the effectiveness of these dune stabilization initiatives, which are key interests for BBOBX and the Town of Nags Head. Very few studies have quantified detailed sediment responses after restoration. Those that have traditionally use cross-shore profile surveys measure by Real Time Kinematic (RTK) GPS that can only measure beach dynamics in 2D whereby changes in sand volume cannot be accurately measured with those limited profiles.

Therefore, quantifying the changes in dune topography in and around beach planting sites will help organizations and coastal managers understand how dune restoration allows sandy beaches to adapt to sea level rise. Ground-based lidar (light detection and ranging), also known as Terrestrial Laser Scanning (TLS), do provide high resolution topographic survey in 3D and greatly improves coastal landscape visualization and interpretation. Our goal is to conduct repeat hyper-resolution topographic surveys using our Coastal Laser Scanner at planted and non-planted beachfront dunes to assess the effectiveness of the stabilization activities which will provide preliminary data for future funding, provide training opportunities for students, and reinforce community partnerships between the ECU Outer Banks Campus, BBOBX, and the Town of Nags Head.

2. **Methods**

2.1. Lidar data collection

We developed a Coastal Laser Scanner that integrates both RTK GPS and Terrestrial Laser Scanning (TLS) technologies to accurately map the beach and dunes at restoration sites with a hyper-spatial resolution (Figure 2a). We scanned a total of 10 dune restoration sites by BBOBX in October 2022 and February 2022 (Table 1). In order to evaluate accuracy of our new scanning system, we also conducted TLS scanning on the stable tripod over a few restoration sites. For each site, all scan positions are shown in Figure 3. Yellow circles are just approximate location for grass planting area. High resolution point cloud can not only capture the topography, but also vegetation structure and details of man-made objects. The sand fence installed on dunes can be clearly seen in point cloud (Figure 4).

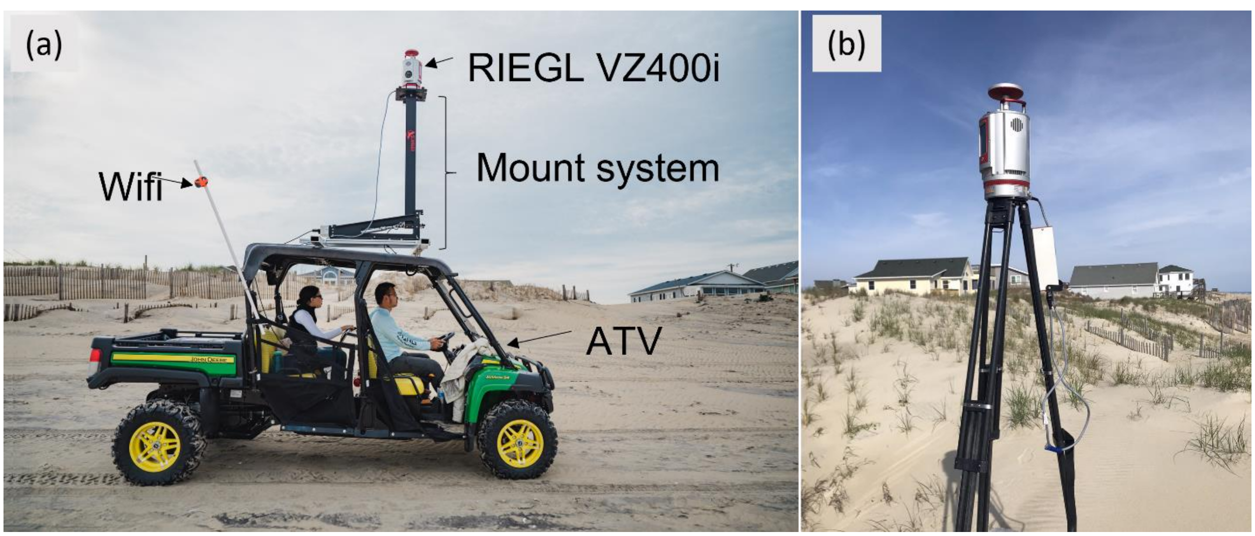

Figure 2 (a) Coastal Laser Scanning System. It includes the RIEGL VZ400i with network RTK GPS function, Scan & Go mount system, and ATV. (b) TLS scanning using RIEGL VZ400i on a tripod.

Table 1 Locations of dune restoration sites by BBOBX

Site number	Street name	Grass planting	Lat	Lon
1	E Hollowell St	2020	35.96879037	-75.62949172
2	Grouse St	NA	35.91764384	-75.60046747
3	E Hardgrove St	2018	35.89866694	-75.59046745
4	E Tides Dr	2020	35.8912571	-75.58598779
5	E June St	2016	35.87594669	-75.57819969
6	Juncos St	2018	35.86953018	-75.57482149
7	E Pelican St	2020	35.85909248	-75.56929812
8	E Proteus Ct	2020	35.85808069	-75.56867672
9	E Seagull Dr	2020	35.85463535	-75.56706868
10	10333A S Old Oregon Inlet Rd	NA	35.85018377	-75.56521494

Figure 3 TLS scan positions at 10 restorations sites. Yellow circles are proposed sites in this project. Dark blue and red circles are scan positions for the time December 2022 and March 2023, respectively. (a) to (i) are sites from 1 to 10 in Table 1. Note that (g) has two restoration sites.

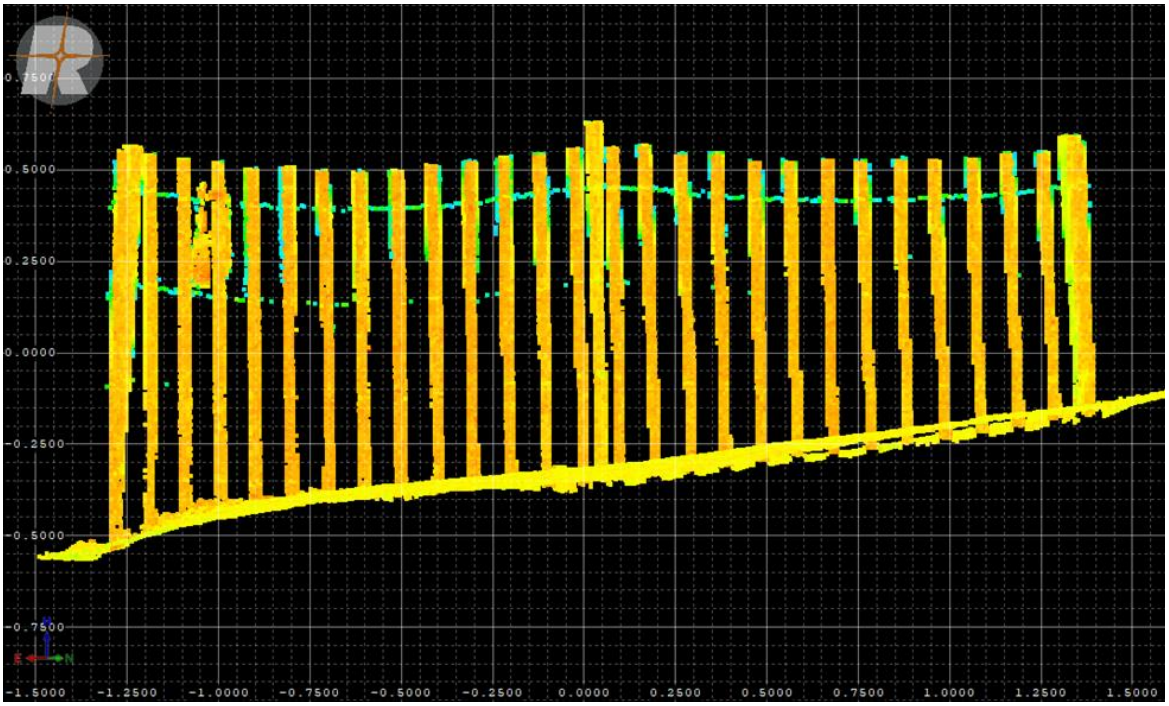

Figure 4 An example of point cloud showing sand fences at Nags Head.

2.2. Data processing

We applied the same rapid survey and modeling approach developed and published by Xiong (et al., 2017, 2019) along the North Carolina coast (Figure 4). Data acquisition and processing will be completed using the RiSCAN-Pro software package (V2.9). This includes managing field data acquisition, data visualization, point registration, terrain filtering, data deduction, and data exporting. During data acquisition, we will use panorama scan (360 degree) mode and the angular resolution is 0.04 degree. Individual scans will be along the coastline with an average distance between two nearby scan positions of 30 m to ensure adequate overlap. We will apply an Iterative Closest Point (ICP) algorithm for point cloud registration (Besl and McKay, 1992). All point clouds will be registered to a global coordinate system defined by UTM coordinates in the horizontal plane (NAD83/ UTM zone 18N) and by the North American Vertical Datum of 1988 (NAVD 88) in the vertical direction. An octree filter employed in the RiSCAN-Pro software will be applied to decimate the raw laser points. The octree filter will recursively subdivide one cube or cuboid into eight equally sized cuboids. In this study, the dimension of the unit cuboid will be set to 10 cm × 10 cm × 3 cm in the east-west (X), north-south (Y), and vertical (Z) directions, respectively (Xiong et al., 2017).

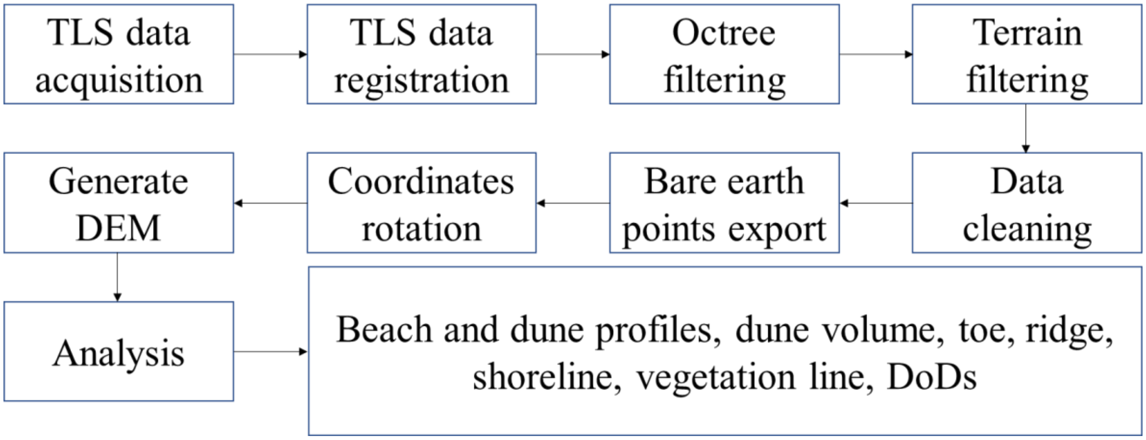

Figure 5 Workflow illustrating processing steps for TLS data in this project, modified from (Xiong et al., 2017; Zhou et al., 2017)

In order to develop a bare-earth DEM, a terrain filter will be employed in the RiSCAN-Pro software package following the octree-filter (Figure 5). The terrain filter is designed to remove off-terrain points (e.g., vegetation, tripods, vehicles, and pedestrians) using anomalous height differences between adjacent points. The distances of the points from an estimated ground surface are then calculated and analyzed during the filtering process. Extraneous points will then be removed manually and exported for further processing.

