Spatial and Temporal Changes in Beach Width and its Effect on the Condition of Foredunes on Dune du Nord, Les Iles de la Madeleine

by

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ABSTRACT

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Changes in coastal environments are a result of interacting hydrodynamic and aerodynamic processes. Spatial and temporal changes in beach width and foredune condition, some of which are influenced by climate change and (consequentially) sea level rise, are documented throughout academic literature. Data was collected from Dune du Nord on Iles-de-la-Madeleine to investigate: a relationship, or lack thereof, between beach width and foredune condition, whether chance plays a role (and to what extent) on dune scarping; and changes in foredune position between 2003 and 2018.

Both fieldwork and satellite image analysis were used to classify foredune condition and measure beach width, and to gather complementary data to provide context for those results. Satellite image analysis showed that between 2003 and 2018 there was significant change in foredune condition and beach width. The data shows that beach width is not a strong indicator of foredune condition on Dune du Nord. The literature shows that foredunes are more easily scarped when in front of a narrow beach, although a large enough storm may erode a foredune with a wider adjacent beach. Because beach width is continuously changing the location of foredune scarping along a beach is largely up to chance. Shifts in beach width were found to be rapid enough to change significantly before a scarped sand dune recovers to a “stable” state. This explains why scarped foredunes were found behind wide beaches. The mean beach width was found to increase from 32.30 meters in 2003 to 39.53 meters in 2018. Foredune position was found to retreat between 2003 and 2018; as 87 out of the 97 data points retreated landward.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction and Literature Review

1.1. Introduction

Coastal sand dunes are landforms deposited landward of the high-water mark of a beach. Sand dunes are typical of coastlines with arid, semi-arid, and temperate climates (Pethick, 1984). A dune field is a feature of the landscape that forms when windblown sand sediments create a series of dune ridges extending inland. The first sand dune in a dune field is called a foredune. Foredunes run parallel to the ocean and adjacent to the beach making it the closest sand dune to the water's edge.

Foredunes can be classified into two main categories based on their developmental stage: incipient and established dunes (Hesp, 2002). Incipient dunes represent the initial stages of an established foredune. They are characterized by sparse vegetation and a gently sloping sand mound. Incipient dunes are sometimes found in front of established foredunes which tend to be larger, steeper, and more densely vegetated (Hesp, 2002). If the conditions for accumulation of sand are present the incipient dune may form into an established dune and replace the previous foredune.

Foredunes are formed by the accumulation of sand above the high spring tide mark. Sand is moved through aeolian transport along the beach. Dry sand grains may move along the beach by saltation, surface creep, or suspension until some interference causes deposition (Maun, 2009). The presence of vegetation causes a reduction in wind speed which allows the sand to deposit, and over time, to accumulate into an incipient dune. Accumulation of sediments provides a favourable environment for the continued growth of vegetation. This further increases the deposition of windblown sand, creating a positive feedback loop. Over time the incipient dune will stabilize and grow, eventually forming a foredune.

Sand dunes act as a buffer between the ocean and inland areas; protecting the land from seawater inundation and storm surges (Davidson et al., 2020). Foredunes are the first line of defense against waves as they absorb wave energy and protect against flooding. They protect both the natural and built environment including wetlands, dune fields, forested areas, roads, buildings, and other man-made infrastructure. The protective aspect of foredunes is of particular importance when considering the increasing rates of sea level rise. Climate change has caused a rise in seawater levels through the melting of glaciers and thermal expansion. This has caused degradation to coastal areas.

Sand dunes are formed adjacent to and on beaches. Beach sediment is sourced from coastal erosion, river discharge, tides, and storm events (Maun, 2009). The width of a beach can change over time and space, depending on the wind and wave climate, sediment supply, and seasonal variations(Davidson-Arnott et al., 2010). The width of the beach may affect the morphology of the foredune. Keijsers et al., (2014) found that "In wider beach sections, dune erosion is less frequent, with lower temporal variability and stronger correlations with time series of transport potential. In erosion-dominated years, eroded volumes decrease from narrow to wider beaches" (p. 1). For beaches narrower than 200 meters, change in dune volume is heavily connected to mean sea level and storminess (Keijsers et al., 2014). Narrow beaches are therefore more vulnerable to sea level rise and dune disturbances.

Foredunes may undergo erosion when reached by a storm wave. Erosion results in scarping, a loss of vegetation, and blowouts. Scarping is an erosional process that causes the mass removal of sand when an ocean wave reaches the dune toe (Davidson et al., 2020). This process results in morphological changes in the foredune, primally, the removal of vegetation, a vertical scarp face, and slump blocks at the base of the dune. A scarped foredune is also more susceptible to wind erosion which can lead to blowouts. Vegetation and a gradually sloping foredune anchor sediments to the dune; when these features are removed via scarping the wind more easily erodes and transport sand sediments (Hesp, 2002). Continued wind erosion on a scarped foredune leads to a morphological feature called a blowout, a rounded depression in the sand dune. Erosion of foredunes can lead to a landward movement of the dune field (Davidson et al., 2020). Water levels, beach width, and beach gradient are the primary control of foredune erosion (Davidson et al., 2020). High-energy weather events are a major source of dune erosion as they produce waves large enough to reach the foredune. For example, on September 24, 2022, hurricane Fiona hit the coast of Cavendish Beach, Prince Edward Island. As seen in Figure 1a the foredune, before the storm, had a partial wind-blown sand ramp adjacent to a wide beach. Figure 1b shows the aftermath of Hurricane Fiona where the foredune is significantly cut back with a near vertical slope face. The red line drawn on the photos points to the approximate base of the foredune and helps to highlight the retreat that occurred because of the storm.

Figure 1.1 Foredune erosion at Cavendish Beach, P.E.I.

a) Foredunes at Cavendish Beach before Hurricane Fiona. The red line indicates the foredune position before the erosion event. Reproduced from: *Coastie Gallery. Coastie Icon. (2022, September). Retrieved September 2022, from* https://coastiecanada.ca/gallery/

b) Foredunes at Cavendish Beach after Hurricane Fiona. The red line indicates the foredune position after the erosion event, red dotted line indicates the foredune position before the erosion event Reproduced from *Coastie Gallery*. Coastie Icon. (2022, September). Retrieved September 2022, from https://coastiecanada.ca/gallery/

1.2. Literature Review

The morphology of a sand dune is impacted by the environment in which they are formed as well as the processes that occur there. Foredunes, the dunes closest to the water's edge forming parallel to the ocean, are the first line of defense of the dune field against inundation. The morphology of a foredune is impacted by its surroundings: local vegetation, wind and wave climate, sediment availability, and beach characteristics. The width along a beach varies in space and time, creating differing conditions for foredunes alongshore. These variables impact the process of erosion, deposition, and transport altering the structure and shape of foredunes.

1.2.1 Coastal Beach Processes

Coastal processes affect and produce sediment transport in the coastal environment. These processes shape the coastline through erosion, transportation, and deposition of sediment (Bird, 2000). Hydrodynamic and aerodynamic processes are the largest contributors to the movement of sediment in a sandy beach environment (Masselink & Hughes, 2003). Hydrodynamic processes include tidal and wave energy, while aerodynamic processes refer to wind energy.

1.2.1.1 Aerodynamic Processes

Strong winds move sediment grains along the sand beach; this is called aeolian sand transport. Wind energy may erode, transport, and deposit sand grains. This process is central to the creation of sand dunes within a beach environment. Aeolian sediment transport is the primary force moving sand grains from the beach to the sand dune (Masselink & Hughes, 2003). The velocity of the wind is the primary control of transport in which grains move in one of three ways: suspension, saltation, and surface creep (Maun, 2009).

Sand grains carried in the air are moved through suspension. This occurs with very small dust-like sediments or with strong winds that overcome the weight of the sediments (Maun, 2009). Saltation is the primary mode of sediment transport on beaches. During this process sand grains are transported for a short distance in the air before falling back to the surface (Maun, 2009). As the grain reaches the surface the impact propels other sand grains into the air causing the process to repeat. This process often occurs continuously to many of the grains along the beach causing the entire surface of the beach to be mobilized. Finally, grains that are too large to be ejected into the air will move through surface creep. These grains move by a dragging or rolling movement across the beach surface (Maun, 2009). These processes are generally agreed upon by writers in coastal geomorphology (Pethick, 1984; Carter, 1988; Davidson-Arnott et al., 2010).

1.2.1.2 Hydrodynamic Processes

Hydrodynamic processes refer to the transport, erosion, and deposition of sediment via waves and tides (Masselink & Hughes, 2003). Hydrodynamic processes precede aerodynamic processes in the sand dune building process. The main role of waves and tides in building sand dunes is to supply the beach with sediment.

Waves are formed through the interaction of wind with the surface of the ocean. Changes to beach morphologies are heavily driven by wave energy. Waves do not interact with the sea floor until the depth of water decreases to less than half that of the wavelength (Bird, 2000). As waves begin to interact with the seabed movement of sediment begins. A process called longshore sediment transport moves sediment along the beach, distributing sand grains from their source along the beach (Davidson-Arnott et al., 2010). This process supplies sediments for the formation of sand dunes.

Tides are the cyclical rise and fall of the edge of the water which is caused by the gravitational pull of the sun and moon. Tides mold the shoreline in two ways. First, the tides bring in large quantities of sediment and eroded bedrock (Maun, 2009). The speed necessary to transport the sediment (typically sand) is generated only under certain conditions -usually in inlets, at the mouths of estuaries, or any other place where there is a constriction in the coast through which tidal exchange must take place (Masselink & Hughes, 2003). Secondly, the water's edge fluctuates with the rise and fall of the tide, creating changes in the depth of water in relation to the position on the beach.

Hydrodynamic processes do not only include the transport and deposition of sediment. Erosion of sediment is a common process related to hydrodynamics its relationship to sand dunes is discussed in the following section.

1.2.2 Beach Width

For this study, we will be using Keijer et al., (2014) definition of beach width, defined as the measurement between the shoreline and the dune toe. This definition is popularly used among researchers in the field (Burroughs & Tebbens, 2008; Galiforni et al., 2019). On a temporal scale beach width can fluctuate in the short-term (months/years) and in the long-term (decades) (Galiforni Silva et. al, 2019). Quartel et al., (2008) noted that these short-term changes could be caused by seasonal changes in climate. For example, beach width is often narrower during winter months and wider during the summer months. Fluctuation in beach width is caused by periods of erosion or accretion of sediments due to changes in weather and climate (Quartel et al., 2008).

The width of a beach can vary spatially, Figure 1.2 provides a visual representation of spatial beach width change. As an example, the coast of Yucatan shows variation in beach width; 31.8% of the coast was 10 m wide, 56.9% of the beach was between 10 and 25 m wide, and 11.3% was wider than 25 m (Jiménez et al., 2016). This variation differs heavily depending on the location.

1.2.3 Coastal Sand Dunes

Coastal sand dunes form behind the high-water mark of a sandy beach. Dunes are formed from dried sediments deposited on the beach by nearshore waves. The wind carries sand particles via suspension, saltation, and surface creep toward the backshore as discussed above (Davidson-Arnott et al., 2010).

Figure 1.2 Spatial beach width change

The photo shows the change in beach width over the length of Dune du Nord. The shadowed curve in the foreground shows where wave action has cut back a section of the beach.

The sand grains are then deposited when wind speeds decrease, this may be caused by the rise in elevation or interference of vegetation. Vegetation reduces the velocity of the wind close to the ground (Yizhaq et al., 2009). As velocity decreases sediment accumulates around the base of the vegetation or at an existing sand dune. This vegetation is referred to as pioneer plants as they have a tolerance to salt, high winds, and the low nutrient conditions found in the area behind the high-water mark (Davidson-Arnott et al., 2020). One common variety of pioneer plant is marram grass *(Ammophila breviligulata)*, the growth of this species increases as sand accumulates over the roots and stems (Davidson-Arnott et al., 2020). When these species grow the dunes continue to stabilize as the root mass holds sediment in place.

1.2.4 Foredunes

Foredunes are considered the primary dune in a succession of sand dune ridges within a dune field (Davidson-Arnott & Houser, 2020). Foredunes lie closest to the water's edge, receiving much of the wind and wave-driven transportation, deposition, and erosion. Foredunes are separated into two main categories, established and incipient (Hesp, 2002). Incipient foredunes are newer dunes developed by the deposition of sand. There are three main types of incipient dunes: ramps, terraces, and ridges (Hesp, 2002). If incipient dunes continue to develop and grow, they will form into an established foredune. Established dunes are often older, larger, taller, and more populated by woody plant species (Maun, 2009; Hesp, 2002).

Established foredunes can undergo a variety of changes. Prograding dunes undergo growth as sand sediment accumulates. Eroding foredunes undergo shrinkage as coastal processes (primarily hydrodynamic) erode sediment. Finally, if a sand dune undergoes no growth or shrinkage, it is described as stable (Yizhaq et al., 2009).

1.2.4.1 Foredune Erosion

Foredunes are the dune field's first defense against ocean water and waves (Davidson et al., 2020). Waves that surpass the beach and reach the dunes, which damage the morphology of the foredune. Rising sea levels, storm surges, and increased extreme weather can increase the risk of damage to foredunes (Hesp, 2002). Scarping is a type of erosion resulting in the mass removal of sand from the foredune. This changes the morphology of the foredune as well as weakens its ability to act as a protective buffer against sea level rise. One of the most significant controls of scarping is the height of seawater levels during the storm; a strong correlation is observed between high water level events and scarping (Davidson et al., 2020). Scarping also removes vegetation and creates a vertical scarp face which weakens the foredune. Scarping results in a near-vertical scarp face which can lead to slumping. In these cases, large masses of the dune slide down the scarp face leaving a slump block at the base of the foredune. Foredunes that have been eroded by waves through scarping or washovers are susceptible to wind erosion. Loose sand sediments exposed during wave erosion may be blown away by strong enough winds. Continued wind erosion can lead to large hollowed-out depressions in the dune called a blowout (Hesp, 2002). Foredunes continually subjected to erosion may move landwards over time causing a large-scale shrinking of the dune field (Davidson et al., 2020).

