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ABSTRACT

Coastal dune systems are becoming increasingly vulnerable to erosion and washover due to sea-level rise and changes in storm activity with changing climate. The impact, however, is not consistent within and across coastal barriers and there is a need to examine the alongshore variability of beach-dune systems to understand dune resiliency. This includes vegetation, which is responsible for trapping transported sediment and initiating dune formation and varies alongshore in response to a poorly understood eco-geomorphological feedback. Identifying how beach-dune systems and vegetation vary alongshore is important for understanding their resiliency. In previous studies it has been suggested that this feedback leads to scale-invariant foredunes in which the maximum potential dune height is directly related to the distance between vegetation and the shoreline (L_{veg}). There is, however, no corresponding field data to support this model result across and within barrier systems. This study involves the collection of field data from three beaches along the North Shore of Prince Edward Island, Canada. The dune systems are primarily vegetated by *Ammophila breviligulata* and vegetation density ranged from 0% to 100% beyond the dune crest, with considerable variability alongshore and between sites. The alongshore variability of the vegetation and its relationship to the morphology of the dune was examined using a 1x1m digital elevation model generated from Structure for Motion using Unoccupied Aerial Vehicles and LiDAR topobathy collected by CBCL Limited. Results suggest that dune morphology is not scale-invariant and that the relationship between dune height and vegetation is dependent on storm surge and beach envelope limits to the establishment of vegetation. Comparison to previously published data from a range of sites supports the scale-variant relationship identified in this study and suggest the need to consider development as a combination of transport, supply, and history.

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1. Introduction

Coastal sand dunes are an integral, landforms of coastal barriers that act as the first line of defence against storm surges and sea-level rise. Found along the coastlines of Canada, the United States, Europe, Australia, and other locations where dune forming conditions exist, dunes are recognized for playing an important role protecting ecosystems and infrastructure farther inland. The development and subsequent evolution of a dune depends on the exchange of sediment between the nearshore and beach (Swift, 1976; Pye, 1980; Aagaard et al., 2004; Houser, 2009), transport by wind from the beach and backshore (Bauer and Davidson-Arnott, 2003), and captured by vegetation (Nickling and Davidson-Arnott 1990; Davidson-Arnott, 2005; Davidson-Arnott et al., 2005). As a result of these interactions, Stallins (2002), describes barrier island dunes as responsive bio-geomorphic systems as opposed to an independent and isolated landform. The behaviour of this eco-geomorphological system is important for the long-term stability and resiliency of coastal barriers in response to sea-level rise and extreme storm events (Stallins, 2002; Feagin, 2015). Climate change has the potential to significantly affect the magnitude, frequency and direction of storm waves and currents (Dugan et al., 2013; Duran and Moore, 2013; Charbonneau et al., 2016). When combined with a rise in sea level and anthropogenic forcing, this has the potential to cause dune erosion (Ollerhead et al., 2013) that in turn reduces barrier resiliency (Moore et al., 2010; Zinnert et al., 2011; Duran and Moore, 2015; Lalimi et al., 2017).

Vegetation is an important if not central control on this eco-geomorphological system and key to coastal dune stability and formation by trapping and fixing sediment (Short and Hesp, 1982; Hesp, 1988; Hesp, 2002; Psuty, 2008; Walker et al., 2013; Lalimi et al., 2017). The distribution of vegetation within beach-dune systems is driven by species-specific tolerances to environmental stressors (Maun, 2009) whereby different species having varying tolerances to sediment burial, salt spray, and wave run up. Burial tolerant species like beach grass develop along the front of the dune closer to the shore because they can withstand moderate slat/saline spray and thrive in moderate sediment burial conditions/environments (Maun, 2009). These species promote vertical growth of a foredune increasing its resilience to washover (Stallins and Parker, 2003). Woody shrubs develop in the back barrier of dune systems because they have very low tolerance to stress caused by the sea; these species create stability in mature dunes (Maun, 2009).

As dunes develop and evolve, they in turn influences environmental forcing and distribution of vegetation (Young et al., 2011; Brantley et al., 2014; Lalimi et al., 2017) and the feedbacks amongst vegetation, topography, sediment supply and other coastal variables create considerable variability in the morphology of the beach-dune system alongshore. As a result, the dune system will respond differently alongshore to the same conditions, with areas of weakness (i.e. low dunes) making adjacent areas vulnerable to erosion. The result is a dune morphology that is not in 'equilibrium' with sediment supply and aeolian transport alone, which suggest that most beach-dune systems may not be scale-invariant. In other words, adjacency and history may be as or more important than the relatively simple exchange of sediment amongst nearshore, beach, and dune.

The scale-invariant model developed by Duran and Moore (2013) is based on the assumption that vegetation zonation is the primary control on maximum potential dune height. Specifically, they argue that the height of the foredunes is directly dependent on the distance of the vegetation to the shoreline (L_{veg}), shoreline defined by the Mean High-Water Level (MHWL) for their study, and the rate of sediment transport (Figure 1). In contrast, Davidson-Arnott et al., (2018) present evidence to suggest that sediment supply from the nearshore to beach to dune determines foredune height and volume and that dune height would increase as the fetch effect (Bauer and Davidson-Arnott, 2003) and sediment supply (Houser, 2009) increase. Neither of these models, however, consider how the relationship between the morphology of the dune and vegetation zonation is dependent on the erosion and recovery history of the dune system

(Davidson-Arnott, 2005; Houser et al., 2018). To test these competing models requires that the relationship between L_{veg} and dune height is examined within and between sites. If the Duran and Moore (2013) model holds for dune systems, then we would expect that there would be no variation in the gradient of a line connecting the dune crest and shoreline (Figure 2A.) with increasing $L_{veg.}$ If, however, sediment supply is the dominant control, then an increasing slope would be expected with increasing L_{veg} (Figure 2B.). If, however, dune morphology and vegetation zonation are controlled by the history of storm activity and sea level rise, a decrease in slope would be expected with an increasing $L_{veg.}$ (Figure 2C.). A comparison of previously published data suggests that coastal dunes in a real-world setting may not be scale-invariant, and that some combination of transport, supply, and history are not accounted for in the Duran and Moore (2013) model (Figure 3). The purpose of this study is to collect data from three sites along the North Shore of Prince Edward Island, Canada (PEI) and test the scale-invariant model of Duran and Moore (2013) as well as characterize the alongshore variability of vegetation and its relationship to beach-dune morphology.

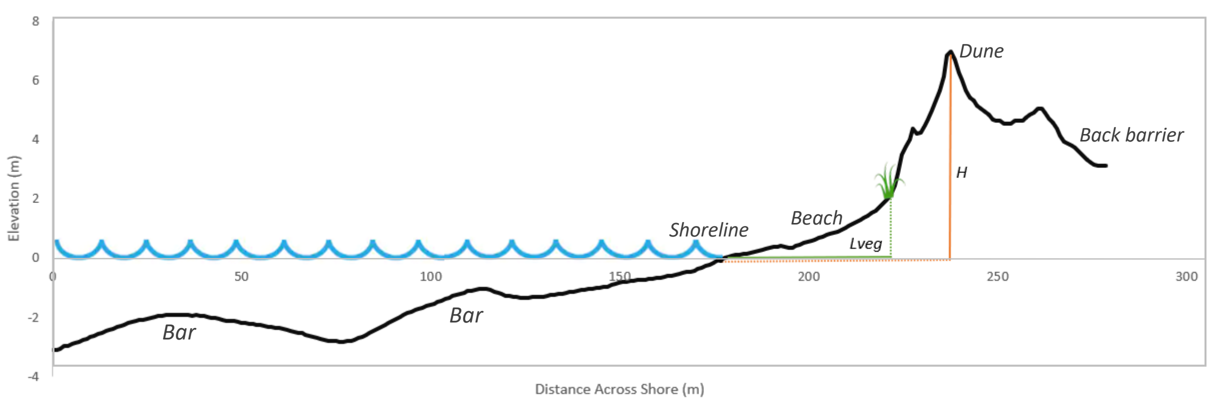


Figure 1. Cross shore profile showing L_{veg} or the distance from the shore the minimum vegetation extent and *H* or dune height.

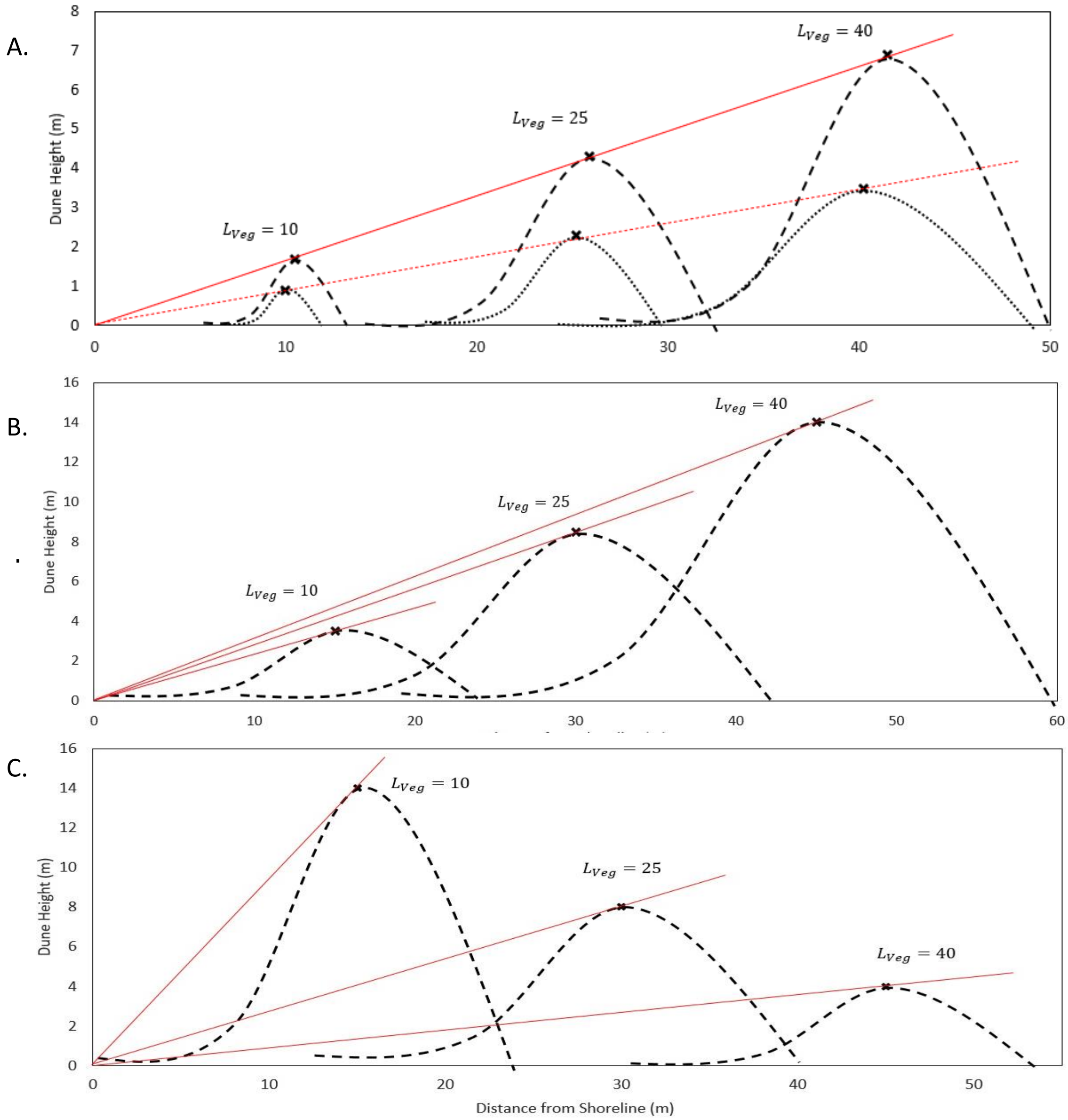


Figure 2. Possible scale-dependent beach-dune morphology shown are (A) the scale-invariant model of Duran and Moore (2013) with high (solid red line) and low (dashed red line) sediment transport as well as alterative scenarios in which (B) supply is the limiting factor and (C) transport is the limiting factor.

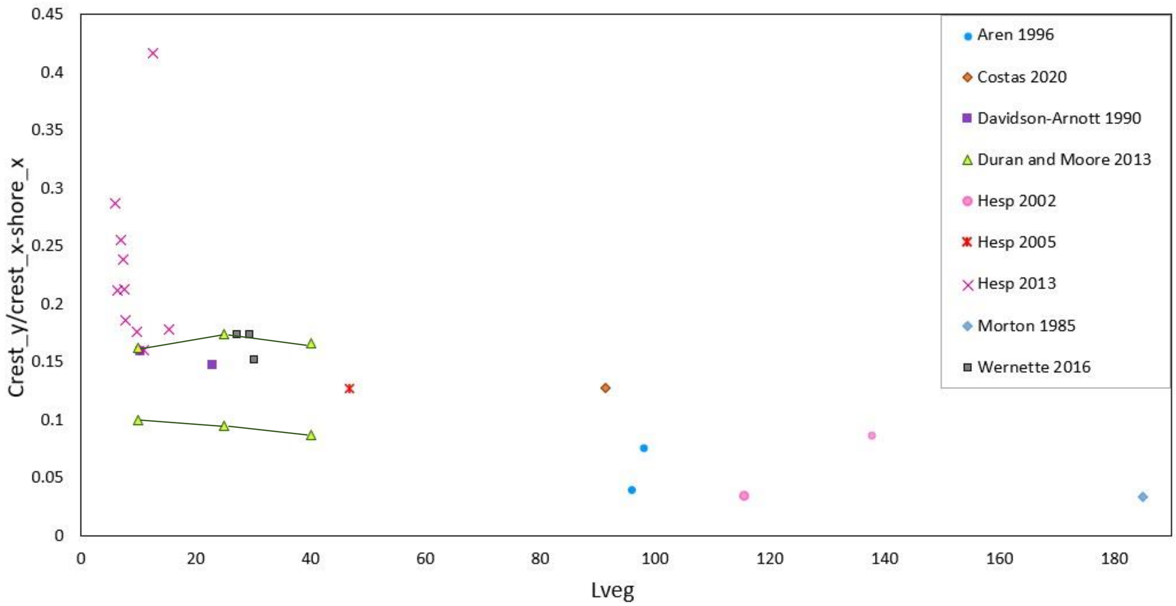


Figure 3. Previously published data of L_{veg}, against the ratio of crest elevation and crest distance from the shoreline. These are plotted with the Duran and Moore (2013) modeled profiles to show comparison.

2. Literature Review

2.1 Sediment exchange

A true test of the L_{veg} model requires an understanding of the different parts of the beach-dune system. The exchange of sediment between the nearshore, beach, and dune is necessary for dune development, growth and recovery. In this respect foredune growth is controlled by the sediment supply and the rate of transport by wind across the beachface (Davidson-Arnott and Law, 1990; Hesp, 2002; Davidson-Arnott, 2018). The nearshore and beach are the primary sources of sand to the dunes and also act as a sink for sediment eroded from the dunes during storms. It follows that the evolution and recovery of dunes result from the spatial and temporal coupling of nearshore and aeolian processes (Houser, 2009). Sediment from the nearshore is transported landward to the beach by the onshore migration and welding of nearshore bars, providing a supply of sediment that may be supplied to the dune by aeolian transport across the beach. The rate of dune formation then depends on wind regime, wave action, temperature, precipitation, sediment supply, sediment size, and vegetation type and density (Jennings, 1964; Ritchie, 1972; Borowka, 1980; Short and Hesp, 1982; Pye, 1982, 1983; Hesp,1989; Klijn, 1990; Davidson-Arnott at al., 2008; Bauer at al., 2009, Zarnetske et al., 2012, 2015; Houser and Ellis, 2013; Moore et al., 2018; Ruggiero et al., 2018; Houser at al., 2018).

How and when sediment is transported from the nearshore, beach and dune is still poorly understood, but it is increasingly recognized that it is episodic and not continuous. For example, wind speeds increase during storms allowing for greater transport potential from the backshore to the dunes, but storms also result in a narrowing of the beachface as the storm surge extends into the backshore. This creates a narrow spatial and temporal window for sediment exchange from the beach to the dune, particularly when the wind angle is directly onshore. As the wind angle becomes more oblique, the fetch increases allowing for greater transport potential, but the sediment is being transported alongshore not directly to the dunes

(Bauer and Davidson-Arnott, 2003). If the supply of sediment is continuous then the foredune will grow in width and height, and the beach sediment budget will become negative leading to a lowering of the beachface (Psuty, 1988). Over a long period of time (tens of years) the continual increase in foredune growth would require a corresponding supply of sediment from the nearshore. Without a positive beach budget, a negative feedback cycle would begin through the narrowing of the beach and scarping of the dune through wave action (Psuty, 1988; Davidson-Arnott and Law, 1990). Changes in sediment supply from offshore and alongshore sources and increasing distance from the sediment source (river estuary, eroding sandy cliff, etc), combined with changes in storm activity (wave heights, direction, wind speed, duration, etc.) and sea level rise have the potential to cause widespread dune erosion and overwash. Understanding how sediment is exchanged and the role that vegetation plays in trapping sediment is therefore key to understanding barrier resiliency -the ability to recover in both form and (morphological, ecological, and economic) function following a storm.

2.2 Dune formation

2.2.1 Aeolian transport-fetch and sediment supply

Dunes have the potential to develop when and where there is adequate sediment supply (Swift, 1976), and sufficient fetch for the exchange of sediment between the beach and backshore (Bauer and Davidson-Arnott, 2003), and vegetation to capture sediment (Nickling and Davidson-Arnott, 1990; Davidson-Arnott, 2005; Davidson-Arnott et al., 2005; Houser and Ellis, 2013). There is a critical fetch length or minimum distance required for sediment transport to reach its maximum (Owen, 1964; Bauer and Davidson-Arnott, 2003; Houser, 2009). As beach width decreases with tidal range, storm surge, and wave run-up the amount of sediment transported does not reach its fullest potential because the beach width is less than the critical fetch (Bauer et al., 2009; Houser, 2009). Critical fetch is often dependent on the spatial distribution of surface moisture due to precipitation and tide, which are the primary controls on sediment transport (Sarre, 1989; Arens, 1996; Yang and Davidson-Arnott, 2005; Houser, 2009).

Low-angle dissipative beaches have the greatest potential for sediment transportation because of the wide fetch, high wave energy, and a wide surf zone with multiple parallel bars (Houser, 2009; Houser et al., 2015). According to Short and Hesp (1982), dissipative beaches cause the least disturbance to boundary-layer development and have the highest potential for large foredunes. As beach slope increases so does flow disturbance, therefore, less wind and wave energy are available for beach and dune development on reflective beaches (Short and Hesp, 1982; Houser, 2009). This is partly moderated by the angle of the wind, which determines the length and slope for boundary layer development, meaning that there is a trade-off between fetch length and wind angle (Bauer and Davidson-Arnott, 2003). Onshore winds at a high angle to the coast increase total sediment transport to the dune system, but there is often a smaller fetch in this direction especially on narrow beaches. As winds become oblique or more shore parallel there is a reduction of sediment transported to the dune system but there is potentially a longer fetch. The amount of aeolian sediment transport across beaches is dependent on this interaction between fetch length and wind angle (Bauer and Davidson-Arnott, 2003).

2.2.2 Trapping by vegetation

Vegetation is required for foredune development as it traps sediment that has been transported from the beach to the dunes by wind. Grasses accumulate sediment more efficiently than woody species or shrubs because of their flexible stems which allow them to move with the wind (Gilbert and Ripley, 2010; Feagin et al., 2015). The spatial pattern of deposition in the foredunes is controlled by wind velocity, dune topography, and vegetation type and density (Hesp, 2002). The impact of vegetation on sediment flow depends on vegetation density, distribution, and height (Hesp, 2002). Airflow created by wind is modified by the topography of vegetation as it increases the surface roughness (z_0) of sand surfaces which reduces the energy of saltating gains and wind velocity trapping sediment. This is one of the essential requirements for dune formation along with prevailing onshore winds above threshold wind velocity and a continuous supply of sediment (Maun, 2009). Plant density is the primary factor in determining z_0, followed by plant height and wind velocity. Hesp 1983, found that vegetation density was a more important factor than vegetation type for influencing dune formation. An increase in density corresponds to an increase in surface roughness and consequently a decrease in wind speed near the surface increasing deposition. Saltating sand would have to rise above the minimum z_0 of a species in order to continue saltating. Upon impact, vegetation absorbs some of the energy from the wind and the saltating grains, reducing the ability of the wind to transport sediment. The resulting trapping of sediment decreases the rate of sand transport and increases deposition around vegetation (Maun, 2009). The greater the variation in vegetation density or distribution or sand supply the greater the morphological variation (Hesp, 2002).

Vegetation dispersal and survival mechanisms are important species-specific characteristics along coastal beach-dune systems as they help develop unique vegetation patterns through time, succession, and in space, zonation, based on the type and level of stress a species of vegetation can thrive in. Dispersal increases the fitness of a species by occupying more diverse habitats which allows for potential adaptation and speciation in response to new selective pressures (Maun, 2009). However, seeds of most coastal species disperse close to their parents (Maun, 2009). Species that have adapted to living near the coast are mainly dispersed to locations along the coast because the primary dispersal mechanisms include water, wind, and animals (Maun, 2009). Distribution by water is typically confined to hydrophytes or species that have adapted to travel in seawater (e.g. fruit bouncy in *Cakile edentula and Caklie maritima*). The fruit or caryopsis of *A. breviligulata* is enclosed by a lemma and palea which form a boat like structure allowing for short-term travel by water (Maun, 1985; Maun, 2009)*.* Many perennial beach species including, *A. breviligulata* (American Beach Grass)*, Ammophila areneria* (European Beach Grass)*,* and *Leymums mollis* (American Dune Grass) are fragmented by storm waves and transported along the shoreline. Although these species can disperse as caryopsis, their primary mode of short-distance dispersal is via the transportation of rhizome fragments by water (Maun, 2009). Maun (1985) studied the survival of *A. breviligulata* plants derived from rhizome fragments and seedlings along Lake Huron shoreline, where 79% of *A. breviligulata* plants from fragments survived to the end of the summer compared to 4% from seedlings. For many coastal species winds may be the most efficient mode of dispersal. Factors such as plant height, wind velocity and accessory structures affect species dispersal by wind. For example, many coastal grasses including *A. breviligulata* have lemma and palea which act as wings to aid in short-distance dispersal. After successful dispersal, the first stage in vegetation establishment is the germination of seeds through sexual reproduction or vegetatively through rhizomes and stolons.

Seed banks are the reservoir of viable seeds found either on the surface or buried in the soil. Thompson et al., (1997) revised the Thompson and Grimes (1979) categorization of seed banks to three main types. Type I is a transient seed bank which is viable for less than a year. The dispersal occurs in the spring and germination in the following fall. This seed bank is short lived and if seeds fail to germinate by the fall, they do not remain viable in the seed bank. Type II is short-term persistent seed banks which include annual and perennial herbs. The dispersal and germination periods occur in the spring and fall as well, however, seeds that do not germinate in the fall have the potential to remain in the seed bank until the following year. Type III is long-term persistent seeds including annual and perennial herbs and shrubs. The majority of seeds in this group enter the long-term seed banks and very few germinate after dispersal. Many foredune species have transient seed banks because adaptations for persistent seed banks are too energetically costly considering the high level of stress and disturbances such as sediment burial, salt spray, wave action, tidal energy, and beach-users on coastlines.

The germination of seeds is controlled by adaptive dormancy mechanisms which will delay germination until species and location specific conditions are met. For example, *A. breviligulata* found at the northern end of their geographic range require cold stratification at <4° for 4-6 weeks to break dormancy but loose this requirement in the south (Seneca, 1972, Maun, 2009). Besides dormancy conditions there are also environmental requirements needed for successful germination to occur. There needs to be adequate oxygen availability, acceptable temperature range, and appropriate moisture (Maun, 2009). Dunes provide these conditions for germination when temperature and moisture are ideal (Maun. 2009). However, there are some stressors such as sediment burial and salt spray that inhibit germination and successful colonization.

Many coastal species expand to new surfaces by producing rhizomes that grow horizontally, eventually changing their orientation and growing upwards thereby emerging from the sand surface (Maun, 2009). As plants begin to germinate and colonize mycorrhizal fungi form an ubiquitous mutualistic symbiotic association with many root systems. These relationships provide necessary benefits in the survival and growth of plants by playing an active role in the nutrient cycle (Maun, 2009). The mycorrhizal fungi depend entirely on plants for carbon which can equate to about 10% of the plant's energy expenditure. In return, the plant gains essential nutrients and water which outweigh the increased energy expenditure. Soil moisture of sandy sediment is an important limiting factor to plant growth. Sand has a high porosity and therefore does not retain a lot of moisture near the surface. Although the upper layer of sand dries out, the lower layers still contain ample moisture for vegetation. Increase in vegetation cover and density increases soil moisture retention. Soil nutrient levels are also vital limiting factors to plant growth. Nitrogen (N), Phosphorous (P), and Potassium (K) are the three micronutrients that dune soils often lack. It has been seen that sparse vegetation has been caused by a deficiency in N and P rather than by other environmental stressors (Willis and Yemm, 1961; Willis, 1963). The addition of N has been shown to change species diversity and composition because of the varying response of species to total N concentration (Tilman, 1986).

2.2.3 Vegetation and morphological feedback

Vegetation can alter a coastal landscape through the interaction between sediment supply and the eco-morphology of the system (Zarnetske et al., 2012). As sediment is transported from the beach to the dunes by wind it is trapped and fixed by vegetation, growing on the foredune (Keijsers, et al., 2014). Species specific morphologies suggest that different species may vary in their ability to trap sediment and their growth response to sediment deposition (Zarmetske et al., 2012). Hacker et al., (2012) found that foredunes, along the coast of Oregon and Washington, dominated by *A. breviligulata* were almost half the height, nearly twice the width, and half as steep as those dominated by *A. arenaria*. *Ammophila breviligulata* dominated foredunes also had higher sand deposition and greater shoreline change rates compared to *A. arenaria* dominated foredunes. The spatial deposition pattern is largely controlled by wind velocity, dune topography and vegetation cover (Hesp, 2002), but when sediment supply is consistent, it is the vegetation that controls dune shape (Hacker et al., 2012) and modifies airflow over the foredune (Keijsers, et al., 2014). Vegetation roughness slows down the onshore airflow, counteracting the topographic acceleration caused by flow compression over seaward slopes (Arens, 1996; Arens et al., 1995; Walker et al., 2009; Keijsers, et al., 2014). The complex airflow patterns strongly influence aeolian transport and deposition along the dune system (Keijsers, et al.,2014). The initiation of dune formation can only occur when vegetation is able to colonize the backshore (Houser et al., 2015). The type of vegetation that colonizes barrier island dune systems depends on the amount of sediment being transported from the beach to the dune and the rate of sand accretion (Houser et al., 2018). Dune vegetation varies in its ability to capture sediment and support vertical growth which depends on the degree to which a species is burial-tolerant (Houser et al., 2018).

Vegetation plays a key role in influencing dune morphology based on their species-specific tolerance and growing patterns in space and time. However, there are feedbacks between dune morphology and vegetation that influence how both systems develop. There are three classes of dune vegetation: dune builders, burial-tolerant stabilizers, and burial-intolerant stabilizers (Miller et al., 2010; Houser et a., 2018). Environmental stressors like storm surges, wind velocity, and salt spray will affect different vegetation types depending on their varying tolerances to those stressors. This variation in tolerance leads to vegetation forming in belt-like zones as you move across the backshore from the beach to the dune system (Maun, 2009). This is known as zonation where plant communities are arranged in zones that are distinctly different from each other (Maun, 2009). Dune-builder vegetation is well-adapted to salt spray and storm surge (Houser et al., 2018), and will be effective in producing steep dune slopes due to slow lateral spread in response to limited burial (Stallins, 2001). This group of vegetation protects interdunes from wave run-up and storm waves (Miller, et al., 2010). Burial-tolerant stabilizers are well-adapted to salt spray and frequent burial (Houser et al., 2018). Their broad network of horizontal rhizomes work to stabilize the dune instead of promoting vertical growth which aids in dune stabilization during storm events (Stallins, 2001). Burial-intolerant stabilizers are inland species that are not adapted to burial but promote dune stabilization (Stallins, 2001). The dunes farthest inland accumulate the most diversity in vegetation over time because this area is the most protected from disturbances and stressors (mature and deeper soils, low salinity, etc).

The frequency of storm events influences the type of vegetation that will colonize a dune system (Houser, 2009). Infrequent storm events can cause dunes to develop into larger systems colonized by burial-intolerant vegetation. With stable topography and an increase in surface roughness, these systems can resist overwash and allow for the development of woody vegetation, increasing stability in the back-dune field (Zinnert et al., 2018). Frequent storm events restrict the recovery of dunes and cause dunes to develop into low-profile, discontinuous systems colonized by species with high tolerances to burial, overwash, and salinity (Stallins and Parker 2003; Houser, 2009; Wolner et al., 2013; Houser et al., 2018). This prevents woody species, which act as dune stabilizers from colonizing the back of the dune field (Zinnert et al., 2018). The feedback between vegetation and dune geomorphology leads to alternating large and small dunes (Miller et al., 2010), due to random perturbations or as a result of a geologic control on nearshore morphology, sediment supply or surge height.

