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Multi-decadal coastal evolution of a North Atlantic shelf-edge vegetated sand island – Sable Island, Canada

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Complete List of Authors:	Eamer, Jordan; Geological Survey of Canada Didier, David; Université du Québec à Rimouski, Géographie; Geological Survey of Canada Kehler, Dan; Parks Canada Sable Island National Park Reserve Manning, Ian; Nova Scotia Community College Colville, David; Nova Scotia Community College Manson, Gavin; Geological Survey of Canada Atlantic; Saint Mary's University Jagot, Alexandre; Geological Survey of Canada; Dalhousie University Kostylev, Vladimir; Geological Survey of Canada
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4 **Multi-decadal coastal evolution of a North Atlantic shelf-edge vegetated**
5 **sand island – Sable Island, Canada**

6 Jordan B.R. Eamer^{1,2*}, David Didier^{1,3}, Dan Kehler⁴, Ian Manning⁵, David Colville⁵, Gavin
7 Manson^{1,6}, Alexandre Jagot^{1,7}, Vladimir E. Kostylev¹,

8 1. Geological Survey of Canada – Atlantic, Dartmouth, Nova Scotia, Canada

9 2. Sable Island Institute, Halifax, Nova Scotia, Canada

10 3. Université du Québec à Rimouski, Rimouski, Québec, Canada

11 4. Parks Canada, Sable Island National Park Reserve, Halifax, Nova Scotia, Canada

12 5. Centre of Geographic Sciences, Nova Scotia Community College, Lawrencetown, Nova
13 Scotia, Canada

14 6. Saint Mary’s University, Halifax, Nova Scotia, Canada

15 7. Dalhousie University, Halifax, Nova Scotia, Canada

16 * Corresponding author: jordan.eamer@canada.ca

Abstract

Impacts from a changing climate, in particular sea-level rise, will be most acutely felt on small oceanic islands. A common configuration of mid-latitude islands is the sandy barrier island. Sable Island, Nova Scotia, Canada is a vegetated sand island near the shelf edge, 160 km from the nearest point of land, that is morphologically similar to a barrier island. This study uses 60 years of airphoto records to analyse changes in coastline position through digitized shore and vegetation (foredune proxy) lines. Rates of coastal movement are analysed to model the future (2039) coastal configuration. The analyses suggest that the majority of the coastline on Sable Island is in retreat, with net retreat on the south side of the island only partially offset by modest net advance on the north side. The different morphologies of the beach-dune systems of South and North Beach, driven by incident wind and waves, yield these different coastline responses. Projected loss of 10 ha by 2039 of the climax heath vegetative community to shoreline retreat suggests a trend toward island instability due to coastline migration. Island-wide dataset trends show support for two different but complementary hypotheses about whole-island evolution: either the island is mobile via bank migration driving southern coastline changes and experiencing sediment transport toward the east, or the island is generally immobile and losing subaerial sediments (and thus shrinking) likely due to ongoing (and accelerating) sea-level rise.

Keywords:

Coastal change; coastal erosion; small island geomorphology; Sable Island; sea-level rise

37 Introduction

38 Small oceanic islands are important scaled-down indicators of coastal change driven by changing
39 ocean dynamics. In particular, sea-level rise (SLR), projected globally to be between 0.26 and
40 0.77 m by 2100 (1.5C of warming; IPCC (2018)) may pose a suite of risks for small islands
41 which may be too small and/or low to adapt. A broad range of geological configurations for
42 small islands exist, and each may react to changes in sea level through different mechanisms.
43 Common examples include coral atoll islands (e.g., Perry et al. 2015; Shope et al. 2017;
44 Masselink et al. 2020), bedrock islands (e.g., Hein et al. 2016; Cooper et al. 2019; Dickinson
45 2000), and sandy barrier islands. The latter are typically low elevation and morphodynamically
46 active (when not anchored by urbanization), and thus are paradoxically both vulnerable to rapid
47 changes in sea level and high-water events as well as uniquely suited to respond via changes in
48 shape, elevation, and shore-normal migration. With adequate sediment supply and
49 accommodation room, barrier islands can persist through large changes in sea level over
50 thousands of years (Raff et al. 2018). However, this dynamic stability can be influenced by a
51 broad range of factors, including geologic (e.g., underlying bedrock geology, foredune
52 connectivity, and surrounding substrate), ecologic (e.g., vegetation assemblage and backbarrier
53 marsh/island interaction), climatic/oceanographic (e.g., tidal range and inlet configuration,
54 storms, and SLR), and anthropogenic (e.g., urbanization and dredging)(Moore et al. 2014;
55 Walters et al. 2014; Vinent and Moore 2015; Fruergaard and Kroon 2016; Miselis and Lorenzo-
56 Trueba 2017; Houser et al. 2018; Shim and Kim 2018; Wernette et al. 2018; Zinnert et al. 2018;
57 Nienhuis and Lorenzo-Trueba 2019).