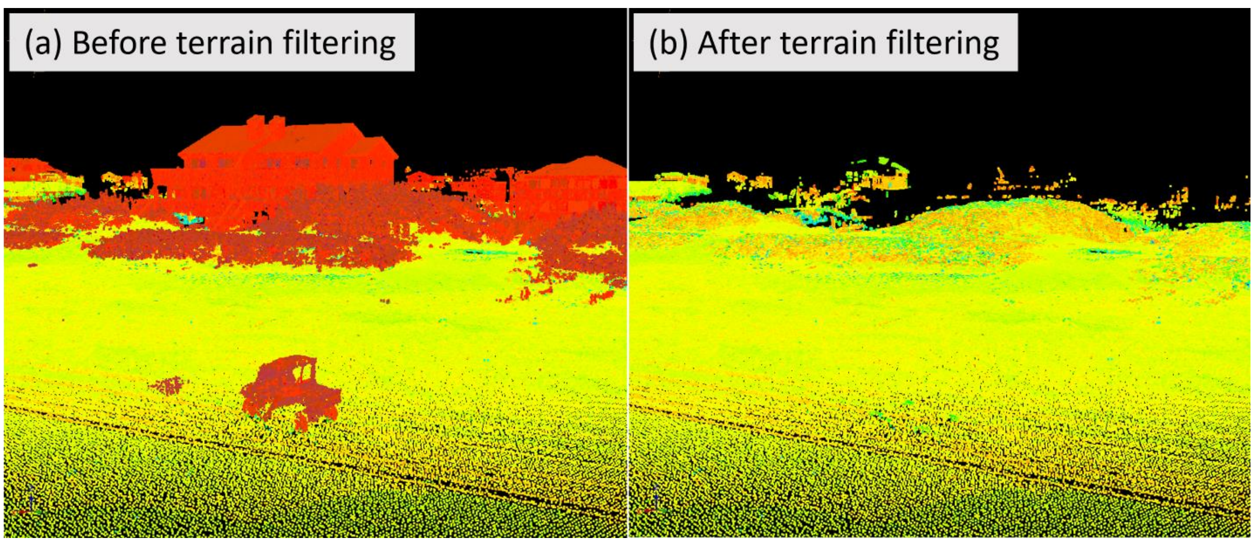

Figure 6 Process of terrain filtering on lidar point cloud. Red color in (a) are none-terrain points including vehicles, chairs, humans, buildings, sand fences, and vegetation. Red of point cloud in (b) are kept for DEM generation.

After pre-processing, high-resolution DEMs will be generated using a nearest-neighbor interpolation method, followed by an anomalous change detection analysis. The integrated RTK-GPS will provide sub-centimeter elevation accuracy of beach topography. Beach profiles, dune volume, toe, ridge, shoreline, and vegetation will be extracted from the DEMs of multiple seasonal acquisitions (Figure 4). Beach and dune profiles will be extracted from DEMs using the command 'grdtrack' in GMT (Generic Mapping Tools), an open-source software of raster image processing tools. Dune and beach volume will be calculated by the GMT command ‘grdvolume’. The volume is the space between the DEM surface and a given contour plan (or zero if not given). Dune ridge and toe lines will be determined using a least cost path (LCP) method, which is a standard GIS technique to find an optimal path between two locations (Hardin et al., 2012, 2014). This method will be implemented in the open-source GRASS software packages. We will combine GMT and GRASS commands in a single shell script (Zhou et al., 2017).

The shoreline, the boundary between wet and dry beach, is generally approximated by the elevation contour of Mean High Water (MHW) (Stockdonf et al., 2002). The MHW relative to NAVD88 is 0.26 m for the coastal zone from Virginia to Cape Lookout (Limber et al., 2005). Here, we use the 0.26 m contour line from lidar DEMs to represent the shoreline in Nags Head. For the vegetation line, we use 4 m contour line (relative to NAVD88) as vegetation line (Brodie et al., 2019). Differences in elevation and foredune volume are determined from repeat acquisitions and grouped into dune restoration categories (e.g., grass plantings, Christmas trees, sand fencing, and absence of protection).

3. **Results**

3.1. Difference of DEMs (DoDs)

The DEMs in December 2022 and March 2023 and the Difference of DEMs (DoDs) at the ten restoration sites are shown in Figure 7 to Figure 24. The coordinates of DEMs at each site was after rotation of 115 degrees in clockwise direction from NAD83/UTM Zone 18N (EPSG: 26918). The height is using vertical datum NAVD88 using the GEOID12B model. Most sand fences are positioned at a 40-degree angle with respect to the shoreline. The length is close to 3 meter and height is 1 m.

For all the 10 sties, we found little sand accretion or erosion for the first 10m width of beach in cross-shore direction staring from the dune toe. However, substantial erosion was observed for the rest of beach on during the 3.5 months period. All sand fences were installed close to dune toe. Generally, we found sand accretion right behind or at the base of sand fences. However, most of the dune crest lost sand during the 3.5 months period.

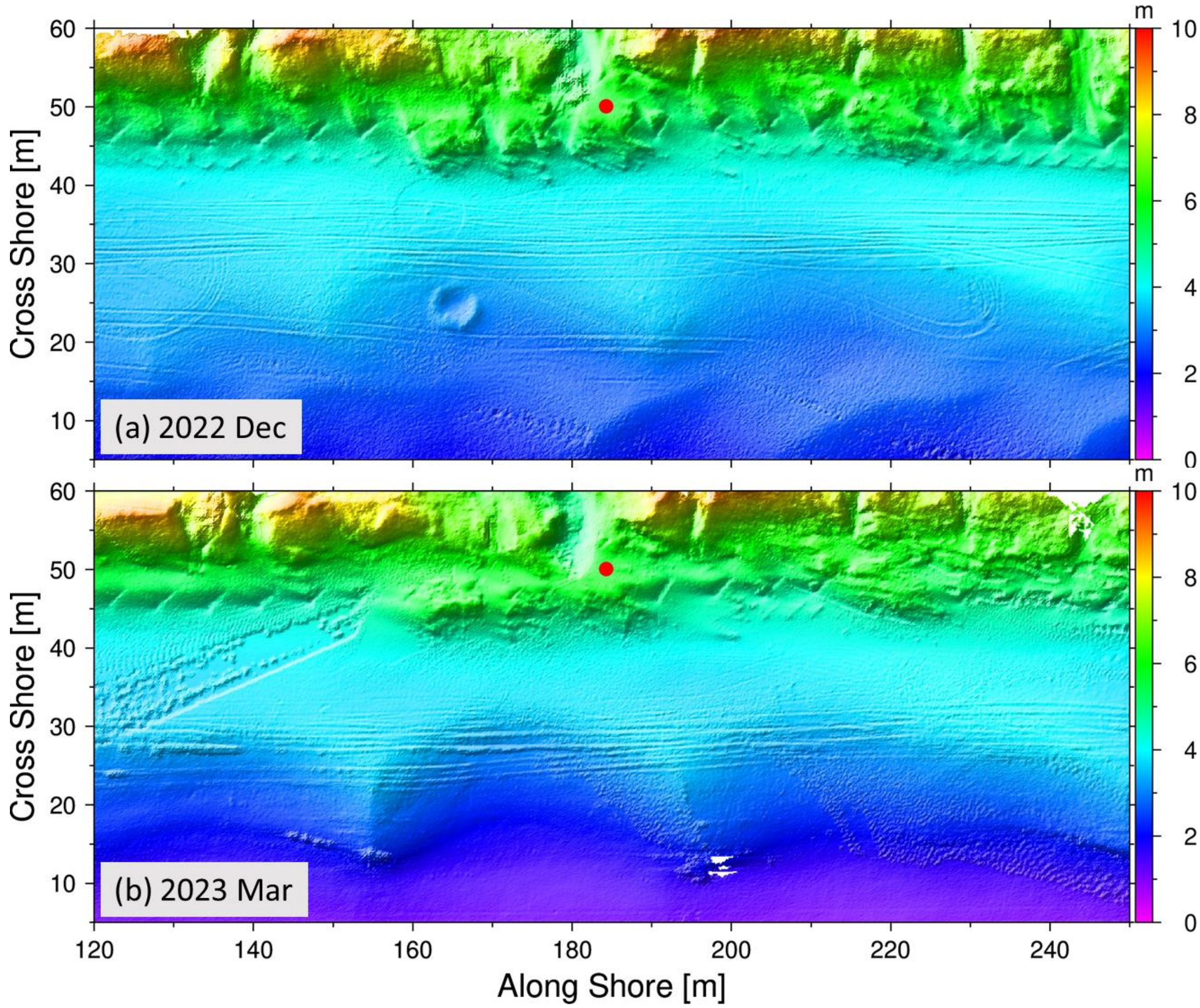

Figure 7 Digital Elevation Models (DEMs) of beach and foredunes at Site 1 (E Hollowell St) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

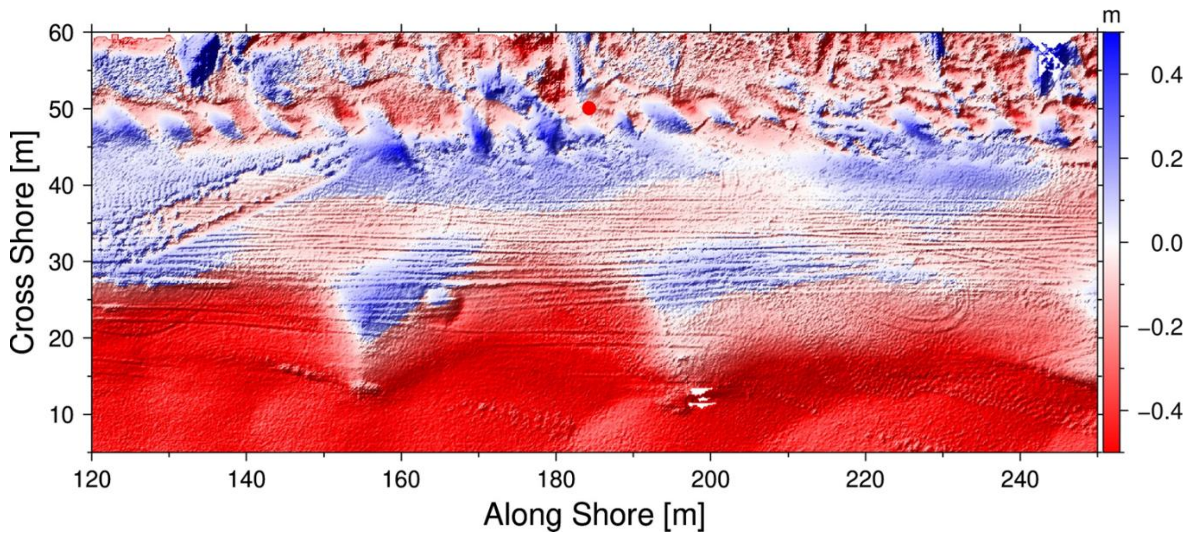

Figure 8 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 1. Blue color shows elevation increase and red color shows elevation decrease.