1.2.4.2 Foredune Erosion in Relation to Beach Width

Overall, the best indicators of susceptibility to dune retreat are pre-existing beach width (Burroughs and Tebbens, 2008). A wide beach allows for the greatest protection against erosion (Itzkin et al., 2021). The same study found that wide, tall foredunes last a longer amount of time when being eroded by storm waves (Itzkin et al., 2021). The study confirmed that the variability of foredune accumulation and erosion is highest in narrow beach sections and the variability of foredune accumulation and erosion is lowest at wider beaches. For beaches with widths narrower than 200-300 meters, the volume of the foredune increases as the beach width increases (Keijer et al., 2014). While wide beaches protect against foredune erosion, the level of storminess may overcome the barrier the beach creates. Recall Figure 1.1, despite the wide beach the foredune was still heavily eroded due to the extreme winds and waves present at Cavendish Beach during Hurricane Fiona.

1.2.5 Coastal Dune Fields

A dune field is a succession of secondary sand dunes running parallel to the water's edge. Dune fields range in width but can extend to several kilometers (Wolfe, 2014). Sand from the beach is transported via wind landward. A succession of plant species forms along the transect of the dune field. Overall, plant density tends to increase further away from the ocean's edge (Hesp, 2013). Pioneer plant species are replaced by shrubbery which in turn are replaced by trees.

1.2.5.1 Implications of Foredune Erosion on the Dune Field

The erosion of foredunes may affect the dune field. For example, transgressive dune fields are known for their landward movement (Hesp, 2013). They consist of many dune ridges and troughs. These dune fields are found in high wind and wave environments. A stable foredune protects the w

Sand dunes may be fixed, active, or partially active, mainly as a function of wind power and vegetation cover. The effects of climate change may cause fixed dune fields to develop into active dune fields, and vice versa (Yizhaq, 2009). This could cause a landward retreat of the coastline.

1.2.6 Implications of Climate Change on Coastal Sand Dunes

Greenhouse gases have caused anthropogenic global warming and changes in climate. Literature suggests that one effect of climate change is the increase of storminess, and extreme weather (Ebi et al., 2021). Both of these effects impact coastal areas. The connection between sand dunes to aerodynamic and hydrodynamic processes means that climate change may affect sand dunes.

1.2.6.1 Implications of Extreme Weather and Sea Level Rise on Sand Dunes

Variability in short-term weather causes higher than normal energy levels in storms. As mentioned above, wave and wind energy are directly connected to the geomorphology of coastlines, beaches, and sand dunes. For example, storms with higher waves may more easily reach beyond the highwater mark and erode sections of the foredune (Yizhaq, 2009). If natural conditions such as high tide and a narrow beach coincide with an extreme weather event foredune erosion may occur at a much higher volume than normal.

Additionally, an increase in erosion may be caused by sea level rise. Global warming has caused a significant melt of ice and snow stores. Additionally, warmer waters undergo thermal expansion. A phenomenon that results in the same amount of water taking up a larger volume because the ocean water has expanded. The higher levels of water can cause immersion of coastal areas reducing the buffer between waves and foredunes.

1.2.6.2 Sand Dunes as an Asset to Climate Change Adaptation

Anthropogenic climate change poses a threat not only to sand dunes but human life. Sand dunes are the first line of defense against flooding and seawater inundation. They act as a buffer zone between the ocean and forests, wetlands, human settlements, and infrastructure. Several studies highlight that a stable dune field is extremely beneficial for coastline protection and climate change adaptation (Burroughs and Tebbens, 2008; Itzkin et al., 2021). The importance of sand dunes goes beyond their intrinsic value, for many communities, the stability of sand dunes is vital to a community's well-being.

1.3 Research Questions

The research will examine foredune conditions and beach width to determine if eroded foredunes are found primarily adjacent to narrow beaches. Foredune scarping is often caused by high energy, infrequent wind, and wave events. A narrow beach provides little buffer between the foredune and waves. However, beach width is continually changing; the rate of beach width change compared to the rate of foredune recovery may impact the relationship between scarped foredunes and narrow beaches. Stive et al., (2002) found that beach width can change within the very long-term (century to millennia) to the short-term (hours to years). Scarped foredunes may be found adjacent to wide beaches because foredunes are more easily scarped at these locations (Yizhaq, 2009). Beach width may undergo short-term changes by widening after damages to a foredune occurs. My honours research will quantify beach width and foredune disturbances along the coast of Dune du Nord, Les Îles-de-la-Madeleine, Quebec.

Research questions include:

1. Is there a relationship between beach width and foredune disturbances?

2. Does chance play a role in whether a foredune will be scarped by waves?

3. Are there trends in the position of the foredune?

1.4 Overview

This thesis will first review the study area, by discussing the location at different scales including the Atlantic Ocean, Gulf of the Saint Lawrence, Les Îles-de-la-Madeleine, and Dune du Nord. This will be followed by the methods used and data collected including a detailed description of fieldwork and satellite image analysis. Chapter four will present the results of the study. This will be followed by a thorough discussion of the results of the study, including the meaning behind the data collected. The results will be compared to relevant literature. Chapter six will conclude the paper with final thoughts and a conclusion.

CHAPTER 2

Study Area

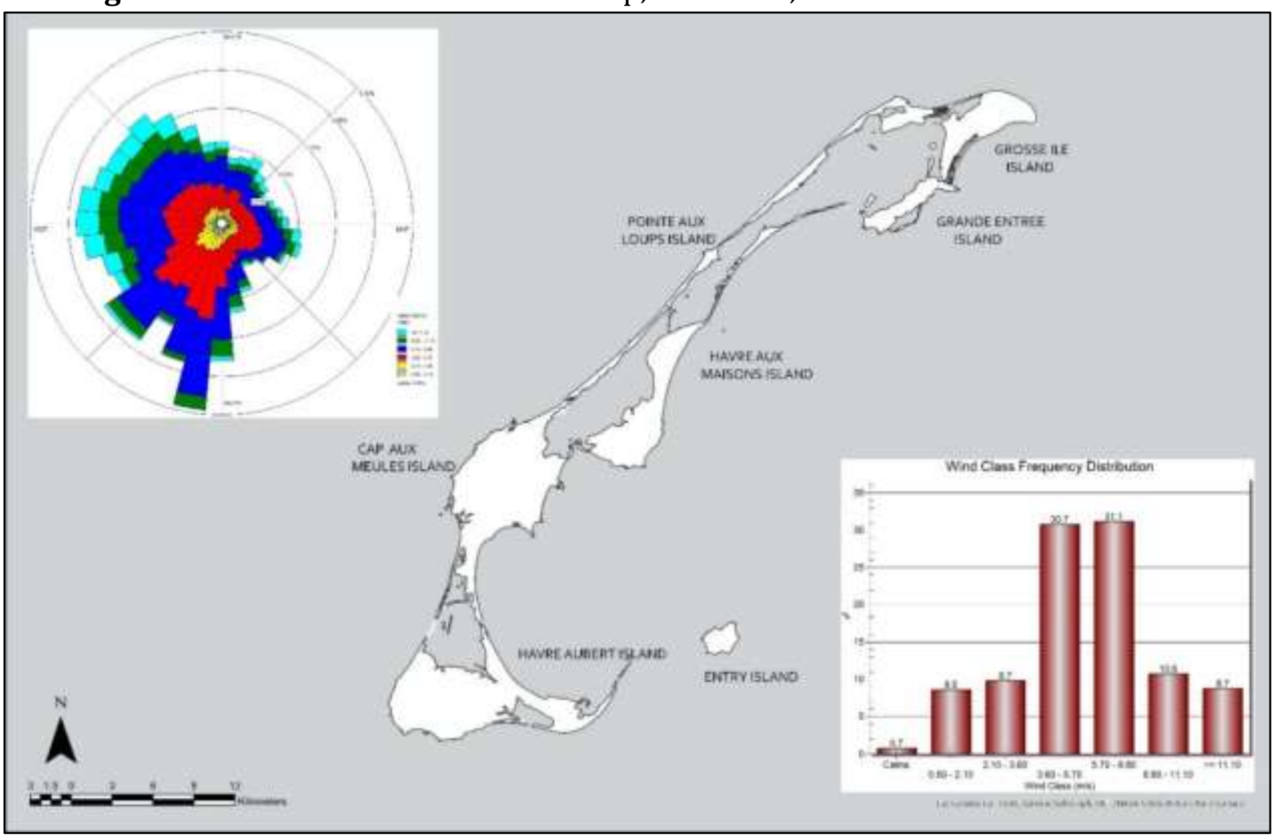
2.1 Les Îles-de-la-Madeleine: An Overview

Les Îles-de-la-Madeleine (also often called the Magdalen Islands) is a grouping of islands apart of the province of Quebec, Canada. Les Îles-de-la-Madeleine is an agglomeration of islands some of which are connected via tombolos, sand barriers, and manmade roads. As seen in Figure 2.1 the islands are located among Atlantic Canadian provinces in the Gulf of the Saint Lawrence. The water that makes up the gulf is supplied through rainfall, the maritime estuary, the Strait of Belle Isle, and the Cabot Strait. The gulf joins together 5 provinces: Quebec, Newfoundland and Labrador, Prince Edwards Island, Nova Scotia, and New Brunswick.

Figure 2.1 Les Îles-de-la-Madeleine in Atlantic Canada

Les Îles-de-la-Madeleine is an archipelago made up of several islands, eight of which are permanently populated and six of which are connected (see Figure 2.2). The island was formed by salt diapirs (Brisebois, 1981). Deformed, faulted, and brecciated mudstone, limestone, gypsum, and sandstone were raised above sea level as the salt diapirs rose due to the low density. The islands are formed from sandstone, siltstone, limestone, conglomerate, basalt pyroclastic rocks, and sediments (Slaymaker et al., 2020). Sediment erosion, transportation, and deposition are largely at the hand of wind and wave velocity. Prevailing winds move sediment along the shore on Dune du Nord, around the eastern side of the island depositing much of the sediments on the south-eastern side of the island.

Figure 2.2 Les Îles-de-la-Madeleine: map, wind rose, and wind class distribution



Data source: Government of Canada / Gouvernement du Canada. (2022, July 17). *Government of Canada / gouvernement du Canada*. Environment and Climate Change Canada. https://climate.weather.gc.ca/prods_servs/engineering_e.html

Les Îles-de-la-Madeleine has a boreal climate that was described by Slaymaker et al., (2020). On the island, January's mean temperature is −6.4 °C, while July's mean temperature is 17.1 °C, making for relatively mild winters and summers. Precipitation patterns are relatively stable year-round totaling to 1037 mm per year. The main defining feature of the islands are the wind patterns. Strong onshore winds occur year-round, driving waves in coastal waters. The wind rose and wind distribution bar graph presented in Figure 2.2 show these patterns (Government of Canada, 2022). The strongest winds occur in the winter ranging from 31 km per hour to 100 km per hour. Some of the strongest high-energy wind events occur in the early fall as hurricanes and post-tropical storms pass through the area. Climate change and land subsidence affect this region, as it's predicted that parts of this region will receive higher than average sea level changes (Wang et al., 2018).

2.2. Dune du Nord

Dune du Nord is a sub-section of the islands found on the northern shore of Les Îles-de-la-Madeleine. An approximately 15-kilometer section of Dune du Nord was used as the study area (as indicated by the red bracket in Figure 2.3). The beginning and end of the section are marked by the Pointe aux Loups Island and Caps aux Meules Island rock formations. Dune du Nord features continuous sand dunes supplied by the sandstone and siltstone sedimentary platforms found at the western and eastern edges of the study area. Waves have weathered sedimentary material from the rock formation. Longshore sand transport then supplies the beach with this weathered material to form the sand dunes and the beach. The area has approximately half of a kilometer-wide strip of dune field that barricades the ocean from the lagoon.

Figure 2.3 Study Area on Dune du Nord

The vegetation found within the study area is largely dependent on the distance from the shore. As mentioned in the literature review, dune fields tend to have a succession of vegetative species that can inhabit the land along a dune field. Closest to the water's edge sparse amounts of pioneer species such as marram grass (*Ammophila breviligulata*), sea rocket (*Cakile edentula)*, and dusty miller (*Jacobaea maritima)* can be found. Slightly further back, as soil conditions improve beach pea (*Lathyrus japonicus)* is able to grow. Figure 2.4a-2.4d shows examples of vegetation and how the plant often coexists in an area. Marram grass is the dominant species for several meters behind the foredune. The beach, foredune, and dune field of Dune du Nord located on the archipelago of Les Îles-de-la-Madeleine contains a wide variation in foredune condition and beach width. The following chapter will begin to discuss what data was collected to provide answers to the research questions presented in chapter one. Additionally, the methods used to collect data on Les Îles-de-la-Madeleine as well as through satellite imagery will be reviewed. The procedure for analysis of both these types of data will be described as well.

Figure 2.4 Common species found on the foredunes of Dune du Nord

a) Marram Grass
(*Ammophila breviligulata)*

b) Sea Rocket
(Cakile edentula)

c) Beach Pea
(*Lathyrus japonicus)*

d) Dusty Miller
(Jacobaea maritima)

CHAPTER 3

Data and Methods

3.1. Introduction

The data used for this project was collected from Dune du Nord on Les Îles-de-la-Madeleine. Data on the dune and beach morphology, vegetation patterns, as well as erosion and deposition patterns, were amassed. Fieldwork was coupled with GIS analysis of satellite imagery to provide input on both a spatial and temporal scale.

Two main methods were employed to collect data. Fieldwork was conducted in the study area to gather contemporary data on the foredunes and beaches within the study area. This allowed for a greater understanding of the overall patterns of foredunes and beach morphology. The second data collection method used satellite imagery. ArcGIS Pro Software was used to analyze these data. This method allowed for the temporal changes to be taken into consideration.