58 Sable Island, Nova Scotia is a narrow, elongate island no higher than 32 m above sea
59 level. It is located near the edge of the continental shelf (160 km from the nearest coast and 40
60 km from the shelf break, Figure 1), and is entirely composed of sand. This unique setting and
61 geology provides a novel study site for investigating the recent historical evolution of its
62 shoreline in the face of a changing climate. The entire island is a Canadian National Park
63 Reserve, and as such managed via the Canada National Parks Act (S.C. 2000, c. 32). The island
64 is the subaerial part of Sable Island Bank and is roughly 40 km long (east-west) and at most 1.5
65 km wide (north-south), with a distinct concave shape toward the north. It is composed of
66 reworked sands that were originally predominantly glaciogenic or glaciofluvial in origin. Since

the arrival of Europeans on Sable Island hundreds of years ago, its evolution and fate has been the subject of speculation and study. Generally, three main hypotheses on the evolution of the island have emerged:

- Hypothesis 1 – the island is migrating eastward and maintaining its present area and sand volume (James and Stanley 1967; Amos and Nadeau 1988; Amos and Judge 1991);
- Hypothesis 2 – the island is migrating eastward with net sediment volume losses into the Gully (a large shelf-edge canyon, see Cameron et al. (2008)) and off the shelf (e.g., Cameron 1965; Stanley et al. 1973); and
- Hypothesis 3 – the island is not migrating and there is ongoing areal loss due to SLR and inundation (e.g., McCann and Byrne 1994).

Given the unique geography of Sable Island, its small size and low elevation, and different interpretations of the evolution of the island in the published literature, an opportunity exists to investigate coastline evolution for this dynamic, small, sand island experiencing open-ocean conditions on all sides. In addition, a detailed interpretation of the island's recent coastal evolution can better inform the future island configuration. Thus the purpose of this study is to assess the multidecadal coastal change of Sable Island with a focus on future island morphometric trajectories. The objectives of this work are threefold:

1. To assess and compare the migration of the shoreline and foredune, and discuss the effectiveness of both for representing coastal change,
2. To assess historical and expected future coastline migration trends of Sable Island and evaluate drivers of that change, and
3. To look at broader-scale trends in the evolution of Sable Island as a whole: will Sable Island continue to exist?

FIGURE 1

Geology and geomorphology of Sable Island and Sable Island Bank

King (2001) provides a useful synthesis of the current understanding of the geology of Sable Island. Sable Island Bank is composed of a series of Tertiary- and Quaternary-aged shelf progradation, glaciogenic, and transgressive sedimentary sequences composed of poorly consolidated sand- and mud-stones. The Sable Island sand body core, from which the ancestral

and modern Sable Island is derived, was deposited atop Late Pleistocene glaciogenic sediments. The latter were deposited at the Last Glacial Maximum (LGM), with the former resulting from a tidewater and subaerial morainal bank deposited during the last re-advance of ice in the area. Following final ice retreat, sea level transgression resulted in extensive modification of the moraine, first with northerly transport of sediment then redistribution into bars, sand ridges and thick sand sheets. Due to changes in sea levels, the subaerial portion of Sable Island was much larger as the Pleistocene transitioned into the Holocene, shrinking in extent as sea levels rose from ~ -100 m to present (Shaw et al. 2002). More recent sea-level change relevant to the temporal scope of this study can be approximated from published curves by Scott et al. (1984) and Vacci et al. (2018) as being between 2 and 4 mm per year. The upper end of this range matches well with the vertical land subsidence at Sable Island of 2.29 mm (Robin et al. 2020) added to eustatic SLR values of 2.1 mm per year for the time period 1970 – 2015 (Oppenheimer et al. 2019). Despite this complex geographical history, pollen recovered from boreholes on Sable Island suggest the island ecosystem structure has remained basically unchanged since the LGM – including a lack of any non-introduced tree species (Terasmae and Mott 1971). Although the dimensions and composition of the island bear striking resemblance to that of a barrier island, there is no geologic or fossil evidence for a back-barrier lagoon (or persistent landmass in the leeward side of the island), so here we refer to it as simply a vegetated sand island.

Cameron (1965) provided one of the original comprehensive studies of the geomorphology of Sable Island, including a terrain map and a historical (charted) landscape evolution (1766 – 1964). Notably, the reconstruction of the island suggested a general lack of a trend for island migration, despite contemporaneous claims of an eastward migration (e.g., James and Stanley 1967). In addition, the reconstruction shows a central lagoon that transitioned to an interior lake (Lake Wallace, infilled by 2013, Figure 1(iii)) and highly mobile and non-permanent terminal spits. James and Stanley (1967) were among the first to suggest the island exists in a state of dynamic stability, where subaerial sand lost through erosion is cycled back to the island due to seasonal littoral and aeolian transport patterns. Work in the 1990s aimed to document the stratigraphy and “dunescape” of Sable Island (Byrne and McCann 1990, 1993, 1995; McCann and Byrne 1994), including the large unvegetated central island dunes (Figures 1(vi), 2A). The authors recognized the importance of the large North Beach foredune (Figures 1(i), 2B) and NW-SE trending parabolic dunes (Figure 1(ii)) to the aeolian sediment transfers on

to and across the island. This work also provides one of the first appreciations of the difference between the beach-dune systems of North and South Beach, where Byrne and McCann (1995) refer to a foredune on North Beach only. It is true that North Beach does host a more typical foredune system, with a large shore-parallel dune receiving aeolian sediment transfers from the beach. There are frequent blowouts and parabolic dunes migrating downwind (Figure 1(i); Figure 2B), which is likely reflective of the most competent transporting winds being onshore (WNW, McCann and Byrne 1994). However, a combination of topographic steering, frequent and competent winds from directions south of west, and appreciable sediment supply means that linear dune ridges found landward of South Beach are still morphodynamically indistinct from foredunes (e.g., Figure 1(vii); Figure 2E,F). Regardless, the different wind regimes (discussed below) are the primary driver of a beach dune system that functions very differently on North Beach and South Beach. Recent work has focussed on nearby shore-attached sand ridges (e.g., Li et al. 2004; Li and King 2007) and associated shoreface gutters (Amos et al. 2003; Li and King 2007), with focus on their relationships to wave attenuation, on- and off-shore sediment transport, and the overall sediment budget of the island.