2.2.4 Morphological feedback of growing dune

Besides vegetation there are also morphological feedbacks that reinforce the height, extent, and volume of the beach-dune system. Variables like sediment availability, wind velocity, beach slope, dune slope, dune height, and beach width influence aeolian processes like sediment transport. The distance of vegetation from the shoreline has been argued to influence dune morphology, specifically the maximum height of a foredune (Duran and Moore, 2013). Using a modified model from Duran and Herrmann (2006), Duran and Moore (2013), argue that foredune growth is limited by a negative feedback between wind flow and topography. The initial foredune growth is caused by the sudden decrease in sand transport due to vegetation increasing surface roughness and trapping all sediment at the vegetation extent (seaward limit of vegetation). They argue that the continued evolution of the foredune is determined by its interaction with wind flow. Vegetation at this point is said to be a passive variable acting as an anchor for the dune crest preventing dune motion. In this simulation the foredune will continue to grow vertically, reducing the wind flow and therefore reducing the shear stress at the surface and sediment transport across the dune. This feedback between wind, sediment transport, and dune height described a stagnation zone at the base of the dune where sediment is trapped by vegetation and cannot move past this zone. They argue that the dune will continue to grow in height until this stagnation zone extends so far that the shear stress at the shoreline is below the threshold for transport and sediment transport will stop. They describe this as a steady state in maximum foredune height.

Duran and Moore (2013) argue that this steady state foredune profile is scale invariant meaning that any size of foredune will deflect the wind in a similar way. Although this claim has never been tested, they support their model with multiple cross shore profiles from other studies plotted on a distance from shore to dune height graph showing all profiles falling along the same scale invariant pattern. Along with the steady state scale invariance of foredune height they also argue that the only vegetation characteristic relevant to dune morphology is that vegetation growth rate (ratio of maximum plant height and typical growth time) needs to be much higher than the maximum rate of erosion/deposition. They suggest that the distance of vegetation from the shoreline is the primary control on dune height with a secondary influence coming from wind intensity. It is argued that since the steady state foredune is determined by its slope, that the farther from the shoreline a dune forms, the larger it can become.

2.2.5 Sediment supply as a limiting factor

Sediment supply is another complex variable in the beach-dune system that has been argued as the limiting factor influencing potential dune height. Davidson-Arnott and Law (1990), state that with continued sediment supply a foredune will continue to grow in height and width and, on a progrodational shoreline, transverse dunes may form. The first weeks or months of foredune development is dependent primarily on volume of sediment transport from the beach (Davidson-Arnott and Law, 1990). As sediment is transported to the dune, it is lost from the beach, over a longer time scale the beach would need a positive sediment budget to accommodate the growth in the dune. Without this a negative feedback would occur as the beach width became narrower and the dune was eroded by wave action (Psuty, 1988; Davidson-Arnott and Law, 1990). Growth of a foredune is controlled by the rate of sediment transport from the beach by wind and the removal of sediment from the foredune during storms (Davidson-Arnott and Law, 1990; Hesp, 2002; Davidson-Arnott et al., 2018). Understanding sediment exchange to and from the dune and beach allows for dune height and width to be determined (Davidson-Arnott et al., 2018). Sediment transport is influenced by many factors such as wind velocity, sediment size, precipitation, moisture levels, salinity levels on the beach, and beach width. Wind angle and fetch length influence how much sediment can be transported to the dune. Some models (Duran and Moore, 2013) simulate continuous, saturated, onshore winds perpendicular to shore, however this condition is unusual (Davidson-Arnott et al., 2018).

Unsteady, non-uniform flow conditions are more common on beach-dune systems and oblique wind angles are prevalent (Davidson-Arnott et al., 2018). Sediment supply to the dune by aeolian processes can continue indefinitely as long as sediment is available and assuming that other variables affecting sediment transport (moisture, vegetation cover, sea-level raise, etc.) do not exceed a threshold (Davidson-Arnott et al., 2018). Davidson-Arnott and Law (1990), found that onshore wind velocity is a good predictor of sediment transport to the foredune and is the most important variable controlling the rate of sediment transport. Beach width was found to be the limiting factor for sediment transport on a beach and on narrow beaches oblique winds may transport more sediment to dunes than onshore winds due to the increase in fetch length. Since the controls on foredune dynamics and evolution are so complex results from simulated models should be validated against empirical evidence (Davidson-Arnott et al., 2018).

2.3 Dune erosion during storms

Beach-dune systems are vulnerable to climate change because of the coupling between ecological processes, geomorphological processes, and storm events (Arkema et al., 2013; Zinnert et al., 2017, Zinnert et al., 2018). Beach-dune systems are under constant stress from the sea due to waves, storms, tides, and sea level rise. If these systems are resilient, they will respond to this stress by maintaining elevation, width, volume and ecological function (Houser et al., 2018). The impact storm events have on beach-dune systems varies from minor scarping to complete overwash and breaching (Sallenger, 2000; Morton and Sallenger, 2003; Donnelly et al., 2006; Matias et al., 2008; Mathew et al., 2010). The vulnerability level a barrier island has to extreme storm events is dependent on the total water level (tide + storm surge + wave run-up) relative to the height and alongshore extent of the foredune (Thieler and Young, 1991; Sallenger, 2000; Morton, 2002; Nott, 2006; Houser and Halmilton, 2009; Houser et al., 2015).

2.4 Dune recovery from storms

Alongshore variation of beach-dune systems influences the impact and recovery to storm events and therefore is an important factor on beach-dune transgression with relative sea-level rise (Houser 2012).Transgression occurs episodically in response to storm events capable of scarping and eroding the foredune (Davidson-Arnott, 2005; Houser, 2012), and creating washovers where the eroded sediment can be transported to the back barrier (Houser 2012). The impact a storm event has on a beach-dune system and the rate of transgression depends on the storm surge elevation relative to the height of the foredune (Houser and Mathew, 2011). Foredune height is dependent on the frequency of storm events which erode sediment from the foredune - the more frequent the erosion and the more unstable the dune system becomes causing greater scarping, washovers and breaching (Houser and Mathew, 2011).

The impact of a storm event can vary from minor scarping of a dune base to overwash and/or breaching of the dune (Houser et al., 2015). When a dune system and beachface are eroded during a storm event, sediment is transferred to the nearshore creating intertidal and offshore bars (Houser, 2009). As offshore bars migrate and weld with the beach, the sediment becomes available for transport and recovery of the dune system (Houser, 2009). Vegetation is needed to trap the transported sediment and aid in recovery. Vegetation will grow in local areas that reflect a range of tolerances to varying stressors (Maun, 2009) and is also influenced by the frequency of disturbance (Wolner et al., 2013; Houser et al., 2018). Areas alongshore that are more prone to washover would be covered by species with short life spans, produce many offspring, and promote low profile dunes (Houser et al., 2018). With frequent disturbance and insufficient time for plant communities to recover these species would then become the dominant vegetation producing low profile dunes vulnerable to washover. Areas with infrequent washover would have be dominated by burial-intolerant vegetation (Stallins and Parker, 2003; Wolner et al., 2013; Houser at al., 2018). With sufficient time for recovery following a disturbance, these species would be able to recolonize and promote tall foredunes capable of resisting washover (Houser et al., 2018). Assuming that dune-building vegetation is present, the ability of a barrier island and dune system to return to their pre-storm equilibrium is dependent on the transfer of sediment from the nearshore to the beach and dune (Houser et al., 2015). Regardless of the mechanism of exchange, return of sediment to the beachface is the first and primary process. For aeolian transportation to occur the backshore needs to expand in order to increases the fetch length which controls the amount of sediment exchange from the beachface to the dune system and wind speeds need to reach the threshold for aeolian transport (Davidson-Arnott, 1988; Davidson-Arnott and Law, 1990; Bauer and Davidson-Arnott, 2003; Houser, 2009; Houser et al., 2015). Typically storm winds that are capable of moving sediment also come with a rise in water levels. The ability for sediment to be transported to the dune before the storm surge extends to the backshore is found in a small spatial and temporal window (Houser et al., 2015). Beach-dune systems are eroding and accreting around an equilibrium in response to a feedback between an energy source (wind and waves) and their morphology before the event (Houser, 2009). This feedback will continue until the energy source is below the threshold for sediment transportation through either the sorting of the sediment (Bauer, 1991) or the windspeed decreases (Houser, 2009). Dune systems begin to recover immediately after a storm event. The duration of recovery can last from a few weeks to years depending on the magnitude and frequency of the storm (Sallenger, 2000; Houser et al., 2015).

2.5 Blowouts and washover channels

A blowout is a morphological depression, ranging from pits to elongated notches, or basins, that develop as sand is eroded from the dune face (Smith 1960; Hesp, 2002). Ritchie (1972) defined four types including cigar-shaped, v-shaped, scooped hollow, and cauldron and corridor (Ritchie, 1972). However, Cooper (1958, 1967) defined two primary blowout types, saucer and trough in which the broad range of blowout morphologies could be categorized into one of the two types (Hesp, 2002). Trough blowouts are elongated with a deep basin and steeper, and longer slopes or walls. While saucer blowouts are semicircular in shape and may be shallow at first with the potential to evolve into a deep bowl basin (Hesp, 2002). All forms are characterized by sharply delineated boundaries of depositional ridges or erosional scarps

(Gares and Nordstrom, 1995). The initiation and development of blowouts are spatially and temporally variable and they evolve as a result of process/form interactions between wind speed and direction, topography, and vegetation cover (Gares and Nordstrom, 1995). Initiation occurs when a disturbance in the foredune results in a weak spot namely caused from erosion of the foredune face, climate change, vegetation variability, intense wave action, intense wind energy and human activity. Blowouts are often initiated by offshore winds along the northeast coast of North America (Gares and Nordstrom, 1995). Blowout size is related to their orientation to the dominate wind patterns. When blowout orientation and wind direction are the same the wind speed within the blowout is accelerated. However, when blowout orientation and wind direction are perpendicular the wind speed within the blowout is lower than onshore wind speeds (Gares and Nordstrom, 1995). Blowouts create discontinuities and increase instability along dune systems. These areas are more vulnerable to stress and disturbances like overwash events and rise in sea-level. Overwash events occur when there is a super-elevation of sea level relative to the dune height (Matias et al., 2008). Overwash events are typically associated with storms and driven by storm surge, spring high tides, or storm waves. The impact an overwash event has on a dune system varies with the level of instability along the system and can be detrimental in the short-term environment. Areas degraded by blowouts would be more suspectable to complete washover during overwash events (Matias et al, 2008).

2.6 Alongshore variation in dune morphology and storm resiliency

Barrier islands respond to storm events differently depending on the rate of post-storm recovery and the frequency of future storm events (Houser et al., 2018). The rate of recovery depends on synchronization of sediment, migration and welding of innermost bars, and the presence of effective dune-building vegetation within the backshore (Houser et al., 2018). Asymmetry exists in the timescale of erosion and recovery for barrier island beach-dune systems. Erosion of the beach and dune systems can occur over hours depending on the strength of the storm surge, while the recovery of the beach and dune can take several years

(Houser et al., 2015). Due to the asymmetry of erosion and recovery, the barrier island stability and dune morphology depend on the magnitude and frequency of the storm events (Houser, 2009; Houser et al., 2015).

Houser et al., (2018) compares the role of a transgressing foredune to a variable resistor in an electrical circuit, where the response of the beach-dune system to sea-level rise is dependent on the strength and function of the resistor. A tall, continuous foredune relative to the storm surge elevation can be considered a strong resistor that limits washover. In contrast, a highly variable beach-dune system can be considered a weak resistor as it allows for washover and breaching of the foredune. The ability of a foredune to prevent washover or act as a strong resistor varies in time and space and depends on how sediment is exchanged between the nearshore, beach, and dune.

It has been suggested that the morphology of beach-dune systems is partly controlled by framework geology affecting the alongshore distribution of sediment and slope of the nearshore and beach (Riggs et al., 1995; Houser and Mathew, 2011; Houser et al., 2018). Framework geology can influence shoreline change rates and nearshore morphology by: i) differential erosion of underlying sediments which creates alongshore variations in shoreline-change rates; ii) relict topographic highs and lows that slow and hasten shoreline retreat, respectively; and iii) relict deposits of sediment which supply local beaches with sand (Honeycutt and Krantz, 2003; Houser at al., 2018). Since dune morphology is directly related to the nearshore and beach morphology (Short and Hesp, 1982; Houser and Mathew, 2011), it can be presumed that dune morphology would closely reflect framework geology over broad spatial and temporal scales (Houser at al., 2018).

2.7 Dune morphology as a combination of morphological feedbacks

Since beach-dune systems are interconnected there are many relationships and feedbacks that drive their evolution. Researchers from varying backgrounds will use their expertise and perspective to address an issue which can result in a narrow solution often leaving out key variables. To understand how beach-dune systems, evolve and respond to disturbances, an eco-geomorphological approach is needed to understand the coevolution of topography and vegetation in response to physical and ecological factors (Duran and Moore, 2013). Foredune formation and evolution is a result of complex relationships between coastal vegetation, aeolian sediment transport, fluid dynamics, beach-dune topography, and storm disturbance (Short and Hesp 1982; Hesp, 1988; Hesp, 2002; Psuty, 2008; Duran and Moore, 2013). With these highly dynamic factors and feedbacks it is difficult to identify primary controls on foredune development and recovery following storms (Duran and Moore, 2013). Largely, sediment supply, including availability and transport potential, as a function of beach morphology and wind regime has been the focus for dune-forming processes (Short and Hesp, 1982; Hesp, 1988; Psuty, 2008; Davidson-Arnott et al., 2005; Bauer and Davidson-Arnott, 2003).

Duran and Moore (2013) argued that plant zonation, rather than sediment supply, determines maximum foredune height which controls dune vulnerability to storms. They used a coastal dune model consisting of differential equations for the physical and biological processes to describe sediment transport on vegetated surfaces at low tide. During the simulation, aeolian transport begins at the foreshore during low tide and sand flux increases to the maximum value wind can sustain. Sediment is blown continuously by a constant onshore wind until trapped by vegetation. The initiation of foredune development is caused by the abrupt decrease in sediment flux introduced by vegetation. The model shows that the growth of the dune causes a deceleration in wind velocity which reduces sediment transport over the dune. This negative feedback seen between wind flow and topography limits foredune growth and describes a scale invariance of the steady-state dune profile. Duran and Moore (2013) explain that small and large dunes deflect wind in a similar way resulting in a scale invariant system which suggests a characterization of foredune development by the windward slope. They also explain that some details of vegetation growth are irrelevant to resulting dune morphology as long as the ratio of maximum plant height and typical growth time is higher than the maximum erosion/deposition rate. They further argue that since the steady state of a foredune is determined by its slope, the farther from the shoreline (MHWL) a foredune forms, the higher it can grow.

2.8 Vegetation changes in response to storms and human activity

As climate change continues to influence the intensity and frequency of storm events and raises sea-level it can be assumed that vegetation will have to respond and adapt to the new degree of stress. If there is adequate habitat available then vegetation is able to shift inland in response to higher sea levels without being completely lost (Brown and McLachlin, 2002; Maun, 2009). Vegetation can re-establish in different locations as long as its needs are met. As marine transgression and progression fluctuates, movements of native species have the potential to reflect the back-and-forth migration (Feagin et al., 2005; Maun, 2009). Besides raising sea-level affecting vegetation location and colonization major storm events and storm surge can increase shoreline stress and influence vegetation. The frequency and intensity of the storm event would determine the lasting affects on vegetation. Wave action and storm surge capable of eroding and scarping the foredune would ultimately remove the majority of vegetation in the disturbed areas. If given enough time to recover, the dune system and vegetation would be able to establish and recover (Houser et al, 2018). Vegetation fragments and roots systems that were less disturbed would begin to recolonize the dune. If storm events were too frequent and did not allow for sufficient recovery of vegetation, then the continued stress and erosion would cause complete removal and destruction of the foredune requiring a longer time for recovery. Erosion of the foredune can often lead to blowouts which alter sediment transport in the local area (Maun, 2009). The adjustment in morphology would impact the type of vegetation that would inhabit the areas of high deposition such as requiring a species that is highly burial tolerant to colonize (Maun, 2009). Besides the anthropogenic influences on climate change which affect sea-levels, other societal influences including agricultural, recreational, and commercial industries can have negative impacts on coastal systems (Maun, 2009). Engineered structures like boardwalks, walkways and jetties interfere with natural sediment transport, vegetation establishment, and recovery processes. Large structures like hotels, residences and commercial buildings restrict the dynamics of the beach-dune systems and prevent the natural landward migration of dune fields in response to sea-level raise.

2.9 Invasive species

Native dune species typically respond positively to natural stresses because they colonize areas that best meets their needs, but they respond negatively to large disturbances like hurricanes, which allow for invasive species to colonize (Hierro et al., 2006; Charbonneau, 2017). Changes to the physical environment caused by variations in frequency or intensity of wind, sediment supply, and wave action can influence ecological changes in species composition, succession trajectories, and vegetation growth (Hacker et al., 2012; Zarnetske et al., 2012). Beach-dune systems experience intermediate levels of disturbance keeping the ecosystem in a dynamic state whereby any open niches are filled quickly. Following strong disturbances these niches can be colonized by invasive species which can have destructive impacts by reducing the ecosystem diversity and thereby reducing resiliency. Some non-native species may be beneficial for dune stabilization over the short term by colonizing and stabilizing bare sand and increasing overall species richness (Charbonneau, 2017). However, over the long-term invasive species can alter nutrient levels, soil moisture, microbial communities and outcompete native species thereby reducing diversity (Leege and Kilgore, 2014; Charbonneau, 2017). For example, *A. breviligulata* is native to the Atlantic coast and Great Lakes of the United States of America and Canada but invasive to the western side of the continent, where it has been displacing native *A. arenaria* along the Washington and Oregon coast (Seabloom et al., 2013). These two species of beach grass have varying abilities to trap sediment and aid in dune formation. Foredunes dominated by *A. breviligulata* are lower than foredune dominated by *A. arenaria* because *A. arenaria* has a greater ability to accumulate sediment (Hacker et al., 2012;

Zarnetske et al., 2012; Seabloom et al., 2013). It is predicted that as *A. breviligulata* continues to displace native *A. Arenaria,* foredune heights will decreases, thereby increasing the susceptibility to coastal flooding during extreme storm events (Seabloom et al., 2013).

2.10 Why we need to study vegetation distribution on dunes

Many coastal areas are becoming densely populated with increasing commercial and recreational infrastructure which reduce levels of biodiversity. With multiple complex feedbacks determining their stability and overall health it is important that we understand the varying location-specific characteristics that influence these beach-dunes systems. Coastal areas are becoming more vulnerable due to sea-level rise and extreme events like hurricanes and floods while also adapting to changes in their environmental ecosystems associated with climate change (Feagin et al., 2015). As these changes threaten the economically and environmentally valuable coastlines, attempts have been made to stabilize these areas. This typically includes traditional hard engineering with jetties and levees (Jackson et al., 2013; Feagin et al., 2015). However, with more research and evidence on how these methods do not function well in dynamic systems, soft-engineering or nature-based solutions (ecological restoration and ecological engineering) have gained more attention (Hanley et al., 2014; Feagin et al., 2015). A growing attention has been brought to the use of vegetation as a protection measure against extreme storm events along coastal systems (Martinez et al., 2011; Feagin et al., 2015). Vegetation is a primary variable in dune formation, but studies have shown that vegetation can also reduce levels of erosion during events like wave breaking, dune overtopping, and overwash (Dean and Bender, 2006; Kobayashi et al., 2013; Feagin et al., 2019). Other studies have relied on experiments and simulations to use artificial representation of vegetation (Duran and Moore, 2013; Martinez et al., 2016) as a result there is a lack of field-based and empirical data that quantify the coupling between vegetation and dune morphology (Feagin et al, 2015). The Duran and Moore (2013) scale-invariant model represents vegetation dynamics in a simplified way with one grass species with a uniform response to erosion and accretion and argue that maximum foredune height is controlled by the distance of vegetation from the shoreline and not sediment supply. There is a disconnect between how systems evolve in nature and how they are modeled. It is important to collect empirical beach-dune and vegetation data to understand how they interact in a complex and ever-changing system.

3. Purpose and Objective

This study aims to identify the alongshore coupling between the eco-geomorphological variables along beach-dune systems of varying degrees of stability. Specifically, this study aims to collect empirical data to identify if vegetation extent determines maximum dune height as proposed by Duran and Moore (2013).

The specific objectives are to:

- Collect sufficient, quality field data to determine if there is coupling between the alongshore vegetation and beach-dune system.
- Quantify the alongshore variation in vegetation structure and density and beach-dune morphology.
- Assess whether if distance of vegetation from shore creates a scale invariant steady state dune morphology as proposed by Duran and Moore (2013).
- Characterize how the alongshore eco-geomorphological patterns vary amongst systems of difference stages of stability.

This study is unique in that it is, to our knowledge, the first to examine the alongshore variation in vegetation cover within and between barrier systems, and to assess the relationship between L_{veg} and dune morphology in the real-world.

4. Study Site

Data were collected at Brackley Beach, Cavendish Beach and Stanhope Beach (Figure 4) within Prince Edward Island National Parks (PEINP) along the North Shore of Prince Edward Island (PEI), Canada. The three locations total ~25 km of exposed north-facing shoreline characterized by a sandy nearshore backed by foredunes of varying stages of recovery. The backshore (crest of the foredune to vegetation extent) is mainly vegetated primarily by *Ammophila breviligulata* (marram grass), a primary colonist dune vegetation along the Atlantic Coast. It is a tall perennial grass that is typically the major dune stabilizer because of its high tolerance to unstable conditions and ability to grow rhizome systems horizontally and spread under the surface (Olson, 1958; Morrison and Yarranton, 1974). *Ammophila breviligulata* thrives with sediment burial (Maun, 2009), able to withstand rates of up to 1m per year (Laing, 1958; Maun and Lapierre, 1986).

Figure 4. Study locations on Prince Edward Island.

4.1 Cavendish

Cavendish beach runs roughly 7km along the coast and is characterised by areas of cliff, spit and highly discontinuous and eroded dune systems (Figure 5). The east end of Cavendish is home to cliffs which act as sediment supply for the beach and the dune system here has evolved over a visible layer of ‘dirty sandstone’ containing up to 50% clay (Figure 5B) (van de Poll, 1989; Wernette and Houser, in review). Cavendish Campground is located on the cliff and is neighboured by an inlet to the east and a spit to the west. The Cavendish spit is about 4.4 km long and is characterised by large discontinuous dunes separated by washover channels that are regularly inundated. This area is highly vulnerable to erosion and is in a constant state of recovery.

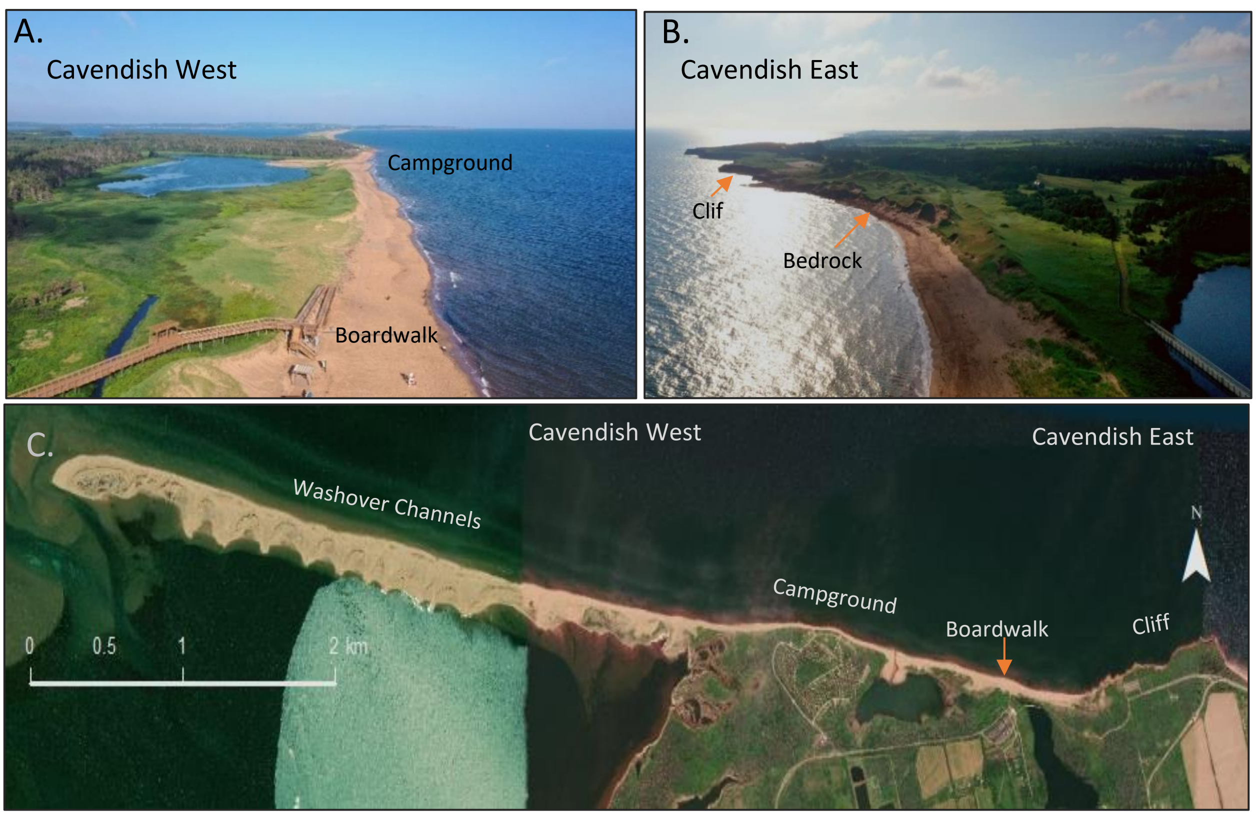


Figure 5. A. July 2019 UAV (unoccupied aerial vehicle) image of Cavendish west showing the campground, boardwalk and dune system. B. July 2019 UAV image of Cavendish east highlighting the cliffs and bedrock alongshore. C. ArcGIS map of Cavendish beach.

4.2 Brackley

Brackley beach extends roughly 9.5 km along the coast. It is less degraded and has a more continuous foredune system than Cavendish beach. However, there is still a wide range of variability within the beach-dune system at this location. The center of Brackley beach is connected to the mainland and extends as barrier islands to the east and west (Figure 6). The continuous foredune system is backed by wetlands and bays and is boarded by estuaries on either side. Brackley east has very large foredunes and large permanent blowouts which are home to endangered Piping Plovers (Figure 6B). The west end of the beach has lower foredunes, a wider beach and large outcrops of sandstone forming headlands (Figure 6A).

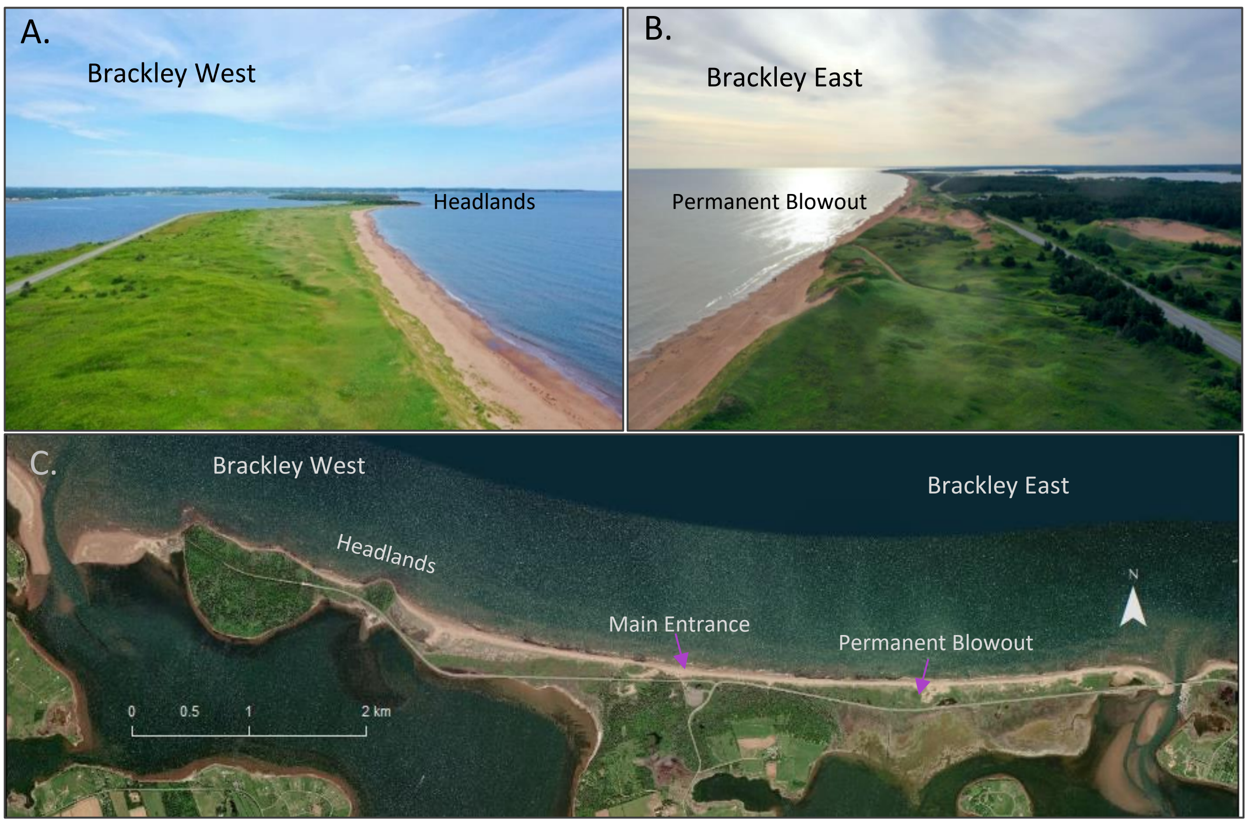


Figure 6. A. July 2019 UAV image of Brackley west showing low continuous dunes and headlands. B. July 2019 UAV image of Brackley east showing the permanent blowout and large foredunes. C. ArcGIS map of Brackley beach.

4.3 Stanhope

Stanhope beach, which runs roughly 8 km along the coast, has a more continuous and less eroded dune system then Brackley and Cavendish beaches. Stanhope beach is directly east of Brackley beach and is separated by an estuary leading to a bay backing the west end of Stanhope. Stanhope beach is backed by small lakes and ponds and has a low continuous foredune system with bluffs and inlets scattered alongshore (Figure 7).