3.2. Field Data Collection

An approximate 15 km section was selected from Dune du Nord. This selection was based on a visual scan done with Google Earth images (Google, 2018). Three entry points to the beach, located roughly at the beginning, middle, and end of the section, were used to access the study area. From August 26th to 31st of 2022 a continuous visual survey was conducted along the study area. Eight categories were used to describe the condition of the foredunes.

One additional category, section nine, was added while in the field to indicate that the dunes were heavily impacted by human activities. This included entrances, a shipwreck, and ATV tracks. Section nine is considered an outlier. The remaining eight sections describe the physical characteristics of the dune and give insight into the differing coastal processes that occurred in recent history to form the sand dune. Figure 3.1 lists the eight classifications of foredune condition and provides example photos.

The classifications create categories in the continuum of foredune conditions. In the field, some foredunes did not clearly fit into a single category. Sections of the foredune that lay on the border between two classifications were assigned the best-fitting category. The location of the beginning and end (also referred to as the north and south points) of each classification was noted using GPS coordinates from a Garmin 60 CSX. The length of each foredune section was calculated using the Pythagorean theorem within ArcGIS Pro. The location data and the attribute data were then added to ArcGIS Pro, a geographic information system software.

Figure 3.1 Classification of foredune condition

1. Blowout

Blowouts are large depressions in the foredune caused by the removal of sand by wind.

There may be vegetation or incipient dunes beginning to form.

2. Fresh trimmed foredune

This class of foredune has a fresh cut, presumably from a wave causing a vegetation displacement.

There is no recovery or aeolian sand deposition.

3. Trimmed foredune, no ramp

This class implies a cut foredune with slightly more recovery than class two.

Minimal aeolian sand deposits are seen yet not enough to be considered a ramp.

Vegetation may be beginning to re-establish.

4. Foredune with partial ramp

This class has a wave-cut foredune, with a sand deposit forming a ramp one to three-quarters up the foredune.

5. Foredune with full ramp

This class is comprised of previously damaged foredune with an aeolian sand ramp formed over three-quarters up the slope.

6. Stable foredune, no wave cutting

This class is made up of foredunes with no evidence of wave cutting.

They are normally gently sloping with established vegetative growth.

7. Trimmed incipient dune in front of foredune

This class has foredunes with an incipient dune in front of it that has been trimmed.

Incipient dune might have a small scarp face and displaced vegetation.

8. Incipient dune, no trimming, prograding

Foredune with an incipient dune in front, both of which are stable, vegetated, and undergoing accumulation

Figure 3.2 Break in beach profile

The beach width was measured from the base of the foredune to the berm. The berm can be observed morphologically as a break in slope on the beach profile and is formed by wave action as seen in Figure 3.2. Profile morphology and vegetation (when present) were used to define the base of the foredune. The positions of the base of the foredune and the beach berm were recorded using GPS coordinates.

The morphology of foredunes was captured using topographic cross-sectional profiles similar to the methods used by Giles and McCann (1997). Cross-sectional profiles were conducted using a surveying tripod, level, and stadia rod. Continuous readings were taken from the stadia rod through the levels viewfinder along a cross-section of the beach and foredune. A total of 16 topographic profile points were collected, two for each of the eight classification categories listed above. The data were processed in Microsoft Excel, then plotted onto x, y graphs. Outputs from this procedure show the form of the surveyed foredune and beach. The elevation and distance along the cross-section of the beach and sand dune are plotted on the vertical and horizontal axis.

Vegetation is an indicator of stability in foredunes, as noted in chapter one. The presence of vegetation was noted along the length of each of the cross-sectional profiles. The types and locations of vegetation were noted, most commonly marram grass, beach pea, dusty miller, and sea rocket. The densities of Ammophila breviligulata (also called marram grass) were classified as very sparse, sparse, moderate, dense, and very dense (see Figure 3.3). The data collection allows for the assurance of normal vegetation patterns. Additionally, the data helps indicate progradation, stability, or erosion along a cross-sectional profile.

Five sets of sand samples were taken along the length of the beach. At each collection location, five samples were collected along the cross-section of the beach. Each sample weighed between 150 to 120 grams. All 25 sand samples were individually sieved using 2000, 1000, 500, 250, 125, and 63 μm sieves. The distribution was then calculated using the GRADISTAT calculator within Microsoft Excel (Blott & Pye, 2001). The five areas that sand was taken from along each of the cross-section locations include:

1. Edge of beach
    - Located at the break in the beach profile
    - Often characterized by a change in slope and beach litter (see Figure 3.2)
2. Middle of beach
    - Approximate midway point between the edge and top of the beach
3. Top of beach
    - Before the beach ends and the foredune begins
    - Marked by aeolian sand deposits

4. Front of foredune
    - The front-facing slope of the dune
5. Back of foredune
    - Behind the crest / high point of the dune

3.3. Analysis of Satellite Imagery in GIS

Satellite imagery was used as a secondary source of data. This allows the foredune conditions, beach width, and dune fields to be examined over a longer time scale. Satellite images were obtained from Google Earth and ArcGIS Pro (originally captured by Maxar Technologies). Data sets from 04/19/2003 and 06/05/2018 were selected based on availability and resolution quality. The 2003 data set was obtained from Google Earth and georeferenced into ArcGIS Pro. At this point in the analysis, the study area was trimmed because the 2003 satellite imagery covers just under 10km of the original study area. The 2018 data was taken directly from ArcGIS Pro's archive of satellite imagery. Both data sets have a WGS 1984 projected coordinate system and a resolution of .5 meters.

A total of 97 points were plotted within ArcGIS Pro to identify beach width and the location of the foredune in 100-meter increments along the study area. This data collection was done on 2003 and 2018 satellite imagery. A simplified classification system was employed because of the limitation of resolution quality. The classification system included:

1. Blowouts
2. Scarped foredune
3. Stable foredune
4. Incipient dune in front of foredune
5. Washovers and human-impacted dunes

Figure 3.3 *Ammophila breviligulata* density levels

a) Very Sparse

b) Sparse

c) Moderate

d) Dense

e) Very Dense

CHAPTER 4

Results

Five primary categories of data are discussed in chapter four: sand samples, vegetation, foredune condition, beach width, and foredune position. These categories of data describe different aspects of the study area and aim to answer the research questions outlined in chapter one.

4.1. Sand Samples

The result of the sand sampling produced data found in Table 4.1. The distribution of sand grain size along the length and width of the beach is represented in percentages. The Excel GRADISTAT calculator determined that the sand found in the study area in Dune du Nord is considered very well-sorted medium sand. Additionally, the samples are statistically considered to be unimodal and very well sorted. Each sand sample is divided by percentages into one of three categories: coarse sand, medium sand, and fine sand. Medium gain sand makes up the majority of each sample, followed by fine and coarse sand respectively. The distribution of sand size for each sample is shown in the respective cells. For instance, at collection location #1 the sample taken at the edge of the beach is made up of .6% coarse sand, 96.8% medium sand, and 2.6% fine sand. Although the samples are very well sorted, fine-grain sand is more abundant towards the back of the beach.

Table 4.1 Sand grain size distribution across the beach and foredune

	Edge of Beach	Middle of Beach	Top of Beach	Front of Dune	Back of Dune
Collection Location #1					
% Coarse Sand:	0.6%	0.9%	2.0%	0.7%	0.2%
% Medium Sand:	96.8%	97.9%	96.1%	93.2%	91.5%
% Fine Sand:	2.6%	1.2%	1.9%	6.1%	8.3%
Collection Location #2					
% Coarse Sand:	0.6%	2.1%	1.8%	0.3%	0.3%
% Medium Sand:	95.2%	96.4%	94.1%	97.2%	90.3%
% Fine Sand:	4.2%	1.5%	4.1%	2.5%	9.4%
Collection Location #3					
% Coarse Sand:	1.3%	1.7%	2.7%	1.3%	0.6%
% Medium Sand:	98.1%	97.9%	96.4%	97.2%	97.8%
% Fine Sand:	0.6%	0.4%	0.9%	1.5%	1.6%
Collection Location #4					
% Coarse Sand:	0.4%	0.5%	1.9%	0.7%	0.5%
% Medium Sand:	99.3%	98.0%	97.2%	95.2%	96.0%
% Fine Sand:	0.2%	1.5%	0.9%	4.1%	3.5%
Collection Location #5					
% Coarse Sand:	3.0%	1.8%	1.2%	0.3%	0.7%
% Medium Sand:	96.6%	97.7%	97.0%	96.9%	95.2%
% Fine Sand:	0.4%	0.5%	1.7%	2.8%	4.1%

4.2. Vegetation

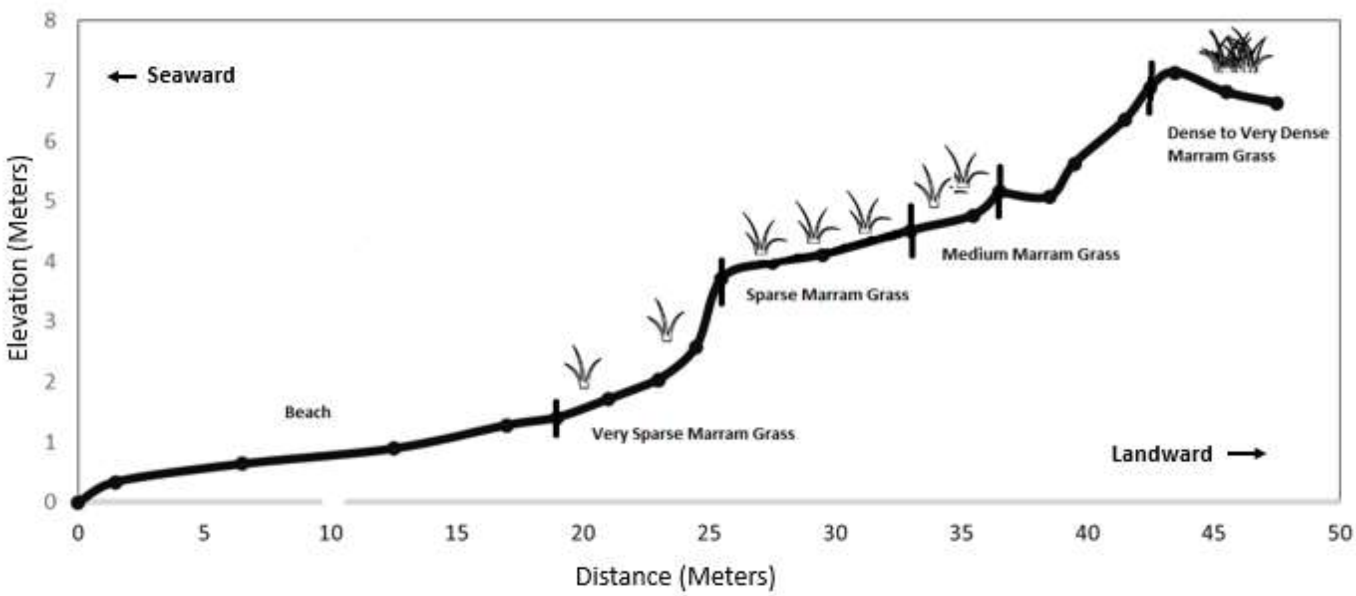
Observations of vegetation confirmed that the four primary species identified throughout the research area were: marram grass, sea rocket, beach pea, and dusty miller. The densities of each species were categorized as: very sparse, sparse, medium, dense, and very

Figure 4.1 Freshly scarped foredune with slump block

dense. The most abundant species found on the beach and the dune was marram grass (*Ammophila breviligulata*). Marram grass can be found from the top of the beach landward. Marram grass normally continued to grow along the stross face of the dune. Medium to dense marram grass was found on the crest and back of the foredune. In cases where scarping had occurred the stross face was left bare often with a slump block at the base of the dune, this is seen in Figure 4.1.

Sea Rocket (*Cakile edentula*) was found sporadically on the seaward side of the foredune. Beach Pea (*Lathyrus japonicus*) was found almost exclusively behind the dune crest, where conditions are further stabilized and have larger quantities of organic materials. Finally, dusty miller (Jacobaea maritima) was found occasionally on static areas of the beach, as well as on and behind the foredune. The general distribution of vegetation is illustrated in Figure 4.2.

Figure 4.2 Typical vegetation patterns across beach and foredune



Vegetation was found primarily in prograding and stable areas. These include the top of a wide beach, incipient dunes, gently sloping sand ramps, and the crest and back of a foredune. Vegetation was not found in areas that had been scarped by waves or in areas where the slope angle was very steep.