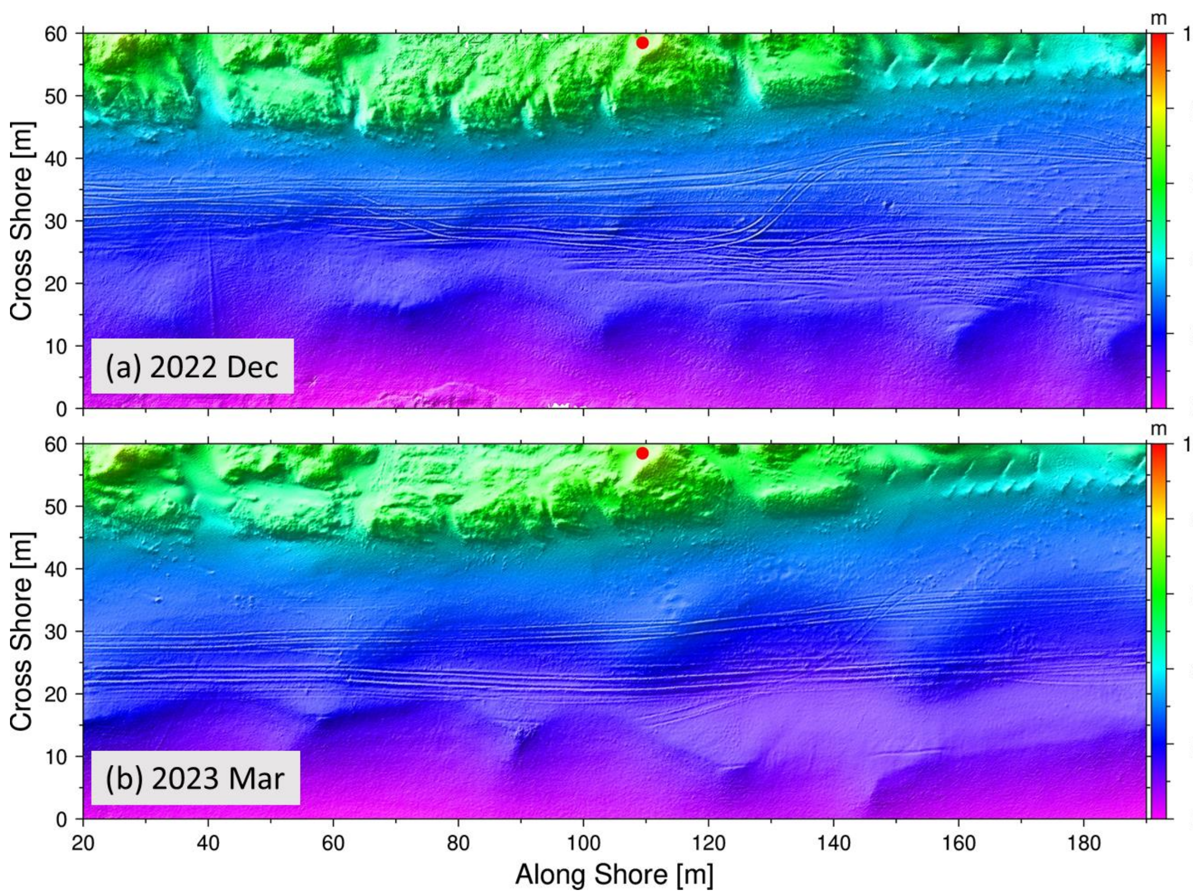

Figure 9 Digital Elevation Models (DEMs) of beach and foredunes at Site 2 (Grouse St) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

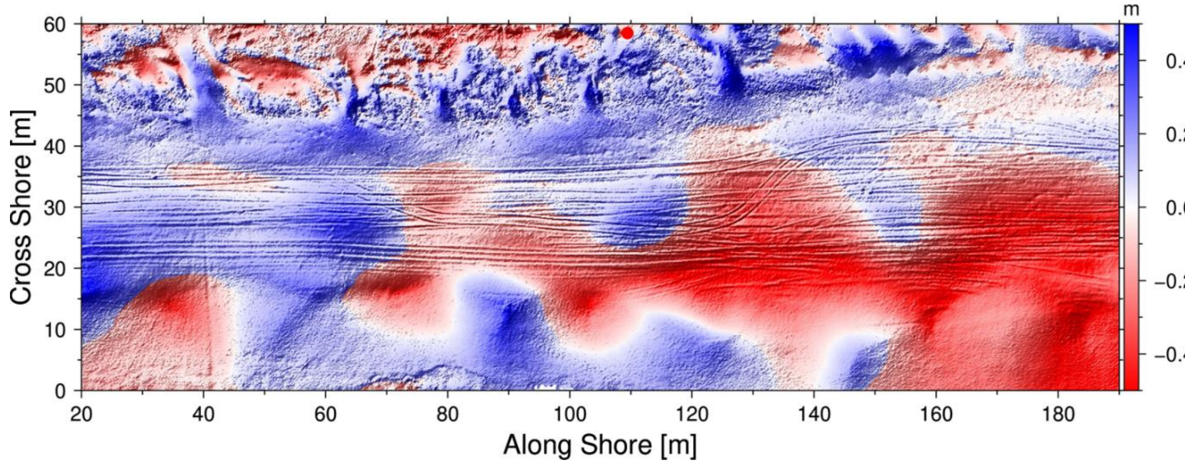

Figure 10 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 2. Blue color shows elevation increase and red color shows elevation decrease.

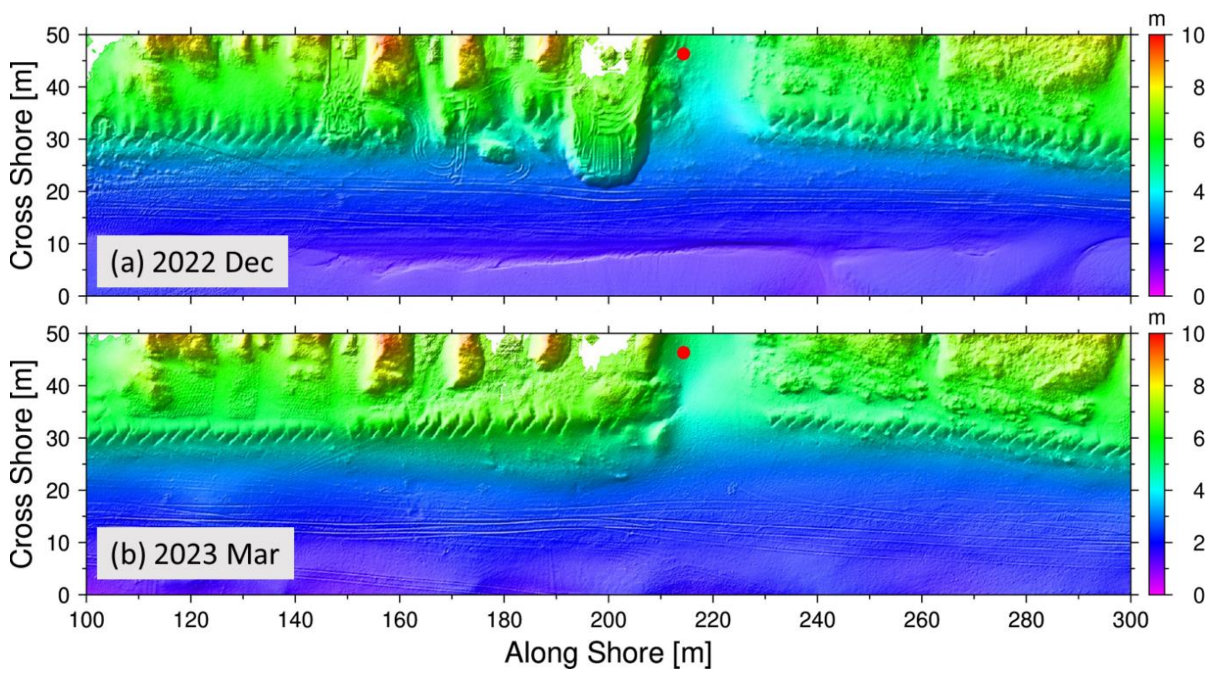

Figure 11 Digital Elevation Models (DEMs) of beach and foredunes at Site 3 (E Hardgrove St) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

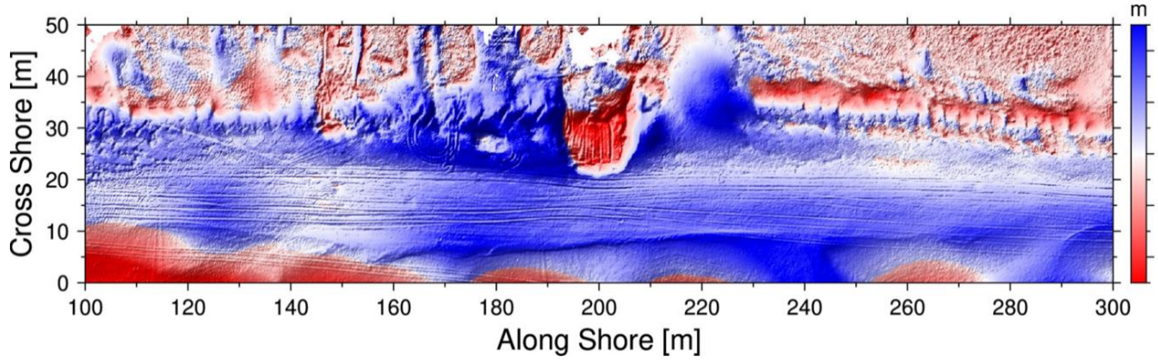

Figure 12 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 3. Blue color shows elevation increase and red color shows elevation decrease.

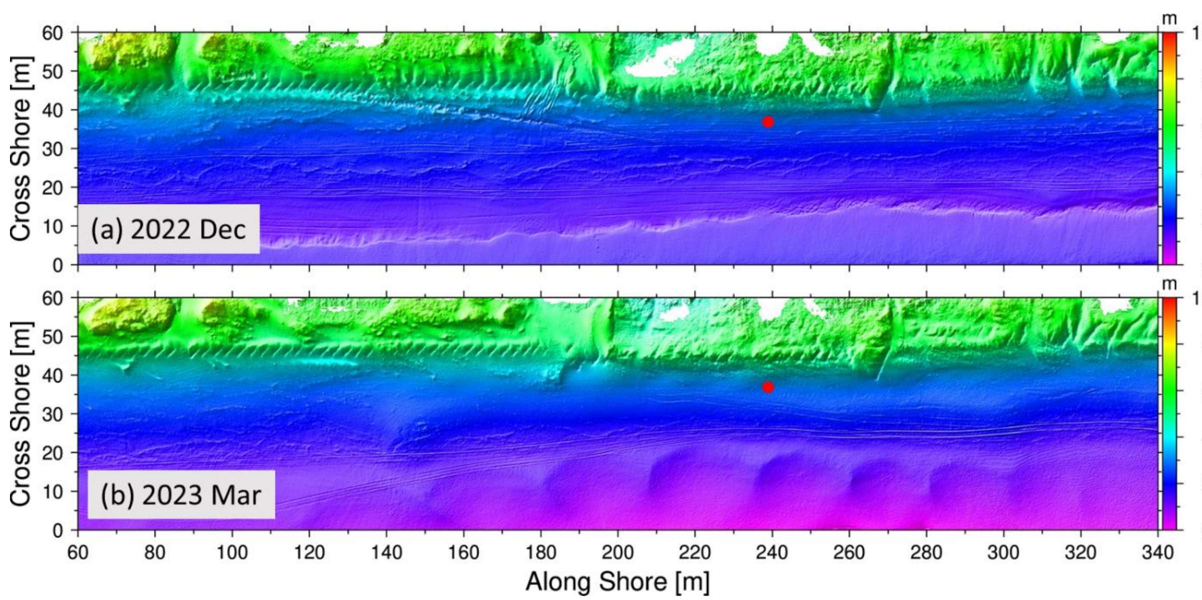

Figure 13 Digital Elevation Models (DEMs) of beach and foredunes at Site 4 (E Tides Dr) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

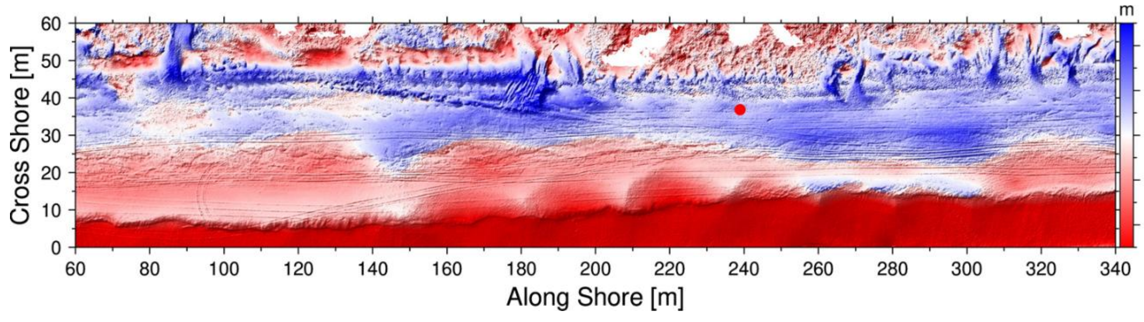

Figure 14 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 4. Blue color shows elevation increase and red color shows elevation decrease.