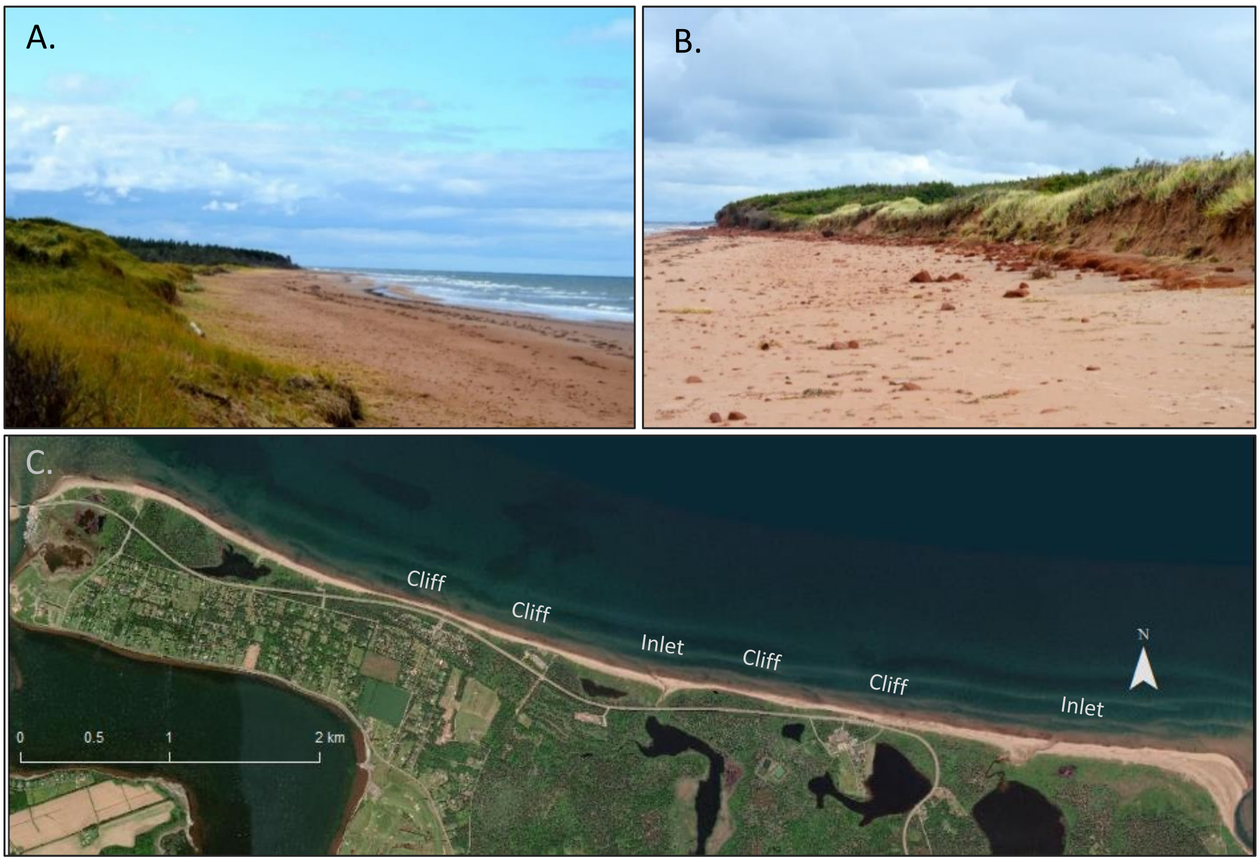


Figure 7. A. September 2019 image showing the low continuous foredunes of Stanhope beach. B. September 2019 image of a bluff alongshore of Stanhope beach. C. ArcGIS map of Stanhope beach.

4.4 Geological Setting

The north coast of PEI is comprised of bluffs, cliffs, barrier islands and spits which are backed by estuaries and lagoons (Forbes et al., 2004). The erosion of coastal cliffs and sandstone is the primary source of new sediment to the littoral zone (Shaw et al., 1998). The topography of PEI was created from glacial imprints during the late Pleistocene period. When the glaciers melted, they left glacial debris and glacial scouring on the exposed land. Framework geology influences bathymetry (Barrett and Houser, 2012), sediment texture (Schupp et al., 2006), and beach-dune morphology (Houser, 2012; Wernette et al., 2018). Variations in bathymetry and sediment texture can lead to semi-permanent rip channels (Wernette and Houser, in review). Semi-permanent rips at Brackley and Cavendish beaches correspond with infilled valleys which align with hydrological features behind the dune, such as lakes and wetlands (Wernette and Houser, in review). PEI is underlain by sandstone and shale with high concentrations of iron oxide making sand and soils red in colour. In most areas' bedrock is overlain with till which is covered by proglacial sediment but is often exposed in the nearshore or covered by sand.

4.5 Wave, Tidal, Wind, and Storms

The northshore of PEI is transgressive (Manson et al., 2016), and heavily influenced by sea-level rise which is at a rate of 0.25-0.3m per century (Scott et al., 1981; Forbes et al., 2004; Davidson-Arnott, 2018) as well as coastal erosion. Long term coastal retreat averaging 0.5m/year has been caused by long-term sea-level rise averaging 0.3m/century over the past 6000 years (Forbes et al., 2004). The shoreline is separated by inlets and estuaries which lead to bays and act as littoral cells (Inman and Frautschy, 1966; Manson et al., 2016). Headlands found alongshore have been thought to limit sediment transport between these littoral cells (Owen and Bowen, 1977; Shaw et al., 2000; Forbes at al., 2004; Manson et al., 2016). The direction of longshore drift varies along the North Shore of PEI and depends on prevailing wind and wave directions relative to the shoreline orientation (Manson et al., 2016).

Spring tides are mixed semi-diurnal with a tidal range of 1.1m. Precipitation averages about 1000 mm/yr with 30% coming as snowfall in the winter. The climate is cool with mean daily temperatures below 0°C in the winter and summer temperature rarely exceeding 30°C. Ice cover is present during the winter along the North Shore of PEI and may be sensitive to small changes in climate (Forbes et al., 2002). Models have predicted that there will be a significant decrease in sea-ice extent and length over coming decades due to climate changes (Flato et al., 2000). This has implications for shoreline erosion and recovery because an increase in open water allows for greater fetch during winter months with strong wind energy and resulting strong wave energy (Forbes et al., 2002). Initial ice formation occurs along the open coast in the nearshore, this combined with freezing wave run up and spray leads to the development of an ice foot located on the beach (Figure 8A and B) (Forbes et al., 2002). Strong wind and wave energy can move non anchored ice (Figure 8C and D) and depending on weather and ice motion the icefoot may be eroded and reformed more than once (Bouchard and Hill, 1995; Forbes, 2002).

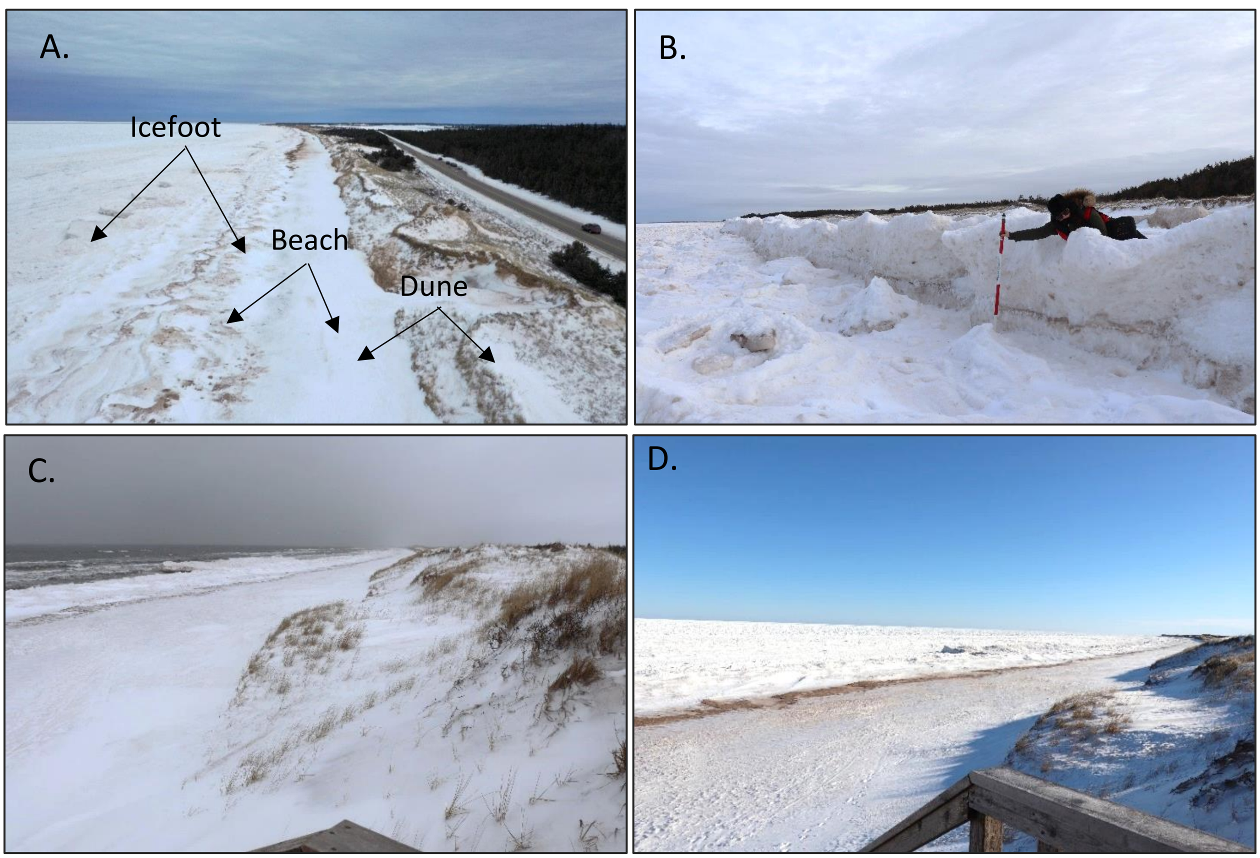


Figure 8. A. UAV image of Brackley beach east from late January 2020 indicating icefoot location. B. Icefoot along Stanhope beach in late January 2020 exceeding 4ft in height. C and D Images looking east from the secondary access point on Brackley beach, C. taken on January 29th during storm winds and wave energy, D. taken January 31st showing the large amount of ice transport along the coast.

Extreme storm events, more so than persistent lower energy processes, effect beach morphodynamics in many coastal settings (Forbes et al., 2004). Storms surges raise sea level and allow storm waves to shoal and break father landward causing erosion and high sediment transport rates (Forbes et al., 2004). Storms along the North Shore of PEI are a major contributor to shoreline erosion with significant wave heights of 3m to 7m and storm surge of up to 2m (Manson et al., 2015; Davidson-Arnott, 2018). Storm winds are typically onshore coming from the northwest, north, and northeast while prevailing winds are from the southwest and west (Davidson-Arnott, 2018).

PEI is vulnerable to hurricanes from June to November as the temperature of the Atlantic Ocean increase enough to produce tropical cyclones, including tropical storms and hurricanes. September 7th and 8th of 2019 PEI was impacted by post-tropical storm Dorian where the peak wind gusts ranged from 93 to 122 km h^{-1} on September 7th and 80 to 104 km h^{-1} on September 8th (George et al., in review). The North Shore experienced 7-8 m significant wave height and 1.2m storm surge during high tide (D of O, 2019; George et al., in review). Brackley beach resulted in an average of 5.8 m^3m^{-1} of sediment eroded from the foredunes (George at al., 2020) (Figure 9). Dorian had lasting effects on the North Shore of PEI as it highly degraded the dune systems along the coast.

In September 2020 Hurricane Teddy began moving towards Atlantic Canada. On September 23rd the Post-Tropical Storm passed the east coast of PEI bringing 39-73 mph winds. The effects of Teddy were lower than predicted and not nearly as severe as Hurricane Dorian. Cavendish was the only location with notable erosion of about 1m.

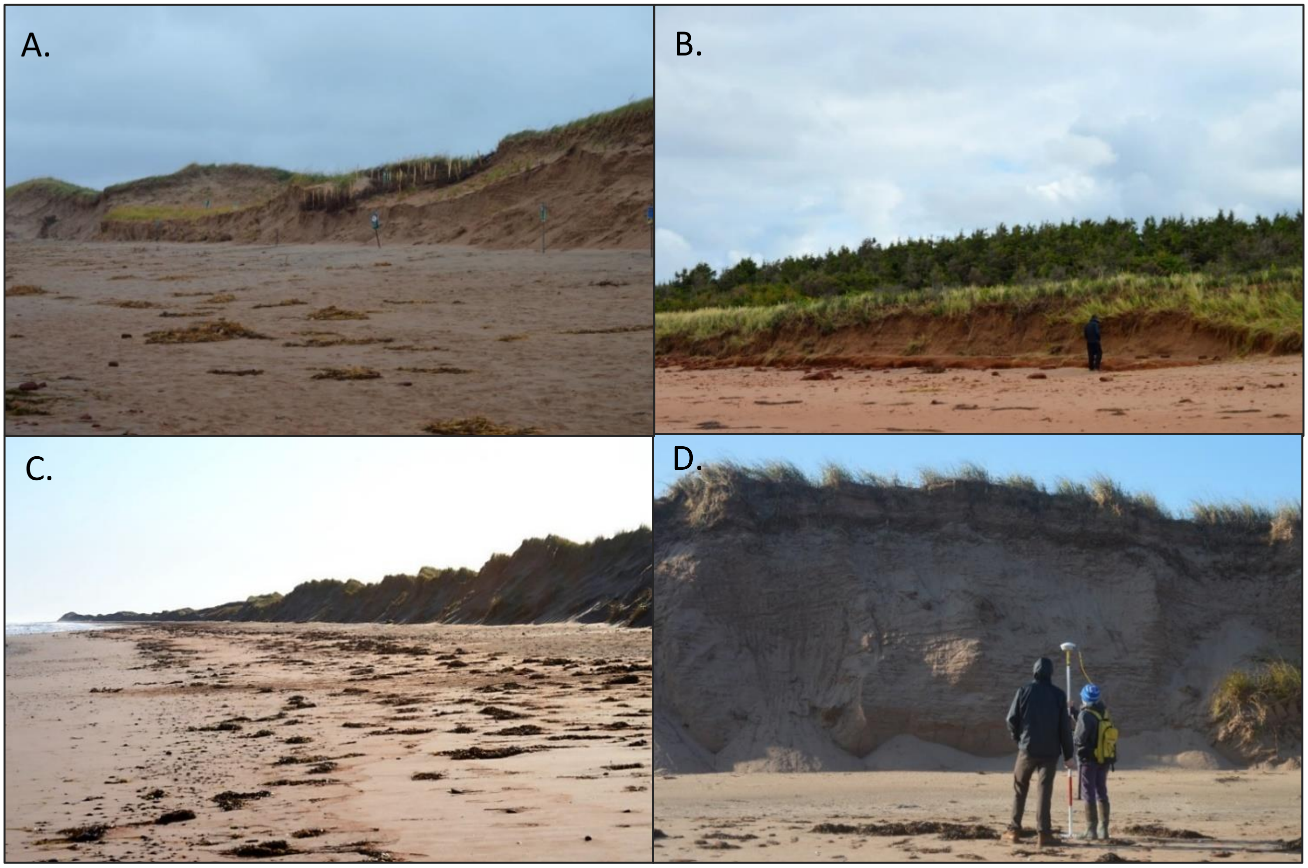


Figure 9. A. Scarping and slumping of Cavendish beach one-week Post Dorian (PD). B. Scarping of Stanhope beach one-week PD. C and D High degree of erosion and scarping at Brackley beach one-week PD.

5. Methodology

5.1 UAV Structure for Motion (SfM)

Roughly 19km of the coast were surveyed between July 1st to July 31st, 2019. A Structure for Motion (SfM) approach using UAVs was used to produce three-dimensional structures from two-dimensional images. UAV images were captured using a Mavic 2 Pro at Brackley and Cavendish Beach and a Phantom 4 equipped with a Sentera Near Infrared (NIR) band addition at the Stanhope location. Flights were completed between 7:00am and 10:00am during periods of low winds to reduce error introduced from shadows and high winds as well as to minimize the number of beach users present. UAV flights were conducted through single flight grids ranging in size from 306m x 91m to 532m x 198m using Pix4DCapture. Flight grids varied to accommodate change in beach angle and to ensure the UAV did not fly over roads, parking lots or campgrounds (Figure 10). Images were captured at a consistent height of 55m which produced a Ground Sampling Distance (GSD) of 1.29cm/px and were taken with 80% frontal overlap and 70% side overlap to increase accuracy during post-processing. Ground Control Points (GCPs) were georeferenced during each flight to increase the accuracy of orthomosaics and point clouds. Pix4DMapper was used to produce high density point clouds which were used to create Digital Surface Models (DSM) and orthomosaics for each flight at a 1.4cm/px resolution.

Figure 10. Soil sampling, vegetation sampling and flight locations for cavendish, Brackley and Stanhope.

Inconsistent Vertical Drone Error was introduced during the flights at all locations. This offset the DSMs for each flight to varying degrees making it difficult to maintain accuracy during post-processing corrections. Poor vertical accuracy caused DSMs to be unreliable for data analysis. Elevation data were obtained from CBCL Limited, with permission from Parks Canada, as part of the Federal Transportation Risk Assessment Initiative. The group used an integrated aerial LiDAR topobathy (topographic and bathymetric) to survey between July 4th and 7th, 2019. The survey was flown at an altitude of 400 m above the ground using a Leica Chioptera II dual sensor Topobathy LiDAR. This sensor was equipped with an infrared (240 kHz) and a green laser (35 kHz) capturing a sampling density of 2.72 points per m (p/m) for the bathymetric and 18.6 p/m for the topographic surfaces. Resulting in 1m x 1m Digital Terrain Model (DTM) of the study site.

5.2 Manual Sampling – Vegetation

Within each flight grid, 1m x 1m PVC frames were used to delineate areas for manual vegetation sampling (Figure 11). Locations, indicated in Figure 10, were chosen randomly within a set of parameters such as: locations had to be accessible without damaging the dune, locations could not be in areas of endangered species and locations needed to have the primary species of interest, *A. breviligulata*. This limited the majority of sampling areas within the vegetation extent and inflection point of the dune. Some flight grids had limited potential areas of sampling because the dunes were highly vulnerable to erosion or damage due to steep dune faces, blowouts and washovers. Other locations had limited potential sampling areas due to instability from boardwalks or presence of endangered species (Piping Plover) in which case sampling was not permitted.

Figure 11. Delineated area for vegetation and soil sampling. Visual quadrants were used as a guide for representative sampling.

Within each delineated area, two ramets (individual plant) were sampled for a total of four ramets per flight grid. *Ammophila breviligulata* are structured where several stems emerge from one base (hypocotyl) and multiple blades emerge from each stem (Figure 12). The number of stems and blades were counted for each of the ramets being sampled. For the remaining measurements the hypocotyl, was used as a reference point to keep measurements consistent across samples (Figure 12). Ramet height was measured as the tallest blade along with the average height from five random blades, measurements taken at blades from each stock. Depth buried by sediment was measured from the hypocotyl to the surface of the sediment. Ramet width was measured at the hypocotyl using an electronic caliper. Root strength has been studied before, (Charbonneau et al., 2017). For this study the method was adapted to better represent the direction of the prevailing onshore winds. Root strength was determined by securing a tensiometer to the hypocotyl and using consistent force in a 45° in the direction of the stoss slope. Max force was recorded when the roots began to lift from the sand.

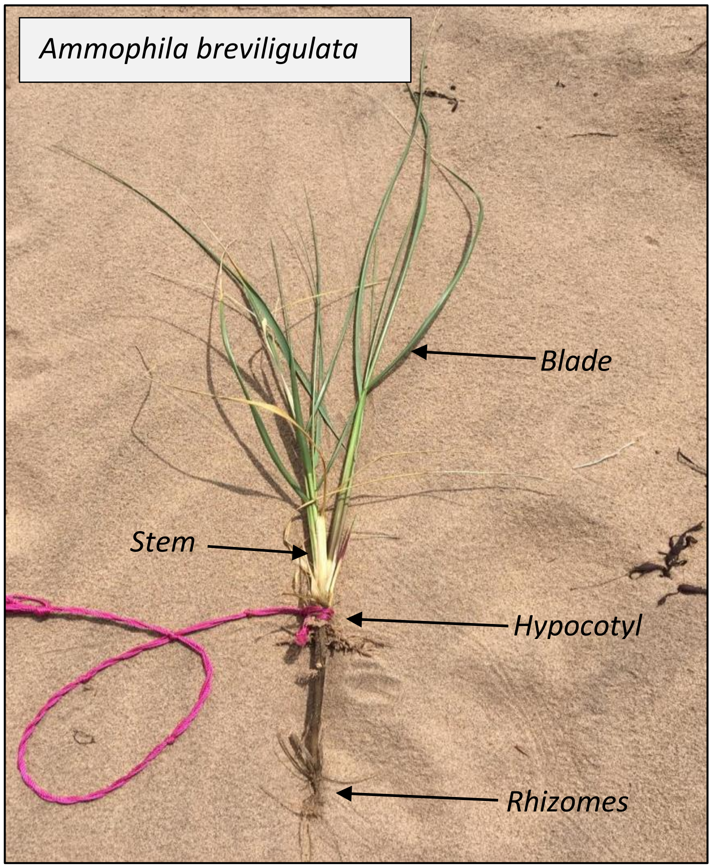


Figure 12. Labeled image of *Ammophila breviligulata.*

5.3 Manual Sampling – Nutrient Availability

Nutrient sampling was conducted along all three sites at locations that were determined by the same parameters used for vegetation sampling (Figure 10). 1m x 1m PVC frames were used to delineate the sampling area where a 1-inch sediment corer was used to extract sediment from a depth of 10cm. Four cores were taken, one from each quadrant of the sampling area to ensure a representative sample (Figure 11). Sediment from the cores of each sampling area were combined and this sediment sample was used from for nutrient and pH testing. A Hanna soil sampling kit was used to test for Nitrogen (N), Phosphorus (P), Potassium (K) and pH of the soil samples. A handheld Garmin GPS was used to gather coordinate information at each sampling site, GPS was consistently placed on the seaward right corner of the frame (Figure 11).

6. Post Processing

6.1 Beach-Dune Profiles and Morphometrics

A total of 31 UAV flights were conducted covering roughly 19km of alongshore coastline in July of 2019. DSM rasters with a 1m/px resolution used to extract beach-dune profiles and morphometrics were provided by CBCL. A Python script was used to extract profiles perpendicular to shore every meter alongshore.

Profile data were used to extract beach-dune morphometrics using a python script. See Table 1 and Figure 13 for equations and definitions used to extract beach-dune morphometrics. The shoreline for this study is defined by the absolute mean sea level (AMSL) and the next four landward cells needed to have a positive slope. The topobathy LiDAR penetrates the water column making the shoreline values independent of tidal fluctuations. Since locations are highly variable alongshore (e.g., cliffs, boardwalks, inlets, etc.) beach-dune morphometrics were filtered to reduce noise based on an empirical knowledge of the three locations. Dune height > 0.50m, beach width > 5.0m, dune toe > 0.80m, dune crest > 0.50m, dune length >1m and <70m were all filtered out. Beach slope and beach volume were removed if beach width was filtered out for that specific profile since beach slope and volume require beach width to be calculated (Table 1). Dune slope and dune volume were removed if dune height and/or dune length were filtered for that specific profile because dune slope and volume require both dune height and length to be calculated (Table 1). Filters were used to reduce the change of misidentifying the dune toe. Including, the greatest deviation between the simplified profile and topographic profile needs to be >2.0m from the crest due to the sharp break in slope typically found at this study site. Additionally, if a prominent berm were at the site this would influence the extraction of the dune tow; however, this was not seen from visual analysis of the profiles and a filter of beach width, >5.0m was included to ensure there was no further misclassification near the shoreline which would be representative of a berm of other morphotopographic feature.

Table 1. Beach and dune morphometrics defined for this study.

Morphometric	Definition	Formula
Shore Line	AMSL, y>0 with a current positive slope and for the next four values.	
Dune Toe (*D_t*)	Simplified profile was predicted by using a third order polynomial and the largest deviation between the true profile and simplified profile was identified as the dune toe.	$Y = Xa^3 + Xb^2 + Xc + d$
Dune Crest (*D_c*)	Largest elevation so far, elevation change of at least 0.6m in the next 20 values.	
Dune Height (*D_h*)	Difference between the crest elevation and the toe elevation.	$= crest_y - toe_y$
Beach Width (*B_w*)	Difference between the distance of the toe and the shore.	$= toe_x - shore_x$
Dune Length (*D_l*)	Difference between the distance of the crest and the toe.	$= crest_x - toe_x$
Beach Slope	The toe elevation subtracted from the shore elevation, divided by the beach width.	$= \frac{toe_y - shore_y}{beach\ width}$
Dune Slope	Dune height divided by dune length.	$= \frac{dune\ height}{dune\ length}$
Beach Volume (*B_v*)	One half the beach width multiplied by the shore elevation subtracted from the toe elevation.	$= \frac{1}{2} beach\ width\ (toe_y - shore_y)$
Dune Volume (*D_v*)	One half the dune length multiplied by the dune height.	$= \frac{1}{2} dune\ length(dune\ height)$

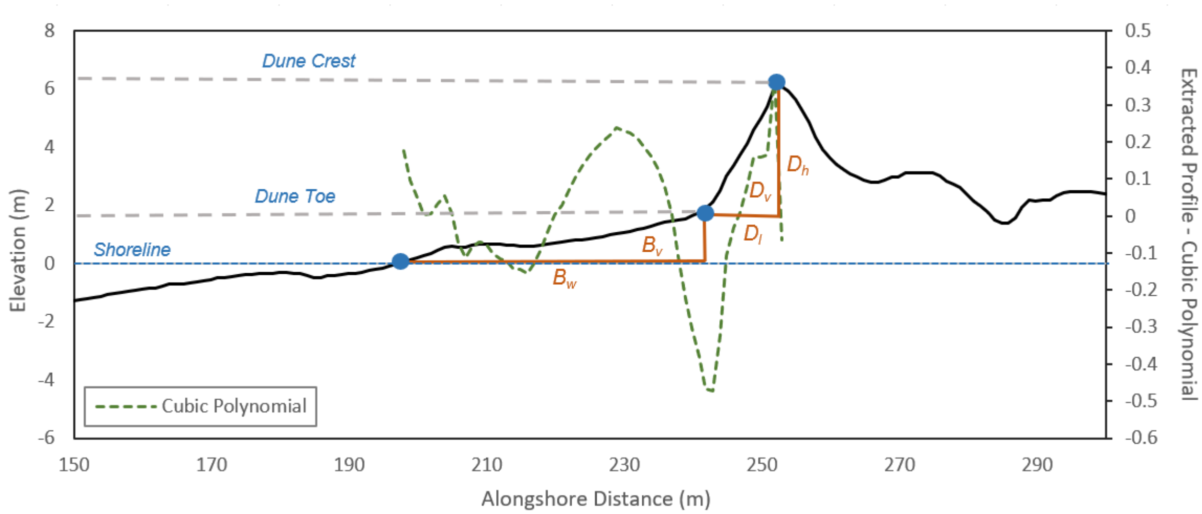


Figure 13. Profile of Brackley indicating beach-dune morphometrics. Shoreline is defined at an elevation of 0m. Dune toe is defined as the largest deviation from the profile - cubic polynomial (dashed green line). Dune crest is the highest/greatest elevation. Beach width is the difference between toe_*x* and shore_*x*. Beach volume is calculated as one half the beach width multiplied by toe_*y*-shore_*y*. Dune length is crest_*x* subtracted from shore_*x*. Dune volume is one half the dune length multiplied by dune height. Dune height is cresy_*y* subtracted from toe_*y*.

6.2 Vegetation Density

Orthomosaics at a resolution of 1.4cm/px were used to identify areas of vegetation and non-vegetation using a Supervised Classification within ArcMap 10.7.1 (Figure 14). Orthomosaics were cropped at the vegetation extent and crest line, this prevented the Supervised Classification from misidentifying water as vegetation. Past the crest line species diversity increases causing greater inaccuracy of classification. Landward of the crest line vegetation can be visually seen as being 100% density. Clusters of pixels of 'vegetation', 'bare sand', 'wet sand', 'shadow' and 'wrack' were manually identified along the cropped orthomosaic, yielding upwards of 3000 pixels per training class (Figure 14B). Raster Calculator was used to set areas of non-vegetation to a value of 0 (Figure 14C). This raster was then averaged every square meter using Block Statistics to go from a resolution of 1.4cm/px to 1m/px (Figure 14D). With the high volume of data in this study this step allowed for cleaner density data that was easier to manage and analyze. The 1m/px vegetation density raster was used for all vegetation calculations past this point.