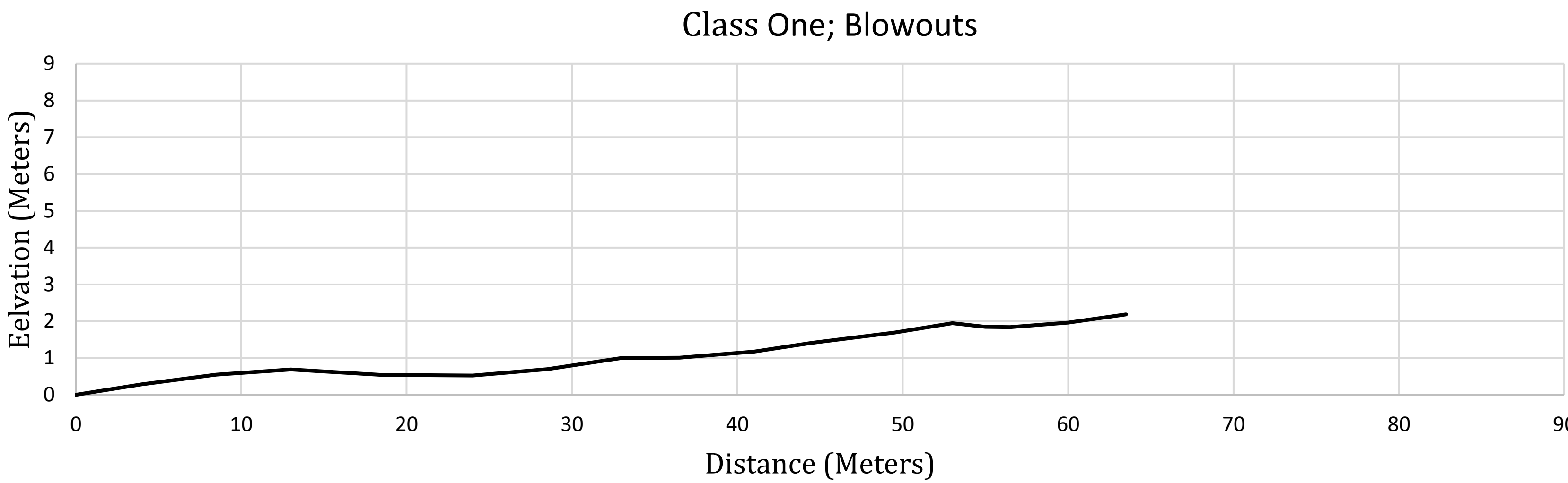
4.3. Classification of Foredune Condition

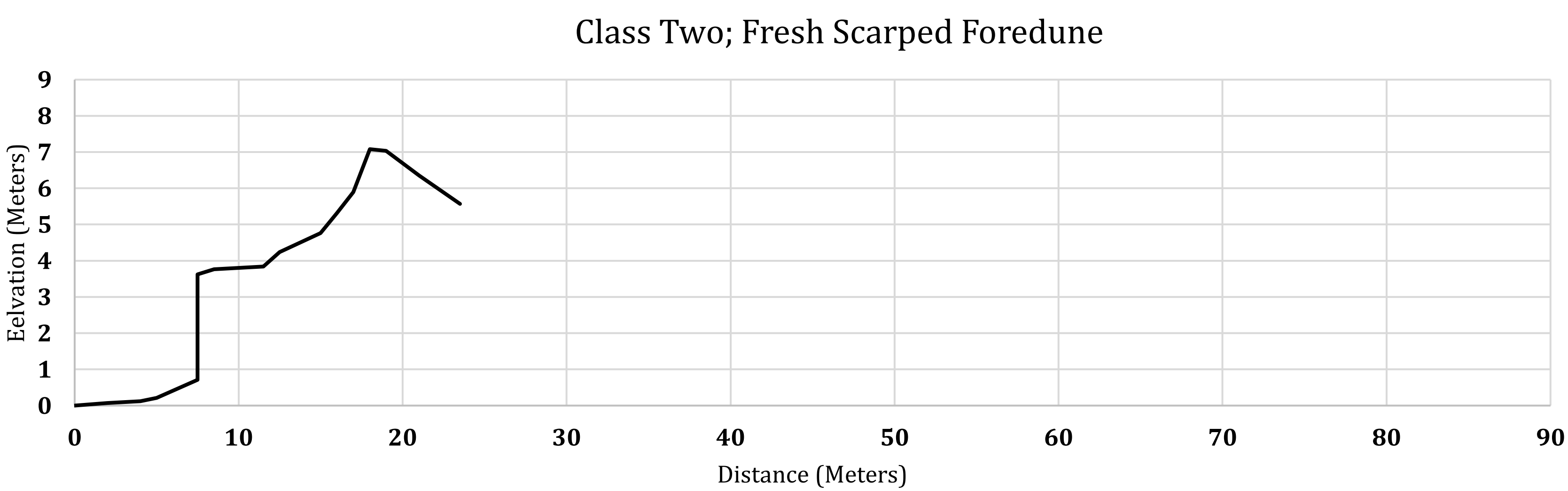
The foredune condition was assessed through topographic profiles and the classification system identified in Chapter Three. The classification system differentiates the various conditions of foredunes in the study area. Topographic profiles were collected to indicate the differing geomorphology of each classification. The condition of a sand dune can indicate its history of development, providing insight into the history of erosion or deposition.

4.3.1. Topographic Profiles

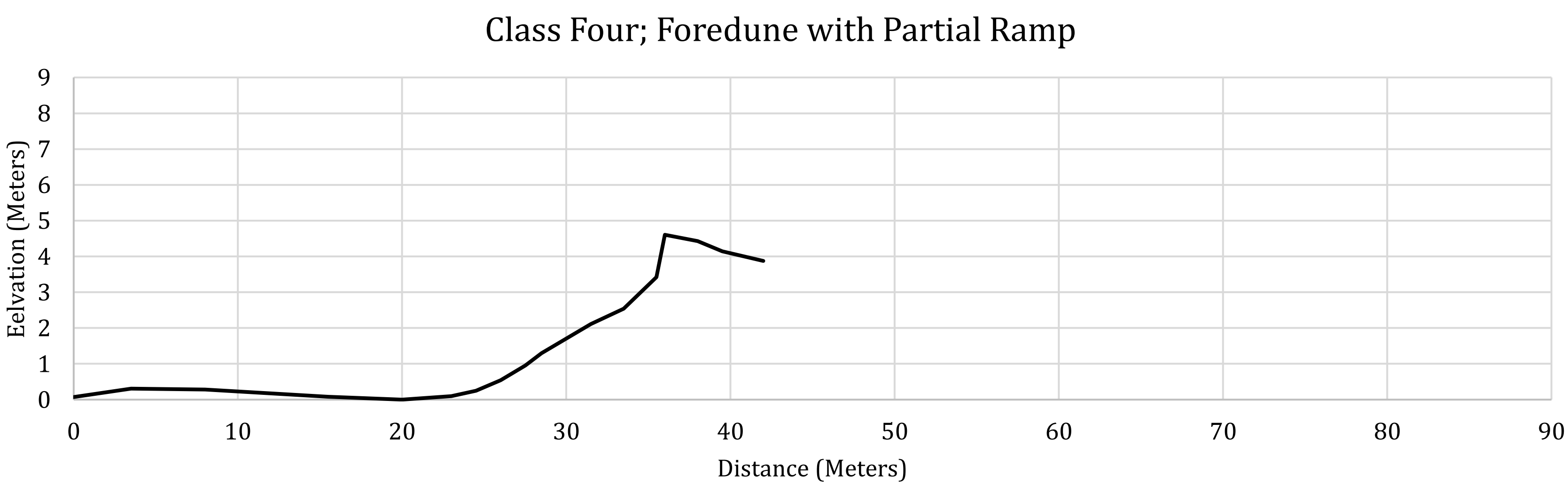
A total of 16 topographic profiles were collected, two for each classification of foredune the topographic profiles collected show the relief of the beach and foredune. The profile is taken from just the seaward of the beach berm to the back of the dune. Figure 4.3 displays one topographic profile for each classification of foredune condition. The vertical and horizontal axis of each profile are the same and therefore can be compared to one another. The cross sections provide a visual representation of the foredune's shape. Sharp angles normally indicated some form of scarping. Smooth curves are seen in foredunes shaped by the wind through erosion or deposition (class one, four, five, and six). The remaining eight topographic profiles can be found in the Appendix.

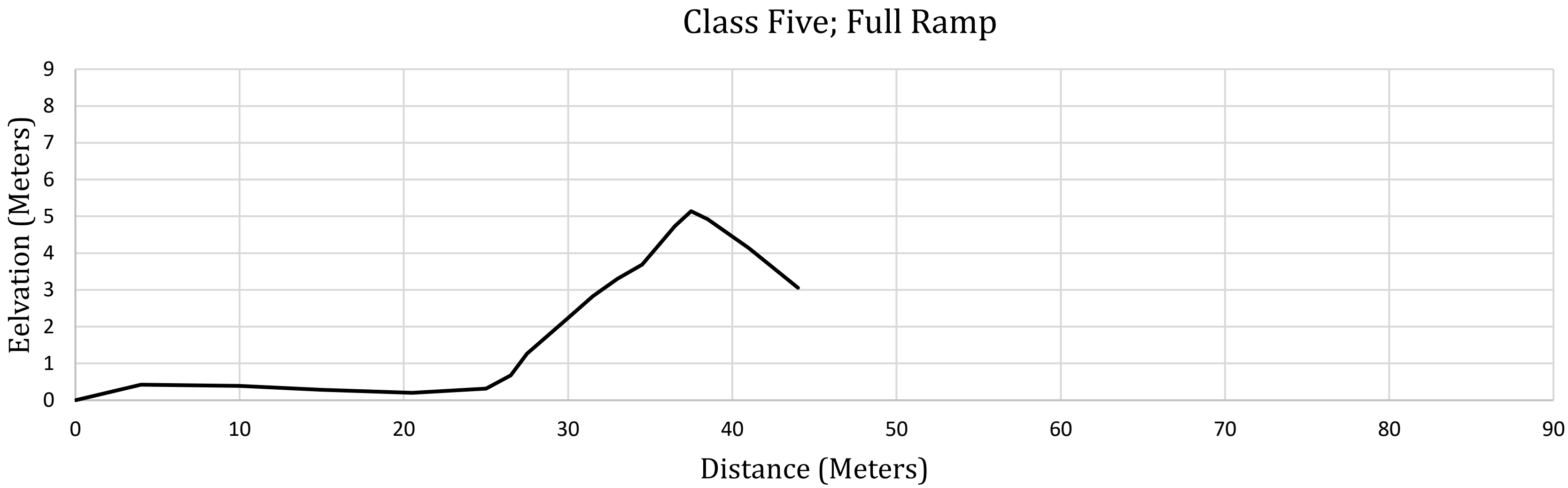
Figure 4.3 Topographic profiles of foredunes