FIGURE 2

Climate and Oceanography

Sable Island's climate is classified as cold with a warm summer, but without a dry season, Dfb in the updated Koppen-Geiger climate classification (Beck et al. 2018). Climate normals (Environment Canada 2011) show mean annual temperature as 7.6°C and annual precipitation as 1459 mm (8% falling as snow). Winds average 26 km/hr annually, with higher than average winds predominantly from the W, WNW, and NW in fall and winter and lower than average winds predominantly from the S, SSW, SW, and WSW in spring and summer (McCann and Byrne 1994). This climate and the sandy substrate generally support three terrestrial plant communities – grassland (dominated by Marram Grass (*Ammophila breviligulata*)) on more dynamic surfaces, mature heath communities on more geomorphically stable surfaces, and a transitional type between the two (Freedman et al. 2011). The mean tidal range in the area is approximately 1.1 m, average wave height from the nearest buoy (Station 44137) is 2.3 m, and the maximum zero-crossing wave height is 58.6 m for records between 1988 and 2021. Energetic storms result in offshore significant wave heights for 1-, 10-, and 100- year events of 8.7 m, 11.7

m, and 15 m, respectively (Li and King 2007). Because the common storm track is from the southwest to the northeast, intense wave action is often from the west and southwest, and sheltering by the island and nearshore bathymetry would conceivably result in a decrease in wave intensity from west to east and from South Beach to North Beach. Model hindcast data from the six surrounding spectral grid nodes from the MSC50 wave model (<https://open.canada.ca/data/en/dataset/f3f0312d-d28b-400c-b14a-28f51ff7f08a>) was unfortunately not able to resolve the island (e.g., no wave-shadow effect was observed in the significant height and direction data) and nearby buoys don't record wave direction.

Climate change may have significant impacts on Sable Island. For the high-emissions RCP8.5 scenario, projected median relative sea-level (RSL) changes for GPS stations on the Nova Scotia mainland range from 77.1 to 81.3 cm by 2100 (James et al. 2014), and modeled change for Sable Island SLR may be as much as 30 cm by 2040 relative to 2005 levels (James et al. 2021). In addition, water level changes due to modified tidal ranges resulting from RSL are significant along the east coast of the Americas, and may contribute additional decimeters of height to water levels not accounted for previously (Pickering et al. 2017). Although there is much debate over links between storminess and climate change, a warming trend across the Atlantic basin may contribute to a more extreme hurricane season (Murakami et al. 2018) and a Scotian Shelf region that is experiencing summer-like temperatures for as much as three weeks longer per decade (Greenan et al. 2018) may increase the length of the tropical storm season and/or reduce the cold-water barrier to development, intensification, or maintenance of storms that track near the island (e.g., Lifetime Maximum Intensity, Bieli et al. 2020). Indeed, a recent analysis shows that the North Atlantic is one of two regions where peak intensities of tropical storms are increasing most rapidly (Elsner 2020).

Methods

Imagery

Airphoto imagery for Sable Island has been collected for decades by various agencies. Airphoto sets used in this study are listed in Table 1. Physical airphotos (collected via analog camera) were scanned at 800 dpi and resampled for processing efficiency. The photos were mosaicked in Agisoft's Photoscan and orthorectified in ESRI's ArcMap, using the 2014 orthophoto mosaic

and associated lidar data as reference. Because there are no bedrock outcrops on Sable Island, and thus the only truly static landscape components are anthropogenic, earlier airphoto georeferencing information was based on data on geolocated historic sites and artifacts provided by Parks Canada, as well as centre points for the 1972 and 1996 airphoto sets. Further information on the 2002, 2009, and 2014 aerial surveys, including sensors, geolocating, and validation, can be found in Colville et al. (2016).

TABLE 1

Shore and dune mapping and analysis

The coastline was digitized using two separate proxies: the shoreline (delineated by the wet-dry line and often referred to as the wetted perimeter) and the vegetation line, used to represent the foredune. The wet-dry line is a commonly used proxy for shoreline position (e.g., Bheeroo et al. 2016; Radosavljevic et al. 2016; Vos et al., 2019) that can be affected by tidal stage and swash dynamics. For this study, these effects are assumed to be reduced due to: a) airphoto campaigns generally taking place at low tide while water levels are located on the lower foreshore, therefore reducing the wave runup around the shoreline, and b) assuming that the temporal range of airphotos (decades) may act to smooth out small scale variations due to high-frequency oscillation in water level. The vegetation line is another commonly used proxy for coastline evolution in marsh environments (e.g., McLoughlin et al. 2015), and has been used in eastern Canada for coastal zone management (Fraser et al. 2017), hazard assessment (Bernatchez et al. 2011; Didier et al. 2017, Didier et al. 2019) and erosion modelling calibration (Caulet et al. 2020). In this study, the dense vegetation line is used as a proxy for the foredune crest as much of the foredune on Sable Island is scarped at the beach-dune interface with a distinct vegetation line (Figure 2B). Migration of the foredune crest has previously been used as an important indicator of beach-dune migration trends (e.g., Psuty and Silveira 2009; Lentz et al. 2013).