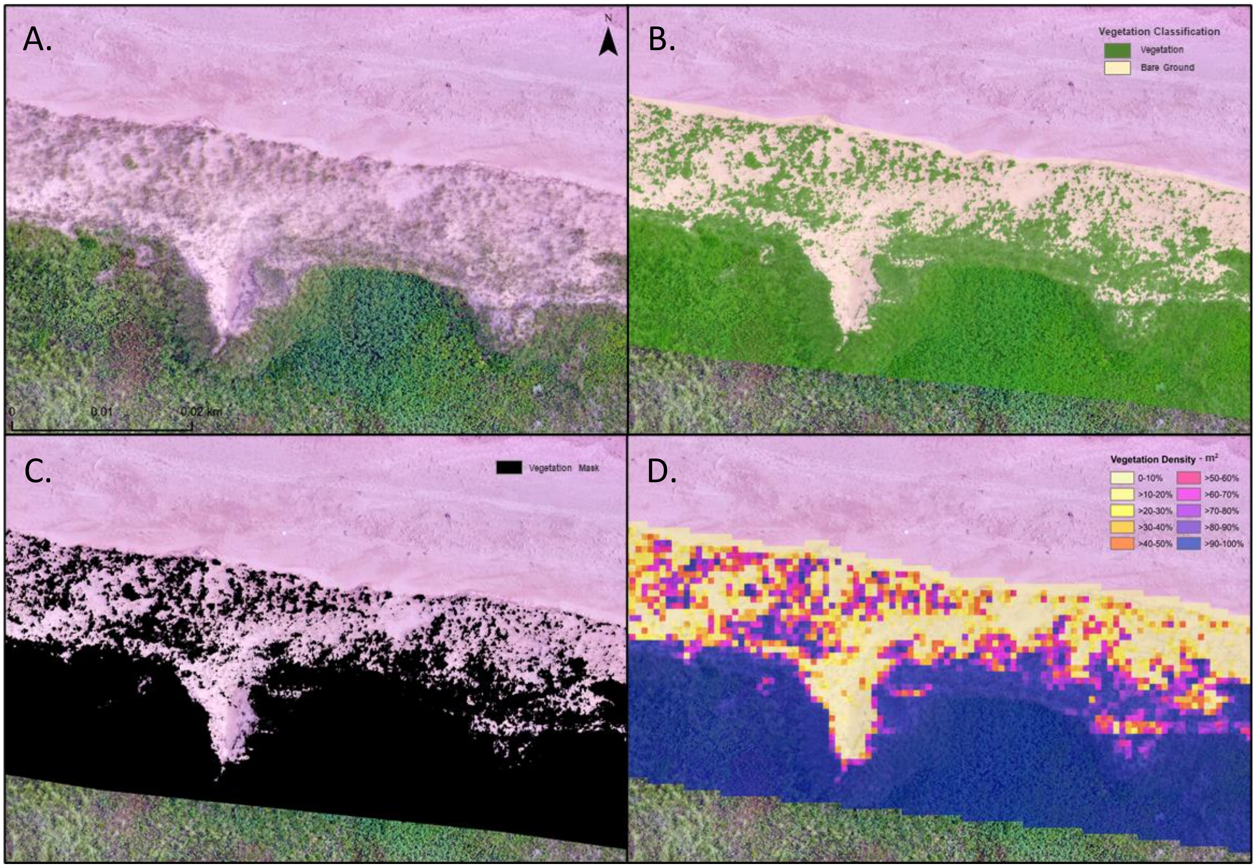


Figure 14. A. 1.4cm/px orthomosaic raster sample from Brackley. B. Supervised classification of vegetation and non-vegetation within the area of interest. C. Vegetation mask with ‘non-vegetation’ set to 0. D. Block Statistics every 1m providing density values for every 1mx1m cell.

6.3 Vegetation Profiles

To maintain consistency of profiles, from the beach-dune morphometrics and vegetation density, the same profiling script and method was used to extract vegetation density profiles every meter. Since the vegetation raster was clipped at the vegetation extent the profiles would not have been relative to the shore. To account for this a mosaic of the DSM raster and the vegetation raster was created. Using Raster Calculator, the DSM was set to a value of 0 indicating no vegetation. The new raster now still contains two values, one for vegetation and one for non-vegetation, however, the vegetation profiles will be relative to the shore and align with the beach-dune profiles.

6.4 Vegetation Extent/Line

The definition of the vegetation line is not consistent within literature (Duran and Moore, 2013; Keijsers et al., 2014). There are frequent disturbances acting on vegetation close to the shoreline making it difficult for it to become established. It is the established vegetation that begins foredune formation (Maun, 2009). To better understand relationships between vegetation and beach-dune morphometrics alongshore the vegetation lines were identified at 5%, 10%, 25%, 50% and 75% density (Figure 15). Vegetation extent is defined as the seaward most point of vegetation for each profile alongshore.

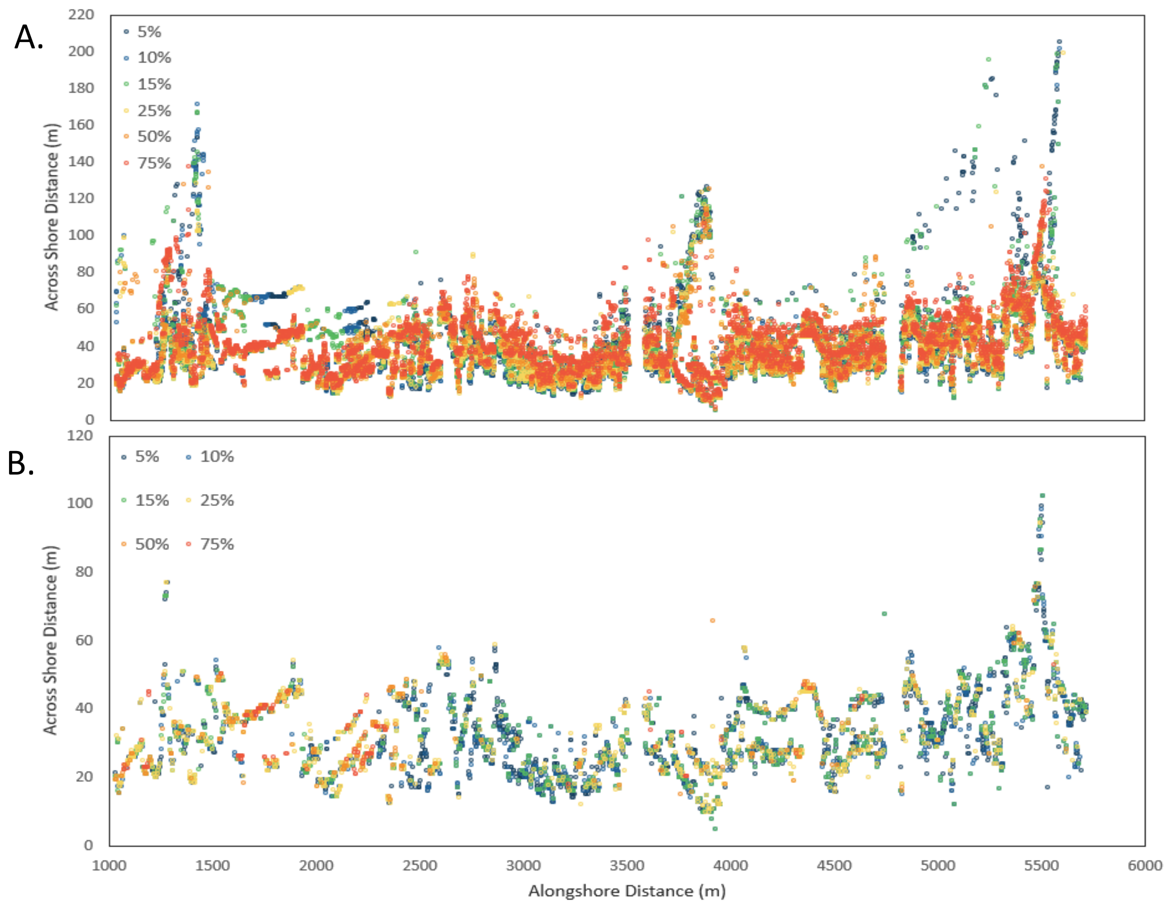


Figure 15. A. Brackley Beach vegetation density profiles for comparison. B. Vegetation extent or the most seaward vegetation from each across shore profile at Brackley Beach.

7. Results

Cavendish, Brackley, and Stanhope are all unique and individually characteristic however, they still all experience considerable alongshore variability in beach-dune morphometrics and vegetation. It is therefore important to consider the alongshore variability these eco-geomorphic variables exhibit. The varying stages of erosion each location is in provides insight on how the vegetation couples with beach-dune recovery following disturbances.

7.1 Beach-Dune Morphometrics

Alongshore beach-dune morphometric graphs for each location including the corresponding box and whisker plots (inserted) are shown below (Figure 16, 17, 18). Since there is a high volume of data and a wide range of variability within each variable the box and whisker plots help to enhance the understanding of each beach-dune metric. For example, Brackley dune height reaches a maximum of 15.2m but this value is considered an outlier within the box and whisker plot, most dune height values for Brackley falling between 1m to 8.5m. This study looks at three different sites at varying levels of erosion and all three sites exhibited a wide interspecific and intraspecific varieties of physical and ecological conditions. This scale dependent variability is seen in the graphs below indicating the alongshore beach-dune morphometrics for Brackley, Cavendish, and Stanhope beaches. Brackley, Cavendish, and Stanhope beach all exhibit considerable variability in beach-dune morphology within and between their locations. Beach-dune morphometric value ranges for all locations can be found in Table 2 and quartile values can be found in tables 3, 4, and 5.

Though Brackley beach has the tallest dune the average dune height is 3.9m, Cavendish beach has a taller dune height on average of 4.2m. Cavendish dune height has the greatest interquartile range (IQR) or greatest variability between the upper and lower quartile values with a value of 5.6m followed by Brackley with 2.4m and Stanhope with 1.7m. Cavendish experiences the most constant erosion especially along the spit and would therefore have more variability in dune height because of the discontinuity due to washover and recovering dunes. Brackley dune height varies alongshore as well but most considerably at locations of disturbances like blowouts (Figure 16A). Stanhope dune height and crest elevation do vary alongshore but to a lesser degree compared to the other two locations. The dune system is continuous but interrupted by multiple inlets and cliffs alongshore (Figure 18A). Some of the variability in dune height along Stanhope corresponds to extreme peaks in beach width which can be explained by beach-dune morphology alongshore. The two major peaks in beach width correspond to a decrease in dune height around 1000m and 3400m are located in areas of inlets. Dune crest elevation at Brackley reach the highest maximum, followed by Cavendish and Stanhope. Similar to dune height Cavendish has higher dune crest elevations on average at 6.7m followed closely by Brackley with 6.6m and Stanhope with 4.6m. The pattern of dune crest IQR followed that of dune height as well.

All locations exhibit considerable variability in beach width, Cavendish has the widest beach with the maximum reaching 223.7m and an average of 64.2m, followed by Stanhope with a maximum of 170.9m and an average of 46.5m. Whereas Brackley has the maximum dune height between locations, it has the smallest maximum beach width. Cavendish has the largest IQR relative to the other location, this followed by Stanhope and then Brackley. The upper range of Cavendish beach width greater than Q3+1.5IQR (>168.8m) are considered outliers and are representing the overwash channels along the spit (Figure 17B). The upper range of Brackley beach width greater than Q3+1.5IQR (>70m) are considered outliers and are found at the far west end of the beach where the beach width is characteristically wide and dune heights are low. At this end of the beach width raises at ~4000m to ~5785m alongshore to ~20m to ~115m respectively. The upper range of Stanhope beach width greater than Q3+1.5IQR (>89m) are considered outliers and are found in locations of inlets alongshore.

Beach slope varies between locations as well with Cavendish having the least steep beach on average, followed by Stanhope and Brackley having the steepest and most narrow beach with an average. The IQR for Cavendish beach slope is 0.05 with 75% of the values less than or equal to 0.07. The IQR for Brackley is smaller than Cavendish with a value of 0.04 and 75% of the values less than or equal to 0.09. Stanhope has the smallest IQR value between the locations with a value of 0.02, and 75% of the values less than or equal to 0.06.

The average beach volume for all locations exceeds their corresponding average dune volumes. Cavendish has the largest average beach volume and largest average dune volume. Brackley has the smallest average beach volume and Stanhope has the smallest average dune volume. Stanhope and Brackley have almost identical beach volume IQR values of 36.0 and 36.6 $m^{3,}$ respectively. Their dune volumes differ more which corresponds to Brackley having a greater dune length average than Stanhope.

Brackley Alongshore

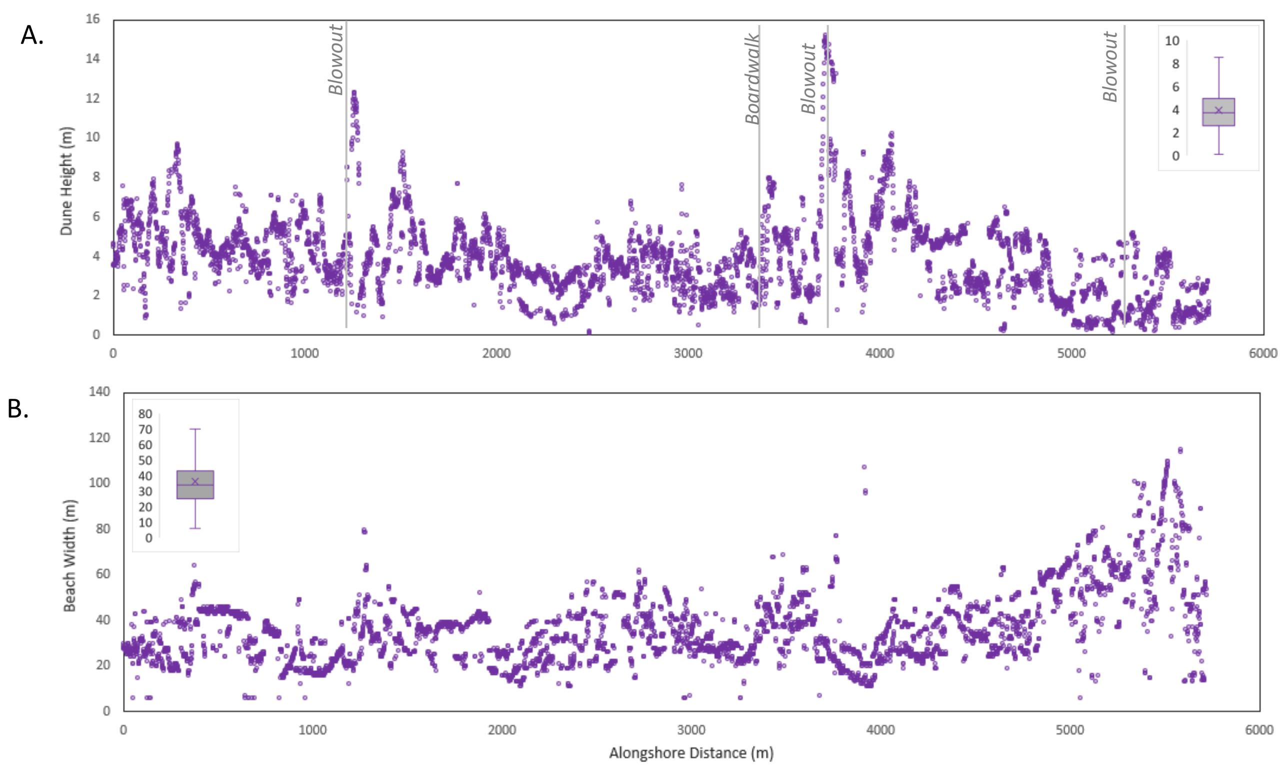


Figure 16. Alongshore beach-dune morphometrics running east to west for Brackley beach. A. dune height, B. beach width.

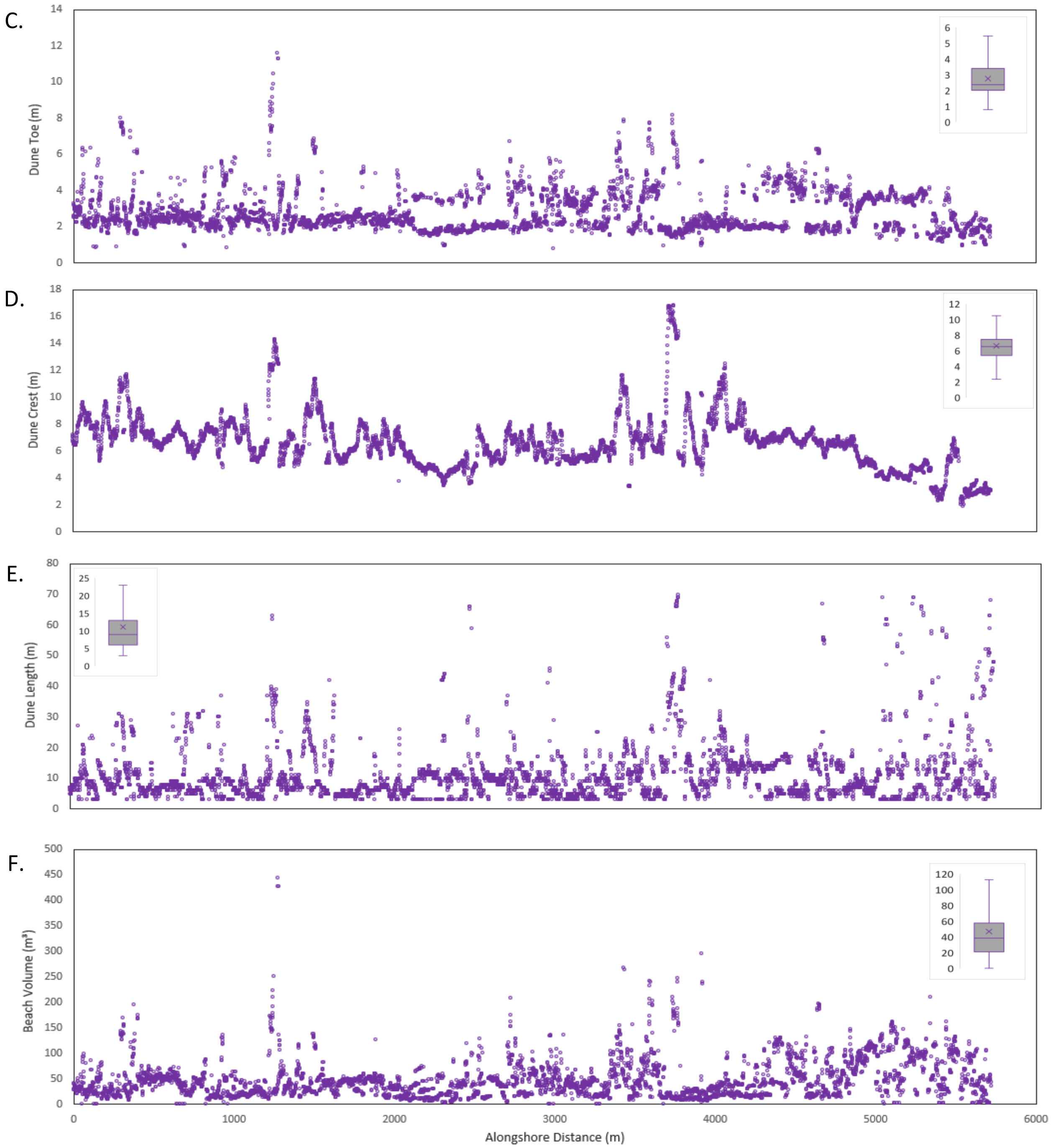


Figure 16 con't. Alongshore beach-dune morphometrics running east to west for Brackley beach. C. dune toe, D. dune crest, E. dune length, F. beach volume.

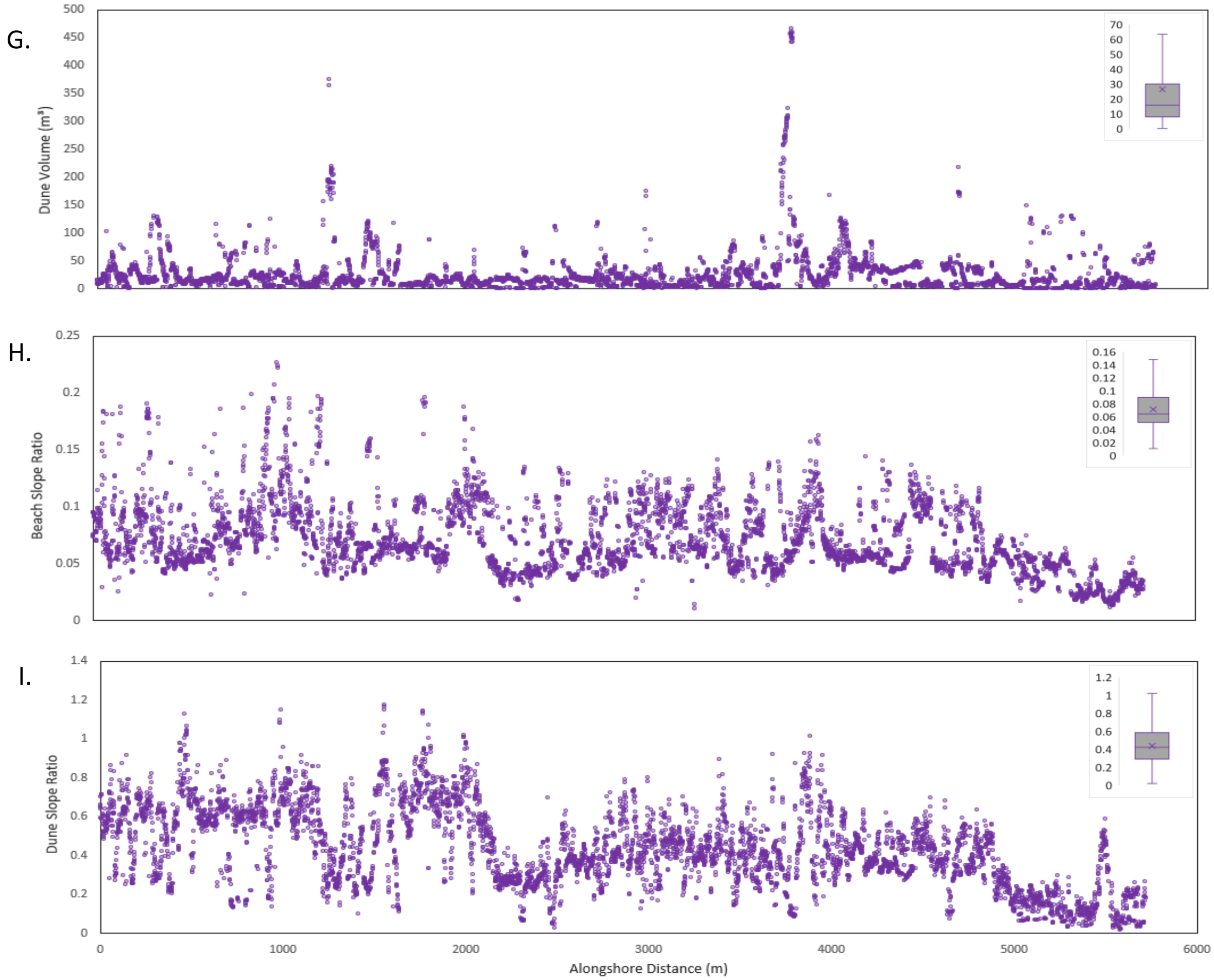


Figure 16 con't. Alongshore beach-dune morphometrics running east to west for Brackley beach. G. dune volume, H. beach slope, I. dune slope.

Cavendish Alongshore

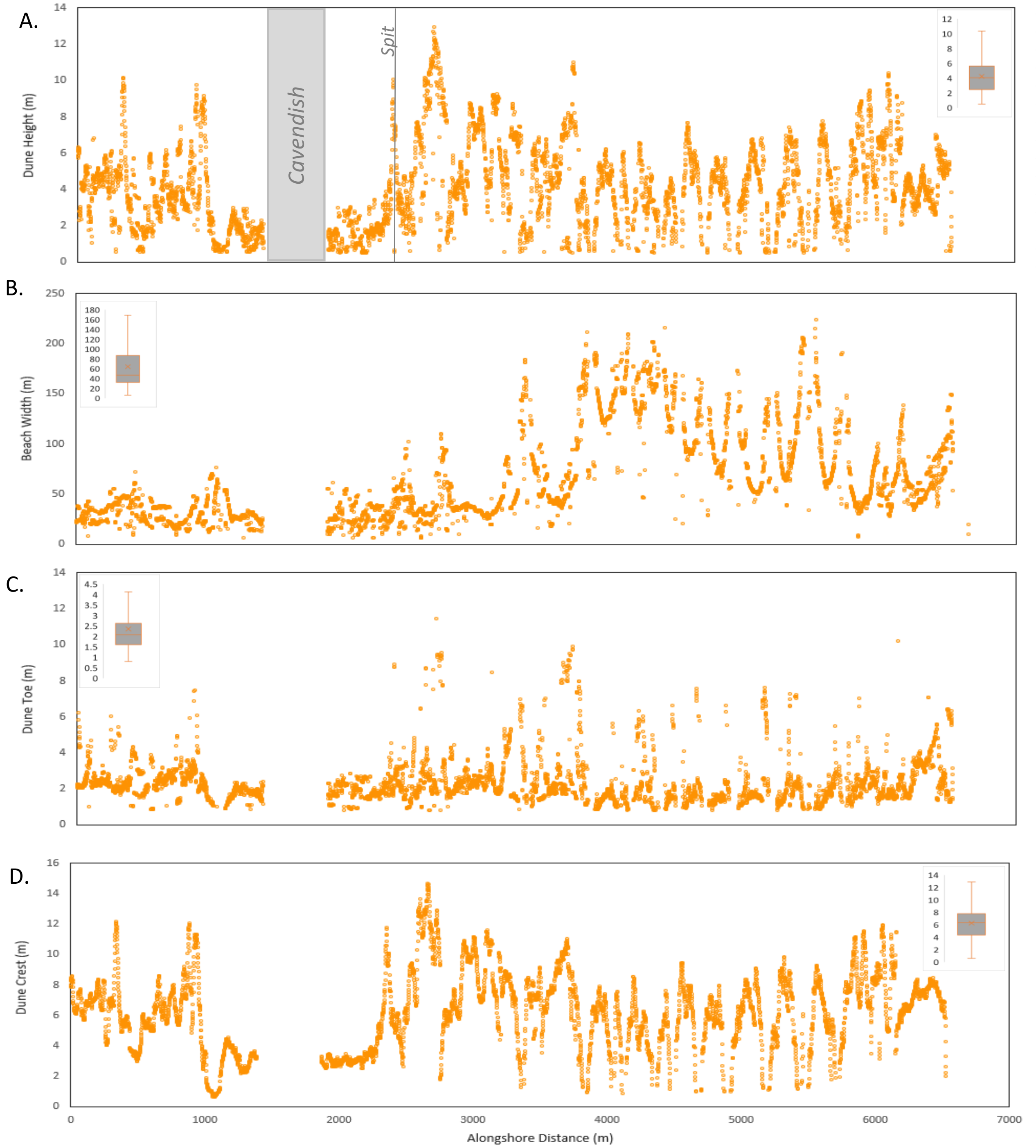


Figure 17. Alongshore beach-dune morphometrics running east to west for Cavendish beach. A. dune height, B. beach width, C. dune toe, D. dune crest.

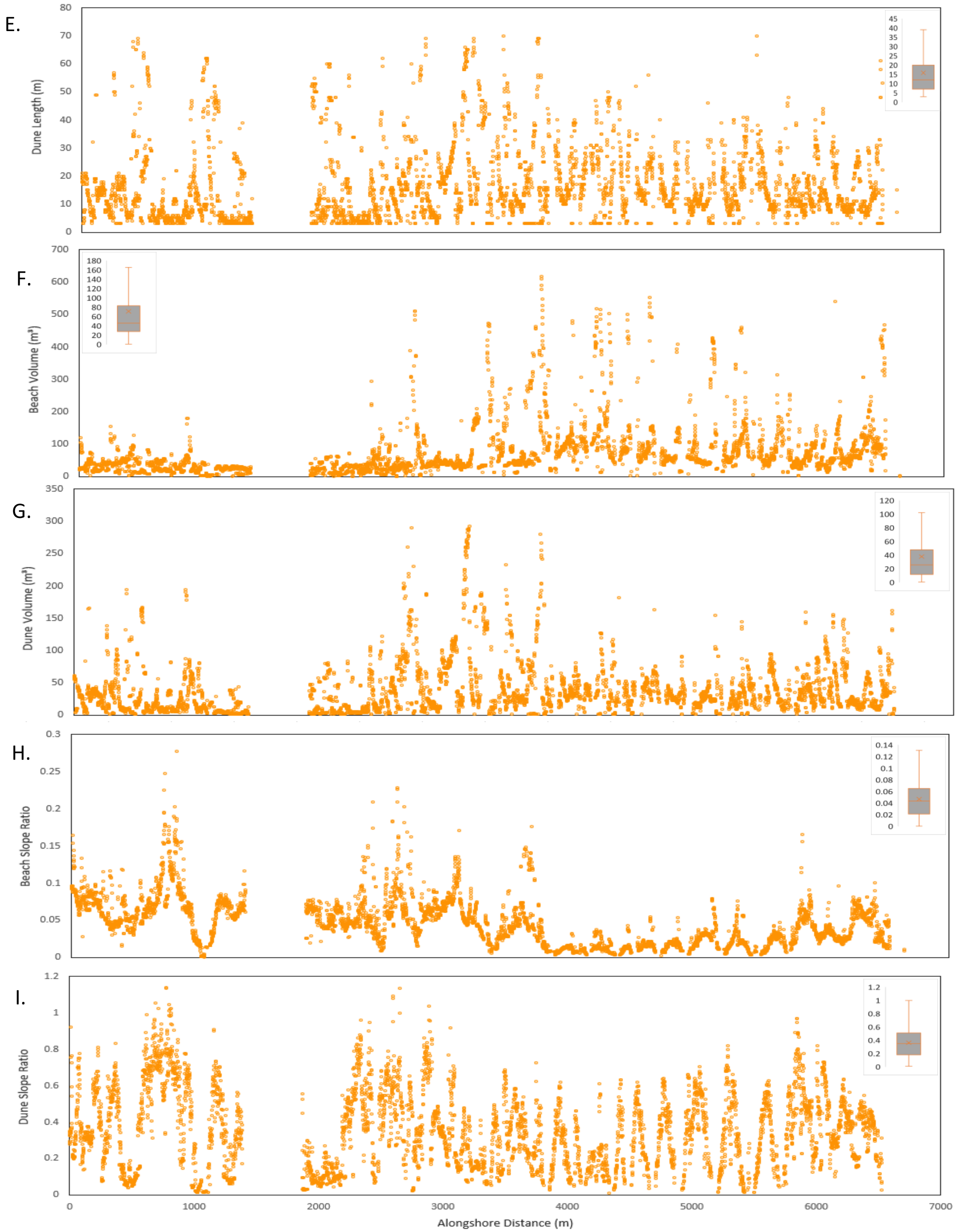


Figure 17 con't. Alongshore beach-dune morphometrics for Cavendish beach. E. dune length, F. beach volume, G. dune volume, H. beach slope, I. dune slope.