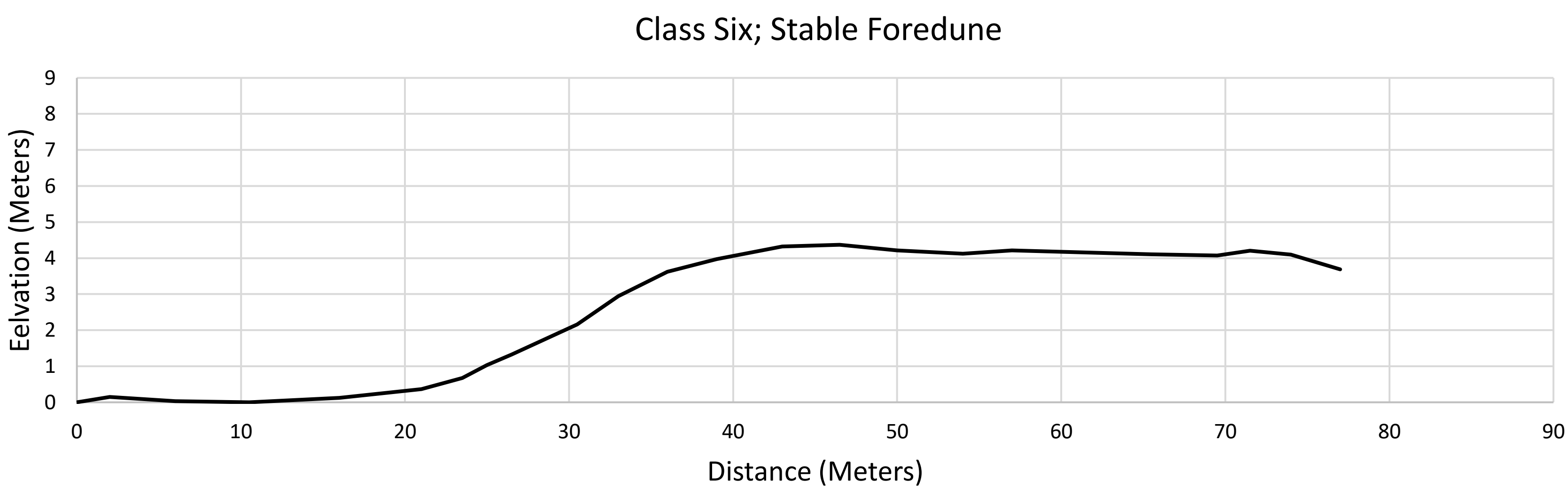


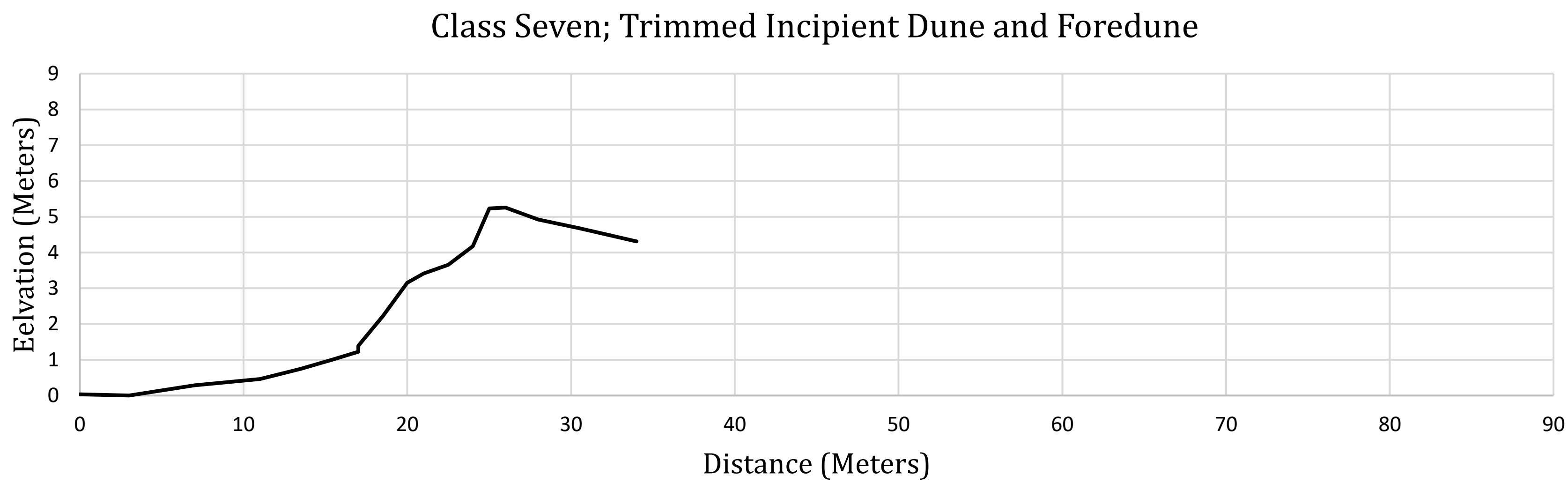


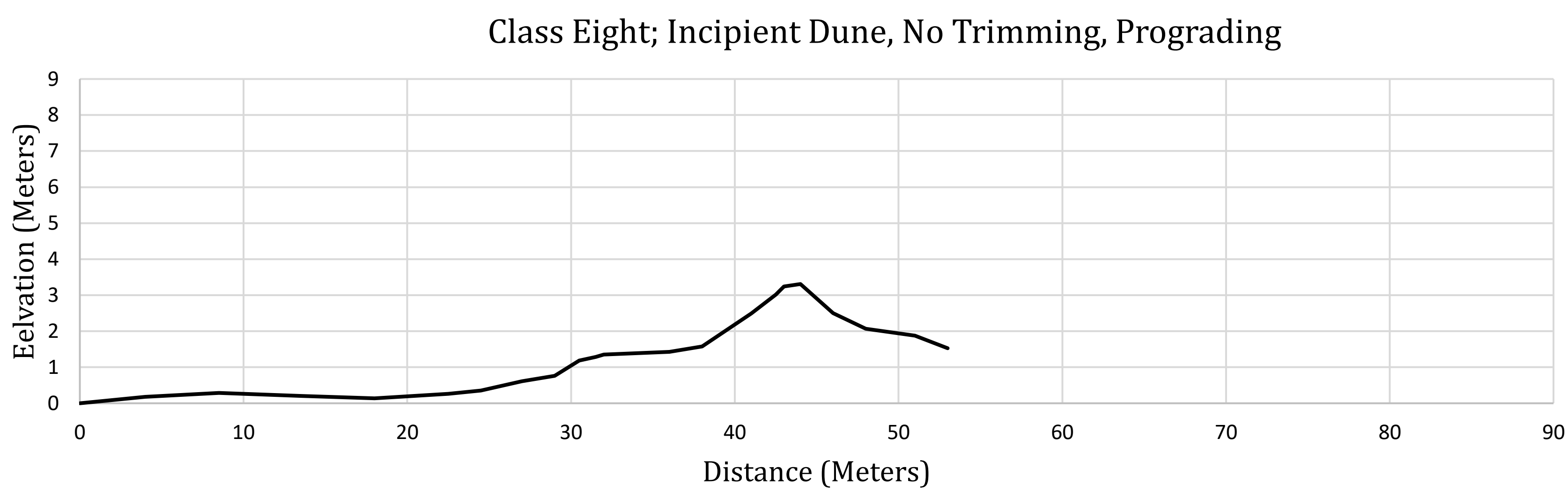

Class Three; Trimmed Foredune, No Ramp
Eelvation (Meters)
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class Four; Foredune with Partial Ramp
Eelvation (Meters)
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class Five; Full Ramp
Eelvation (Meters)
Distance (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90


Class Six; Stable Foredune
Eelvation (Meters)
Distance (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90


Class Seven; Trimmed Incipient Dune and Foredune
Eelvation (Meters)
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class Eight; Incipient Dune, No Trimming, Prograding
Eelvation (Meters)
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
Distance (Meters)

4.3.2. Visual Description of Foredune Condition in the Field

A total of 139 sections were identified along the study area as a result of the visual survey of foredune condition. The observations of foredune condition are found in Table 4.2. The findings show that all eight classifications were found in the study area. An additional category was implemented in the field to describe areas of the dune that were heavily impacted by human interaction or had washovers, this was labeled class nine.

Table 4.2 Foredune classification of condition on Dune du Nord, Ile de la Madeleine

CLASS	FREQUENCY OF SECTION	CUMULATIVE LENGTH (M)	MEAN LENGTH (M)	MAX LENGTH (M)	MIN LENGTH (M)
1	27	1580	59	320	22
2	1	21	21	21	21
3	26	3229	124	389	24
4	39	6685	171	538	43
5	5	493	99	138	56
6	23	3761	164	803	36
7	7	820	117	210	45
8	9	1137	126	232	35
9	2	183	92	111	73

This table displays the frequency (the number of times each section was found), cumulative length (the total length of all the sections in that class measured), and mean, the minimum and maximum length of section found in each class distribution of foredune condition found in the field. All measurements for cumulative, mean, maximum, and minimum length are in meters rounded to the nearest whole meter.

Class names: 1. Blowout, 2. Fresh trimmed foredune, 3. Trimmed foredune & no ramp, 4. Foredune with partial ramp, 5. Foredune with full ramp 6. Stable foredune & no wave cutting 7. Trimmed incipient dune in front of the foredune. 8. Incipient dune, no trimming, prograding

The least frequent section found was the fresh trimmed foredune at only one occurrence. The most frequent section found was class 4 (foredune with a partial ramp), 39 different sections were found totaling up to 6,685 meters.

4.3.3. Visual Description of Foredune Condition from Satellite Imagery

The visual description of the foredune condition using classifications was applied to satellite imagery to provide data on past foredune conditions. The results for the 2003 and 2018 data are found in Table 4.3 and Table 4.4 respectively.

Table 4.3 Foredune classification of condition on Dune du Nord, Ile de la Madeleine; 2003 satellite imagery

CLASS	FREQUENCY OF SECTION	CUMULATIVE LENGTH (M)	MEAN LENGTH (M)
1	20	3111	156
2	16	1796	112
3	7	1832	262
4	12	2953	246
5	6	1431	239

This table shows the breakdown of the foredune in the study area by classification as well that the cumulative length of each classification. All lengths are measured in meters and rounded to the nearest whole meter.

Table 4.4 Foredune classification of condition on
Dune du Nord, Ile de la Madeleine; 2018 satellite imagery

CLASS	FREQUENCY OF SECTION	CUMULATIVE LENGTH (M)	MEAN LENGTH (M)
1	19	2470	130
2	24	1931	80
3	10	1393	139
4	30	4718	157
5	7	609	87

This table shows the breakdown of the foredune in the study area by classification as well that the cumulative length of each classification. All lengths are measured in meters and rounded to the nearest whole meter.

All classifications were found, the most frequent in 2003 being blowouts and scarped foredunes while in 2018 it was incipient dunes and scarped foredunes. The least frequent for both data sets were class five and three (stable foredunes).

4.4. Beach Width

Results of the beach width measurements show spatial and temporal changes in the study area. Figure 4.4 is a photo taken of the study area; the red lines indicate how beach width varies along the study area. Satellite images allowed for an analysis of spatial and temporal changes in the beach width. A total of 97 points were measured for beach width, each spaced 100 meters apart from each other. Table 4.5 displays the beach widths for both the 2003 and 2018 data.

Figure 4.4 Spatial change in beach width

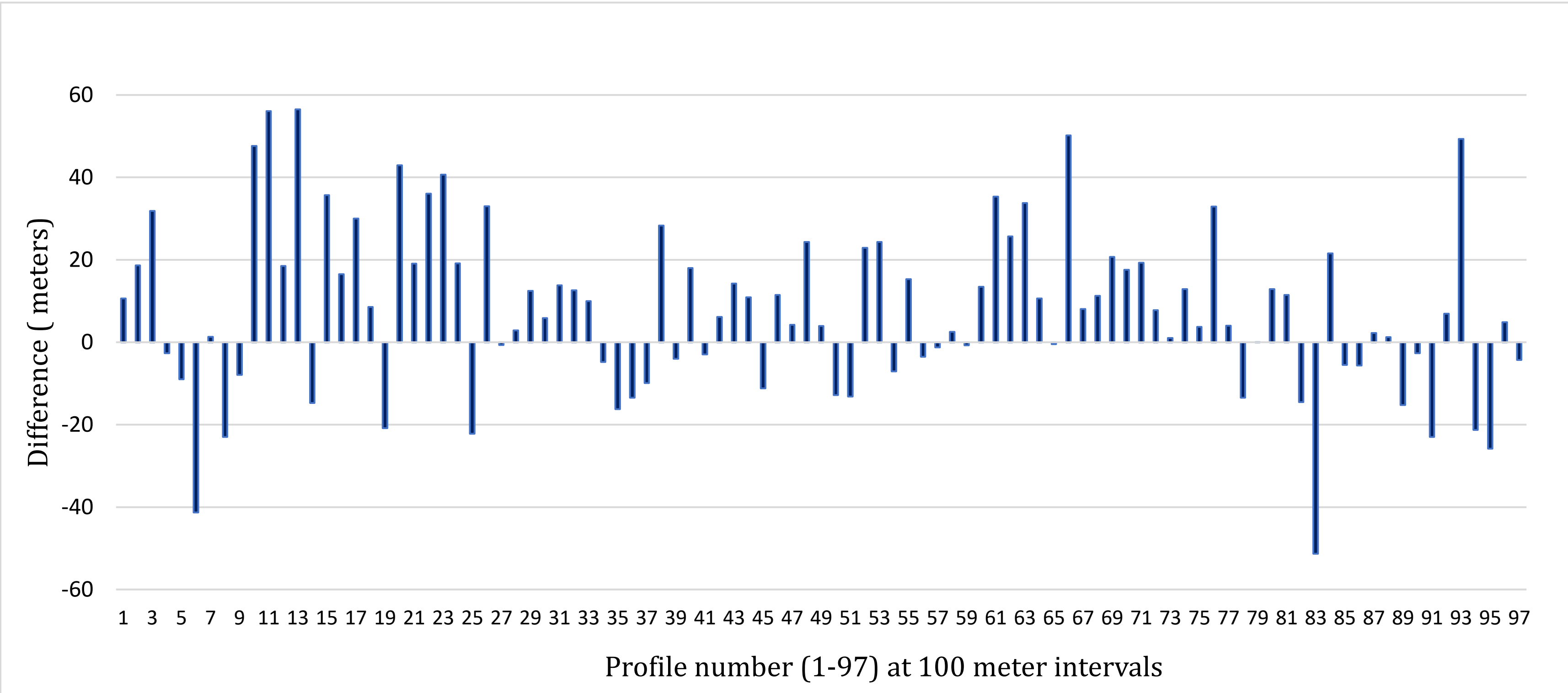
Table 4.5 Beach width along Dune Du Nord, 2003 and 2018

	COUNT	MEAN	MINIMUM	MAXIMUM	STANDARD DEVIATION
2003 WIDTH (METERS)	97	32	6	107	16
2018 WIDTH (METERS)	97	40	16	103	16
DIFFERENCE BETWEEN DATA (METERS)	97	8	0	56	20

The mean beach width (As seen in Table 4.5) summarizes the changes seen in beach width on Dune du Nord, however in some instances this statistic minimized the reality of the beach width change at an individual points seen in the data sets. Figure 4.5 shows the change in beach width at each collection location. The graph indicates that 62 collection locations experienced a widening in the beach, 33 collection locations experienced retreat and 2 collection locations saw no change in beach width. These values are the 2003 measurement subtracted from the 2018 beach width measurements.

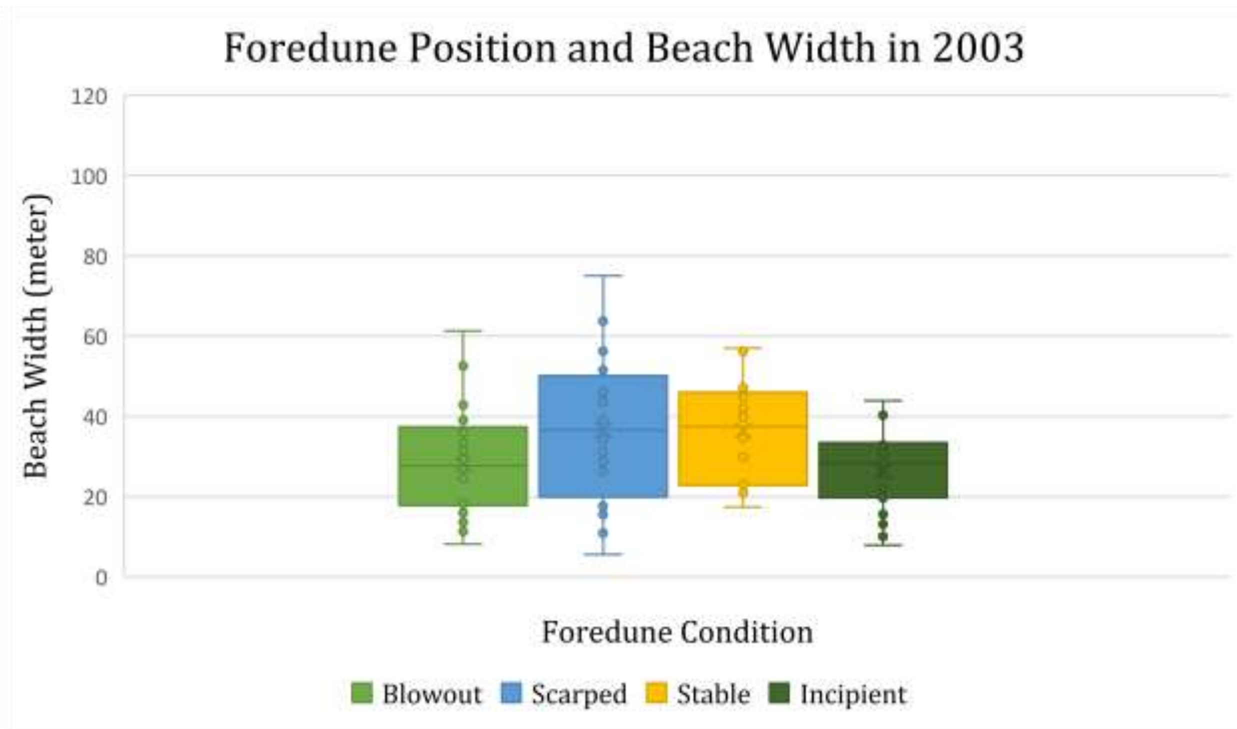
Figure 4.6 shows the beach widths associated with foredunes condition classifications. The vertical axes represent the width of the beach measured in meters. The plotted boxes indicate the foredune condition in relation to the beach width. The box indicates where the majority of data lies, while the lines extending represent the upper and lower extremes. The widest range in beach width is found particularly in front of scarped foredunes in both 2003 and 2018 data sets.