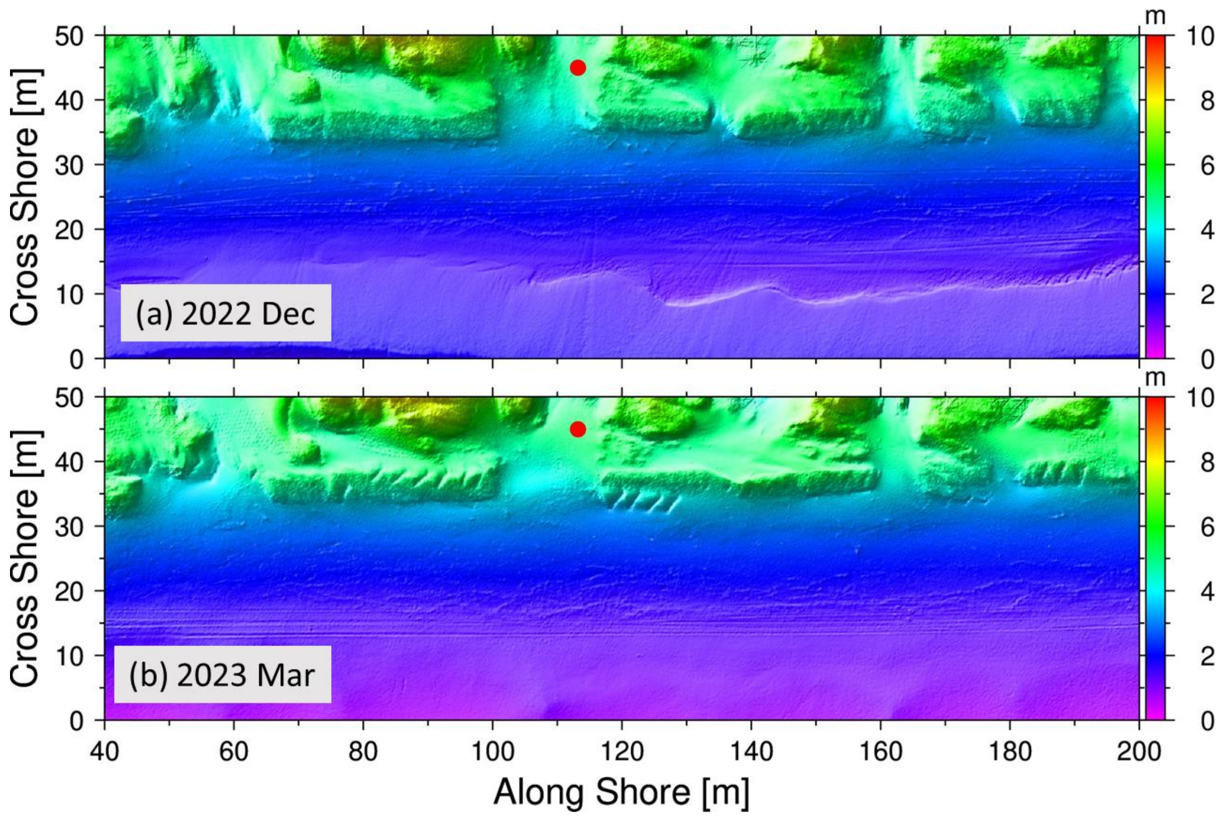

Figure 15 Digital Elevation Models (DEMs) of beach and foredunes at Site 5 (E June St) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

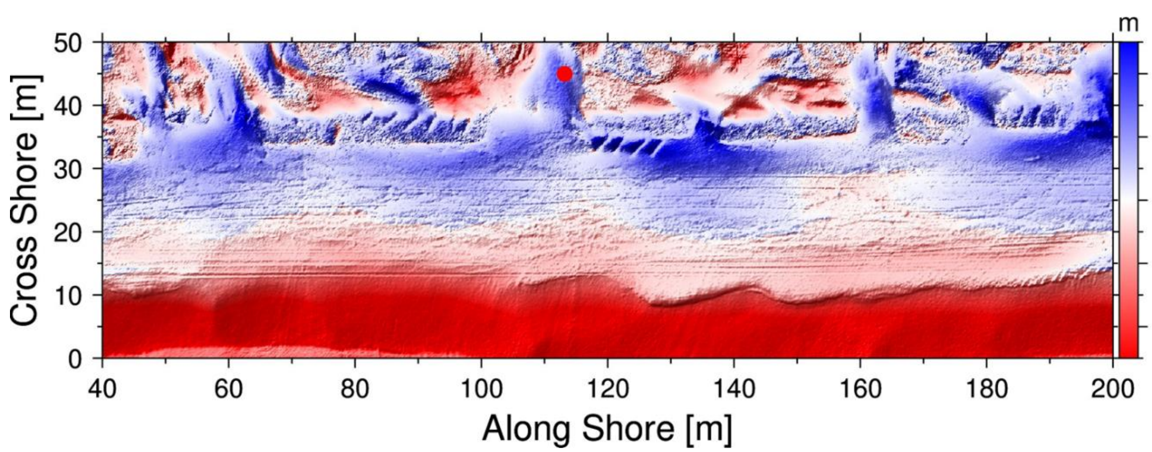

Figure 16 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 5. Blue color shows elevation increase and red color shows elevation decrease.

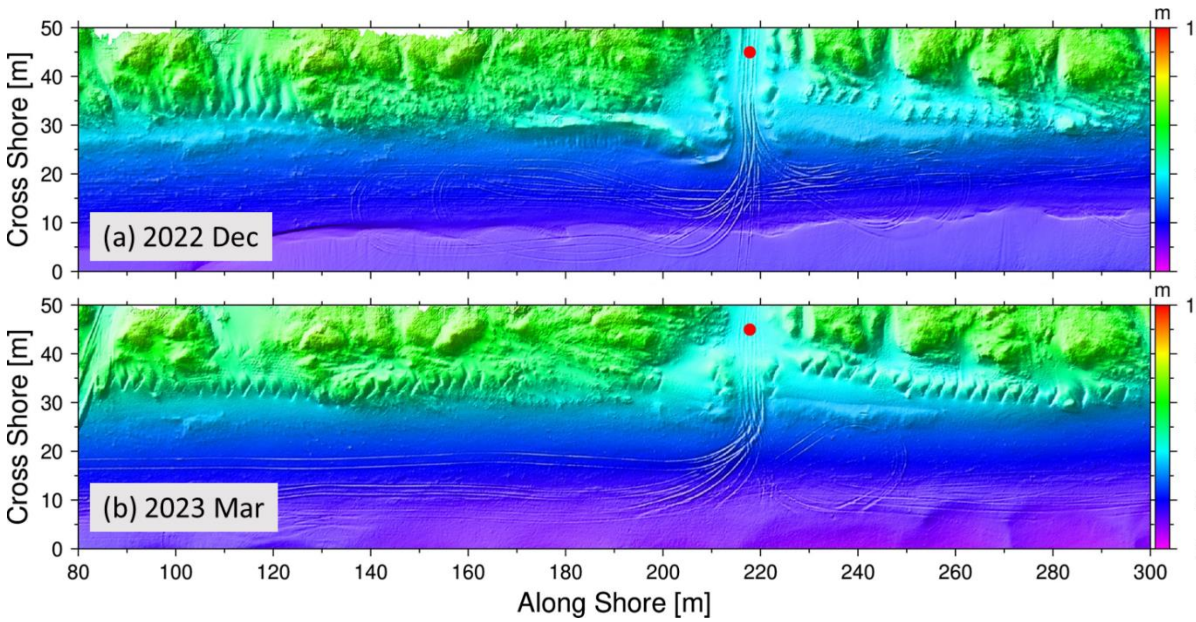

Figure 17 Digital Elevation Models (DEMs) of beach and foredunes at Site 6 (Juncos St) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

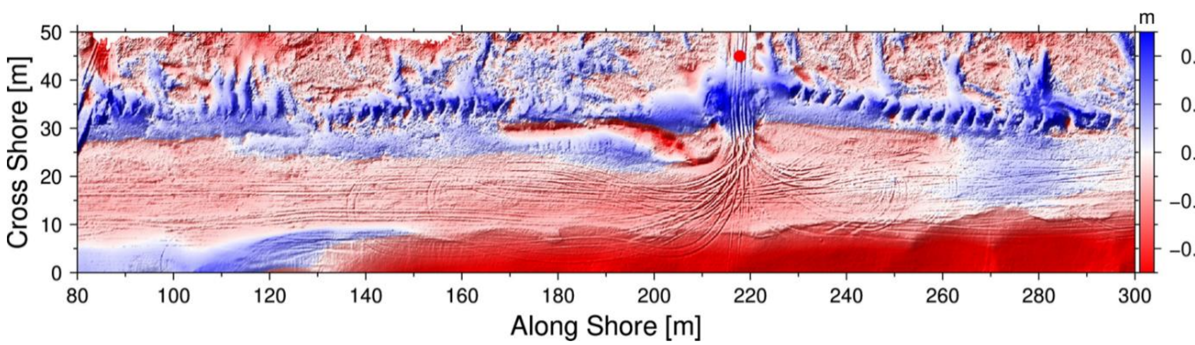

Figure 18 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 6. Blue color shows elevation increase and red color shows elevation decrease.

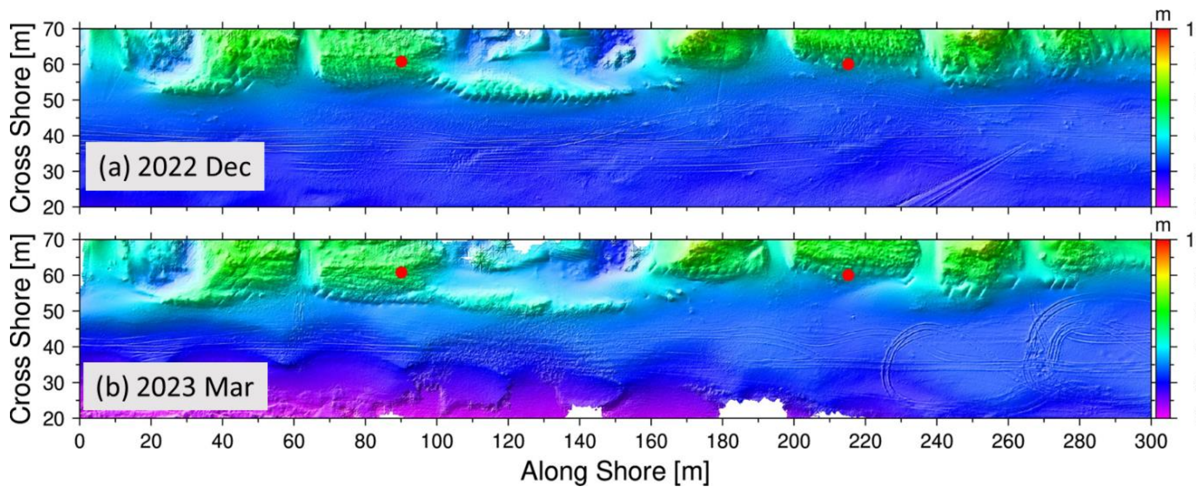

Figure 19 Digital Elevation Models (DEMs) of beach and foredunes at Site 7 and 8 (E Pelican St and E Proteus Ct) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

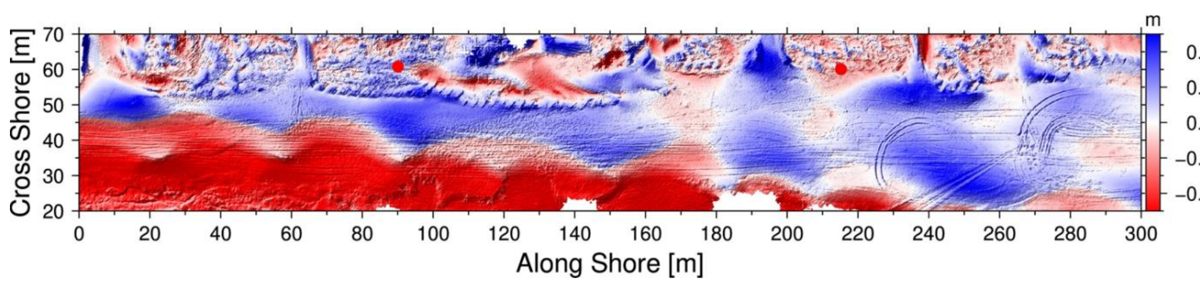

Figure 20 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 7 and 8. Blue color shows elevation increase and red color shows elevation decrease.