Stanhope Alongshore

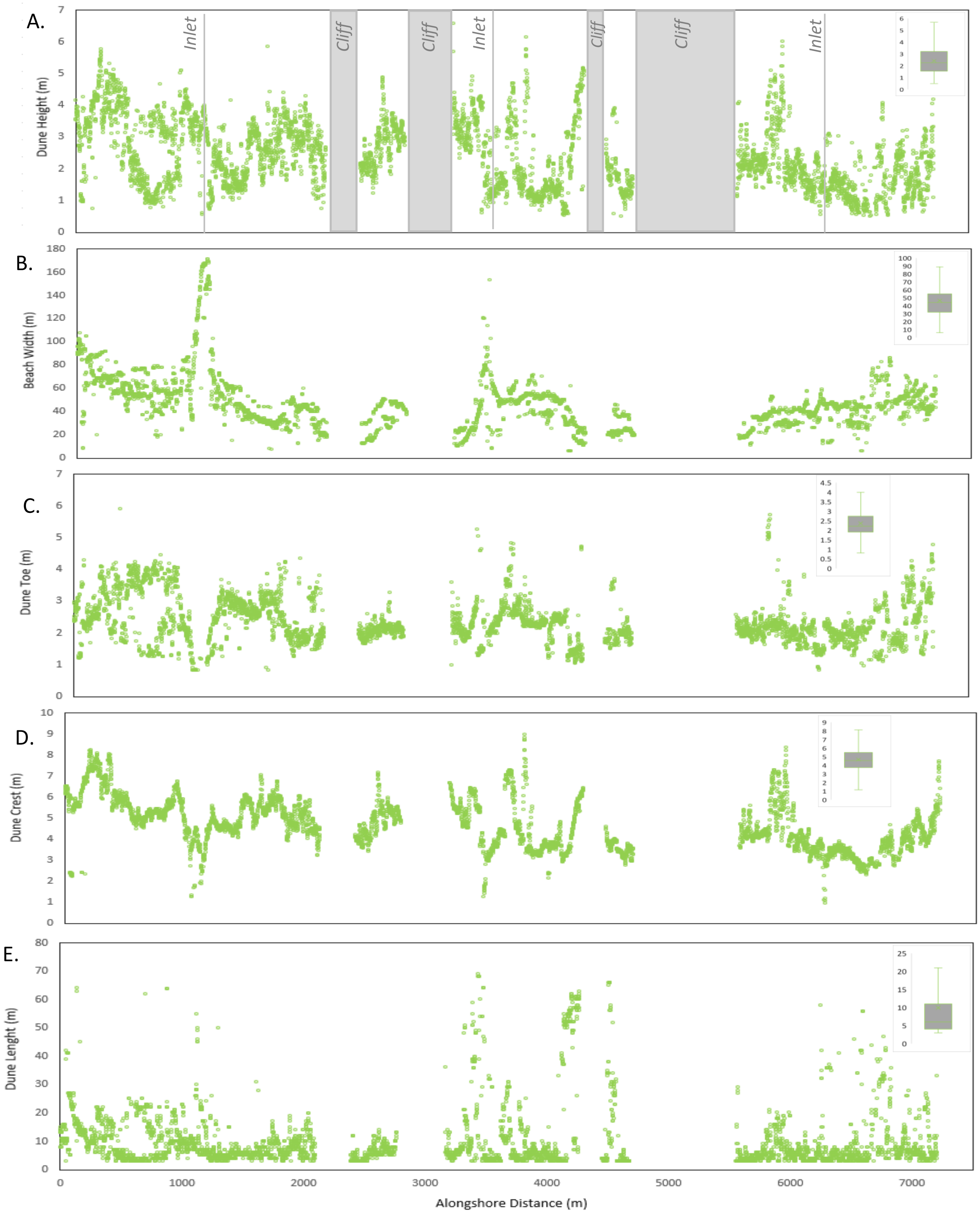


Figure 18. Alongshore beach-dune morphometrics running east to west for Stanhope beach. A. dune height, B. beach width, C. dune toe, D. dune crest, E. dune length.

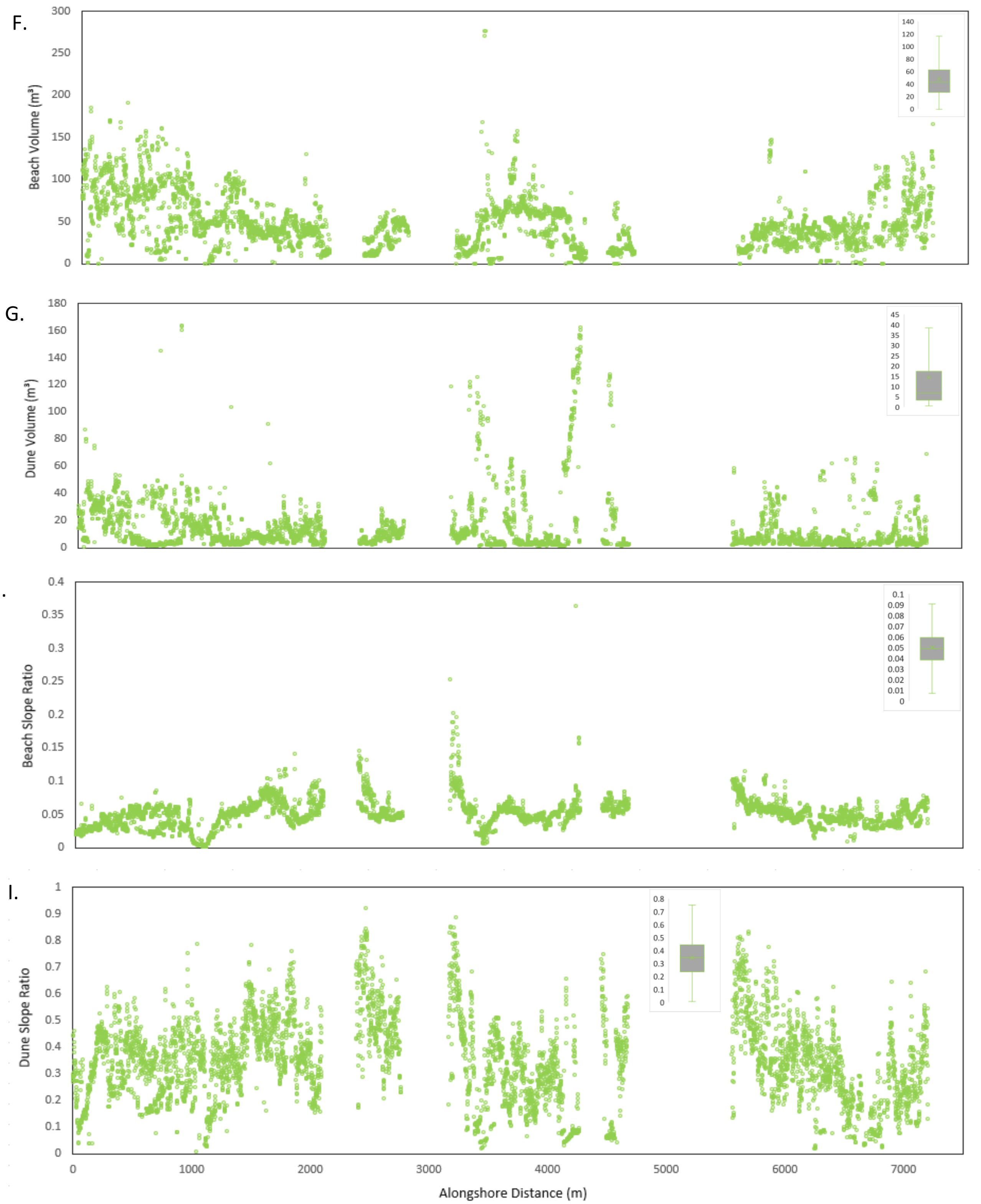


Figure 18 con't. Alongshore beach-dune morphometrics for Stanhope beach, F. beach volume, G. dune volume, H. beach slope, I. dune slope.

Table 2. Average and range of complete data set for Cavendish, Brackley, and Stanhope

	Cavendish		Brackley		Stanhope	
Morphometric	Range	Average	Range	Average	Range	Average
D_h (m)	0.5 –12.8	4.2	0.1 – 15.2	3.9	0.5 – 6.5	2.4
B_w (m)	5.9 – 223.7	64.2	5.9 – 114.9	36.1	5.9 – 170.9	46.5
D_t (m)	0.8 –11.4	2.3	0.8 – 11.5	2.7	0.8 – 5.9	2.3
D_c (m)	0.6 –14.6	6.7	1.9 – 16.8	6.6	0.9 – 8.9 m	4.6
D_l (m)	2.9 – 69.9	15.8	2.9 – 69.8	11.1	2.9 – 68.9	9.9
B_v (m^3)	0.3 – 615.3	70.9	0.3 – 444.4	46.9	0.007 – 275.7	48.1
D_v (m^3)	0.5 – 291.6	37.8	0.1 – 466.6	26.4	0.5 – 163.1	14.4
B_s	0.0002 – 0.2	0.04	0.01 – 0.2	0.07	0.0001 – 0.3	0.05
D_S	0.007 – 1.1	0.3	0.01 – 1.1	0.4	0.005 – 0.9	0.3

The box and whisker plots provide a summary of the distribution of data points alongshore. This allows for ideal comparisons between the three sites because they provide the center, range, and entire spread of the data set. The box and whisker plots show that most of the morphometrics are either normally distributed or positively skewed.

Table 3. Cavendish beach-dune morphometric box and whisker plot data

Morphometric	Q1	Q2	Q3	IQR	Q1-1.5IQR – Q3+1.5xIQR
D_h (m)	2.5	4.1	5.6	3.1	0.5-10.4
B_w (m)	31.9	47.0	86.9	55	6.0-168.8
D_t (m)	1.6	2.1	2.6	1	0.8-4.1
D_c (m)	4.4	6.4	7.8	3.4	0.6-12.9
D_l (m)	7.0	12.0	20.0	13.0	3.0-39.0
B_v (m^3)	27.8	45.3	82.9	55.1	0.4-165.4
D_v (m^3)	11.5	25.6	47.8	36.3	0.6-102.1
B_s	0.02	0.04	0.07	0.05	0.0002-0.1
D_S	0.2	0.3	0.5	0.3	0.008-1.0

Table 4. Brackley beach-dune morphometric box and whisker plot data

Morphometric	Q1	Q2	Q3	IQR	Q1-1.5IQR – Q3+1.5xIQR
D_h (m)	2.6	3.7	5.0	2.4	0.1-8.5
B_w (m)	25.0	33.9	43.0	18.0	6.0 – 70.0
D_t (m)	2.0	2.4	3.4	1.4	0.8-5.5
D_c (m)	5.4	6.5	7.5	2.1	2.3-10.5
D_l (m)	6.0	9.0	13.0	7.0	3.0 – 23.0
B_v (m^3)	21.2	38.5	57.8	36.6	0.3-112.6
D_v (m^3)	7.8	15.8	30.2	22.4	0.1-63.6
B_s	0.05	0.06	0.09	0.04	0.01-0.15
D_S	0.3	0.4	0.6	0.3	0.02-1.0

Table 5. Stanhope beach-dune morphometric box and whisker plot data

Morphometric	Q1	Q2	Q3	IQR	Q1-1.5IQR – Q3+1.5xIQR
D_h (m)	1.5	2.2	3.2	1.7	0.5-5.7
B_w (m)	32.0	44.0	55.0	23.0	6.0-89.0
D_t (m)	1.9	2.2	2.7	0.8	0.8-4.0
D_c (m)	3.7	4.6	5.5	1.8	1.2-8.1
D_l (m)	4.0	6.0	11.0	7.0	3.0-21.0
B_v (m^3)	26.4	42.7	62.4	36.0	0.8-116.4
D_v (m^3)	3.4	6.9	17.4	14.0	0.5-38.4
B_s	0.04	0.05	0.06	0.02	0.007-0.09
D_S	0.2	0.3	0.4	0.2	0.005-0.75

7.2 Vegetation

Consistent with beach-dune morphometrics there is high volume of data and considerable variability within alongshore vegetation lines. Box and whisker plots (inserted) were used to enhance understanding of the vegetation density profiles at each location (Figure 19, 20, 21).

Cavendish

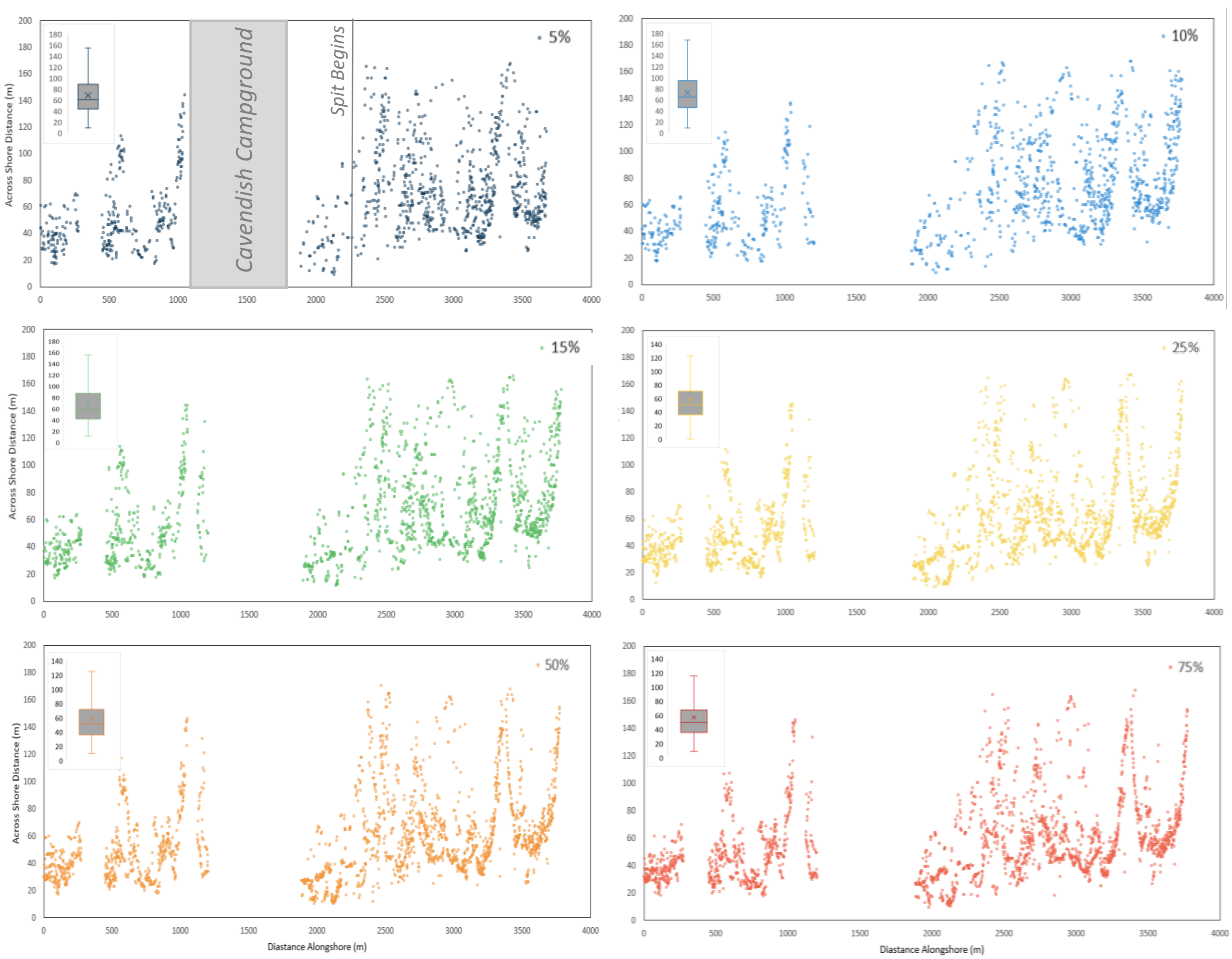


Figure 19. All density values for profiles every meter alongshore taken at every meter across shore going east to west. Density values range from 5% to 75%.

Brackley

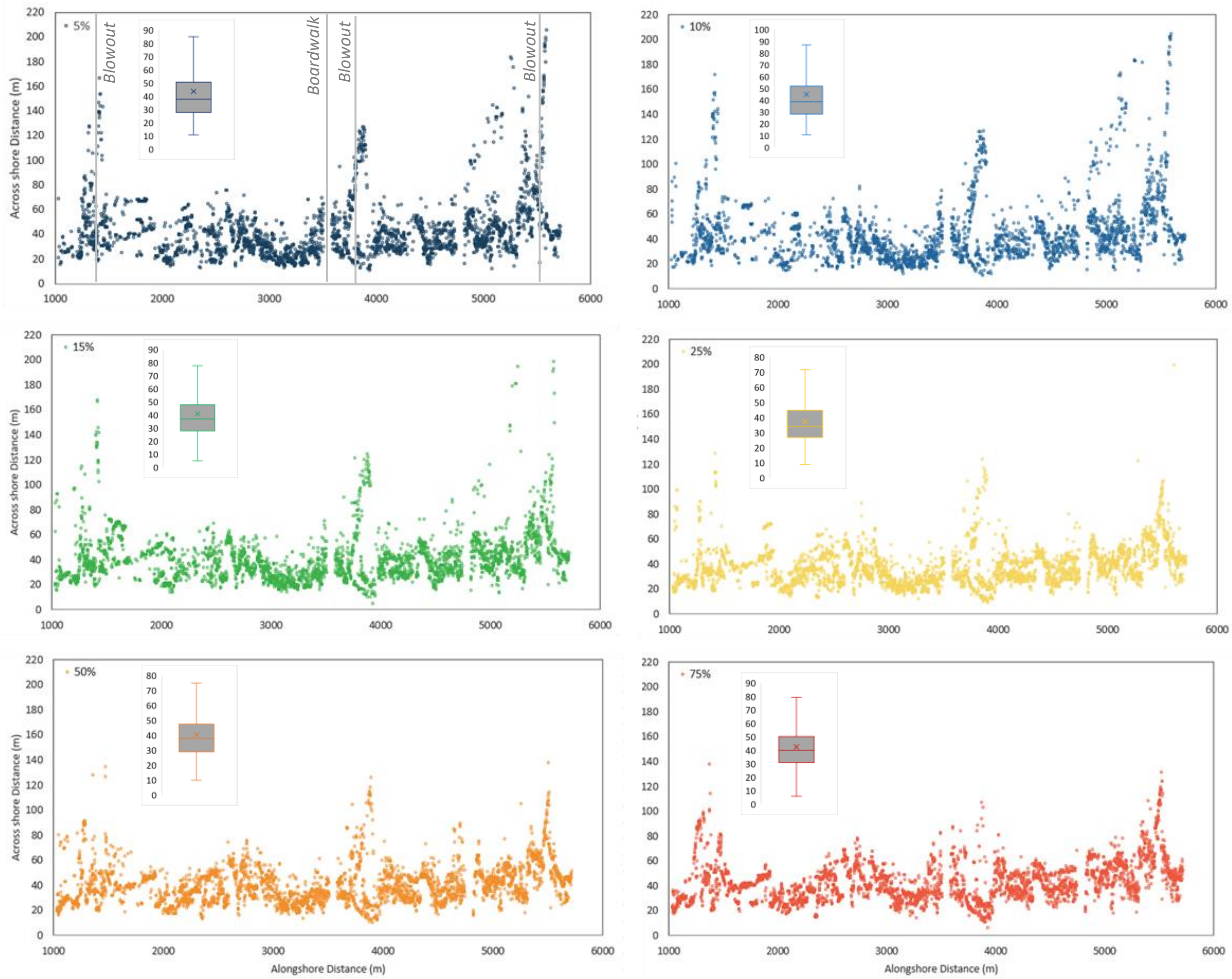


Figure 20. All density values for profiles every meter alongshore taken at every meter across shore going east to west. Density values range from 5% to 75%.

Stanhope

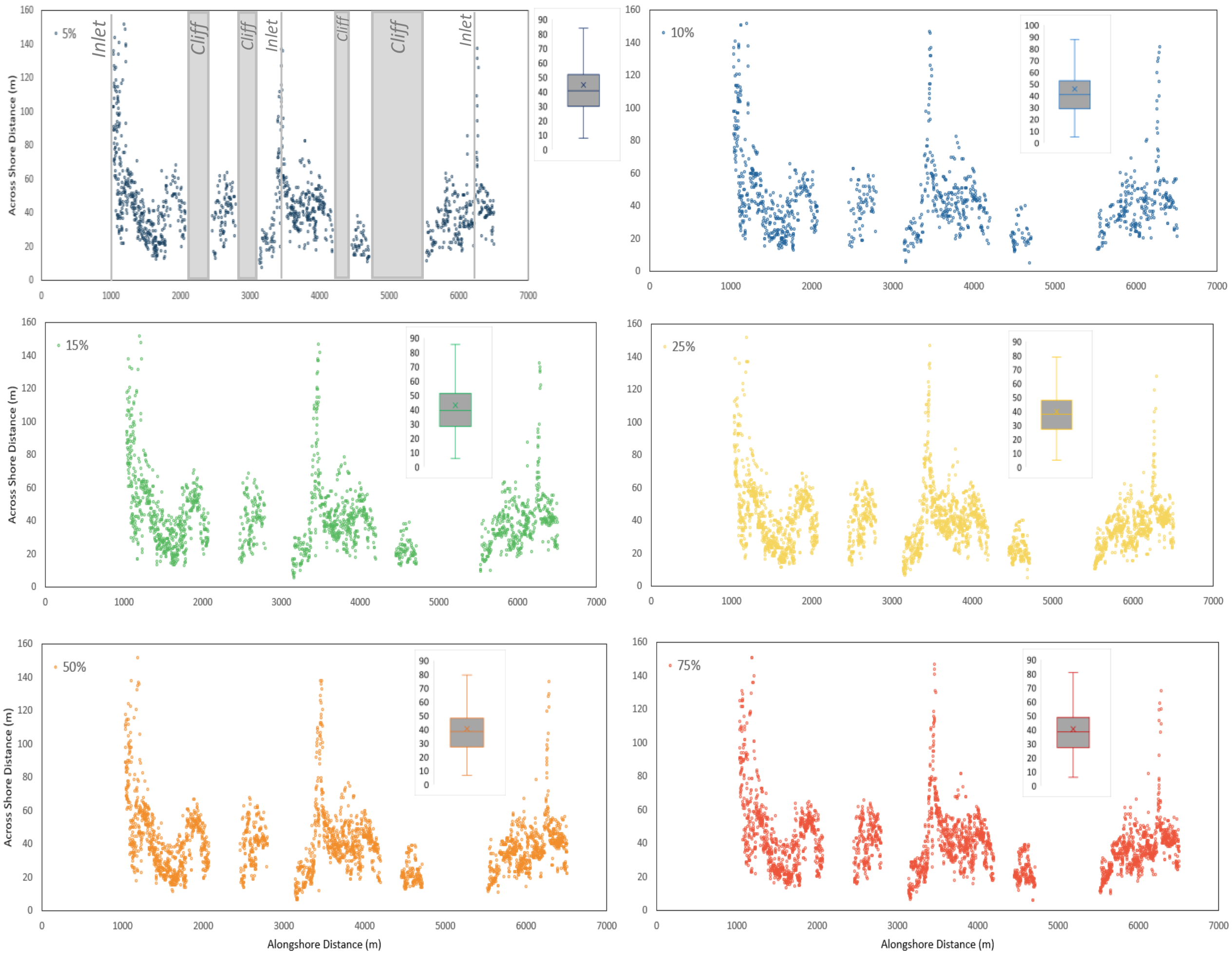


Figure 21. All density values for profiles every meter alongshore taken at every meter across shore going east to west. Density values range from 5% to 75%.

Table 6. Cavendish vegetation density box and whisker data

Density	Q1	Q2	Q3	IQR	Average	Q1-1.5IQR – Q3+1.5IQR
5%	44.0	60.9	88.7	44.7	68.5	9.5- 154.9
10%	45.9	64.9	94.8	48.9	72.6	9.0-167.6
15%	41.9	58.8	87.8	45.9	66.9	11.5-156.0
25%	36.0	50.9	70.8	34.8	58.6	9.0-122.9
50%	36.1	51.8	71.9	35.8	58.8	10.1-125.1
75%	36.0	50.0	67.9	31.9	57.1	9.1-115.7

Table 7. Brackley vegetation density box and whisker data

Density	Q1	Q2	Q3	IQR	Average	Q1-1.5IQR – Q3+1.5IQR
5%	27.8	37.8	50.8	23.0	43.7	10.9-85.1
10%	28.3	38.8	52.0	23.7	45.0	10.8-87.1
15%	27.8	36.9	47.8	20.0	41.0	4.9-77.7
25%	26.8	34.0	44.7	17.9	37.3	8.9-71.6
50%	28.9	37.8	47.4	18.5	40.2	9.9-75.0
75%	30.9	40.0	50.3	19.4	42.5	5.9-79.3

Table 8. Stanhope vegetation density box and whisker data

Density	Q1	Q2	Q3	IQR	Average	Q1-1.5IQR – Q3+1.5IQR
5%	29.0	40.9	53.4	24.4	45.2	7.7-89.9
10%	27.0	40.5	53.7	26.7	45.5	5.1-92.8
15%	26.9	38.7	52.0	25.1	42.8	5.8-88.9
25%	25.9	37.9	49.0	23.1	39.8	5.0-83.8
50%	25.6	37.9	49.7	24.1	40.4	6.7-85.9
75%	25.6	37.9	50.5	24.9	40.5	6.0-86.9

7.2.1 Vegetation Density Alongshore

Tables 6, 7, and 8 show the box and whisker plot data for each location. Cavendish has the greatest IQR and average for all density vegetation lines. Brackley and Stanhope are similar in their IQR and averages however, the IQR for Brackley has an overall decrease from 5% to 75% whereas the IQR for Stanhope is more consistent. Cavendish has the greatest upper whisker values (Q3+1.5IQR) while Brackley and Stanhope are more similar but Brackley has an overall decrease from 5%-75%.

7.2.2 Vegetation Density Extent Alongshore

The plots for the horizontal and vertical position of vegetation extent for Cavendish beach does not show a strong relationship (Figure 22). Data is clustered above 1m elevation with one outlier falling below this threshold.

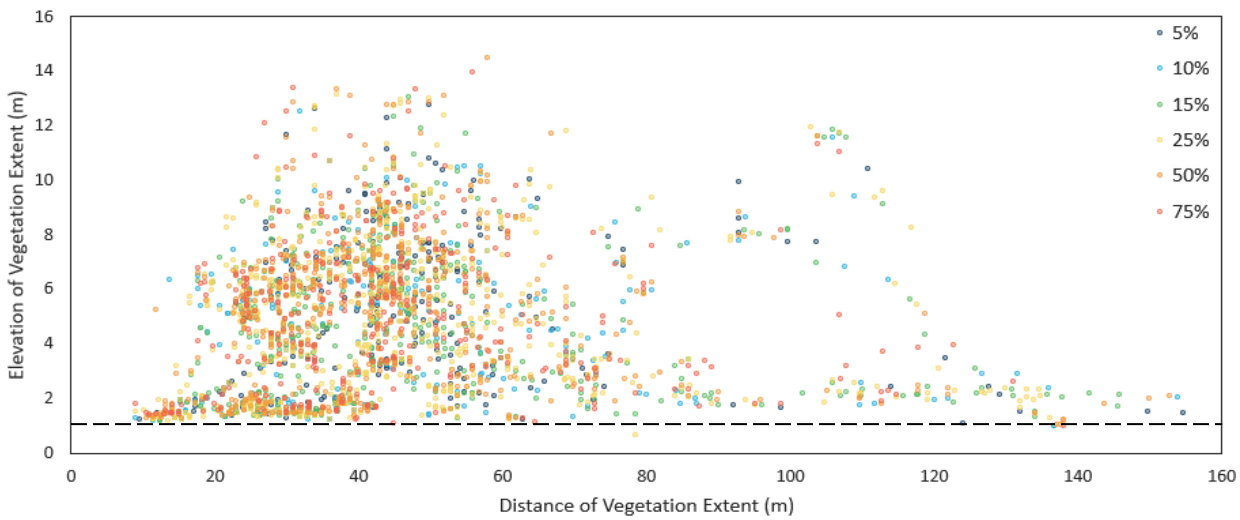


Figure 22. Plots of vertical and horizontal vegetation extent for each profile along Cavendish beach. Dashed line indicating 1m where majority of values fall above.

Vertical position of vegetation extent alongshore shows how vegetation elevation varies with beach-dune morphology such as blowout, inlets, and washover channels along Cavendish beach (Figure 23). The majority of elevation values fall above 1m elevation.