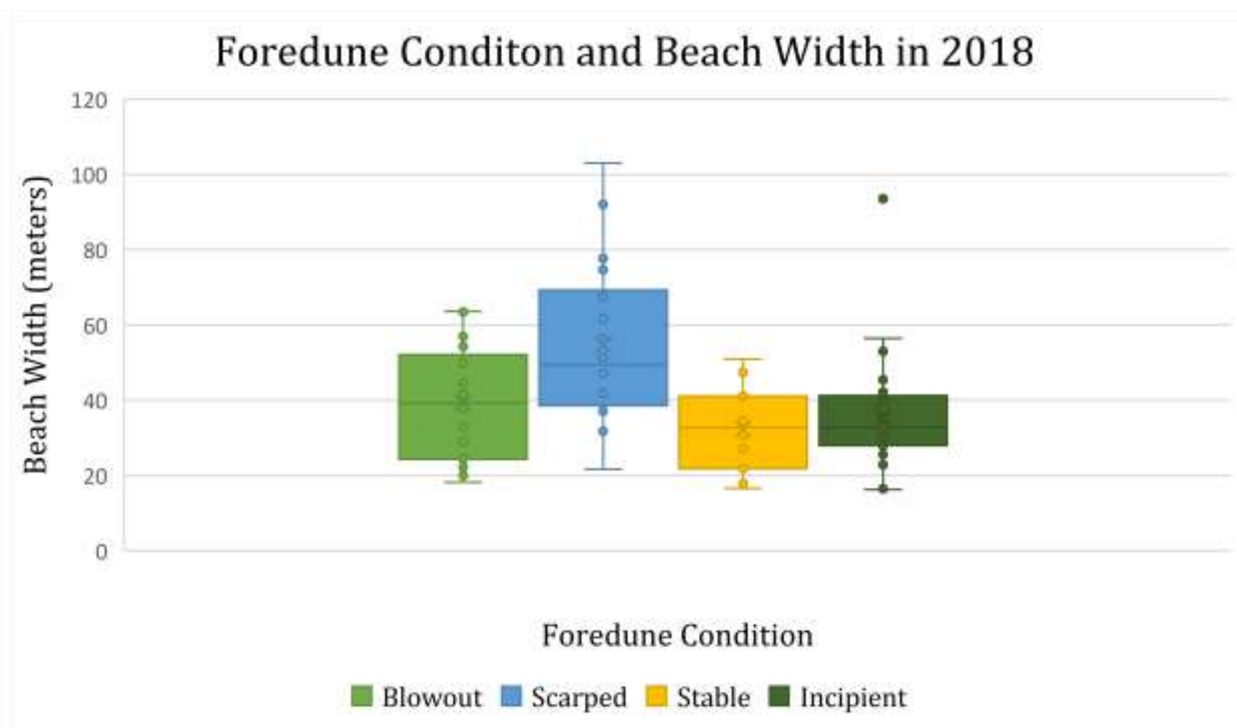
Figure 4.5 Differences in beach width measurements from 2003 to 2018



This figure graphs the changes in measurement of beach width at individual points in 100-meter intervals. The data from 2003 was subtracted from 2018 data. A negative value on the vertical axis indicates that the beach width narrowed, and a positive value indicates that the beach widened.

Figure 4.6 Relationship between foredune condition and beach width





4.5. Foredune Position

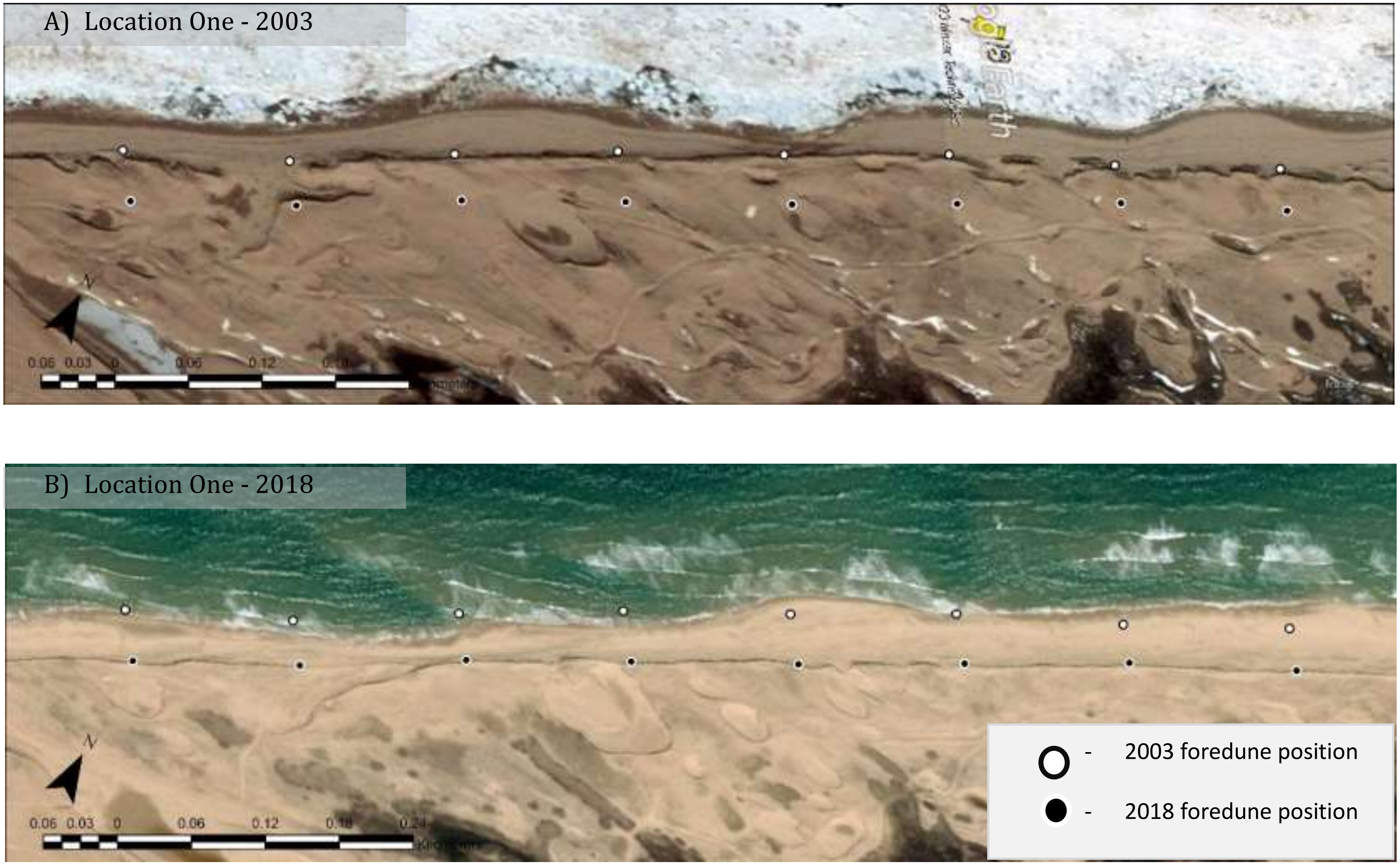
The results of the foredune position analysis showed the landward movement of the foredune over the 15 years between 2003 and 2018. 97 points were evaluated in 100-meter increments in both the 2003 and 2018 data. Table 4.6 shows that 87 out of the 97 points plotted retreated landward; this is almost 90% of the points. The ten remaining data points experienced progradation seaward. Three of these ten points were located close to a beached shipwreck which has significantly artificially modified the foredune and beach morphology. The results of the satellite image analysis are shown in Figure 4.7 in three staggered locations selected as examples. The image for each pair is at the exact same location and position, the only difference is the date of the images.

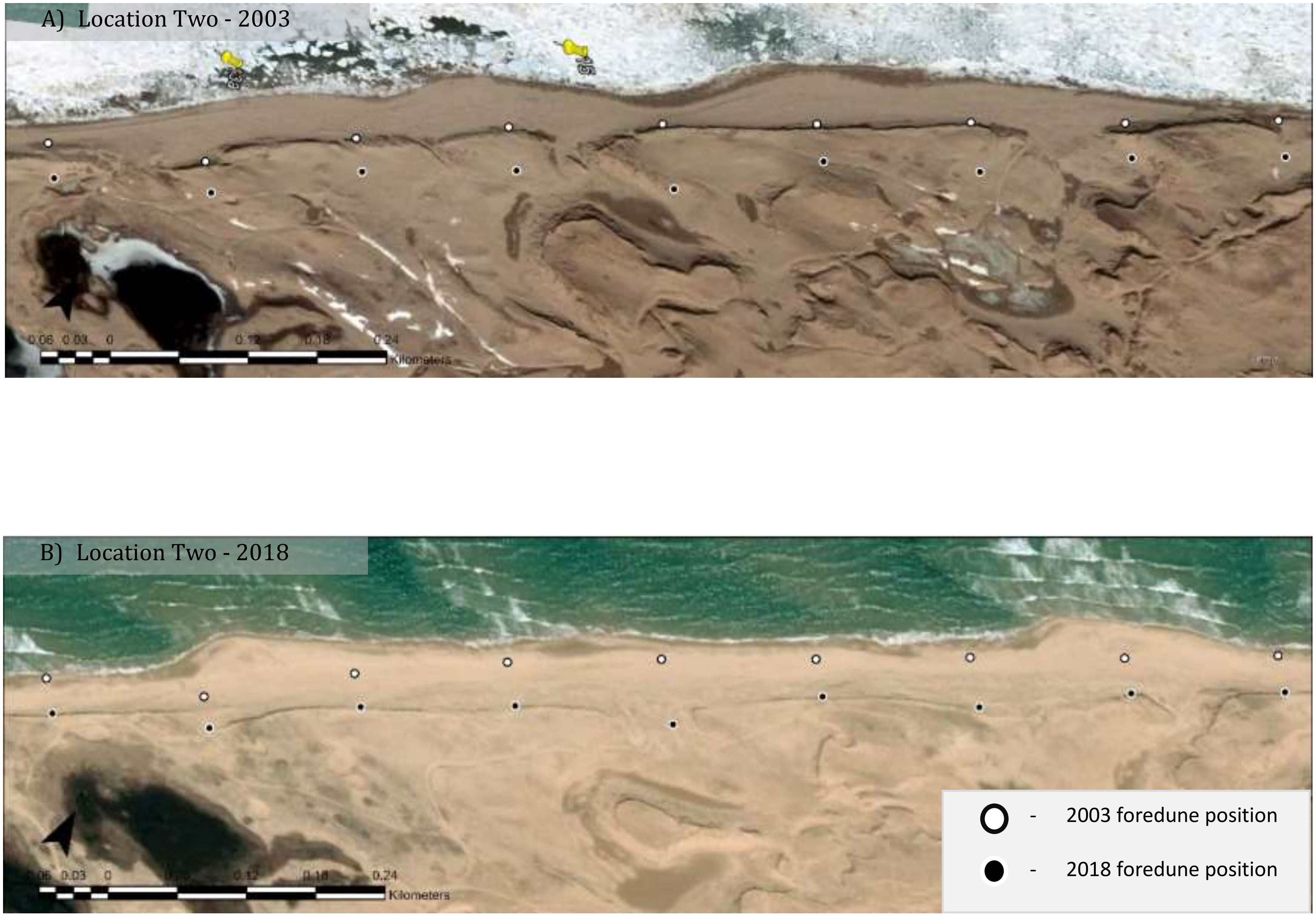
Table 4.6 Foredune position change (measured in meters) between 2003 and 2018

	COUNT	MEAN	MINIMUM	MAXIMUM	STANDARD DEVIATION
RETREAT	87	-27.4	-2	-90	15.6
PROGRADATION	10	12.1	0	27	8.1
ALL LOCATIONS	97	-22.9	0	90	15.9

This table shows the change in foredune position from 2003 to 2018. A negative value indicates a landward movement while a positive value indicates a seaward movement of the foredune.

Figure 4.7 Change in foredune position from 2003 to 2018 for three selected sections of coastline




A) Location Two - 2003
0.06 0.03 0 0.12 0.18 0.24
Kilometers
B) Location Two - 2018
0.06 0.03 0 0.12 0.18 0.24
Kilometers
- 2003 foredune position
- 2018 foredune position


C) Location Three - 2003
N
0.06 0.03 0 0.06 0.12 0.18 0.24
Kilometers


D) Location Three - 2018
N
0.06 0.03 0 0.06 0.12 0.18 0.24
Kilometers
- 2003 foredune position
- 2018 foredune position

CHAPTER 5

Discussion

5.1. Relationship Between Beach Width and Foredune Disturbance

No relationship was found between beach width and foredune disturbance within the study area on Dune du Nord. The width of a beach at a given location does not indicate the condition of the bordering foredune. Figure 4.6 shows the relationship between beach width and foredune conditions. The initial expectation was to see a correlation between narrower beaches and scarped foredunes; as well as wide beaches and stable foredunes. This was based on a study done by Yizhaq (2009) which indicates that foredunes are more easily scarped in front of narrower beaches. The opposite is true, wider beaches act as a protective barrier against wave erosion (Itzkin et al., 2021). Scarped foredunes in 2003 had adjacent beaches with widths ranging from 5 to 75 meters, a similar range was seen in the 2018 data with a range of 21 to 103 meters (see figure 4.6). Stable and prograding dunes in 2003 were found next to beaches 8 to 57 meters wide, similarly, these types of dunes were found next to beaches 16 to 94 meters wide in 2018. Results from field observations show that wider beaches were found adjacent to almost all the classifications of foredune condition. The one exception is the class two fresh trimmed foredune. The fieldwork results showed only one section of this classification and it was found next to a 5- to 10-meter-wide beach. This was the only instance of a fresh-cut foredune as the resolution of imagery data did not allow for this class to be distinguished among the scarped foredunes.