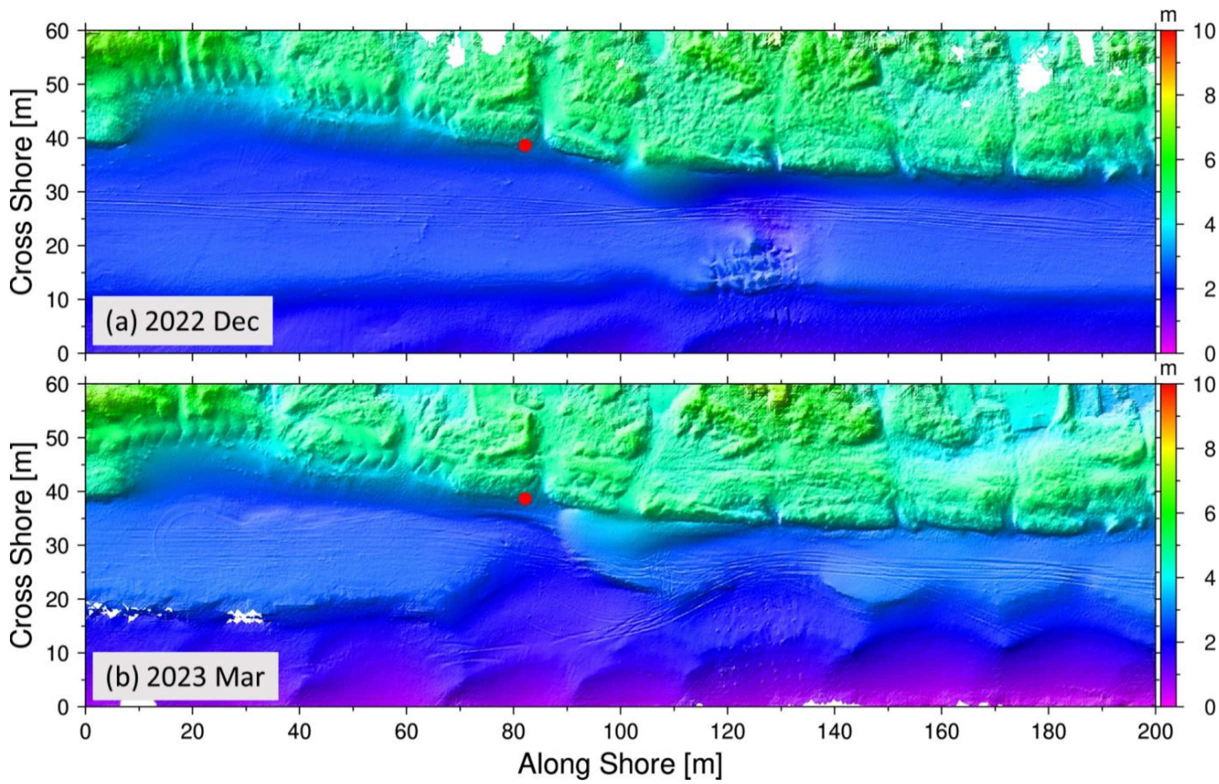

Figure 21 Digital Elevation Models (DEMs) of beach and foredunes at Site 9 (E Seagull Dr) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

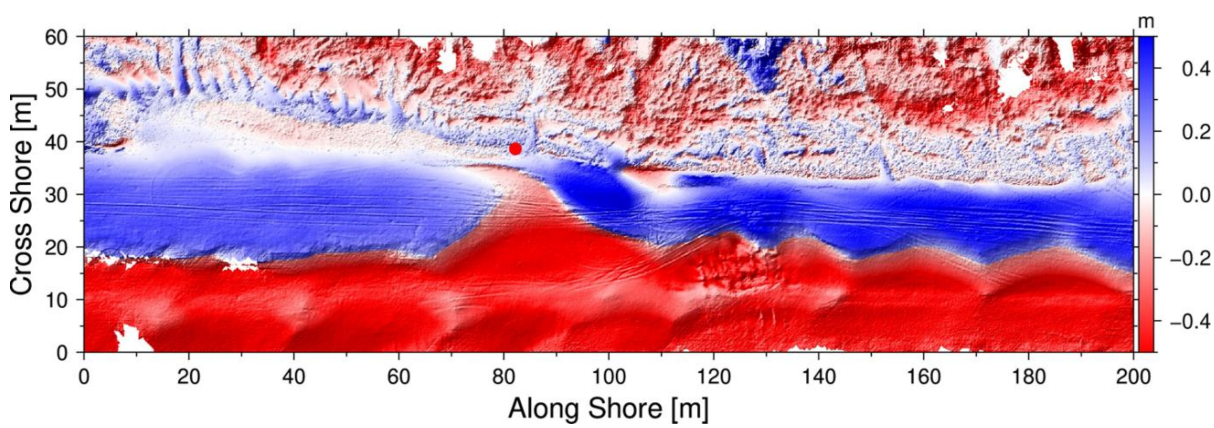

Figure 22 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 9. Blue color shows elevation increase and red color shows elevation decrease.

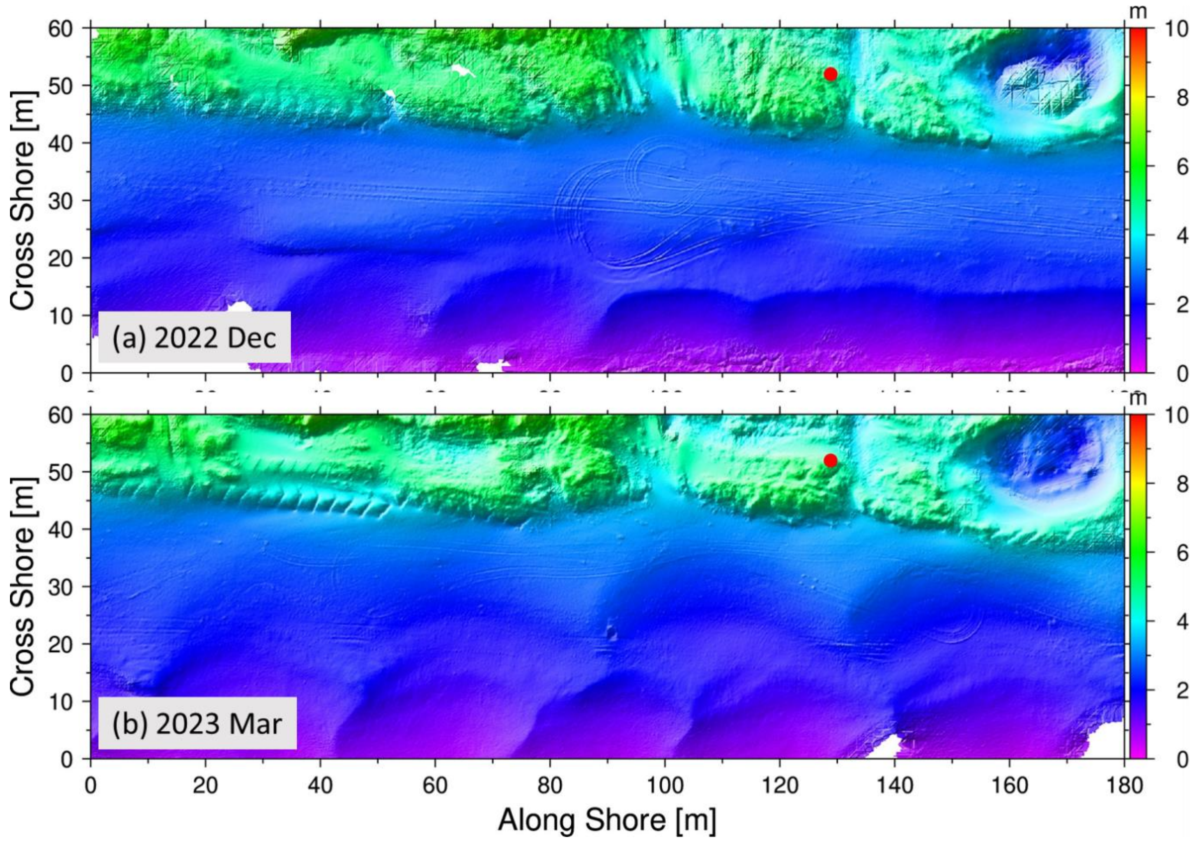

Figure 23 Digital Elevation Models (DEMs) of beach and foredunes at Site 10 (10333A S Old Oregon Inlet Rd) in December 2022 (a) and March 2023 (b). Red circle is approximate location with grass planting. The grid size of DEM is 10cm by 10cm.

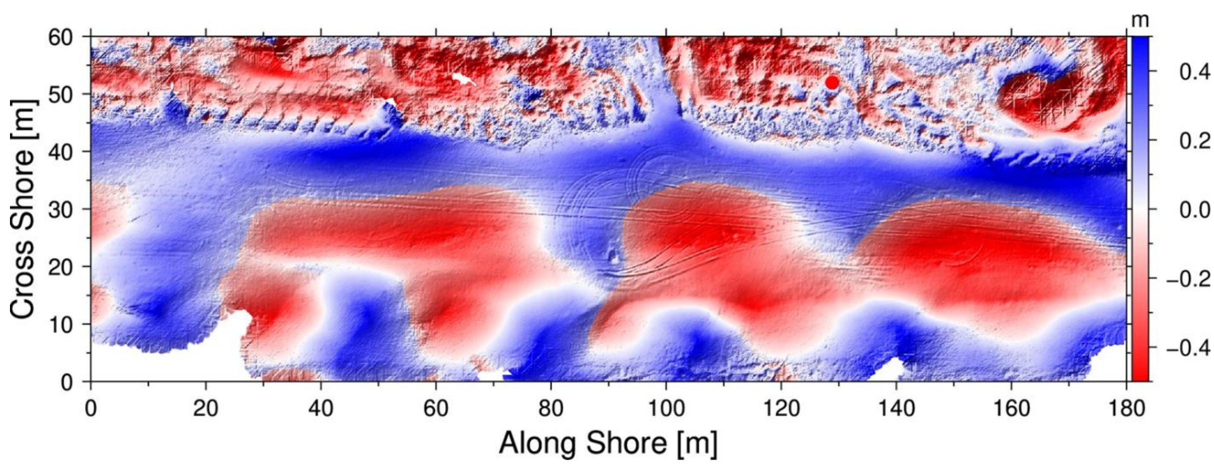

Figure 24 Difference of DEMs (DoDs) between December 2022 and March 2023 for Site 10. Blue color shows elevation increase and red color shows elevation decrease.

3.2. Beach and foredune profile changes

Beach and foredune profiles are extracted from the high resolution DEMs (10cm by 10cm) across the 10 sites in both December 2022 and March 2023 (Figure 25 to Figure 33). Most dune crest is about 6m among the 10 sites. Only two profiles at Site 1 show the dune crest can reach to 8m (Figure 25a and c). Most profiles show the dune toe is about 4 m relative to NAVD88.

About the first 30m in cross-shore direction, we found sand erosion and maximum elevation decrease is not more than 1m. From Y=30m to the dune toe (about Y=40m), the elevation change is usually positive and small. A few profiles show elevation increased about half meter (Site 9, Figure 32c and d). From the dune toe to dune crest, the similar pattern of no or small positive change is also observed. We noted that in Site 3 (Figure 27(b)), the elevation increased about 2m at Y=35m. The large change is not liked caused by natural wind or waves.