To estimate image rectification and shoreline delineation error, we followed the methods of Radosavljevic et al. (2016), a study with similar analyses and outputs (Table 1). In this approach, georectification error represented the root mean square difference between location information from rectified imagery and ground control points (GCPs) obtained during the georectification process (values from MacKinnon and Colville 2019). Pixel error was either the digital airphoto resolution or ground resolution of analog photos using a “worst case” camera

resolution of 20 line pairs per mm along with Equation 1 from Lo et al. (2007), pp 291-292. Digitization error was based on the analysts' resolvable distance at the scale used for digitization – constant for all imagery at 1:1200.

Digitized coastlines were imported to the Digital Shoreline Analysis Software (DSAS) package for ArcGIS (Himmelstoss et al. 2018). Shore normal transects were drawn for both coastline metrics at 50 m longshore intervals. Baselines, important for determining transect orientation, were developed oceanward of digitized shorelines using a 500 m buffer for the shoreline and a 10 m buffer for the vegetation line, both buffered from merged datasets for their respective measures (and thus buffered from the most oceanward digitized line at any given point). The tighter baseline for the vegetation line allowed for a higher variation in transect orientation, important for the more dynamic data the vegetation line provided.

The net shoreline movement (NSM) and linear regression rate (LRR) were used to characterise shoreline change in this study. Note that “regression” in LRR refers to the statistical regression applied to the coastline data (of which the LRR value is the slope) and not to the geomorphic process of coastal regression. These metrics best capture total observed changes to infer sediment fluxes (NSM) as well as determine rates of change (LRR). In shoreline change studies, a wide range of statistical parameters exist and LRR is often used to represent shoreline change (e.g., Brooks and Spencer 2010; McLoughlin et al. 2015; Bheeroo et al. 2016; Rodsavljevic et al. 2016). Note that when reporting results for this study, retreat (and negative NSM or LRR values) signify coastline translation toward the centre of the island, and advance (and positive change values) signify coastline translation away from the centre of the island. For example, on South Beach, retreat signifies a coastline translating northward.

Regional assessments and forecasts of coastal changes

The island was split into five regions for analysis – West Spit, West End, Centre, East End, and East Spit (Figure 1). Regions were created based on previous assessments of Sable Island (e.g., Catling et al. 1984; McCann and Byrne 1994; Tissier et al. 2013). Parks Canada maps combined with land cover classifications from the Nova Scotia Community College from 2014 airphoto and lidar data (see Colville et al. 2016) were used for data on dense heath community vegetation cover.

Following the historical shoreline change analysis, a forecast was produced for 20-year shoreline and vegetation line positions using the shoreline forecasting tool in DSAS (for description, see Himmelstoss et al. 2018). This was used to approximate future impacts due to shoreline changes that may occur over the next 20 years. For this study the full uncertainty band that accompanies the forecast was used to encompass the range of possible outcomes from this forecasting tool. These results were overlain on the heath community landcover type data (Figure 2C), representative of geomorphically stable inland sites (Catling et al. 1984). Using this overlay, any future shoreline or beach encroachment on heath community sites represents geomorphic change occurring faster than the biogeomorphic species redistribution on the island.

Whole-island evolution

The results from the above analyses provide an opportunity to investigate the various hypotheses put forward about the long-term trajectory of Sable Island. To elucidate global (island-wide) dataset trends from the shoreline analyses, a linear regression was performed between Easting coordinates (in metres) and NSM (also in metres) to highlight any relationship between shoreline migration and location along the east-west axis of the island. For this analysis, the spits were removed from the data so as to focus on trends of the densely vegetated, stable core of the island rather than the highly mobile and more ephemeral spits. In addition, because the shoreline polylines form a closed loop (around the subaerial portion of the island), centroids were calculated for the resultant polygons (including the spits) to give an approximation of the general trend in island migration.

Results

Changes in shoreline position

Coastlines have been highly dynamic along Sable Island since 1959. Figure 3 shows maps of the LRR for both the vegetation line (top) and shoreline (bottom), and Figure 4 shows larger scale maps of selected areas for more detail, paired with annotated airphotos to highlight observed changes. For ease of interpretation, the vegetation line is depicted as a colour ramp superimposed on the transects (from baseline to landward-most digitized vegetation line (Figure 3, top)) whereas the shoreline is depicted as the same colour ramp superimposed on the 2019 shoreline (Figure 3, bottom). Both display their respective uncertainties (within measurement error) as

white (no detectable change). Box plots of the LRR for the west-east sections of the island, and the island as a whole, are shown in Figure 5 for South and North Beach.

Generally, the shoreline is retreating on South Beach, predominantly in the centre and west. Accretion is mostly limited to the west. These patterns are similar for the vegetation line, with a notable divergence in the centre of South Beach, where the vegetation line is advancing most rapidly. Vegetation migration rates across the whole island are generally negative (indicating retreat) along South Beach ($-0.52 \text{ m/a} \pm 2.4 \text{ m}$), reaching up to -10.8 m/a within the West End where the maximum landward migration of $660 \text{ m} (\pm 126 \text{ m})$ is observed. This area is highlighted in Figure 4(ii), where the inset airphotos show the burial by windblown sand and overwash processes of hundreds of metres of landcover. This process results in ponds and established heath/shrub communities being converted to a low elevation sand flat. Note that this doesn't represent foredune retreat; rather the foredune was fully eroded and there is an ongoing re-establishment of a new shore-parallel dune ridge further inland (e.g., Figure 2F). Higher maximum rates of retreat ($-16.3 \text{ m/a}, \pm 3 \text{ m}$) are observed on the shoreline over the whole of South Beach, with vegetation line retreat likely offset by the large area of advance observed in the centre portion of the island (Figures 2D, 4(iii)). On North Beach, the coastline response is more muted, with advance on the spits yielding to retreat in the centre of the island. An advancing vegetation line averages $+0.38 \text{ m/y}$ and $+0.57 \text{ m/y}$ on northern West End and West Spit, respectively, driving the slightly net advancing overall vegetation line, while overall net advance of the shoreline is driven by advance at the spits at the expense of retreat in the other regions. Generally, when looking at island-wide patterns, the island's coasts are retreating on both sides in the centre (thinning) and advancing northwards at the ends. Looking at the net coastline movement, South Beach is retreating and North Beach is advancing, albeit the latter at a lesser rate. An example of this is in Figures 2D and 4(i), where a translation of the island as a whole results in North Beach advance at the expense of South Beach retreat.