The rate of beach width change is a possible explanation as to why no correlation is found. Stive et al., (2002) found that beach width can change within a short period ranging from hours to years. Satellite beach width measurements showed both significant retreat and progradation at the individual points that were measured. This type of change is likely caused by seasonal climate variations in wave, tidal, and surge conditions (Stive et al., 2002). The rate of recovery for foredunes ranges drastically, depending on sediment supply, wind and wave conditions, as well as fetch width. Many studies agree that it most often takes decades (Castelle et al., 2017) (Walker & Hesp, 2013). Castelle et al., (2017) concluded that:

> "[E]ven after the most severe winter over the last 68 years in terms of average wave energy arriving at the coast, beach recovery can be a relatively fast process along high-energy sandy beaches backed by large dunes. In contrast foredune recovery, which timing and magnitude can provide a proxy measure for the resilience of the system to climatic variability and change, is a much slower process that can take years to decades." (p. 1)

Dune du Nord also had a wide range of dune heights (as seen in Figure: 4.3 and Appendix one) from two and a half to nine meters. Taller dunes were also seen on site but were not surveyed. Taller scarped foredunes (8-12 meters) take longer to recover than smaller foredunes (Houser et al., 2015; Mathew et al., 2010). The lack of correlation is caused by the difference between beach and foredune rate of recovery.

5.2. The Role of Chance in Foredune Scarping

There are three primary controls on dune scarping: water level height, beach width, and beach grain size (Davidson et al., 2020). Davidson et al., (2020) state that these "primary controls determine whether scarping will occur or not by either allowing or restricting high water level from reaching the toe of the foredune" (p. 938). In order for scarping to occur there must be high water levels, a narrow enough beach, and fine grain sand.

The sand sampling conducted within the study area showed that the entire length of the beach had very well-sorted medium sand. For the case of Dune du Nord beach width and water height (due to tidal range and weather-based conditions) are variables within this model. The location of foredune scarping is dependent on the location of narrower beach sections at the time of a high-water event/wave impact. Table 4.5 and Figure 4.5 indicated the change in beach width along the study area between 2003 and 2018. These shifts in beach widths are agreed upon by many researchers (e.g., Galiforni Silva et. al, 2019; Jiménez et al., 2016; Quartel et al., 2008). Because the width of the beach is continually changing the location of dune erosion is random as it's dependent on the alignment of beach width at the time of wave impact. The location of a foredune being scarped is up to chance, as it is dependent on the width of the adjacent beach at the time of wave impact.

Davidson et al., (2020) did not mention the impact of storm intensity on the primary controls. A storm with a high enough magnitude may have enough wave power to overcome the buffer of a wider beach to reach the foredune and cause erosion (Itzkin et al., 2021). In these scenarios, the limiting factor of narrow beaches may be largely overridden.

Figure: 1.1 is an example of this. In that scenario, hurricane Fiona generated a storm surge and large waves are able to erode foredunes behind a wide beach.

5.3. Trends of Foredune Position

The foredune position refers to the location (x, y, coordinates) of the start of the foredune ramp. Foredunes can stay stable, move landward or move seaward (Yizhaq et al., 2009). A landward movement of the foredune condition would be considered a retreating dune field, caused by a higher level of erosion than deposition. If the landward edge of a dune field remains stable a retreating foredune will eventually cause the dune field to thin. This could be problematic in situations such as Dune du Nord where the dune field acts as a barrier between the ocean and the lagoon. If a retreat occurs over time the likelihood of washouts increases. A seaward-moving dune field is called a prograding dune. This is where the foredune position moves towards the sea. If the back of the dune field remains stable then this could cause a thickening in the dune field.

Section 4.5 indicated that 90% of the data points saw a retreat in the foredunes. These observations could be a result of various factors. Generally, the largest force of erosion in a coastal beach environment is wave energy (Herbich and Haney, 1982). Scarping of the foredune weakens the structural integrity of the foredune. A scarped foredune is more susceptible to further erosion by either wave or wind. The removal of vegetation and sand through scarping creates an opportunity for blowouts to form. These are large depressions found along the foredunes. This process is driven by wind and can be difficult to recover from. Fieldwork done on the Les Îles-de-la-Madeleine shows that sections of blown-out foredunes are frequent. They were the second most frequent classification foredune condition.

Most scarping incidents occur as a result of a high-water event or a storm (Herbich and Haney, 1982). An increase in storminess could be a potential reason for the foredune retreat. Worldwide researchers have seen an increase in extreme weather. Little data is out on the storminess of the study area, however more broadly speaking Atlantic Canada has seen an increase in storminess (Wang et al., 2018). Rising sea levels may also be a cause of foredune retreat. Wang et al., 2018 (p. 349) stated that "Due to land subsidence, parts of Atlantic Canada are projected to experience relative sea-level change higher than the global average during the coming century (high confidence). This will cause an increase in the frequency and magnitude of extreme high water-level events.

5.4. Limitations

The limitation of this study defines the shortcomings of the research design and methods used to provide results which answer the research questions. Limitations may affect the validity of the results, discussion, and conclusions.

The resolution of the satellite imagery is a limitation when measuring beach width, identifying foredune position, and classifying foredune condition. The data that was used had a resolution of .5 meters. Any features on Dune du Nord that are smaller than .5 meters would be generalized within the data set. These generalizations make it difficult to identify foredune condition, the beach berm, and the dune toe, all of which are vital for analysis. A higher resolution of imagery would have provided greater detail of ground objects, which would allow for a more accurate analysis. This limitation in satellite imagery led to the simplified classification system described in Chapter Three. For example, the different classes of scarped foredunes identified in the field were simplified into one category for satellite image analysis.

The available satellite imagery for the study area, provide limited in time span to analyze. The data sets were from 2003 and 2018, providing a 15-year period to measure temporal change. The rate of foredune recovery occurs on a decadal scale; therefore, the time period may not be long enough to make observations about full foredune recovery. Older data sets would have allowed the study to provide results on the long-term changes in Dune du Nord.

The seasons in which the satellite imagery was collected is a limitation. The first data set was collected just after the winter season in April 2003; the second data set was collected in the summer season in June 2018. This results in a biased comparison as dune and beach morphology varies differently between seasons. A more accurate comparison would have evaluated imagery from the same season.

Finally, the measurement of beach width was done at regular 100-meter intervals. This sampling method may not account for patterns in beach width. For example, beach cusps occur on Dune du Nord as a series of horns and embayment. If the occurrence of beach cusps is repeatably patterned along the study area the measurement locations may be biased to a specific area in the beach cusp.

CHAPTER 6

Conclusion

Despite the limitations of the study, this research identified a lack of relationship between beach width and foredune condition, the role of chance in dune scarping, and the retreat of the foredune. The existing body of knowledge was reviewed in the literature review located in chapter one. Some areas of research that need further development were then presented in the form of research questions:

1. Is there a relationship between beach width and foredune disturbances?
2. Does chance play a role in whether a foredune will be scarped by waves?
3. Are there trends in the position of the foredune?

A 15-km stretch of beach and dunes located on Dune du Nord, Les Îles-de-la-Madeleine, was chosen for the study area. The methods of data collection utilized fieldwork and GIS software to amalgamate data. Five main categories of data were collected: sand samples, vegetation observations, foredune condition, beach width, and foredune position. Satellite imagery from 2003 and 2018 provided the ability to look at the temporal changes in the study area.

The results show that there is no correlation between beach width and foredune condition. Beach width changes faster than foredunes recover, and this allows for wider and narrower beaches to be found in front of scarped and unscarped foredunes. Additionally, the results showed that the likelihood of a foredune being scarped is largely up to chance. Finally, data on the foredune position showed that between 2003 and 2018 there was a landward retreat of the foredune position. The long-term implications of this trend could cause an increase in washovers and deterioration of the dune field.

Further research is needed to develop the existing body of knowledge. Replicating this study in a different location may provide additional insight. Key controls in the rate of change of beach width and dune recovery should be identified and modeled. Integration of computer modeling would allow for differing circumstances to be accounted for as researchers work toward predicting and preparing for a changing environment.

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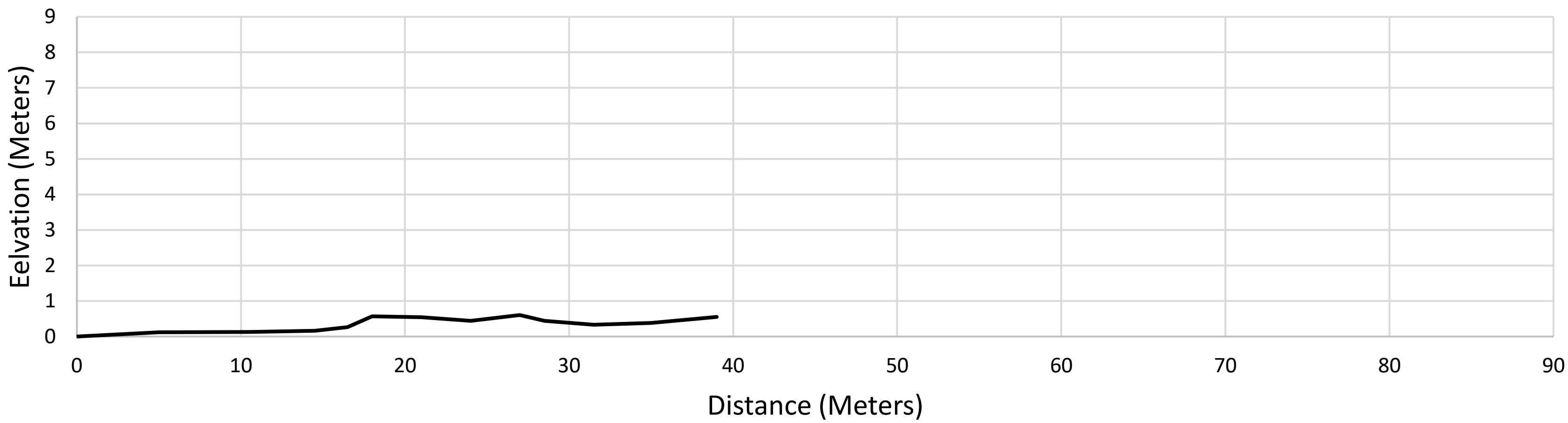
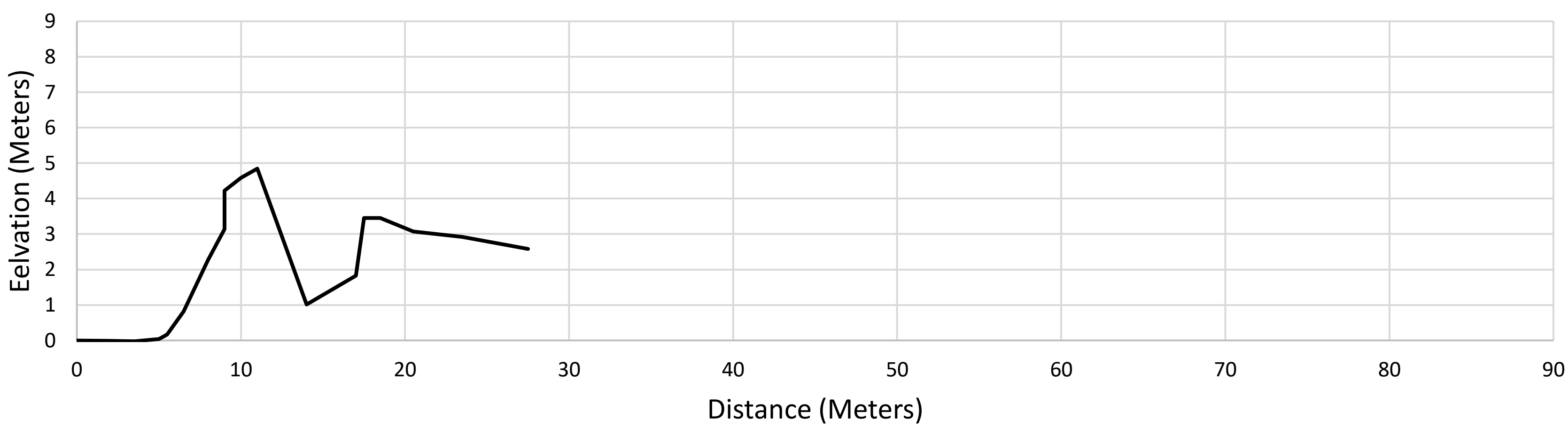
APPENDIX

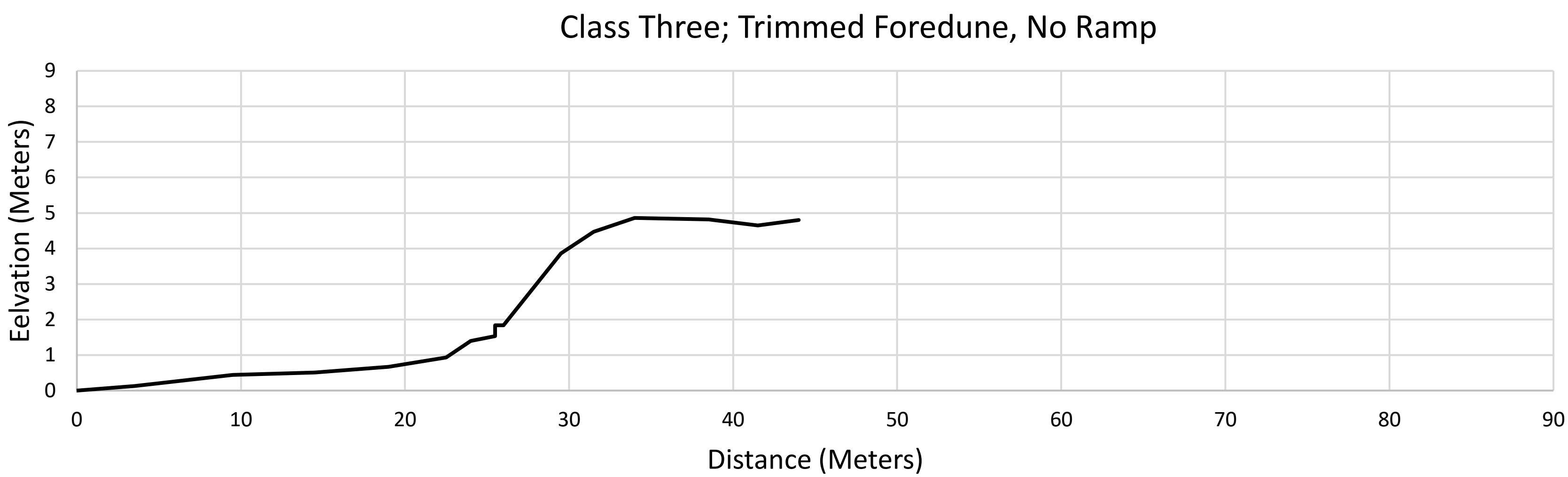
Topographic Profiles from Les Îles-de-la-Madeleine