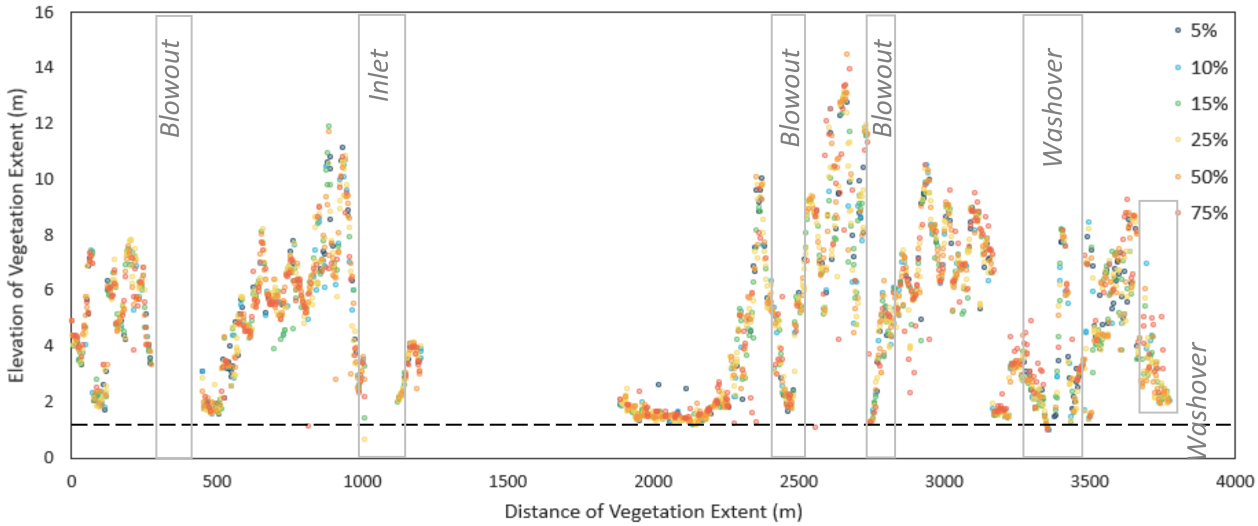


Figure 23. Vertical position of vegetation extent alongshore for Cavendish beach. Dashed line indicating 1m elevation where majority of vegetation falls above. Grey rectangles indicate locations of blowouts, inlets, and washovers.

The box and whisker plots for the vertical position of vegetation extent and Cavendish shows that the average elevation is roughly 5m for all densities (Figure 24). The upper whisker for all densities is roughly 12.5-13.5m with the lower whisker never reaching lower than 1m for all densities.

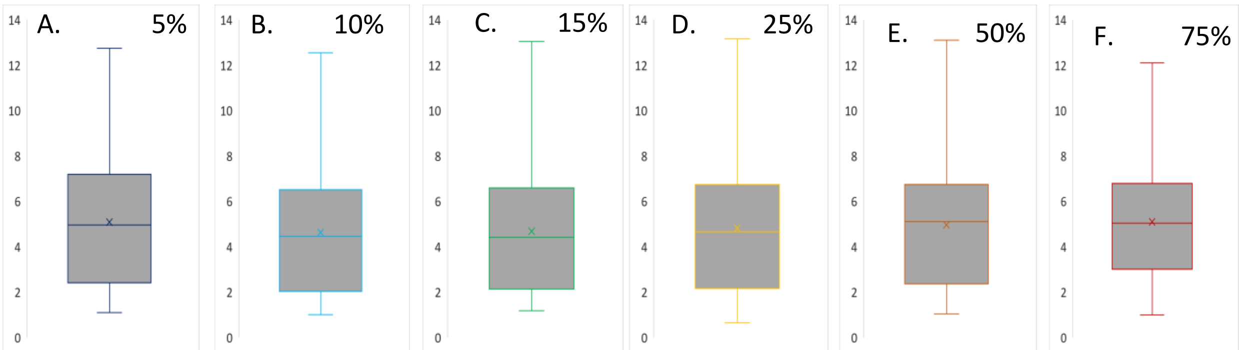


Figure 24. Box and whisker plots of the elevation corresponding to the minimum vegetation extent for each density value. Median and average values are very similar for all density values.

Horizontal position of vegetation extent shows variability in areas of beach and dune disturbances such as blowouts, inlets, and washover channels (Figure 25). Vegetation does not appear closer than 9m to the shoreline with the majority not appearing less than 18m to the shoreline.

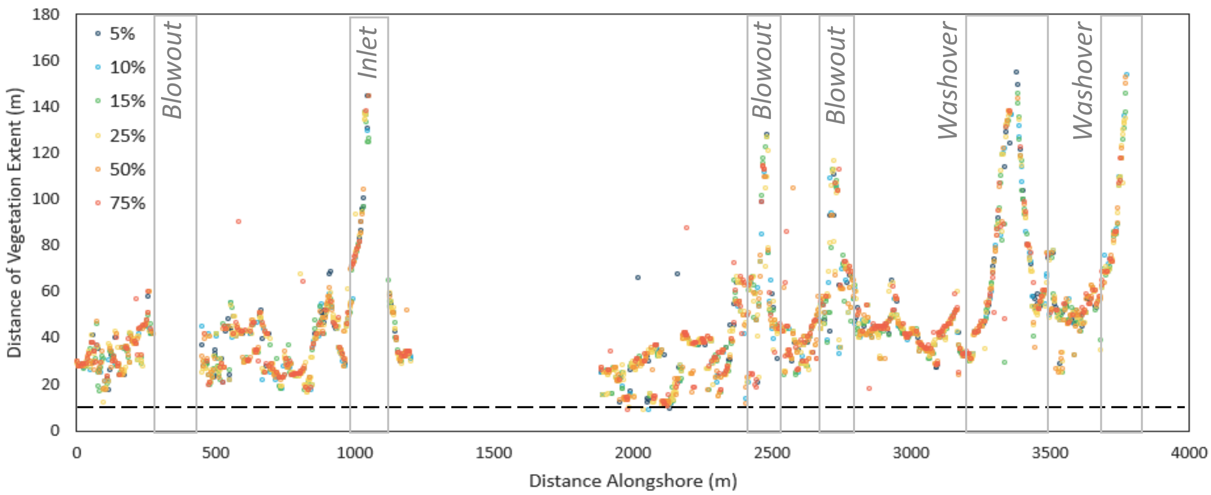


Figure 25. Horizontal position of vegetation extent of Cavendish. Dashed line indicating a distance of 9m where majority of vegetation falls above. Grey rectangles represent blowouts, inlets, and washover channels.

Most of the vegetation at Cavendish falls between 2-7m in elevation and 18-60m cross-shore never appearing lower than 1m or closer than 9m to the shoreline. The data point that falls below 1m elevation (1000m) is located at an inlet (Figure 26). Areas of vegetation that fall near 1m elevation can be seen alongshore in figure 23, these values are all in areas of discontinuities or blowouts (Figure 27 and 28). Alongshore vertical position of vegetation extent values between 1890-2300m do not follow the same discontinuous patterns that Cavendish exhibits. This area is unique because it is bordered to the east by a cliff (Cavendish Campground) and to the west by a spit. This area has low profile dunes with consistent vegetation elevation of 1-2m, though the horizontal position of vegetation from shore is not as consistent, see figure 25. The horizontal position of vegetation extent in this area account for the values that are closer than 20m from the shore can be seen in figure 29. Overall, the vegetation extent values vary in elevation and distance from shoreline as you move alongshore.

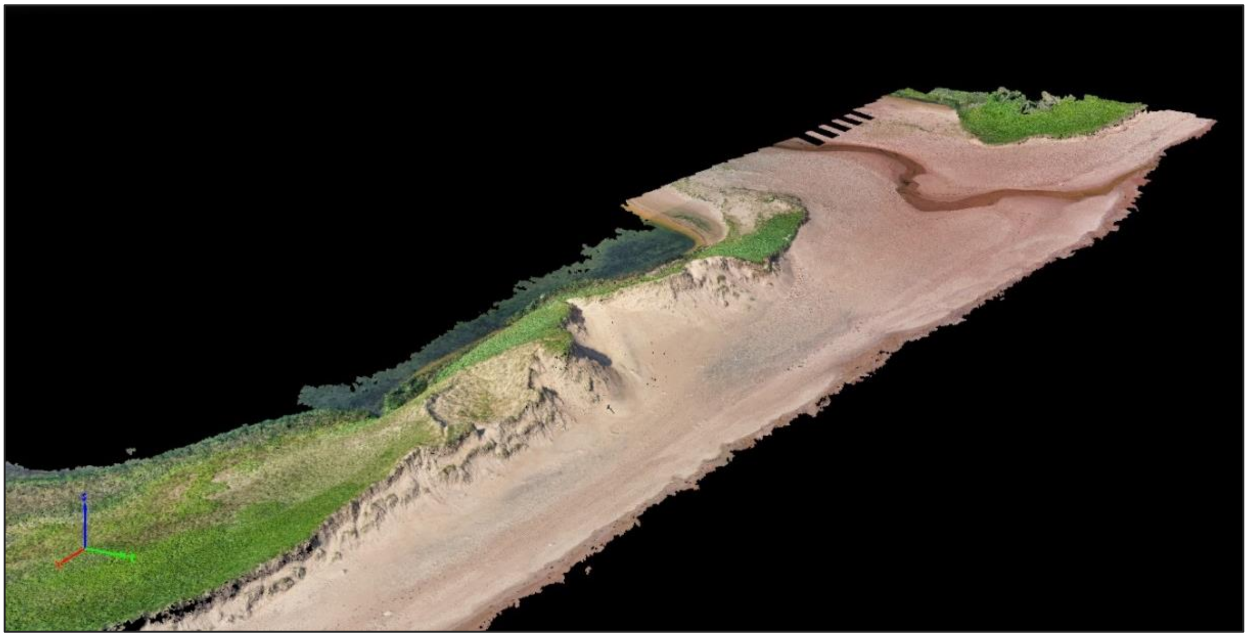


Figure 26. High density point cloud produced by Pix4D Mapper showing the inlet on Cavendish beach, east of the campground. Alongshore profile ~967-1153m.

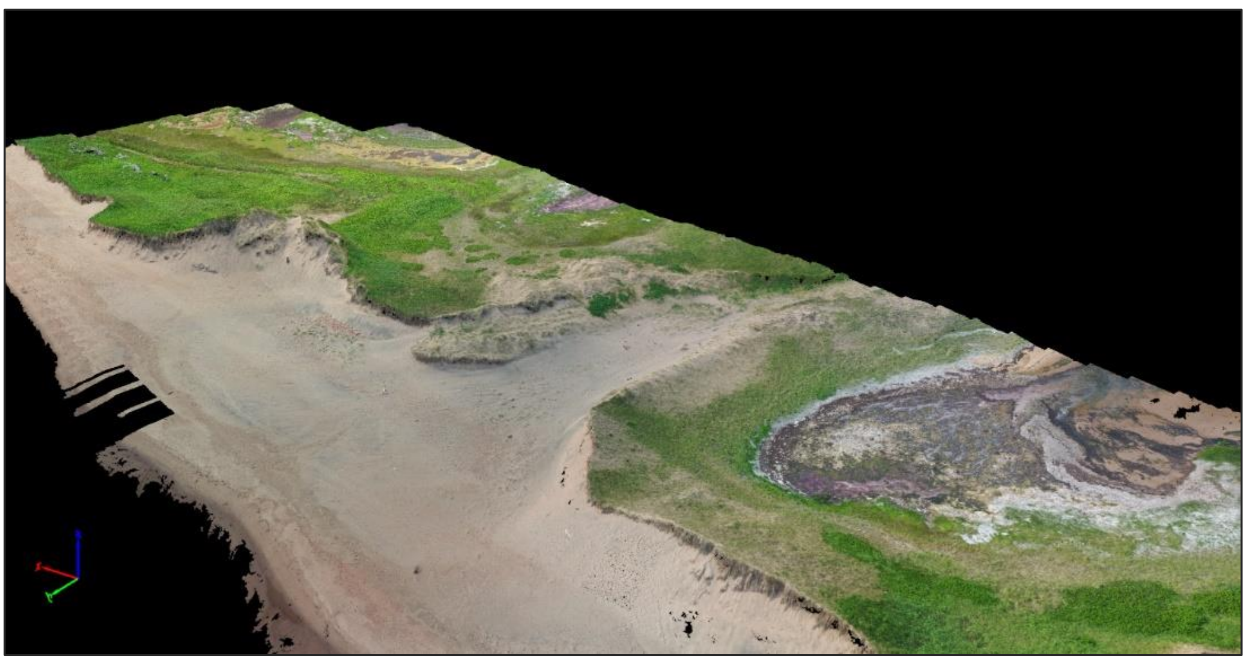


Figure 27. High density point cloud produced in Pix4DMapper showing a blowout along Cavendish, west of the campground. Alongshore profile ~2510-2565m.

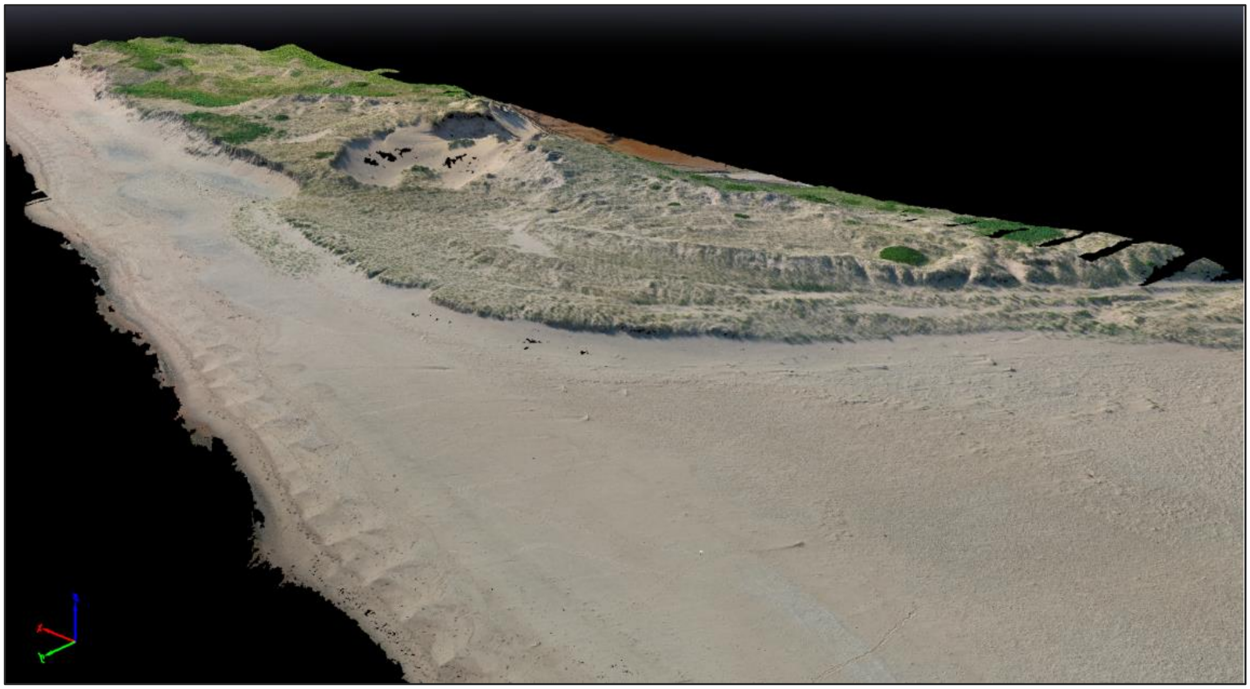


Figure 28. High density point cloud of a wash-over channel along the Cavendish spit, profiles ~3360m-3500m.

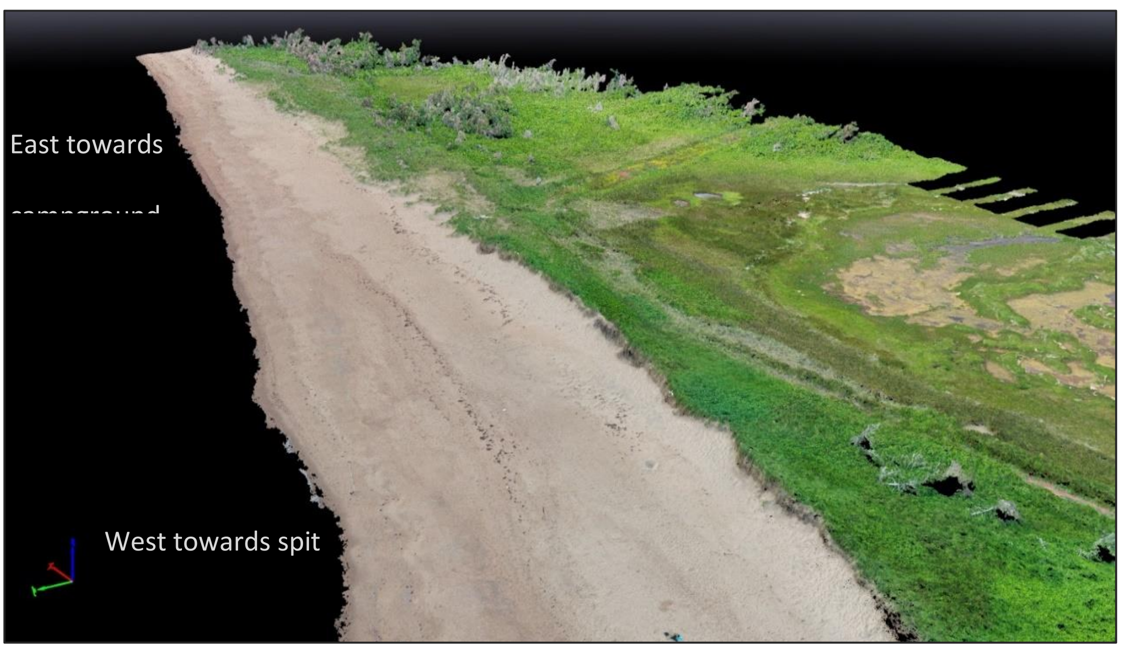


Figure 29. High density point cloud produced in Pix4DMapper showing low profile dunes along Cavendish beach. Alongshore profiles ~1890-2300m.

The plots for the vertical and horizontal positions of vegetation extent Brackley beach does not show a strong relationship (Figure 30). Data are clustered above 1m elevation with no outliers falling below this threshold.

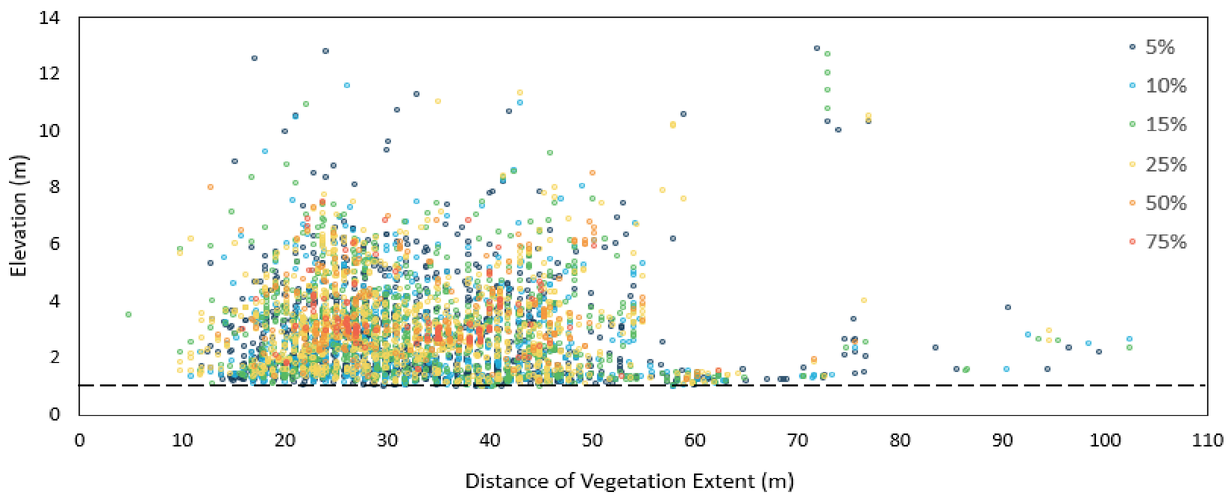


Figure 30. Plot of vertical and horizontal vegetation extent for each profile along Brackley beach. Dashed line indicating 1m where majority of values fall above.

Vertical position of vegetation extent alongshore shows how vegetation elevation varies with beach-dune morphology such as blowout along Brackley beach (Figure 31). All elevation values fall above 1m.

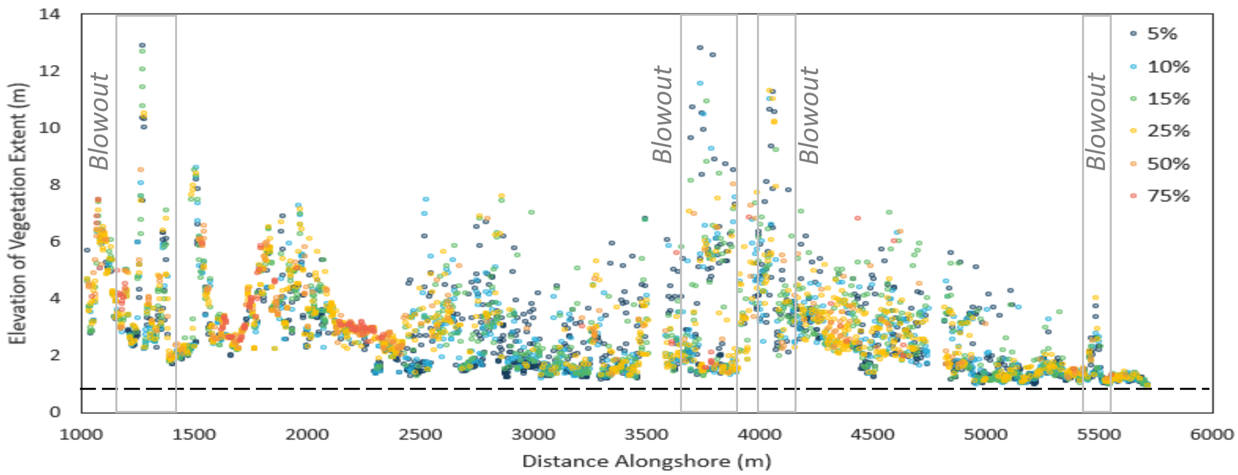


Figure 31. Vertical position of vegetation extent alongshore for Brackley beach. Dashed line indicating 1m elevation. Grey rectangles represent areas of blowouts alongshore.

The box and whisker plots for the vertical position of vegetation extent and Brackley shows that the average elevation is ranges from about 2.75m – 3.5m with a general increase from 5% to 75% density (Figure 32). The IQR generally decreases from 5% to 75% meaning there is less variability in elevation values for 50% and 75% densities. The upper whiskers are lower than Cavendish beach and are roughly 6.25-7m with the lower whisker never reaching lower than 1m for all densities.

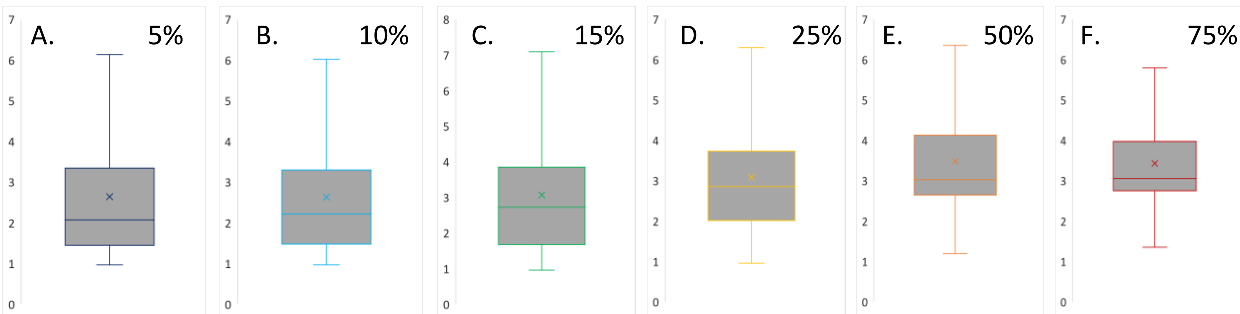


Figure 32. Box and whisker plots of the elevation corresponding to the minimum vegetation extent for each density value. IQR decreases from 5%-75%.

Horizontal position of vegetation extent shows variability in areas of beach-dune morphology disturbances such as blowouts (Figure 33). Vegetation does not appear closer than 9.8m to the shoreline with the majority not appearing closer than 15m to the shoreline.

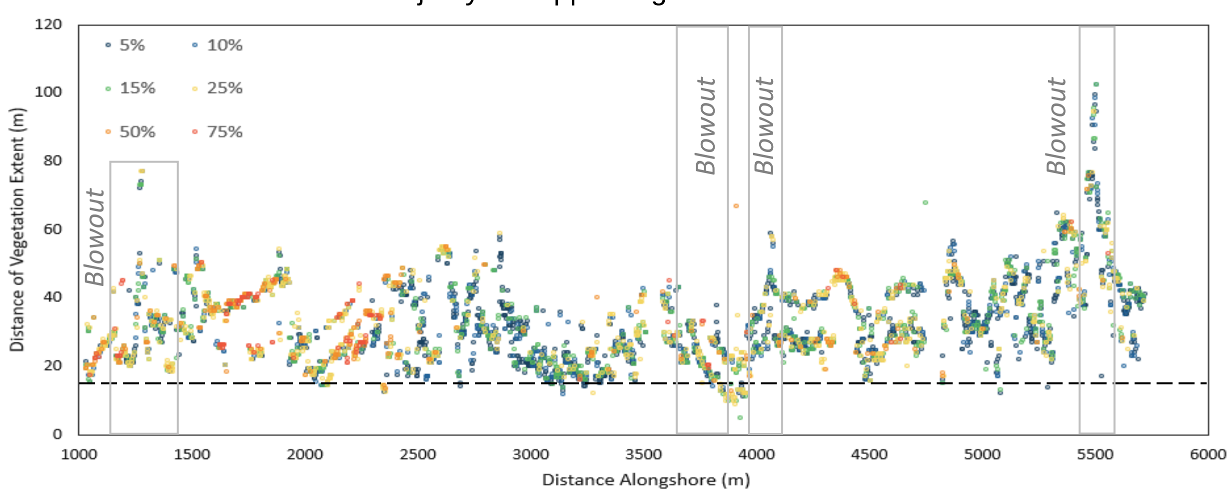


Figure 33. Distance of vegetation extent from shoreline alongshore of Brackley. Dashed line indicating a distance of 9.8m. Grey rectangles representing areas of blowouts.

Vegetation along Brackley beach does not appear closer than 9.8m to the shore, except for an outlier (Figure 33). The points that are closer than 10m to the shore can be seen in figure 34, this point on the beach is a small ramp in the sand connecting a pathway to the beach which has narrowed the beach in front of it. The elevation values are all above the 1m mark as seen in the alongshore graph (Figure 31). Vertical position of vegetation extent becomes consistently close to 1m along the west end of the beach. This location has characteristically low dune profiles and a wide beach (Figure 35). The alongshore elevation extent values in rectangles seen in figure 31 represent areas of large blowouts contributing to the discontinuity of the dune profiles and vegetation alongshore (Figure 36).

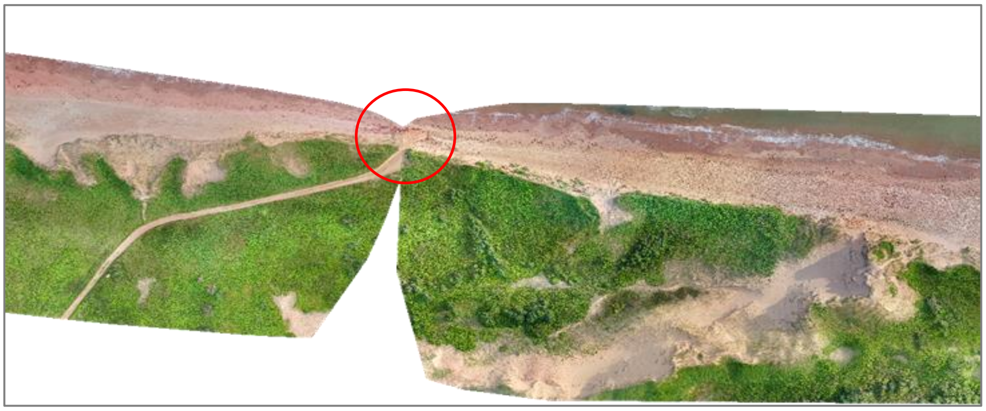


Figure 34. 1.4cm/px resolution orthomosaics showing the location along Brackley beach, profile ~3920m, where a ramp connecting the beach to an access point decreases the beach width.

Figure 35. High density point cloud produced in Pix4DMapper showing the low-profile dunes and wide beach of Brackley west beginning around 4300m.