FIGURE 3

FIGURE 4

FIGURE 5

Future trends

20-year projected shorelines were generated for both the shoreline and vegetation line datasets. Figure 6 shows the range of outcomes overlain on the 2019 airphoto mosaic for selected locations. In the west, projections indicate that South Beach is retreating faster than North Beach is advancing, which would result in an increasingly narrow overwash area (Figure 6A), possibly resulting in breaches and reduced island connectivity. At several locations (Figure 6B), the shoreline is forecasted to retreat at a much higher rate than the vegetation line, suggesting that wave action will erode the foredune at a greater rate than aeolian inputs to and over the foredune can drive inland migration. This result is only observed on South Beach at this magnitude. The highly variable predictions for the vegetation line backing North Beach (e.g., Figure 6E) reflect blowout/parabolic dune complexes that develop and migrate obliquely to the shoreline and foredune. This is different than much of the foredune structure of South Beach (Figure 1(vii)). Foredunes on South Beach are largely built on relict former foredunes, wave-eroded parabolic dunes migrated from North Beach, and contain blowouts at more acute angles to the shoreline.

An advancing vegetation line and retreating shoreline results in a general shrinking of the sand flats of the former Lake Wallace area (Figure 6D) (see also Figure 4(iii) and (iv); Figure 2E), a process that likely began as the former Lake Wallace area began infilling with sand (e.g., Figure 4(iv)). In addition, although not shown in the projection data, the hummocky appearance of the sand flats (Figure 6D) and to the east show developing *Ammophila*-anchored nebkha dunes. These will likely join to form a new established foredune, considering the high rainfall and favourable climate on Sable Island (Hesp et al. 2021), unless shoreline retreat erodes them before this process is completed. This will result in the landward linear dune becoming a relict foredune. Despite this new vegetation, upper estimates for the area of heath community landcover lost to shoreline retreat is 5.47 ha, with an additional 4.62 ha lost to vegetation line retreat. The vegetation line for North and South Beaches are projected to meet in several new locations (Figure 6C), suggesting new overwash locations may develop.

FIGURE 6

Island-wide trends

Figure 7 shows the relationship between the NSM data and position along the east-west axis. The only linear relationship is an increasing shoreline retreat toward the east on South Beach ($R^2 = 0.74$). The vegetation line does not follow any trend, which is in contrast with the overall evolution of the sandy foreshore based on the shoreline proxy. The evolution of the island centroid through the study period is shown in the top map of Figure 6, and is likely dominated by the spits, which were included in these data. The extension of east spit was at a maximum in 2002 and 2009, which moved the island centre to the northeast. It then rapidly became a submerged sandbar, and West Spit generally extended and became vegetated throughout the study period, resulting in the island centre migrating southwest.

FIGURE 7

Discussion

Comparison of shoreline and vegetation line as proxies for shoreline change

Our results underline the complementarity of both the shoreline and vegetation line approaches to assess coastal changes on highly dynamic dune-beach systems such as Sable Island. Using both shoreline proxies in this study has led to additional information (e.g., dune advance despite shoreline retreat; foreshore retreat outpacing foredune retreat resulting in dune loss rather than accommodation) than could be provided by one proxy alone. To compare the mean migration rates from shorelines and vegetation lines, results were binned into a number of areas with overlapping data for comparing LRR and NSM across the West End, Centre, and East End (Figure 8). For both metrics, erosion (retreat) rates and distances are larger using the shoreline when compared to the vegetation line method for long-term coastal evolution assessment. The overall coastal evolution trends appear to generally agree, but both methods are poorly correlated ($R^2 < 0.5$). Higher landward migration rates of the shoreline compared to dune vegetation changes highlight the complex nature of coastline responses to storm dynamics. It is likely that the vegetation line is resilient to low-magnitude, high-frequency events despite persistent shoreline migration due to coastal dune building and growth as a result of plant burial and vertical accretion (Maun 1998). Changes in shape and coastline position are common on barrier islands (Plant et al. 2017), but complex interactions between overwash and breaching also add local longshore variability on coastline location. This is perhaps more visible through the

changes in vegetation line than in the shoreline as a result of various plant species' response to hydrodynamics and aeolian forcing (Wolner et al. 2013). Similar to observations on reef islands, SLR on Sable Island could trigger more frequent wave-driven inundation regimes of the upper beach berm (van Dongeren et al. 2017) and could ultimately affect the currently established foredune system (Ruggiero et al. 2018) and potentially freshwater tables (Storlazzi et al. 2018), which is important for Sable Island biodiversity and management (Kurylyk et al. 2019).