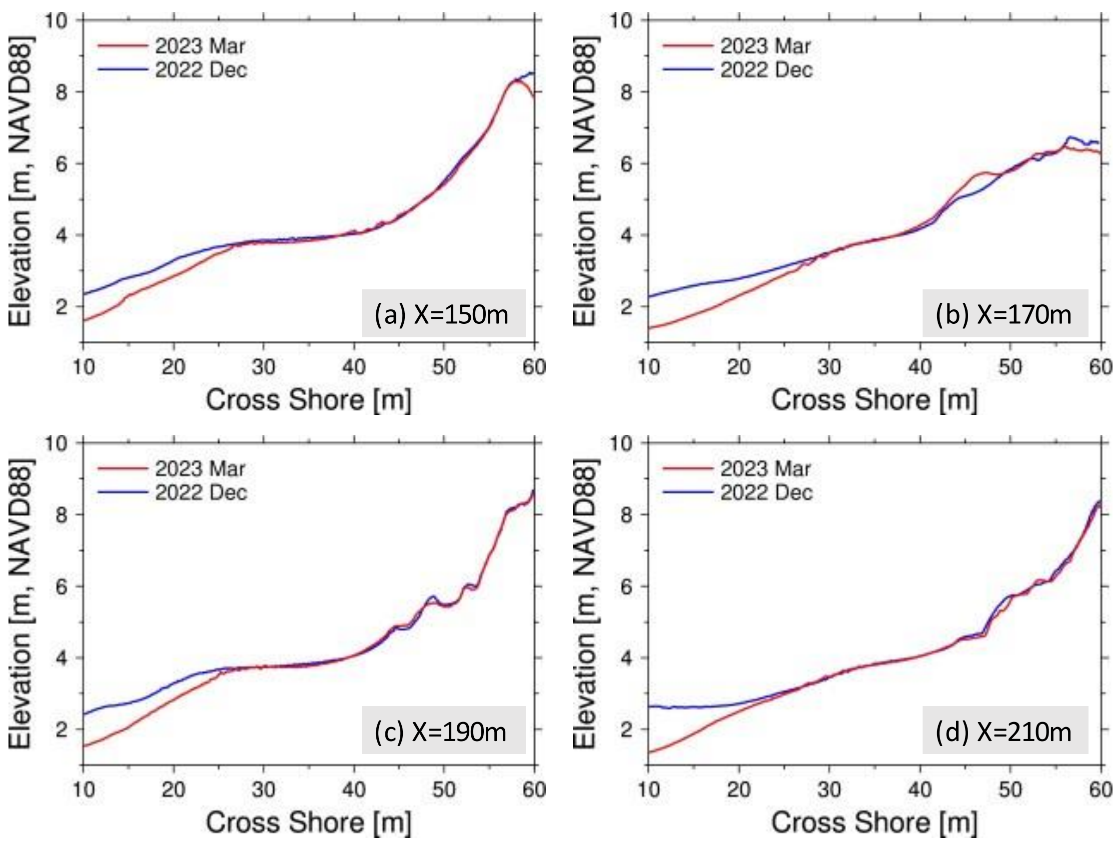

Figure 25 Beach and foredune profiles in December 2022 and March 2023 at Site 1.

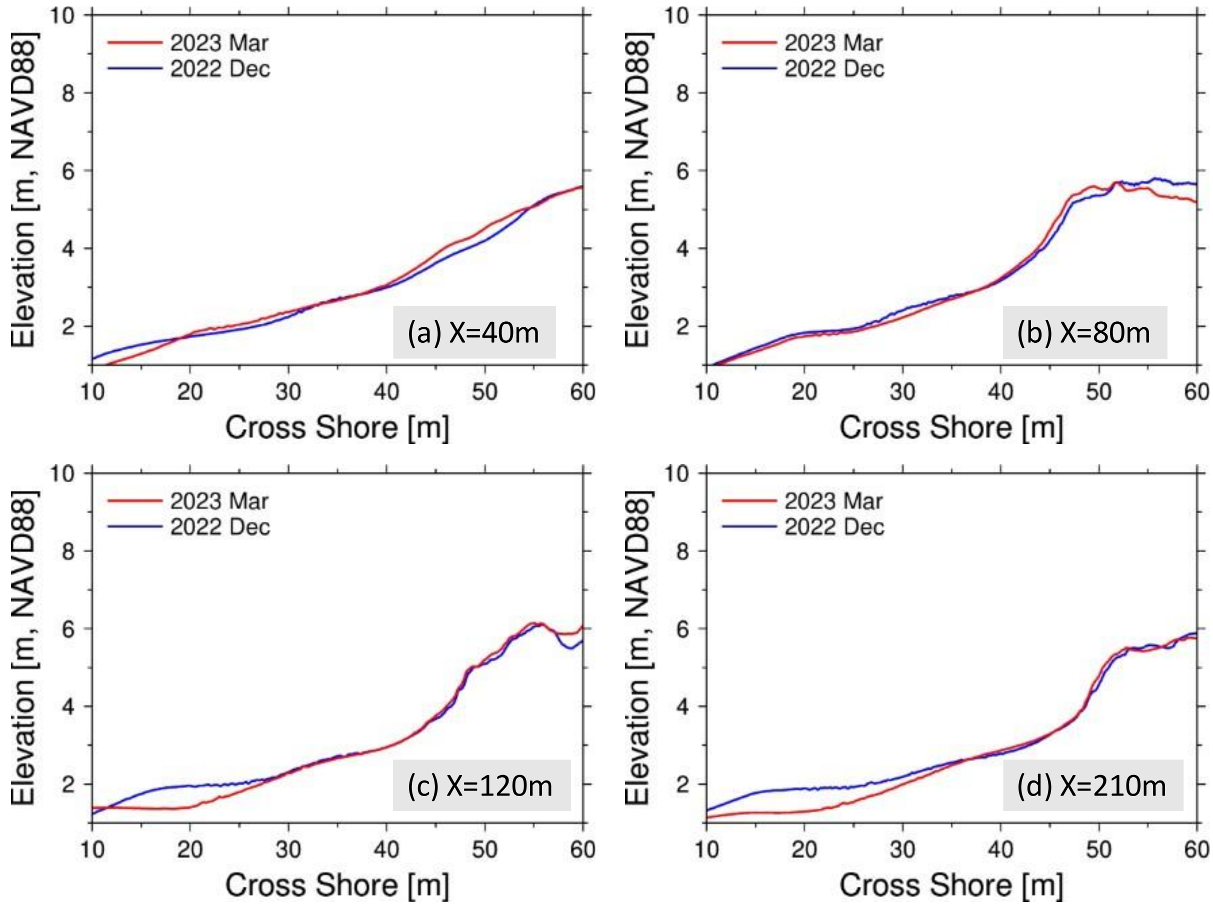

Figure 26 Beach and foredune profiles in December 2022 and March 2023 at Site 2.

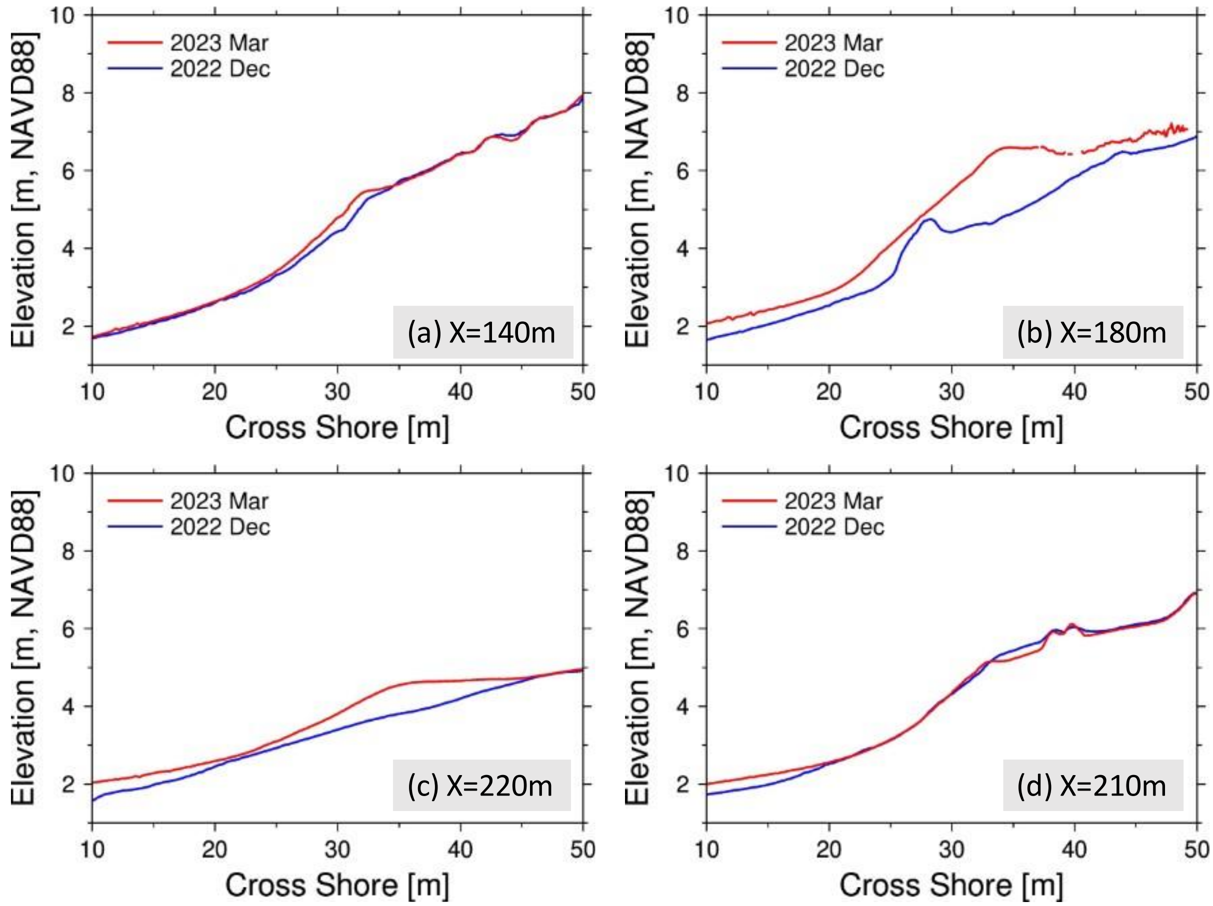

Figure 27 Beach and foredune profiles in December 2022 and March 2023 at Site 3.

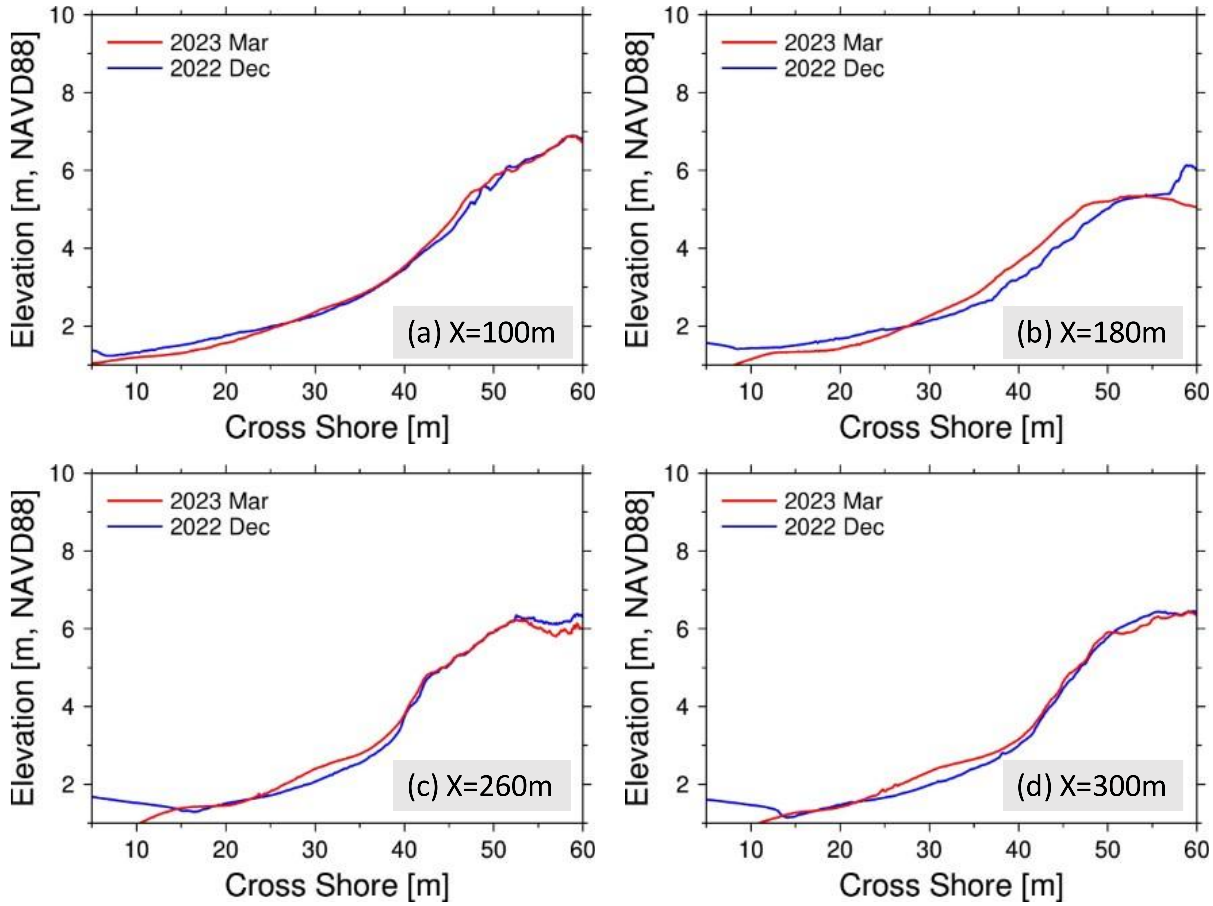

Figure 28 Beach and foredune profiles in December 2022 and March 2023 at Site 4.