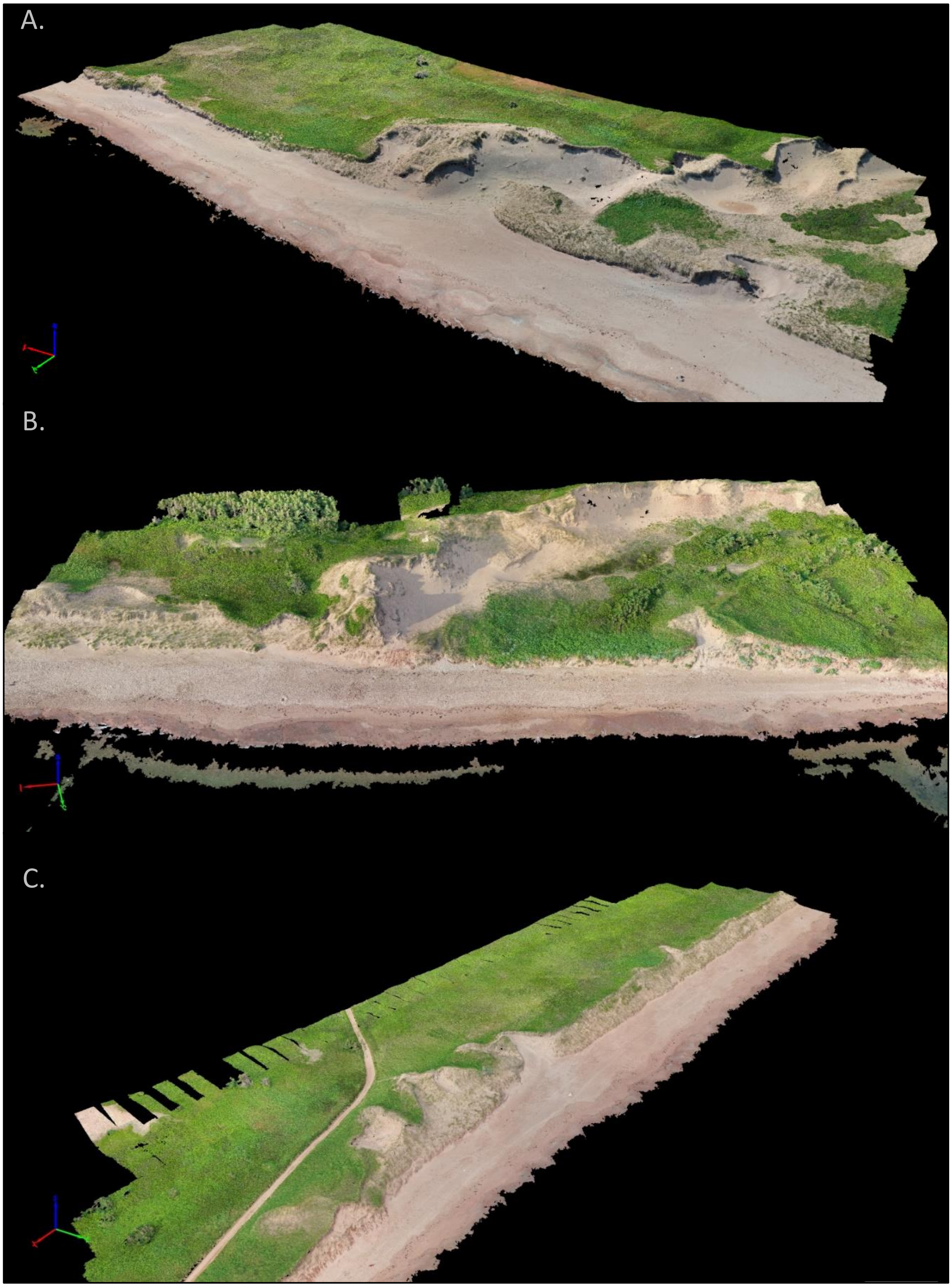


Figure 36. High density point cloud of Brackley. A. Permanent blowout where areas of recovery and discontinuous dune morphometrics can be seen at profiles ~1220m-1500m. B. Permanent blowout at profiles ~3700-3900m. C. Series of blowouts at profiles ~4000-4115m.

The plot for vertical and horizontal positions of vegetation extent at Stanhope beach does not show a strong relationship (Figure 37). Data are clustered above 1m elevation with a few outliers falling below this threshold.

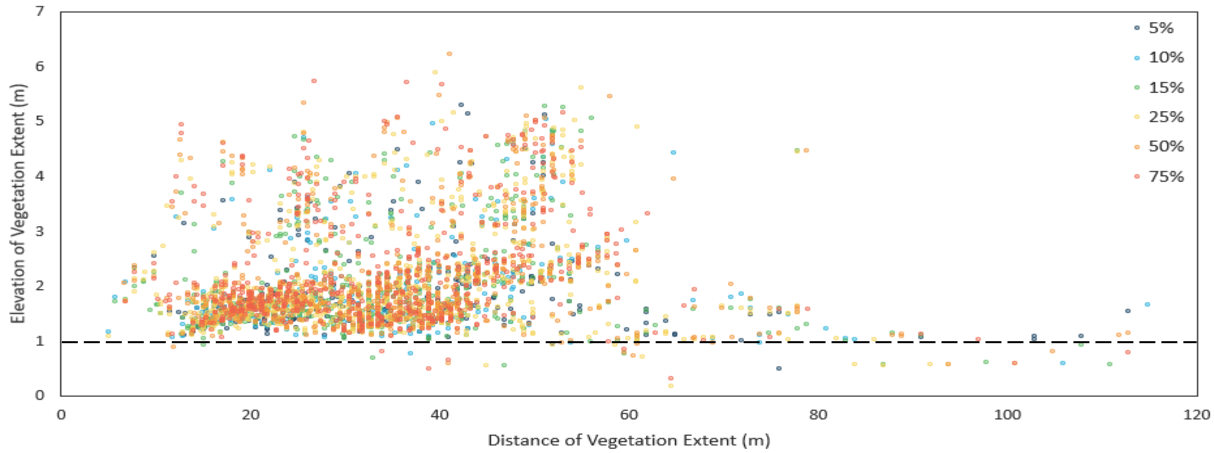


Figure 37. Plot of vertical and horizontal position of vegetation extent for each profile along Stanhope beach. Dashed line indicating 1m.

Vertical position of vegetation extent alongshore shows how vegetation elevation varies with beach-dune morphology such as cliffs and inlets along Stanhope beach (Figure 38). The majority of elevation values fall above 1m elevation.

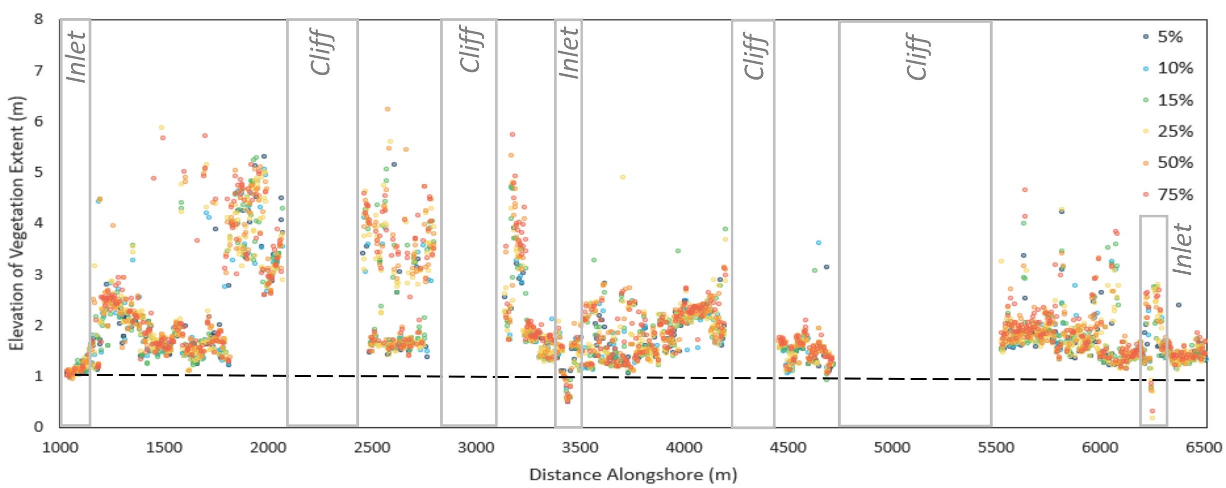


Figure 38. Vertical position of vegetation extent alongshore for Stanhope beach. Dashed line indicating 1m elevation. Grey rectangles represent areas of inlets or cliffs.

The box and whisker plots for the vertical position of vegetation extent at Stanhope shows that the average elevation is close to 2m for all densities (Figure 39). The IQR is generally consistent with a slight increase for 75% density meaning there is similar variability for 5-50% densities and a greater variability for 75% density. The upper whiskers are lower than Cavendish and Brackley beach and are roughly 3-4m with the lower whiskers falling below 1m for all densities.

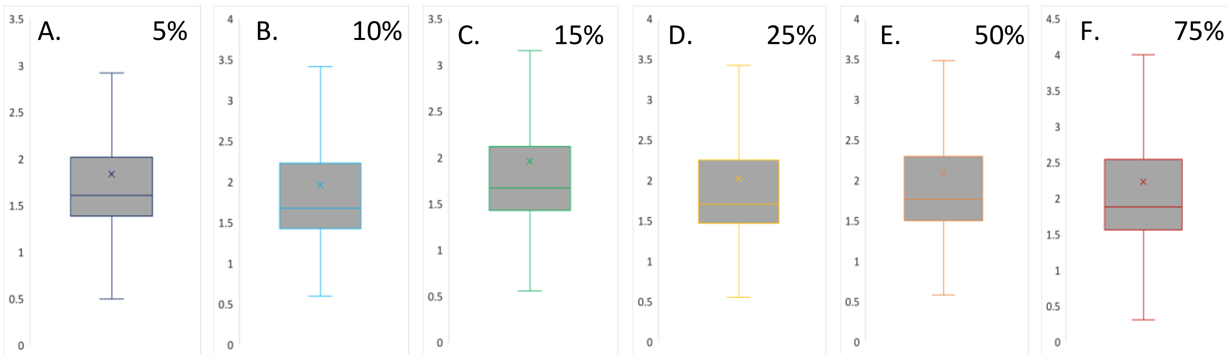


Figure 39. Box and whisker plots of the elevation corresponding to the minimum vegetation extent for each density value. IQR are similar between 5%-75% density elevations.

Horizontal position of vegetation extent shows variability in areas of beach-dune morphology disturbances such as inlets and cliffs (Figure 40). Vegetation does not appear closer than 11m to the shoreline with most of it not appearing closer than 15m to the shoreline.

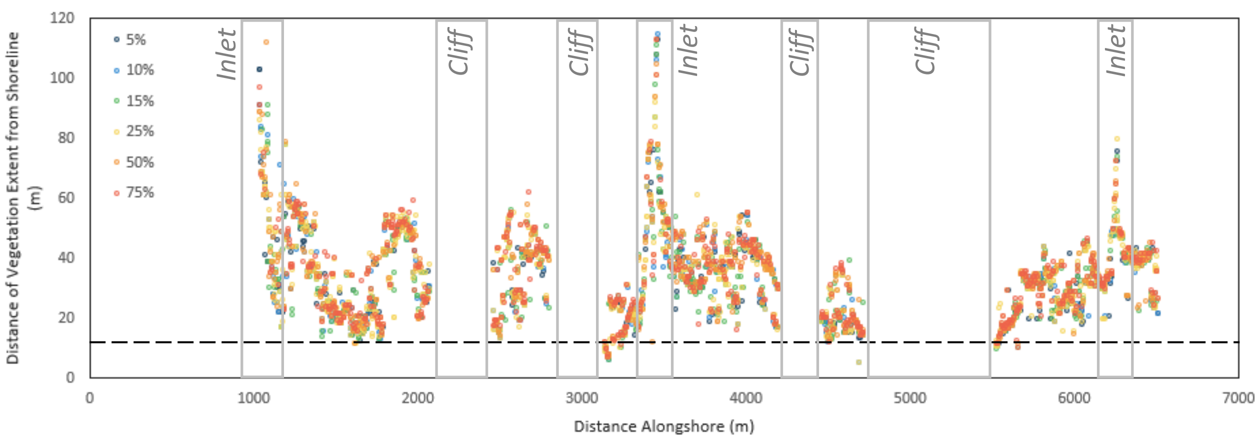


Figure 40. Horizontal position of vegetation extent from shoreline alongshore of Stanhope Beach. Dashed line indicating a distance of 11 m where majority of vegetation falls above.

Figure 37 shows the plot between the vertical and horizontal position of vegetation extent at Stanhope beach. The data points cluster but do not show a relationship. Figure 38 and figure 40 show the alongshore distribution of the vertical and horizontal position of vegetation extent, respectively. Vegetation along Stanhope does not appear closer than 5m to the shoreline however, the majority of values are not closer than 11m as seen in figure 40. The values that are closer than 11m are ones that boarder cliffs along the beach. The vegetation extent that are found far inland are located along inlets (Figure 41). The values that are closer than 11m are ones that boarder cliffs along the beach. Half the vegetation is found between 1.5-2.5m in elevation with the majority falling above 1m elevation. These values that fall below 1m can be seen alongshore in figure 42 and 43. These locations alongshore are located at inlets, see figure 38.

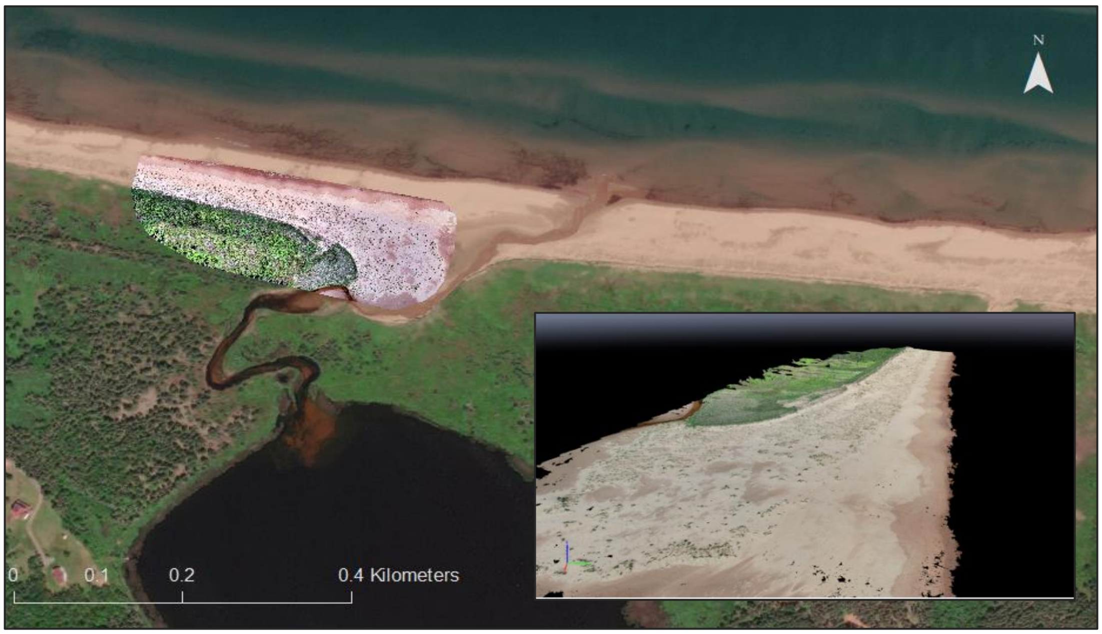


Figure 41. A) Pix4DMapper produced high density point cloud of a large blowout along east Stanhope, ~1020m – 1160m. B) ArcGIS map with 1.4cm/px orthophoto showing the inlet that runs from the nearshore through the blowout to Campbells Pond.

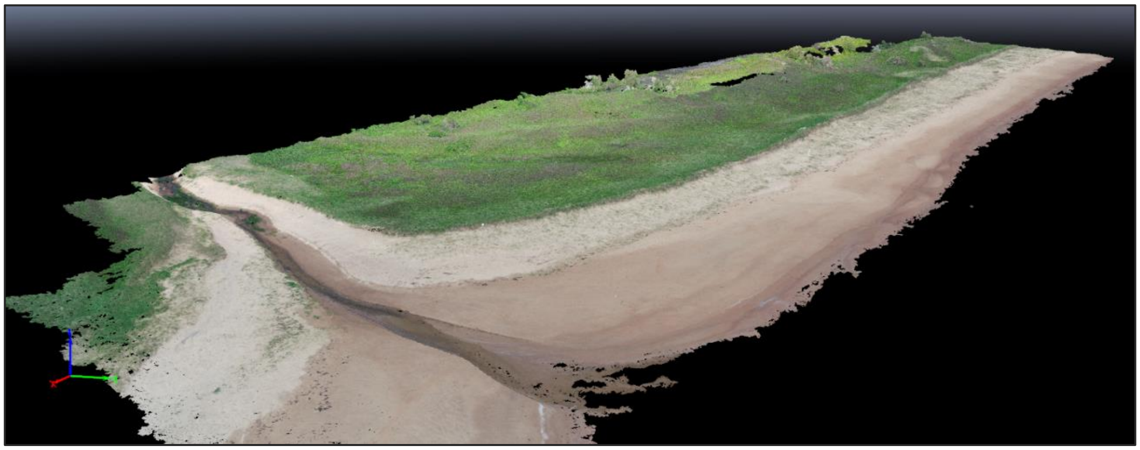


Figure 42. High density point cloud of the inlet found in Stanhope beach that runs from the nearshore to Long Pond at about profiles 3400m – 3500m.

Figure 43. High density point cloud of the inlet found in Stanhope beach at profiles 6290m – 6320m.

Table 9. Vegetation extent ranges and average values.

	Cavendish		Brackley		Stanhope	
Vegetation Extent	Range	Average	Range	Average	Range	Average
Distance (m)	8.99 – 154.65	45.92	4.91 – 102.46	32.60	5.05 – 114.81	34.13
Elevation (m)	0.215 – 14.51	4.84	0.96 – 12.89	2.91	0.18 – 6.23	2.04

7.2.3 Statistical analysis

Linear and non-linear (power) regression analysis was performed for beach slope and elevation of vegetation extent and distance of vegetation extent, respectively.

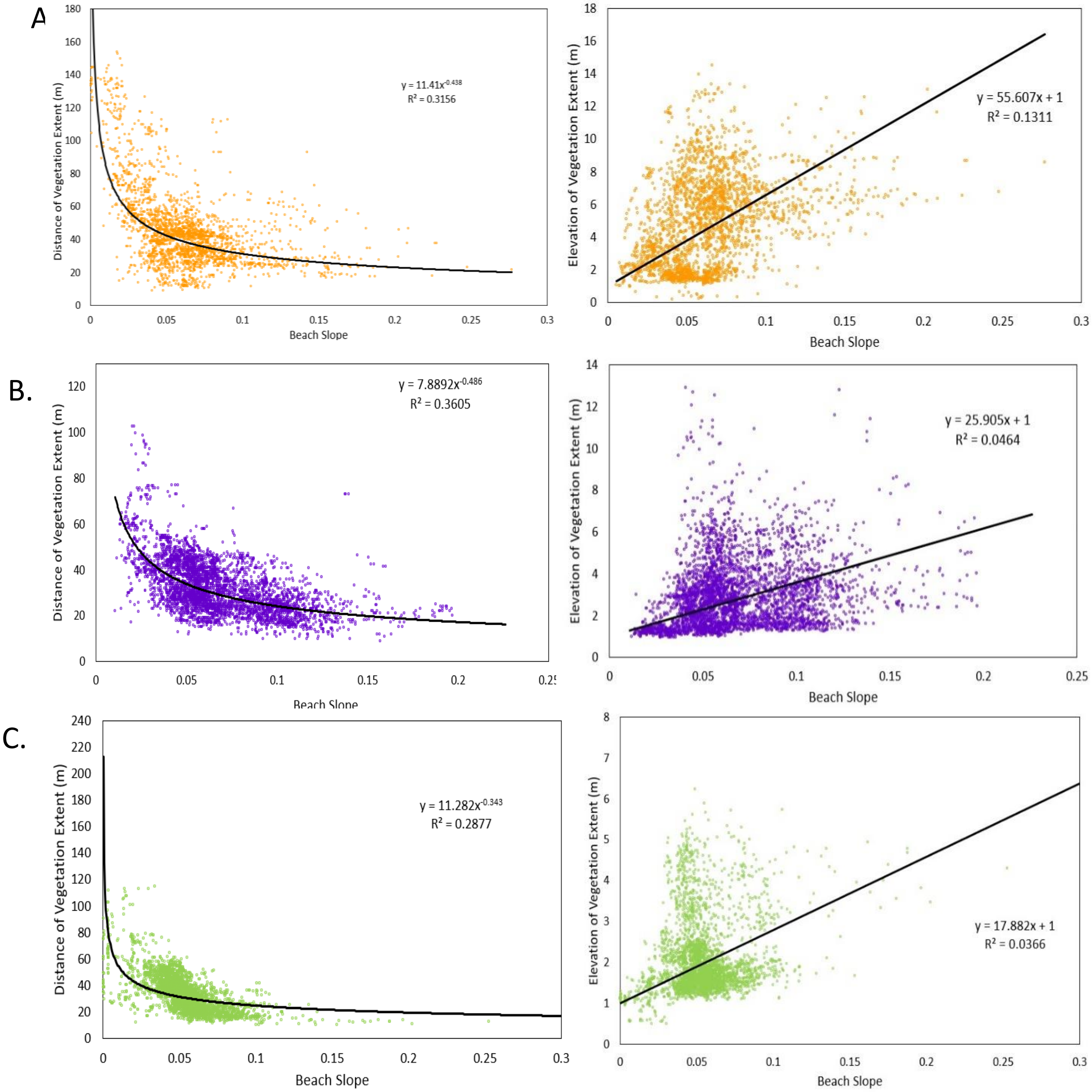


Figure 44. A. Regression for Cavendish vegetation, left: non-linear regression, of beach slope and distance of vegetation extent, right: linear regression of beach slope and elevation of vegetation extent. B. regression for Brackley vegetation, left: non- linear regression of beach slope and distance of vegetation extent, right: linear regression of beach slope and elevation of vegetation extent. C. regression for Stanhope vegetation, left: non-linear regression for beach slope and distance of vegetation extent, right: linear regression for beach slope and elevation of vegetation extent.

The regressions analyses as seen in figure 44 show two distinct relationships involving beach slope and the horizontal and vertical position of vegetation or L_{veg}. Figure 44A shows this relationship at Cavendish beach with *n*=2610 for horizontal position of vegetation (V_x) and *n*=2546 for the vertical position of vegetation (V_y). There is a statistically significant correlation between beach slope and the horizontal position of vegetation extent (V_x) at the 95% confidence level (p=0.0001, r^2=0.3156). For every 0.1° increase in slope there is a 31.28m decrease in V_x ($V_x=11.41x^{-0.438}$), with 32% of the variability in V_x being explained by beach slope. There is a statistically significant correlation between beach slope and vertical position of vegetation extent (V_y) at the 95% confidence level (p=0.0001, r^2=0.131). For every 0.1° increase in beach slope there is a 55.6m increase in V_y (V_y=55.608x + 1), with 13% of the variability in V_y is explained by beach slope.

Figure 44B shows the relationship for Brackley beach with *n*=4531 for V_x and *n*=4067 for V_y. There is statistically significant correlation between beach slope and V_x at the 95% confidence level (p=0.0001, r^2=0.3605). For every 0.1° increase in beach slope there is a 24.15m decrease in V_x ($V_x=7.8892x^{-.486}$), with 36% of the variability in V_x can be explained by beach slope. There is also a statistically significant correlation between beach slope and V_y at the 95% confidence level (p=0.0001, r^2=0.0464). For every 0.1° increase in beach slope results in a 25.9m increase in V_y (V_y=25.905x + 1), with 5% of the variability in V_y is explained by beach slope.

Figure 44C shows the relationship for Stanhope beach with *n*=3686 for V_x and *n*=3677 for V_y. There is statistically significant correlation between beach slope and V_x at the 95% confidence level (p=0.0001, r^2 =0.2877). For every 0.1° increase in beach slope there is a 24.85m decrease in V_x ($V_x=11.282x^{-0.343}$), with 29% of the variability in V_x can be explained by beach slope. There is statistically significant correlation between beach slope and V_y at the 95% confidence level (p=0.0001, r^2 =0.0366). For every 0.1° increase in beach slope there is a

17.9m increase in V_y (V_y=17.882x + 1), with 4% of the variability in V_x can be explained by beach slope.

7.2.4 Backshore Vegetation Density

Sediment transport rates decrease exponentially when the sand moves from unvegetated to vegetated areas initiating dune formation (Hesp, 1983; Sarre, 1989; Davidson-Arnott and Law, 1990; Arens, 1996). Vegetation density has been found to be more important than vegetation type in terms of dune formation (Hesp, 1983). An increase in vegetation density increases roughness and decreases wind speed near the surface and at a high density the vegetation traps most of the transported sand (Hesp, 1983). Average backshore density was calculated from the vegetation extent to the dune crest (Figure 45). All density values at each profile were averaged to represent the overall vegetation distribution along the seaward side of the foredune. From these results there is no clear relationship between backshore vegetation density and dune morphology.

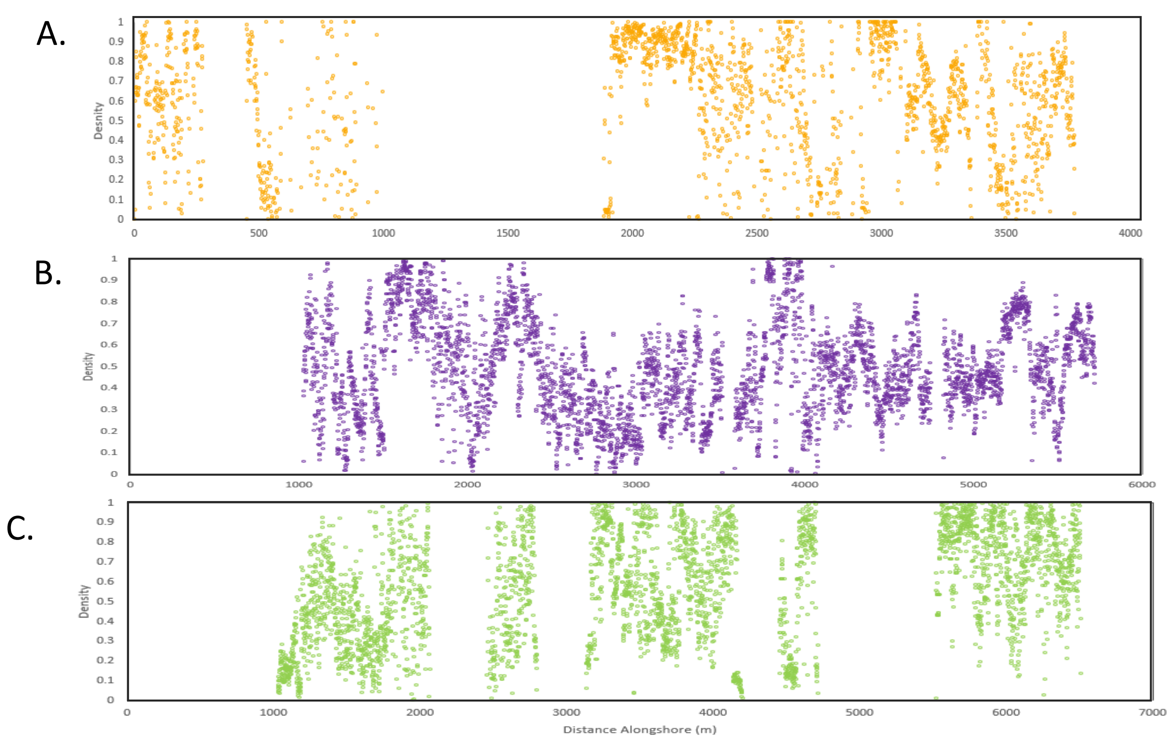
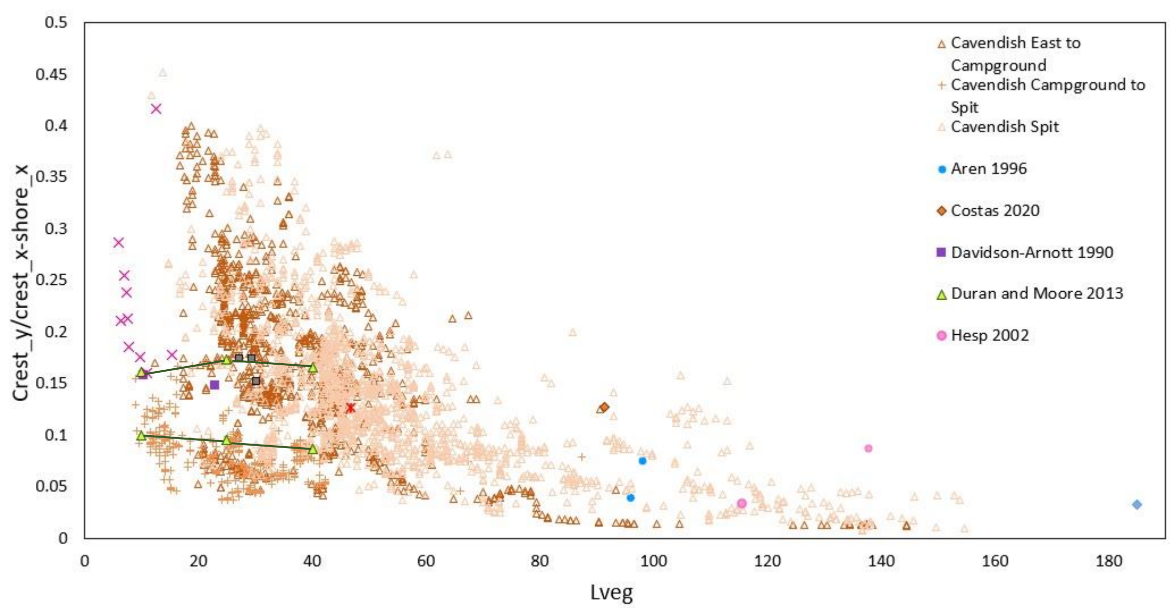


Figure 45. Total average backshore density measured from vegetation extent to the crest line at A) Cavendish beach, B) Brackley Beach, and C) Stanhope beach along each profile.