FIGURE 8

Shoreline trends and potential drivers

In Figures 3, 4, and 5, the general picture of the future position of the beach-dune system is one of retreat along South Beach and relative stability on North Beach. With respect to the latter, the general exceptions include a retreating centre portion of the island, where perhaps the most accommodation room exists for this retreat to occur due to island width. Larger scale changes are generally associated with the vegetation line in regions where the dynamic foredune is changing, often obliquely and not in a true shore-normal retreat. It is likely that the variable vegetation line migration isn't driven by shoreline migration but due to the aeolian processes of foredune blowout and depositional lobe formation. These processes generally progress to the formation and migration of parabolic dunes, and the deflation basins remaining near to North Beach are often more susceptible to flooding via overwash through the foredune blowout. This is a common coastal configuration (c.f., Hesp 2002), and although present in many locations along South Beach, is ubiquitous along the North Beach coastline. This foredune morphology on North Beach, where most of the change is in blowout and parabolic dune formation and migration rather than broad scale foredune erosion, seems to modulate the response of the foredune to continued retreat of the shoreline. That is, continued onshore sand supply from the competent WNW winds assists in foredune maintenance, accretion, and recovery following wave erosion events. This process occurs less frequently on South Beach because the most competent winds are obliquely offshore to much of the beach-dune system on this beach. This would explain why the areas of oceanward dune growth (Figure 4B) are where there is both appreciable sand supply upwind (west) and accommodation room seaward – in the location of the former Lake Wallace (Figure 2E, 4(iii)). Elsewhere on South Beach, shoreline and vegetation line retreat are appreciable, and much greater than that found on North Beach. Along large portions of the West

End, the retreat of the shoreline outpaces the retreat of the vegetation line, suggesting that there may be a loss of the protective foredune in the future. Nowhere is this more evident than at the large pond complex in the west end (Figure 4(ii)), where both the shoreline and vegetation line retreated by hundreds of metres on South Beach with much smaller magnitude retreat on North Beach.

If areas of heath community can be considered as representative of the geomorphically stable core of the island (the climax community with relative intolerance to burial) then the loss of 10 hectares of heath community (~4% of the total 2014 coverage) represents a gradual erosion of the subaerial sediments forming the island core. However, several caveats are worth noting – while this analysis has no means for accounting for any heath community growth elsewhere, it also doesn't account for heath community loss due to burial from inland dune migration, and the 10 hectares of loss projected over the period of 2019 – 2039 is ~4 times less than was observed from 2002 to 2014 (Colville et al. 2016). Regardless, this analysis suggests that heath community loss due to shoreline and vegetation line encroachment is certainly reflective of a permanent change in habitat from geomorphically inactive to active as the coastline migrates into and over these areas.

Evolution of Sable Island and potential future trajectories

Recalling the three hypotheses on island evolution from the introduction, it is evident that key data to test these hypotheses lies in wait offshore (e.g., Eamer et al. 2020). In particular, testing the hypothesis 1, where Amos and Nadeau (1988) and Amos and Judge (1991) suggested the bulk of sediment transport driving island migration is offshore (transport documented in Li and King (2007)), would require more offshore oceanographic and seabed data. However, certain patterns are evident. During the study time period, West Spit experienced growth (Figures 3,5), East Spit grew and subsequently retreated (Figures 5, 6(top)), and the centre of the island experienced retreat on both South and North Beaches. Movement of the centroids (Figure 6(top)) indicates the island migrated southwest, then northeast, then southwest again, largely driven by spit growth and retreat. This process may respond to cyclical climate patterns, such as the Atlantic Multi-Decadal Oscillation (Trenberth and Shea 2006), through changes in storm magnitude and track and vegetation growth patterns. Figure 7 suggests that the only significant linear trend is greater losses of South Beach in the west than the east, yet these sediments don't

appear to be translated to the spits. This agrees well with the wave climate observations of Li and King (2007) (diminishing wave energy from west to east), and suggests the bulk of sediment transport is offshore.

However, a lack of clear trend in the vegetation line net shoreline movement suggests a relatively static “core” of the island (Figure 7). If the bulk of sediment transport is offshore, shoreline response is predominantly related to ongoing SLR. North Beach, with its more typical morphology (owed to dominant transporting winds obliquely onshore), is able to “keep up” with SLR because of dynamic changes toward certain states of equilibrium by accreting vertically (Davidson-Arnott 2005; Costa et al. 2019, Masselink et al. 2020). South Beach, with oblique offshore dominant sand-transporting winds, doesn’t have this capacity, and is thus retreating. Taken together, the island’s shorelines are in net retreat, as this quasi-closed sediment budget isn’t replenished when island area is lost to inundation resulting from SLR, currently estimated at a rate of ~ 4 mm per year and increasing, and subaerial sediments become submarine. This fits with the third hypothesis for island evolution – it is relatively static and shrinking due to inundation resulting from SLR.

Conclusions

In this study, coastlines on Sable Island, Nova Scotia were digitized from historical airphotos using both the shoreline and vegetation line. The objectives of the study were threefold: to assess the use of both the shoreline and vegetation line proxies for coastline migration; to characterize historical and future coastline migration trends; and to look at broader-scale trends in the evolution of the island as a whole. The main conclusions are:

1. When compared, the results from the shoreline and vegetation line were poorly correlated, suggesting using either in isolation could result in different conclusions being drawn about coastline evolution. In addition, using both proxies together yielded new information about future trajectories, such as a shrinking foreshore resulting in an increased potential for foredune erosion;
2. In general, the majority of the coastline is in retreat, particularly in the centre and centre-west of the island. Net shoreline movement suggests retreat on South Beach is partially offset by advance on North Beach. Shoreline retreat is greatest along the Centre and West

End of South Beach but broad new sources of aeolian sediment due to infilling of many freshwater lakes has led to advance of South Beach foredunes. North Beach has a typical established foredune and blowout morphology due to the dominance of oblique-onshore winds and likely reduced wave energy, and has experienced a lower magnitude of coastline change.