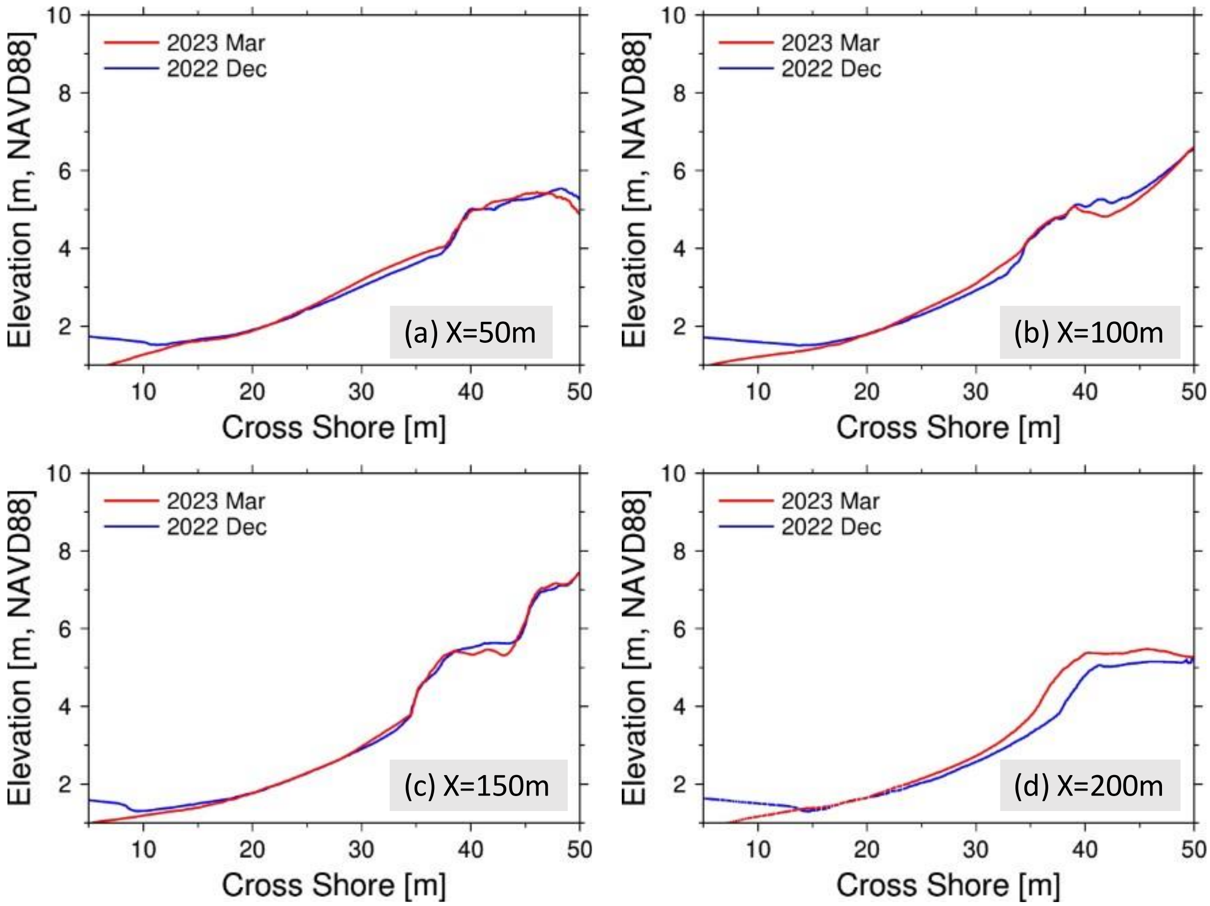

Figure 29 Beach and foredune profiles in December 2022 and March 2023 at Site 5.

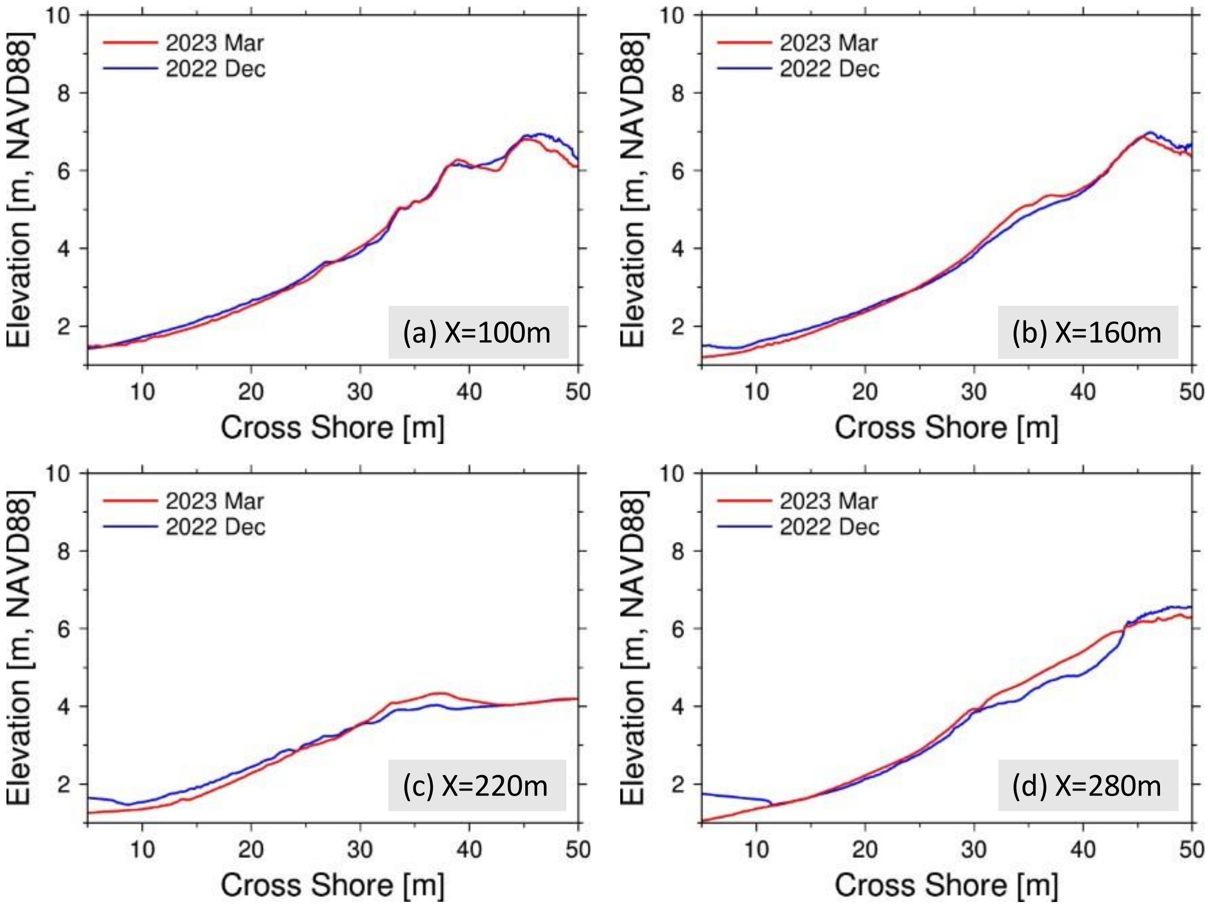

Figure 30 Beach and foredune profiles in December 2022 and March 2023 at Site 6.

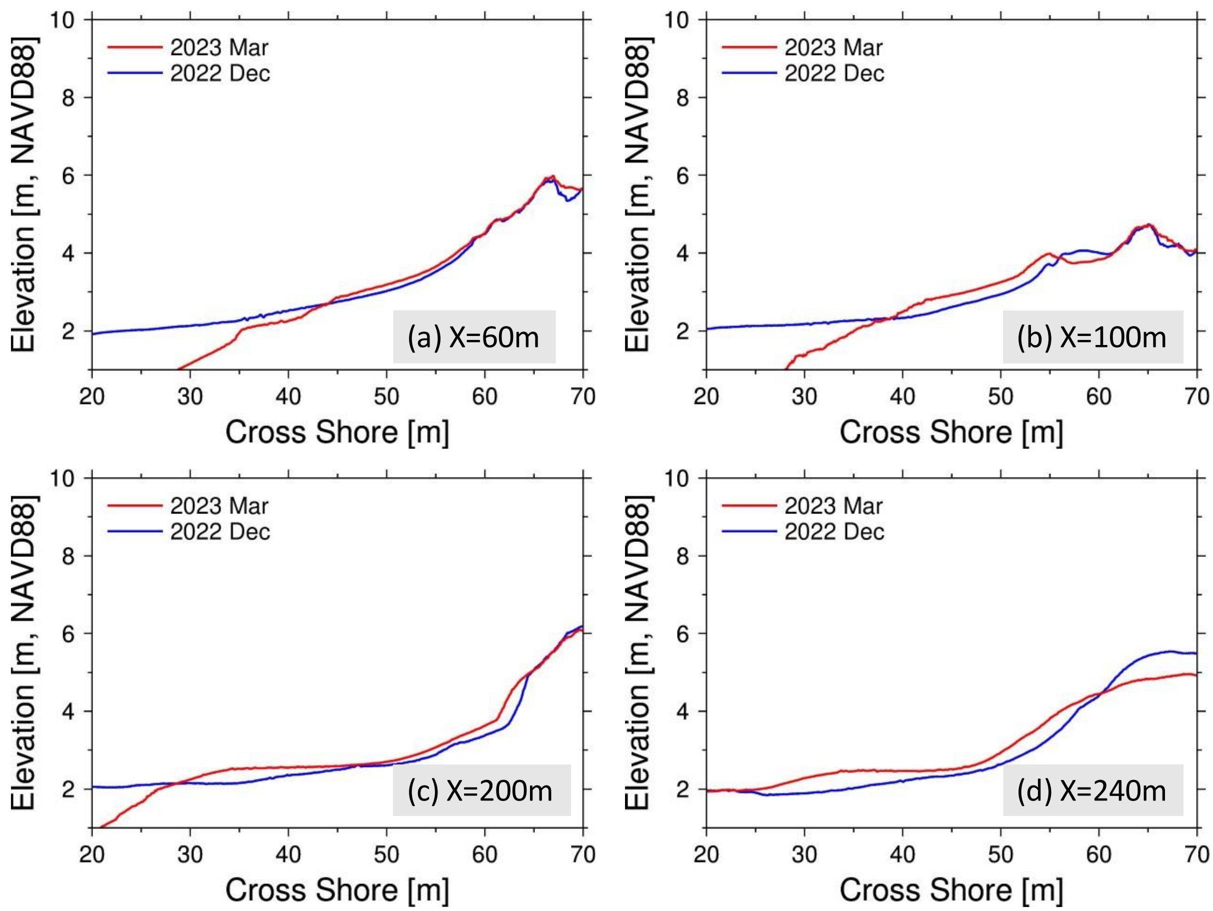

Figure 31 Beach and foredune profiles in December 2022 and March 2023 at Site 7 and 8.