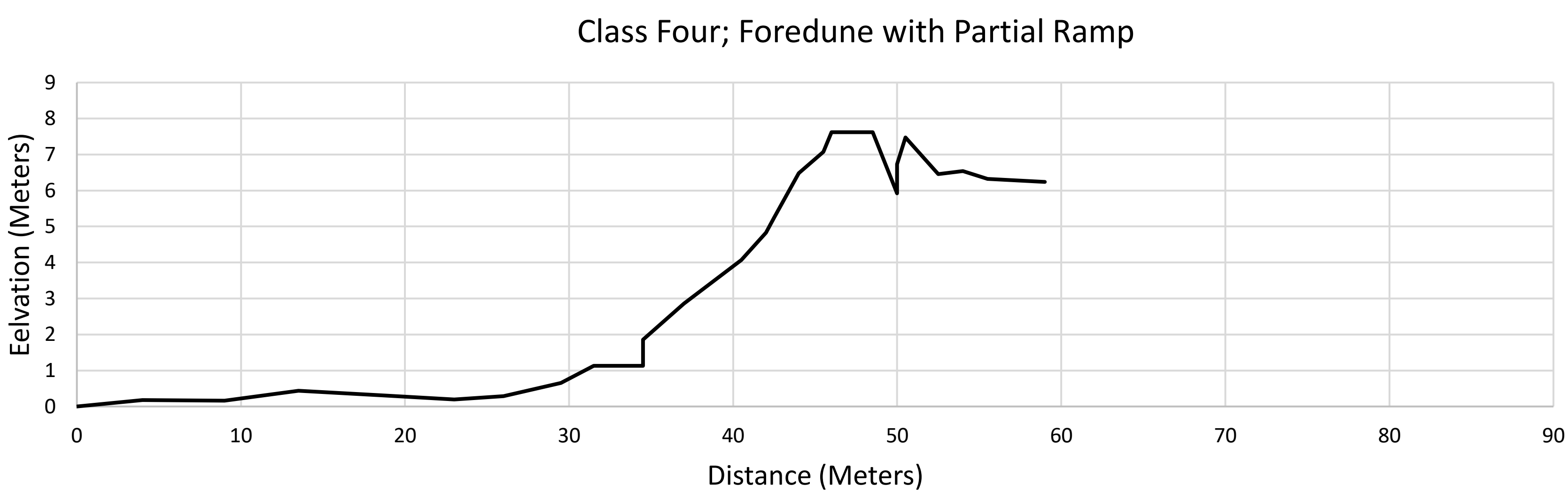
Class One; Blowout

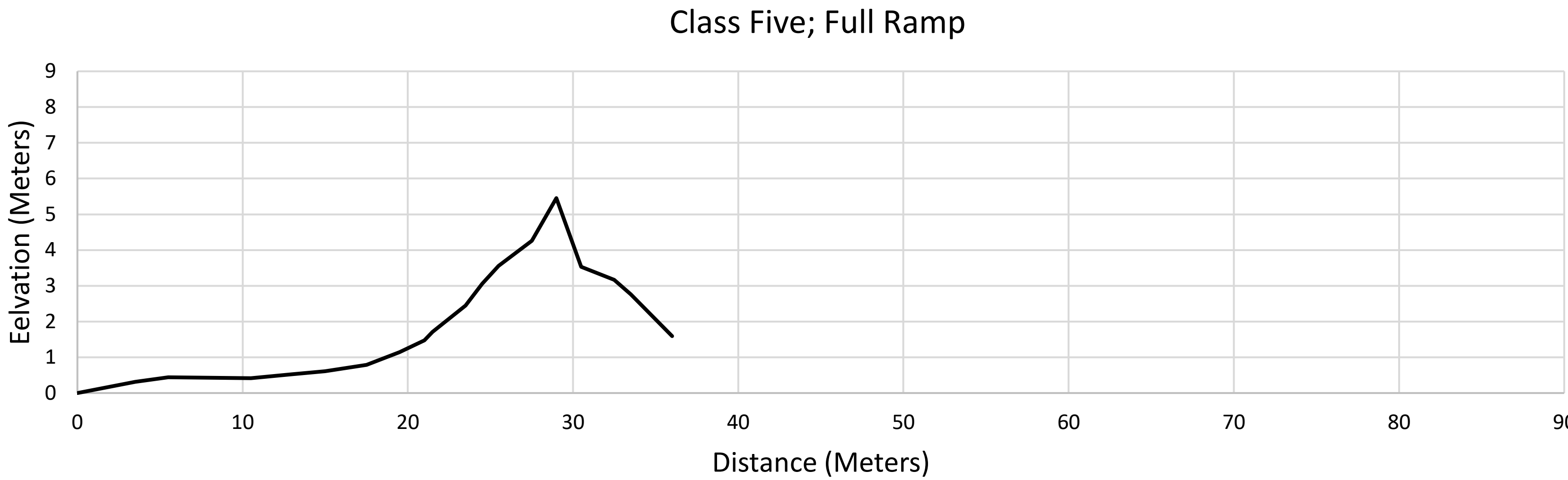


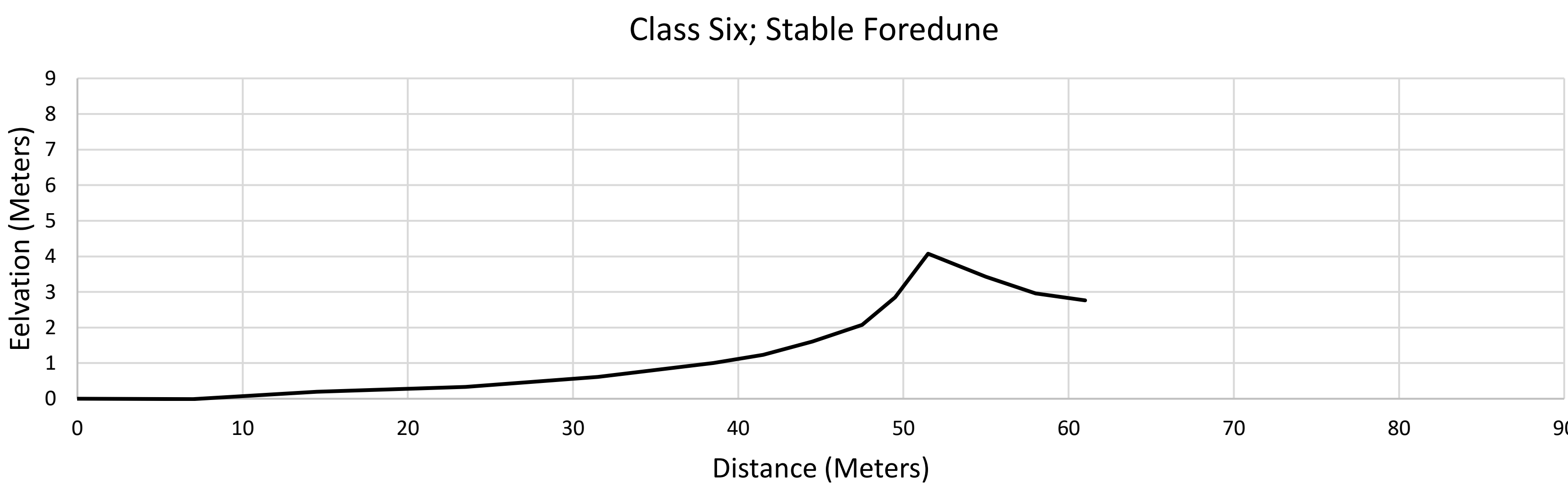
Class Two; Fresh Scarped Fordune

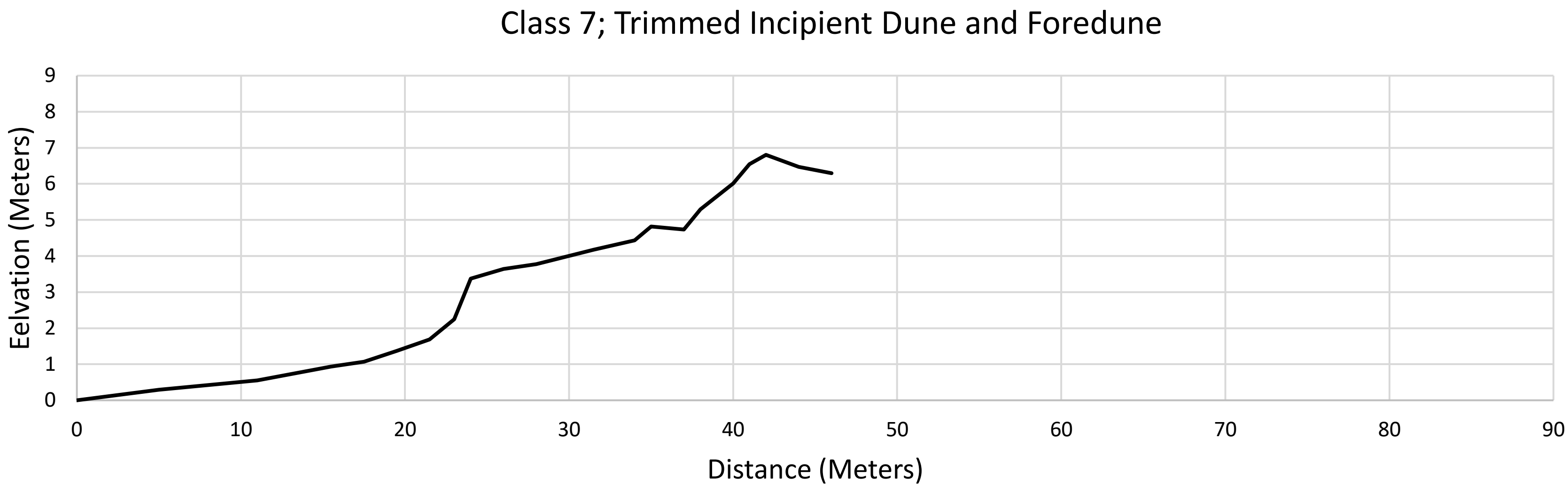


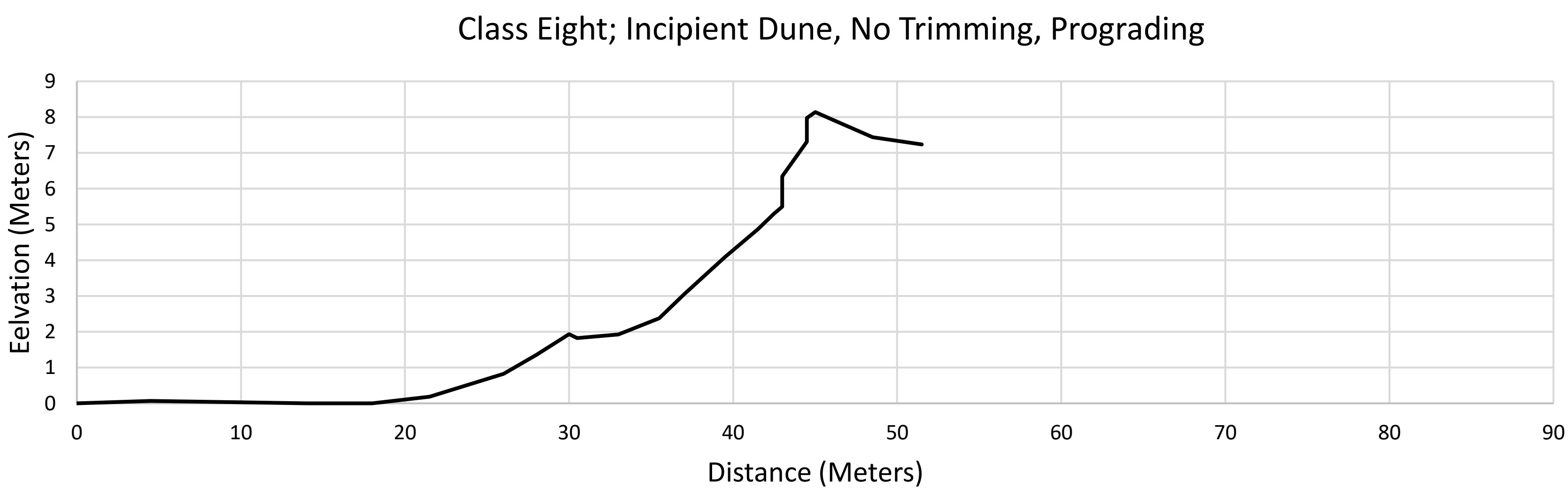

Class Three; Trimmed Foredune, No Ramp
Eelvation (Meters)
Distance (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90


Class Four; Foredune with Partial Ramp
Eelvation (Meters)
Distance (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90


Class Five; Full Ramp
Eelvation (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class Six; Stable Foredune
Eelvation (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class 7; Trimmed Incipient Dune and Foredune
Eelvation (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
Distance (Meters)


Class Eight; Incipient Dune, No Trimming, Prograding
Eelvation (Meters)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
Distance (Meters)