3. By 2039, the impacts of a migrating foredune may mean whole-island overwash is possible in several new locations, as well as (paired with South Beach shoreline retreat) a reduction in aeolian fetch in the infilled freshwater lakes areas. Developing nebkha dunes in this area will be affected by a reduction in sediment as well as shoreline retreat;
4. Island-wide data suggest that the island may be migrating eastward mostly via bedload transport offshore to the south of the island, with a South Beach shoreline response reflecting this. However, generally the subaerial portion is eroding and this may show a stronger signal than eastward migration.

The conclusions drawn and projections made from these data are based on the sea level changes and climate patterns of the past 60 years (e.g., ~24 cm of SLR). Climate change is resulting in accelerated local SLR (e.g., 77 – 81 cm in the next ~80 years) and changes in storm patterns and intensities that suggest these results should be treated as a baseline for future changes to Sable Island. Future work should focus on furthering our understanding of the trajectory of the island, including: a finer temporal scale investigation of island evolution enabled by new methods (e.g., Grottoli et al. 2021); using new satellite methodology to investigate nearshore and shallow shelf sediment transport, sedimentary environments and bedforms (e.g., Sagawa et al. 2019), and finally an updated characterization of the modern geomorphology of the island, in the spirit of Cameron (1965), James and Stanley (1967), and McCann and Byrne (1994).

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Figure Captions

Figure 1. Location of Sable Island, near the edge of the continental shelf east of Nova Scotia in Canada. Inset map shows the five regions discussed in the study and locations for topographic profiles at the bottom. Topographic profile axes in metres (elevation above CGVD2013 and distance along profile) and are derived from an airborne lidar dataset collected in 2019 (contemporaneously with the digital orthophoto). Profile labels are as follows: (i) North Beach foredune; (ii) landward deposition of aeolian sand from North Beach foredune blowouts; (iii) infilled lake bed at the location of former Lake Wallace (see Figure 4(iv)); (iv) nebkha dunes forming in the location of former Lake Wallace, likely trending toward another established foredune ridge; (v) deflation basin located landward of foredune and upwind (NW) of a large active central dune (vi); (vii) South Beach foredune. Overview map created using QGIS (QGIS.org 2021), using vector data from DIVA-GIS (Hijmans et al. 2012) and bathymetry from Google (2021).

Figure 2. (A) A large unvegetated dune in the centre-east of the island. (B) The large, wave scarped North Beach foredune looking East, with person for scale (white arrow, very small) and blowout in the foreground (black arrow). (C) Horse path through dense heath community landcover type. (D) Photo in 1982 of the former drill rig staging area (see Figure 4(i)), with pipe racks and concrete pads still located on North Beach (looking north, photo credit Robert Taylor, Geological Survey of Canada). (E) South Beach sand flats at the site of the former Lake Wallace, with South Beach relict, accreting foredune on the right. Arrow shows tire tracks for scale, looking west. Note sand ribbons migrating toward the photographer, providing aeolian sediment inputs to the dune. (F) Lily Pond North, looking east, after a recent high water event, showing an overwashed foredune and depositional fan in the pond, which is now brackish and conspicuously lily-free.

Figure 3. Rate of change (LRR, m/a) for vegetation line (top) and shoreline (bottom). Inset maps locations for figures 4 and 6 identified with black boxes. Note that the colour ramps are identical except for the error range (white), where results were within the uncertainty determined in Table 1.

Figure 4. (a) Close up of high retreat rates found in the West End (for colour ramp, see Figure 3), where a former drill rig staging area (i) highlights retreat on South Beach offset by advance on North Beach, with remaining infrastructure (2019, bottom) outlined in red, and where overwash and aeolian infilling (ii) resulted in the loss of a protective foredune and infilling of a number of freshwater ponds (common locations indicated by arrows). (b) A portion of the Centre region where the deepening and/or migrating blowout morphology is evident in the vegetation line results and an advancing vegetation line is shown (iii) despite a retreating shoreline in the sandy plain at the former Lake Wallace area (iv, lake area outlined in blue).

Figure 5. Box plots of Linear Regression Rate (LRR) for each region (see Figure 1 for locations) and all of Sable Island with centre line representing the median, “x” the mean, and outliers removed for scale.

Figure 6. Full uncertainty bands for shoreline change by 2039 on Sable Island for the West End and Centre regions (top) and select locations (see Figure 3). Centroids for each delineated shoreline polygon, representing the centre of the island through time, shown in their true location

relative to the top map. Note the centroids are located north of the island due to the island's crescent shape. Heath community landcover data from Colville et al. (2014). (A) whole island overwash is likely to increase in frequency; (B) shoreline retreat outpaces vegetation line retreat; (C) the vegetation line from both beaches is forecasted to meet; (D) area of former Lake Wallace, where nebkha dunes are developing; (E) variable predictions for the North Beach vegetation line. Refer to manuscript text for more thorough discussion.

Figure 7. Net shoreline movement (NSM) plotted on the west-east axis (against Eastings) with linear regression including equation and R^2 values shown. Note that the regression analysis for VL on North Beach (upper right) was not significant ($p = 0.14$) but all others were ($p = 0.00$).