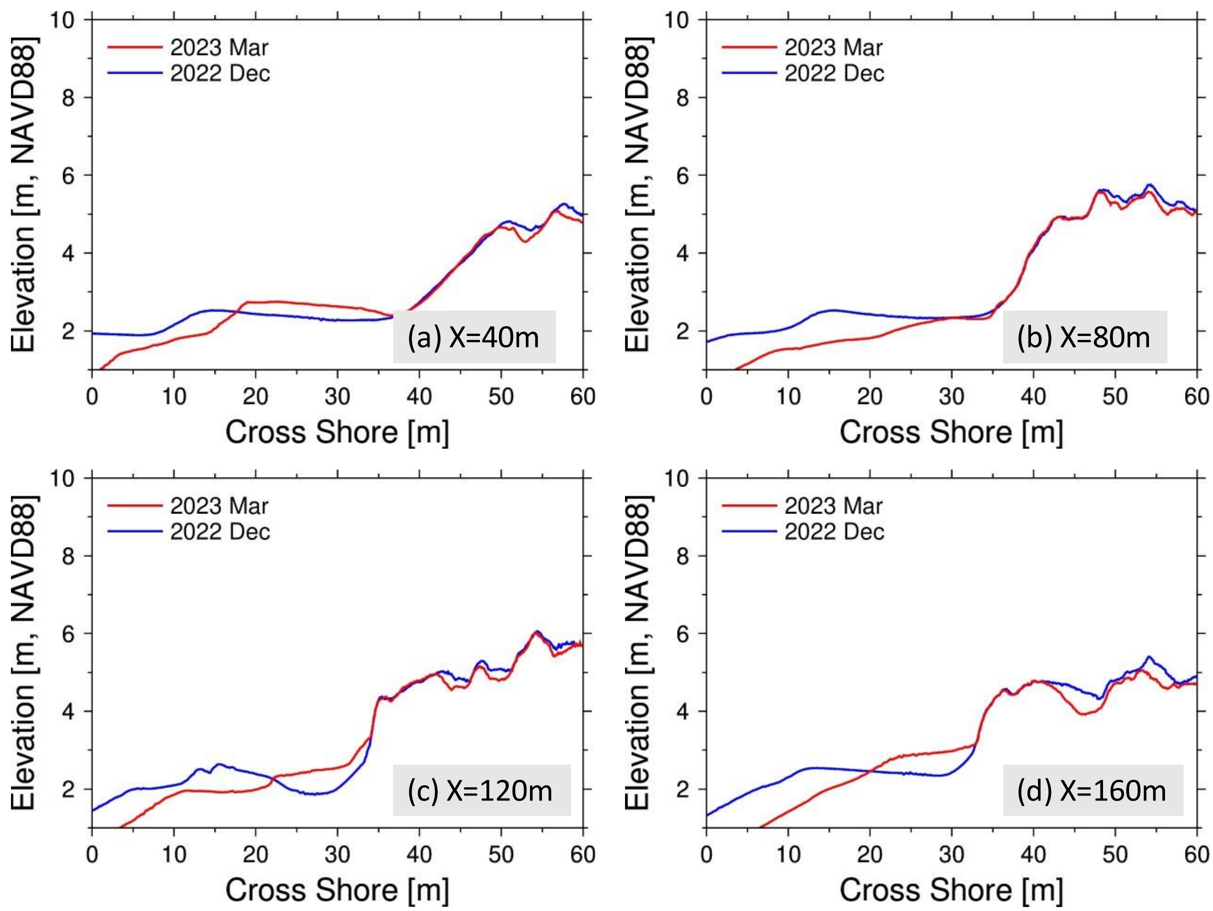

Figure 32 Beach and foredune profiles in December 2022 and March 2023 at Site 9.

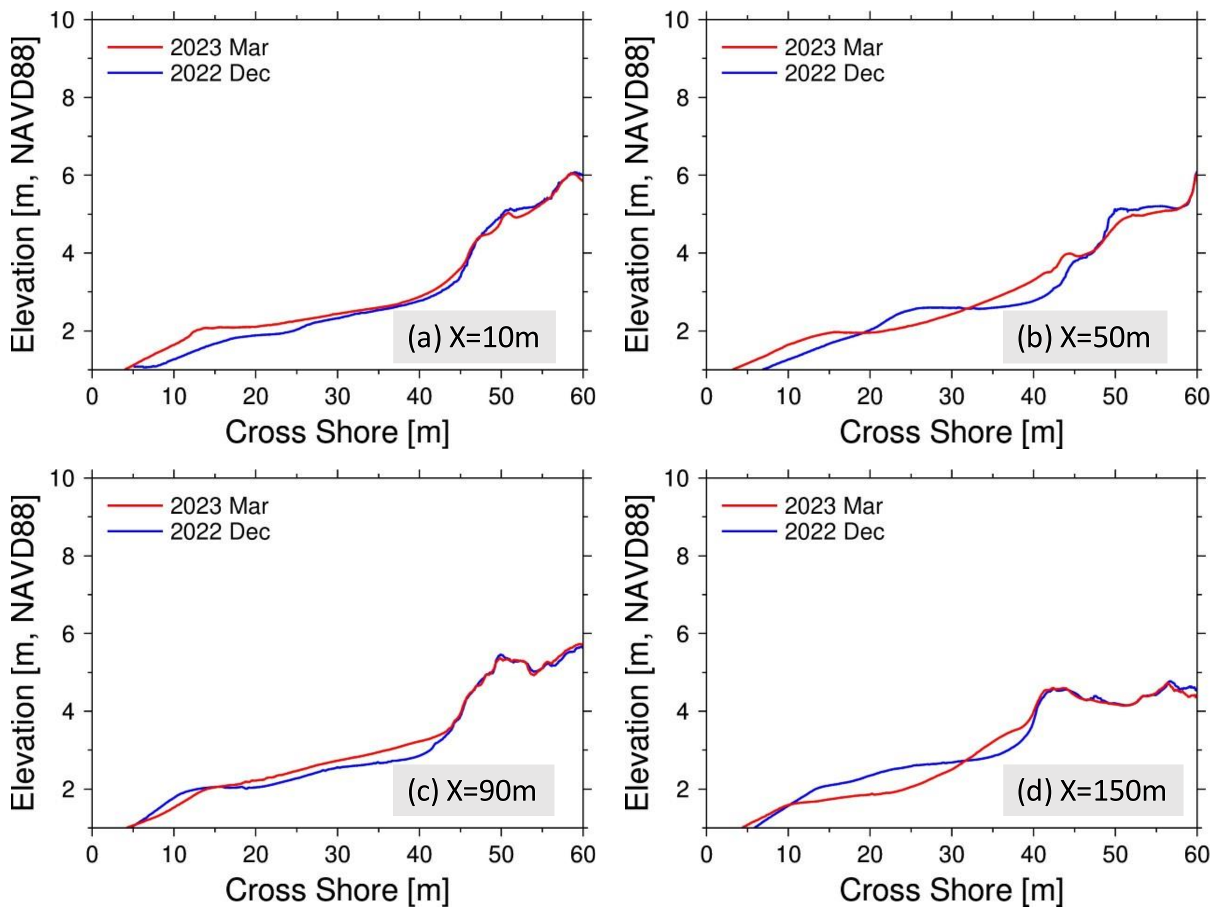

Figure 33 Beach and foredune profiles in December 2022 and March 2023 at Site 10.

3.3. Foredune volume changes

The foredune volume is calculated from dune toe to the dune. We use 4m contour line relative to NAVD88 in Nags Head (Brodie et al., 2019). The foredune experienced a small amount of sand loss equivalent to 0.54% at Site 1. From Site 2 to Site 8, the foredunes gained sand from a percentage of 1.85% to 4.49%. However, at Site 9 and Site 10, the volume of foredunes decreased significantly with a value of -12.51% and -15.41%.

Table 2 Foredune volume changes from December 2022 to March 2023

Site	Average Height in March 2022 (m)	Volume in December 2022 (m^3)	Average Height in March 2023 (m)	Volume in March 2023 (m^3)	Change (m^3)	Percent Change (%)
1	5.65	4539.84	5.62	4515.35	-24.49	-0.54
2	5.28	2668.10	5.52	2787.92	119.82	4.49
3	5.94	8267.36	6.21	8636.37	369.01	4.46
4	5.53	6981.53	5.66	7148.85	167.32	2.40

5	5.23	2839.91	5.45	2960.78	120.87	4.26
6	5.37	5323.54	5.56	5508.20	184.66	3.47
7 and 8	5.10	2979.95	5.19	3035.10	55.15	1.85
9	4.96	3847.33	4.34	3366.26	-481.07	-12.50
10	4.94	2328.45	4.18	1969.55	-358.90	-15.41

4. Discussion

In this project, we conducted repeat hyper-resolution topographic surveys using our Coastal Laser Scanner at planted and non-planted beachfront dunes to assess the effectiveness of the stabilization activities. We found that among the 10 sites, 7 of them gained sand in terms of foredune volume changes after 3.5 months. Site 1 (E Hollowell St) remained relative stable. The last two sites (E Seagull Dr and 10333A S Old Oregon Inlet Rd), which are close to the southern end of Nags Head, experience significant erosion (>12%). The lower elevation of dunes at these two sites may be the reason for the erosion.

We found all dune restoration sites were installed with sand fences (Figure 34). The mixed effects of sand fencing and grass planting lead to the sand accretion of foredunes. The DoDs of all 10 sites show the sand deposition areas are behind or around sand fences during the 3.5 months. Sand fences seems to have a more pronounced impact on short-term sand movement. Future research should prioritize long-term monitoring to explore the relationship between grass growth and sand accumulation, providing deeper insights into the vegetation's capacity to stabilize sand over time.

Our project has quantified the changes in dune topography in and around 10 beach planting sites in December 2022 and March 2023. The result can help organizations and coastal managers understand how dune restoration allows sandy beaches to adapt to sea level rise. While the foredunes remain relatively stable across most sites, erosion is consistently observed in the dune crest areas. We propose that future beach planting efforts should focus more on the dune crest to address this issue.

Figure 34 (a) Sand fences and beach grass on the dunes. (b) Sand fences and Christmas trees on the dunes

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6. Outreach

(1) We held a discussion meeting with the engineers from Town of Nags Head and the manager of BBOBX.
(2) The final report will be presented to the Town of Nags Head and BBOBX.
(3) We talked about the purpose of this project to many local residents during the field work.

7. Students supported

We trained a PhD student and two research technician for the lidar data collection and processing.

8. News/Media coverage of this project

Our work is reported by the local media – CURRENT TV. The details are in this webpage (https://currenttv.org/show/csi-assesing-the-impacts-of-dune-restoration/).

9. **Data Management Plan Progress**

(1) All the point cloud data is in las format. The horizontal datum will use NAD83 / UTM zone 18N (EPSG: 26918). The vertical datum is North American Vertical Datum of 1988 (NAVD 88) using GEOID18. The point cloud data will include 3D coordinates and intensity as well.

(2) All the DEMs are generated at a 10cm resolution.

(3) The processing code is open to public in github (https://github.com/linxiongecu/nags_head)

(4) The raw LAS point cloud data will be available to public upon request starting in November 2023. Contact the PI for more information or to make a data request.

(5) Data is archived and processed in Coasts and Oceans Observing Laboratory at CSI and will be managed following FAIR (Findable, Accessible, Interoperable, and Reusable) principles.