Figure 8. Vegetation line LRR (Linear Regression Rate) for 21 contiguous areas along the island are plotted against the shoreline in A. B uses the NSM (Net Shoreline Movement) in a similar plot. The red and blue zones represent coastline erosion and accumulation, respectively, and the dotted line represents the fitted regression for which the equation and R^2 is at the bottom of the graph.

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Figure 1. Location of Sable Island, near the edge of the continental shelf east of Nova Scotia in Canada. Inset map shows the five regions discussed in the study and locations for topographic profiles at the bottom. Topographic profile axes in metres (elevation above CGVD2013 and distance along profile) and are derived from an airborne lidar dataset collected in 2019 (contemporaneously with the digital orthophoto). Profile labels are as follows: (i) North Beach foredune; (ii) landward deposition of aeolian sand from North Beach foredune blowouts; (iii) infilled lake bed at the location of former Lake Wallace (see Figure 4(iv)); (iv) nebkha dunes forming in the location of former Lake Wallace, likely trending toward another established foredune ridge; (v) deflation basin located landward of foredune and upwind (NW) of a large active central dune (vi); (vii) South Beach foredune. Overview map created using QGIS (QGIS.org 2021), using vector data from DIVA-GIS (Hijmans et al. 2012) and bathymetry from Google (2021).

222x214mm (600 x 600 DPI)

Figure 2. (A) A large unvegetated dune in the centre-east of the island. (B) The large, wave scaped North Beach foredune looking East, with person for scale (white arrow, very small) and blowout in the foreground (black arrow). (C) Horse path through dense heath community landcover type. (D) Photo in 1982 of the former drill rig staging area (see Figure 4(i)), with pipe racks and concrete pads still located on North Beach (looking north, photo credit Robert Taylor, Geological Survey of Canada). (E) South Beach sand flats at the site of the former Lake Wallace, with South Beach relict, accreting foredune on the right. Arrow shows tire tracks for scale, looking west. Note sand ribbons migrating toward the photographer, providing aeolian sediment inputs to the dune. (F) Lily Pond North, looking east, after a recent high water event, showing an overwashed foredune and depositional fan in the pond, which is now brackish and conspicuously lily-free.

81x112mm (300 x 300 DPI)

Figure 3. Rate of change (LRR, m/a) for vegetation line (top) and shoreline (bottom). Inset maps locations for figures 4 and 6 identified with black boxes. Note that the colour ramps are identical except for the error range (white), where results were within the uncertainty determined in Table 1.

296x209mm (600 x 600 DPI)

Figure 4. (a) Close up of high retreat rates found in the West End (for colour ramp, see Figure 3), where a former drill rig staging area (i) highlights retreat on South Beach offset by advance on North Beach, with remaining infrastructure (2019, bottom) outlined in red, and where overwash and aeolian infilling (ii) resulted in the loss of a protective foredune and infilling of a number of freshwater ponds (common locations indicated by arrows). (b) A portion of the Centre region where the deepening and/or migrating blowout morphology is evident in the vegetation line results and an advancing vegetation line is shown (iii) despite a retreating shoreline in the sandy plain at the former Lake Wallace area (iv, lake area outlined in blue).

146x157mm (600 x 600 DPI)

Figure 5. Box plots of Linear Regression Rate (LRR) for each region (see Figure 1 for locations) and all of Sable Island with centre line representing the median, "x" the mean, and outliers removed for scale.

164x126mm (300 x 300 DPI)

Figure 6. Full uncertainty bands for shoreline change by 2039 on Sable Island for the West End and Centre regions (top) and select locations (see Figure 3). Centroids for each delineated shoreline polygon, representing the centre of the island through time, shown in their true location relative to the top map. Note the centroids are located north of the island due to the island's crescent shape. Heath community landcover data from Colville et al. (2014). (A) whole island overwash is likely to increase in frequency; (B) shoreline retreat outpaces vegetation line retreat; (C) the vegetation line from both beaches is forecasted to meet; (D) area of former Lake Wallace, where nebkha dunes are developing; (E) variable predictions for the North Beach vegetation line. Refer to manuscript text for more thorough discussion.

158x199mm (600 x 600 DPI)

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Table 1. Airphoto sets used and error estimates

Airphoto year	Source¹	Collection method	Month collected	Scale	Digital resolution	Georectification error RMS (m)	Pixel error (m)	Digitizing error (m)	Total error estimate (m)
1959	NAPL	Analog (b/w)	April	1:12000	20 cm	0.34	0.6	5	5.05
1963	NAPL	Analog (b/w)	May	1:20000	20 cm	2.76	1.0	2	3.55
1972	Nova Scotia	Analog (c)	May	1:6000 and 1:8000	20 cm	0.48	0.4	1	1.18
1996	Nova Scotia	Analog (c)	June	1:10000	20 cm	3.47	0.5	1	3.65
2002	AGR / SIPT	Digital	October		50 cm		0.5	1	1.12
2009	AGR / CWS	Digital	August		15 cm		0.15	0.5	0.52
2014	AGR / LEG / PCA	Digital	September		10 cm		0.1	0.25	0.27
2019	AGR / LEG / PCA	Digital	August		10 cm		0.1	0.25	0.27

¹ Acronyms: NAPL: National Air Photo Library (Canada); AGR: Applied Geospatial Research Group (Nova Scotia); SIPT: Sable Island Preservation Trust (Nova Scotia); CWS: Canadian Wildlife Service (Canada); LEG: Leading Edge Geomatics (New Brunswick); PCA: Parks Canada Agency (Canada)