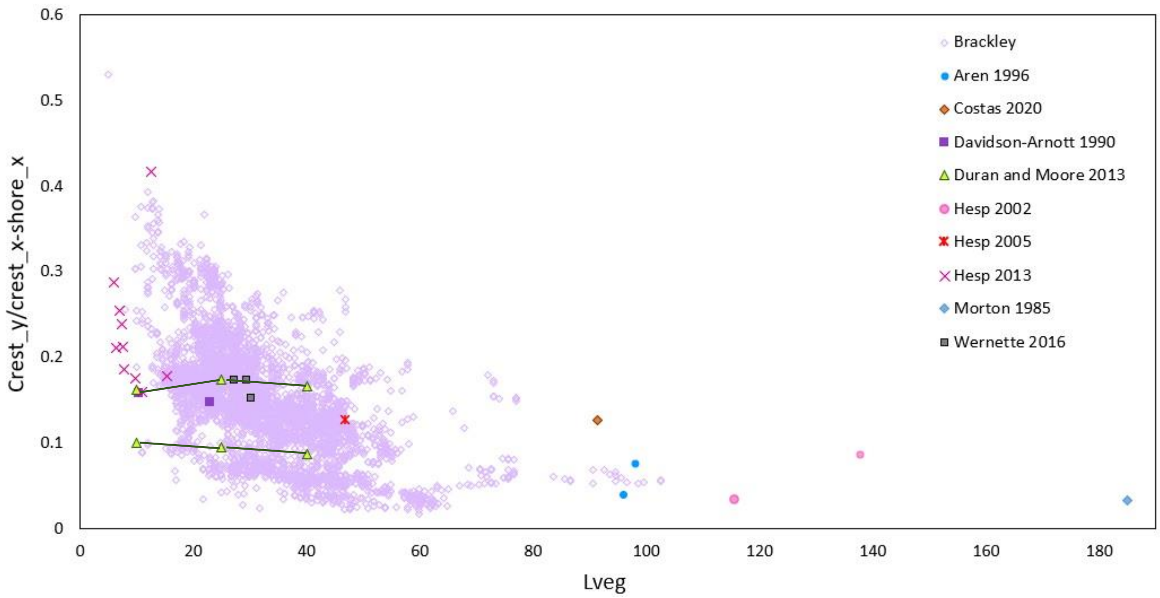
7.2.5 Lveg

L_{veg}, crest elevation, and crest distance from shore were measured for over 19km of beach at three locations with varying levels of erosion/recovery. Figure 46 shows the extracted profile data from the literature, including Duran and Moore (2013), and the empirical PEI data. Cavendish data showed three clusters and these clusters are in different geographic locations along the beach. The area between Cavendish east and the Cavendish campground followed a similar curve to Brackley and Stanhope. The area between Cavendish campground and the spit is clustered towards the bottom left of the graph. This area is more limited in dune development since it is neighboured by a cliff and a spit creating little variability in beach-dune morphometrics. The spit shows a curve similar to Brackley and Stanhope but shifted to the right and the tail of the data extends far to the right. This is because the spit experiences high variability with extremes in both dune height and L_{veg} distance. Overall, the data show that vegetation farther from the shore (large L_{veg}) correspond to lower L_{crest} ratios whereas vegetation closer to the shore (small L_{veg}) corresponded to larger L_{crest} ratios.

A.



B.



C.

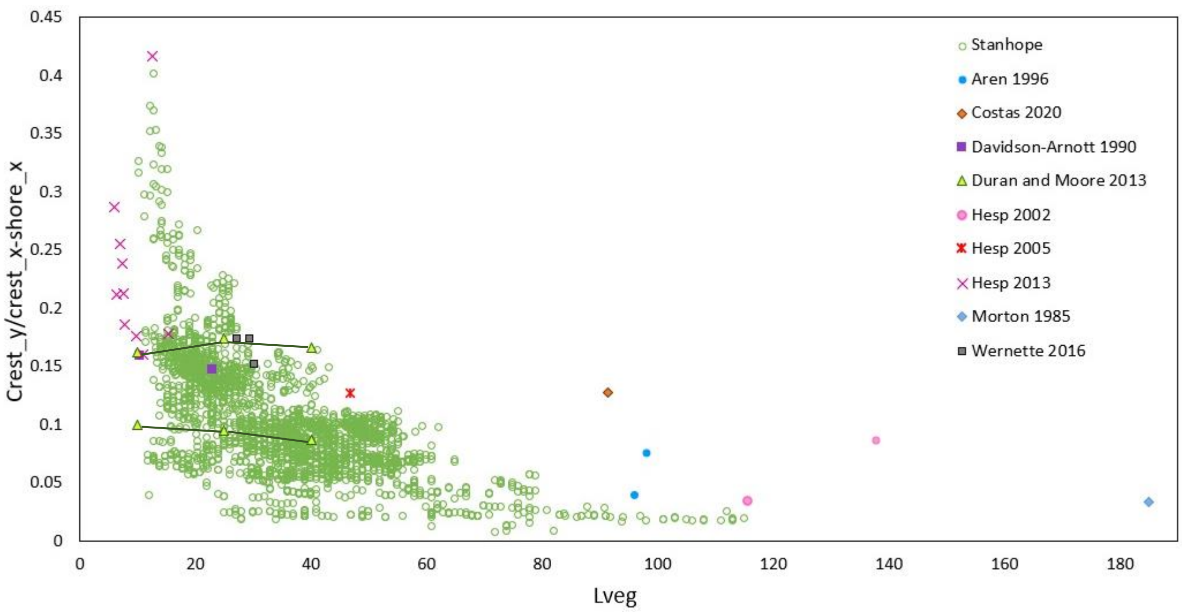


Figure 46. PEI empirical data of L_{veg} and L_{crest} ratio plotted against previously published data and Duran and Moore (2013) modeled results. PEI and previously published data show an over all decreasing relationship, as L_{veg} increases the crest ratio decreases indicating scale-variance in the dune system. Duran and Moore (2013) modeled results show no relationship between L_{veg} and the crest ratio indicating scale-invariance in the dune system. A. Cavendish Beach B. Brackley Beach, C. Stanhope Beach.

7.3 Manual Vegetation Sampling

Vegetation characteristics have been suggested to influence sediment trapping capabilities and level dune stabilization (Arens, 1996, Zarnetske et al., 2012; Charbonneau et al., 2017). Multiple vegetation measurements were recorded manually including number of stems, number of blades, tallest blade, average blade height, depth buried, stock width, and root strength. The results range at each beach with no significant trends (Figure 47, 48, 49). The average number of blades were 12.75, 17.26, and 13.89 at Cavendish, Brackley and Stanhope, respectively. Average height, which is 57.13, 57.18, and 57.82cm at Cavendish, Brackley, and Stanhope, respectively does not vary greatly at each location. Average burial depth was 11.28, 9.01, and 8.75cm at Cavendish, Brackley and Stanhope, respectively. From these results there is no clear relationship between plant morphology and dune morphology.

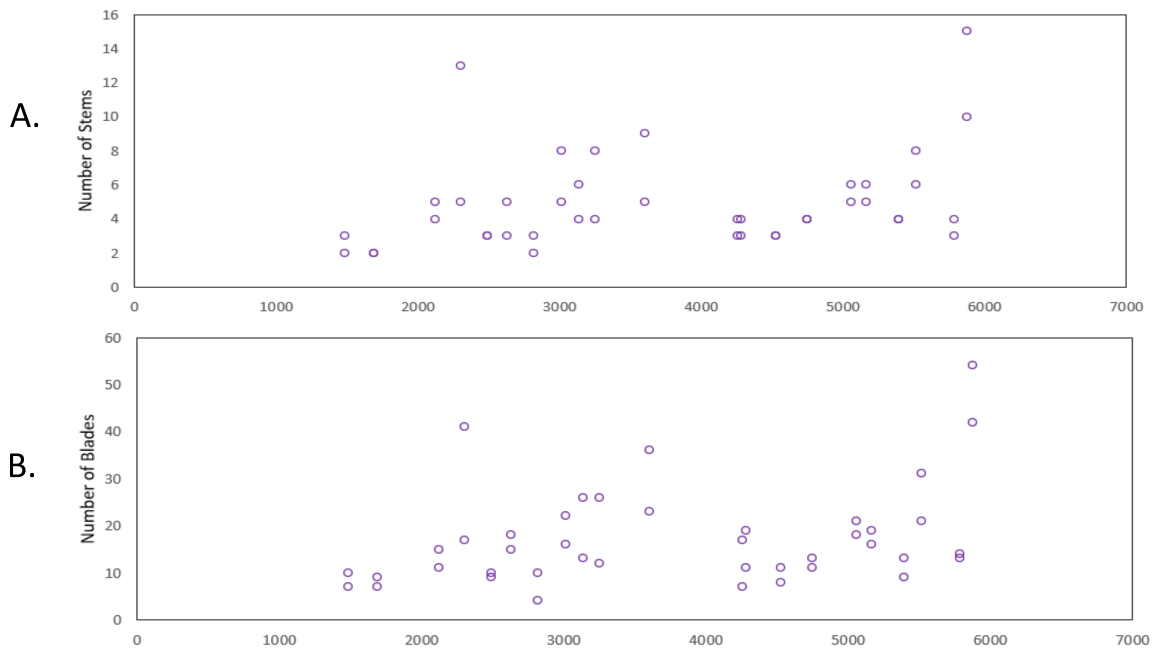


Figure 47. Brackley Beach manual *A. breviligulata* measurements, A) Number of stems, B) Number of blades.

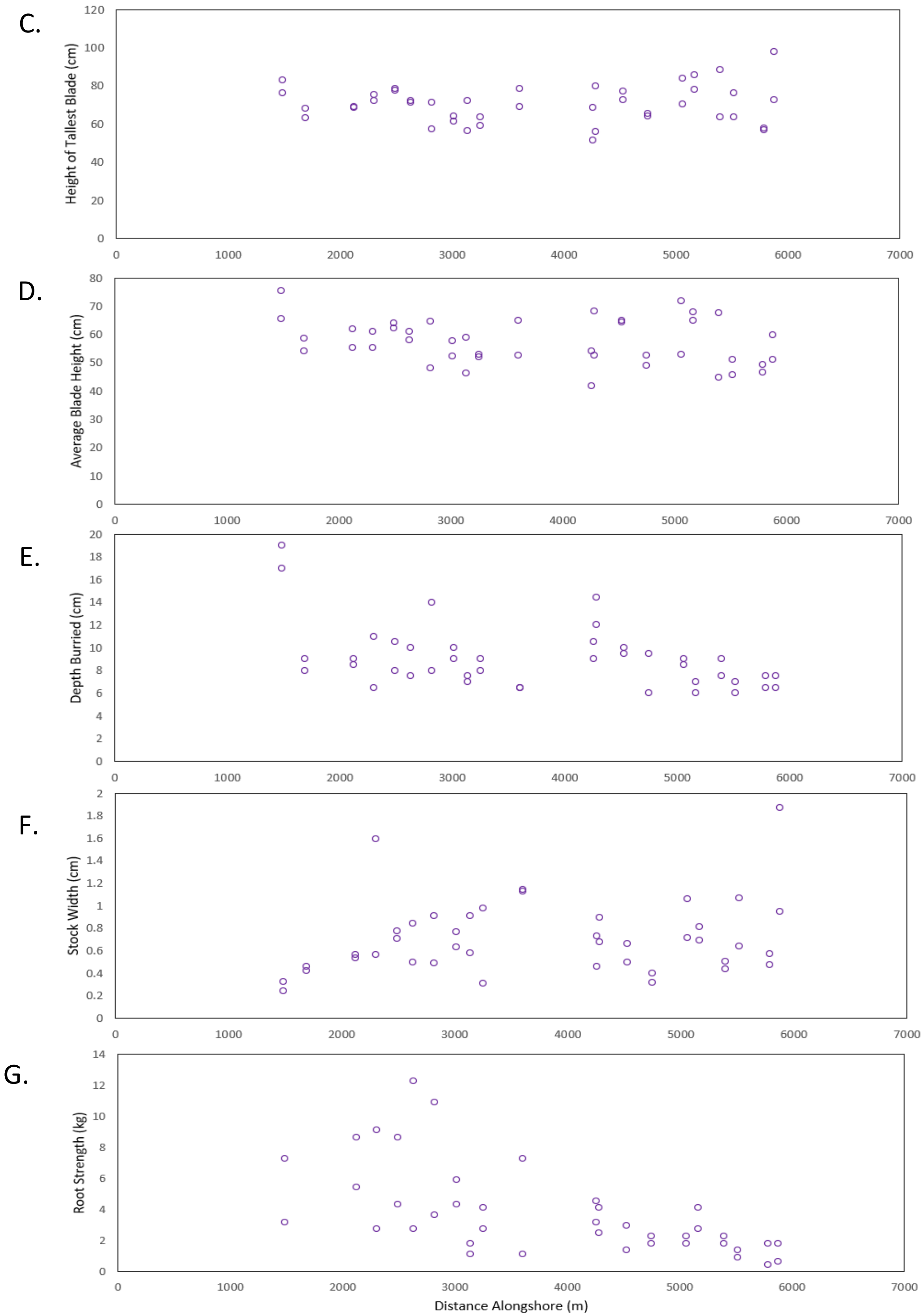


Figure 47 con't. Brackley Beach manual *A. breviligulata* measurements, C) Height of tallest blade, D) Average height of blades.

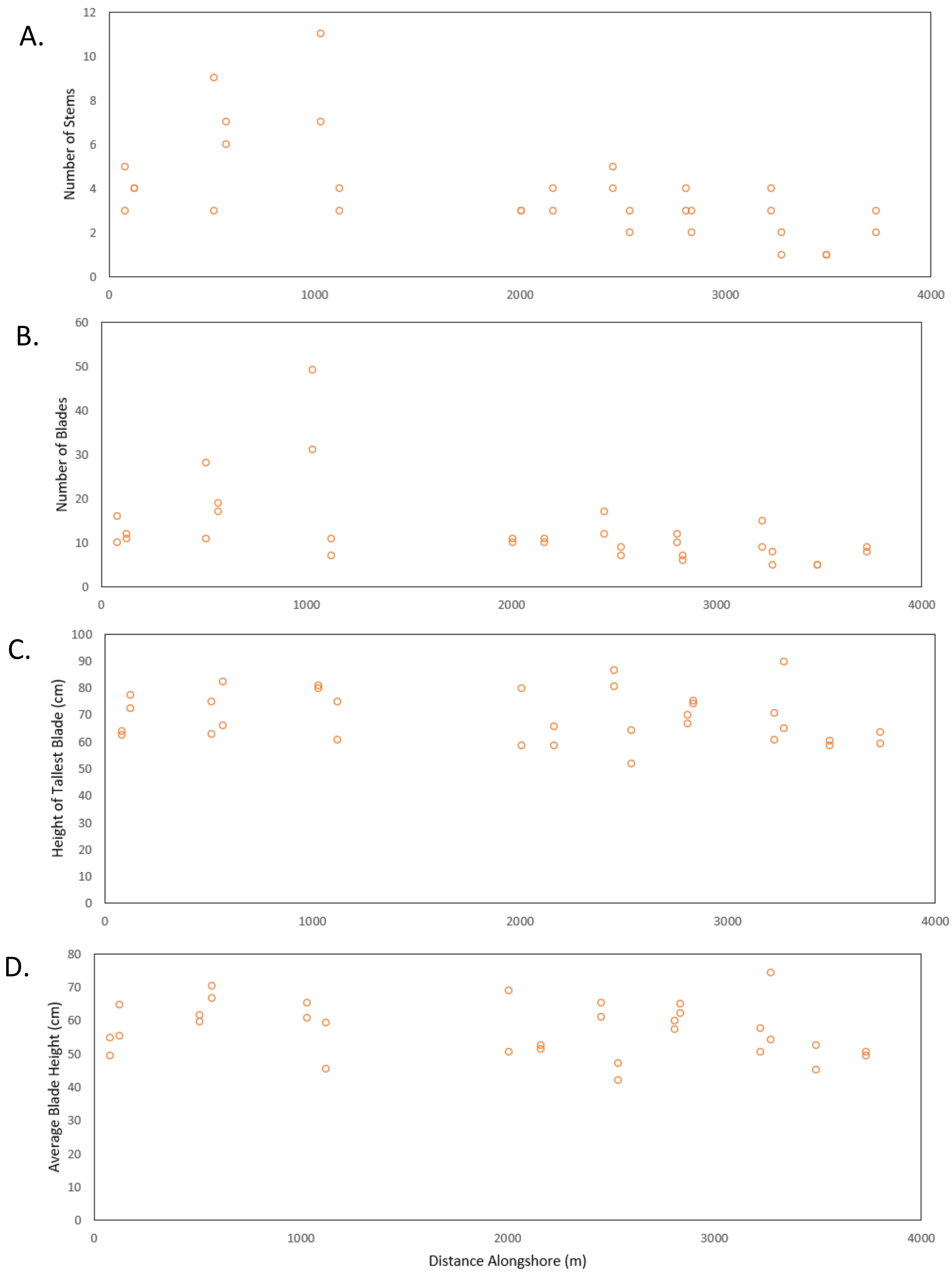


Figure 48. Cavendish Beach manual *A. breviligulata* measurements, A) Number of stems, B) Number of blades, C) Height of tallest blade, D) Average height of blades.

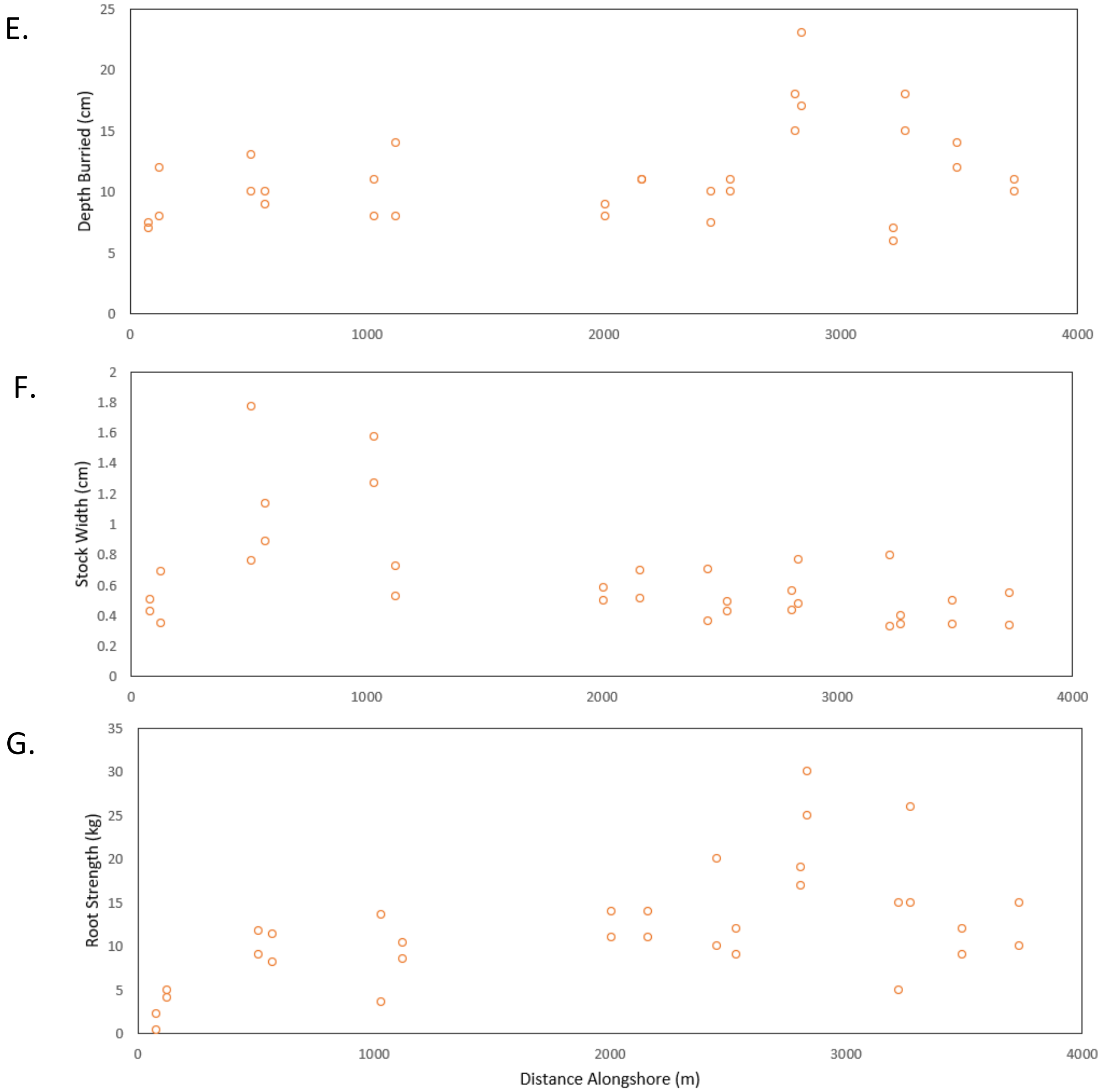


Figure 48 con't. Cavendish Beach manual *A. breviligulata* measurements, E) Depth buried, F) Stock width, G) Root strength

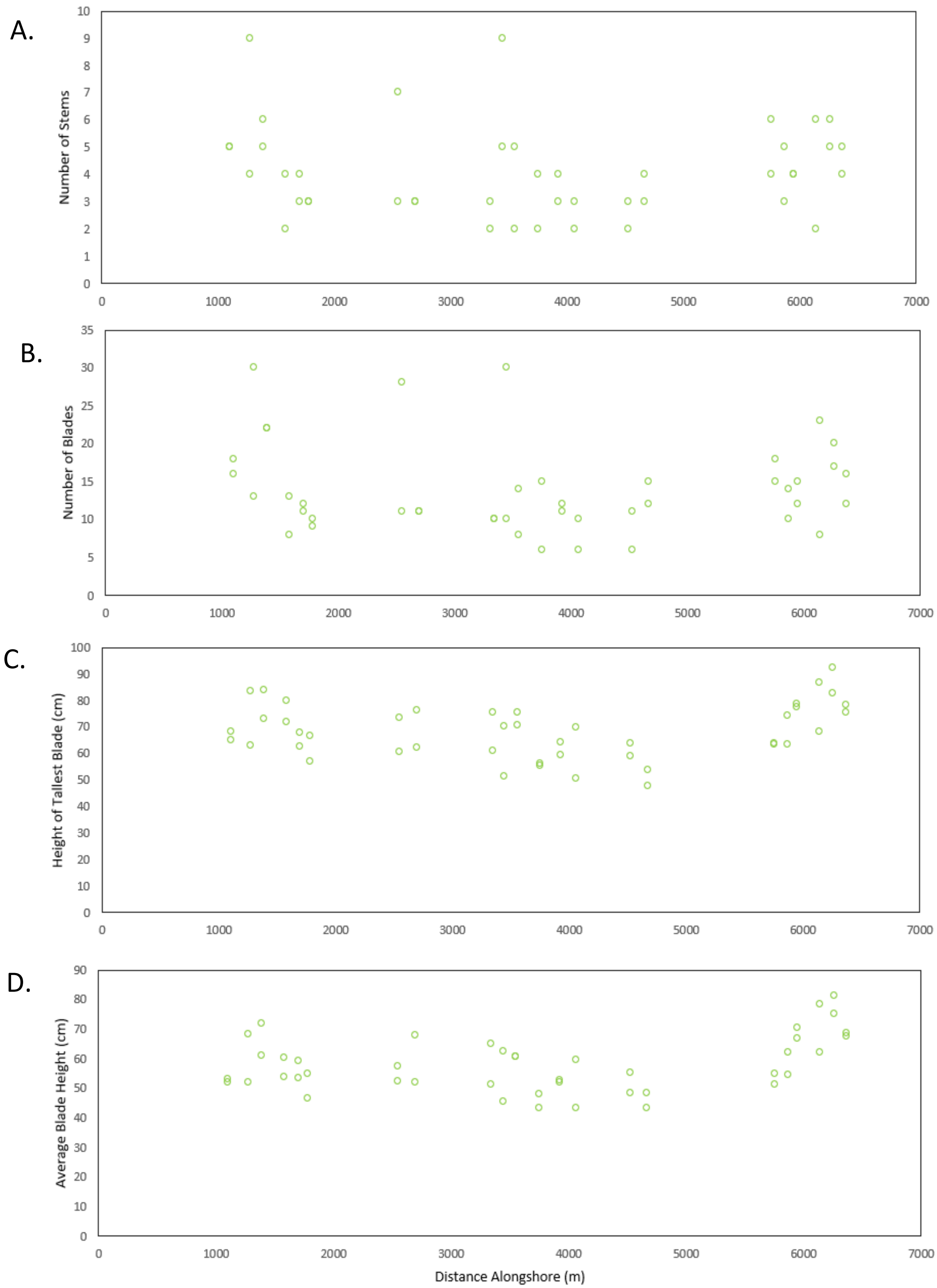


Figure 49. Stanhope Beach manual *A. breviligulata* measurements, A) Number of stems, B) Number of blades, C) Height of tallest blade, D) Average height of blades.

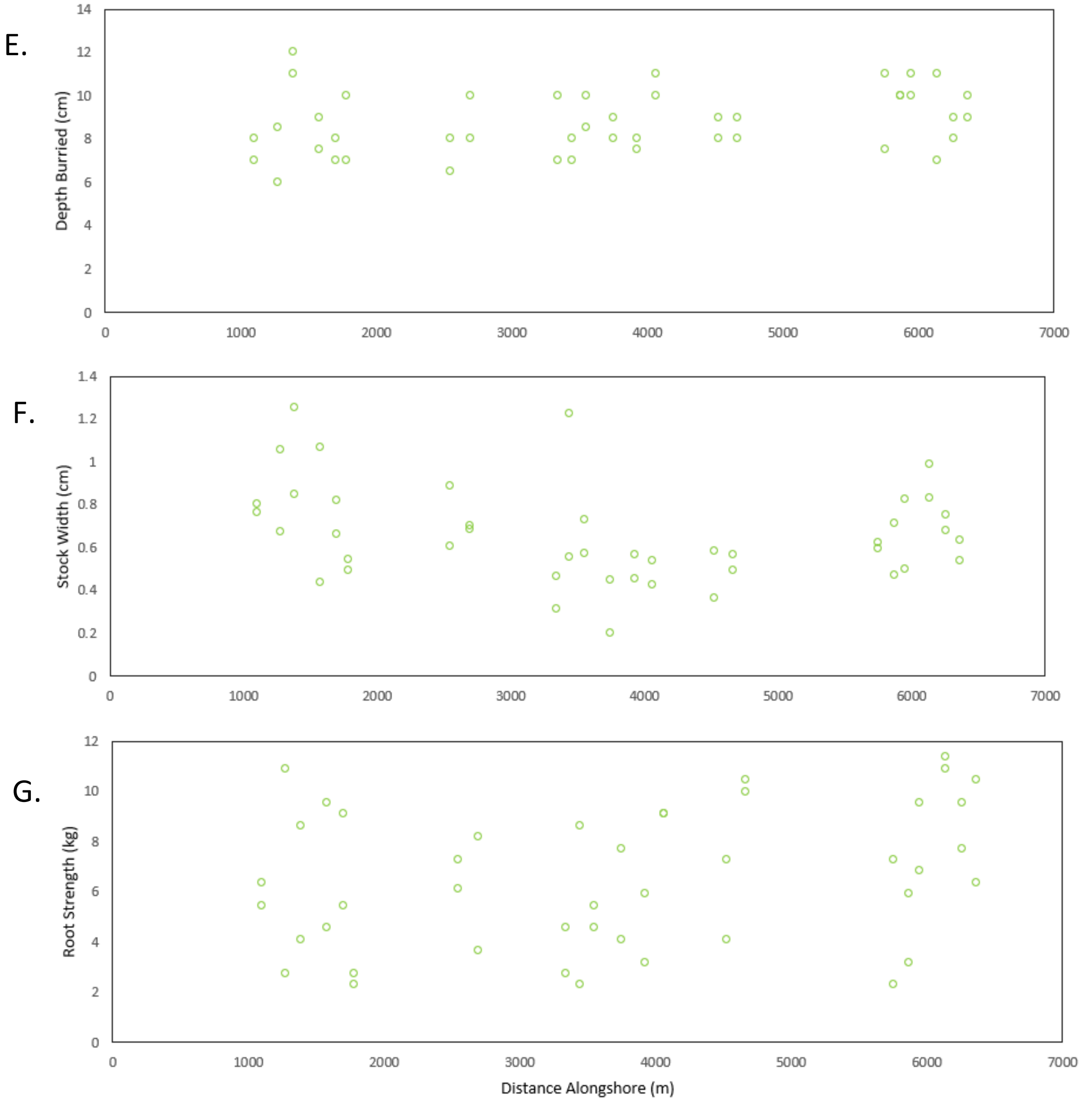


Figure 49 con't. Stanhope Beach manual *A. breviligulata* measurements, E) Depth buried, F) Stock width, G) Root strength

Table 10. Manual vegetation measurement ranges and averages.

	Cavendish		Brackley		Stanhope	
	Range	Average	Range	Average	Range	Average
Number of Stems	1 - 11	3.81	2 – 15	4.95	2 - 9	4.07
Number of Blades	5 - 49	12.75	4 - 54	17.26	6 - 30	13.89
Height of Tallest Blade (cm)	51.8 – 89.5	69.21	51.6 – 97.9	70.38	47.6 – 92.4	68.13
Average Height of Blades (cm)	41.96 – 74.18	57.13	41.8 – 75.4	57.18	43.26 – 81.14	57.82
Depth Buried (cm)	6 - 23	11.28	6 – 19	9.01	6 - 12	8.75
Stock Width (cm)	0.33 – 1.77	0.65	0.24 – 1.87	0.71	0.20 – 1.25	0.66
Root Strength (kg)	0.45 - 30	12.12	0.45 – 12.25	3.79	2.27 – 11.34	6.52

7.4 Nutrient sampling

It has been suggested that sparse vegetation is caused by a lack of major nutrients rather than lack a of water or other environmental stressors (Willis and Yemm, 1961; Willis, 1963; Kachi and Hirose, 1983). Low nutrient levels in soil create competition between species because many species cannot thrive in low level environments (Koerselman and Meuleman, 1996). The three micronutrients that dune soils often lack are Nitrogen (N), Phosphorus (P), and Potassium (K). An increase in N levels has been shown to change species diversity and composition due to species specific responses to N concentrations (Tilman, 1986; Maun 2009). No clear relationship was found between N, P, K, or pH levels and vegetation density or dune morphology (Figure 50, 51, 52). All locations showed less than trace levels of P, little variability in K levels, and pH levels all around neutral (7pH). N levels varied the most alongshore, but no clear relationship was found between vegetation density or dune morphology.

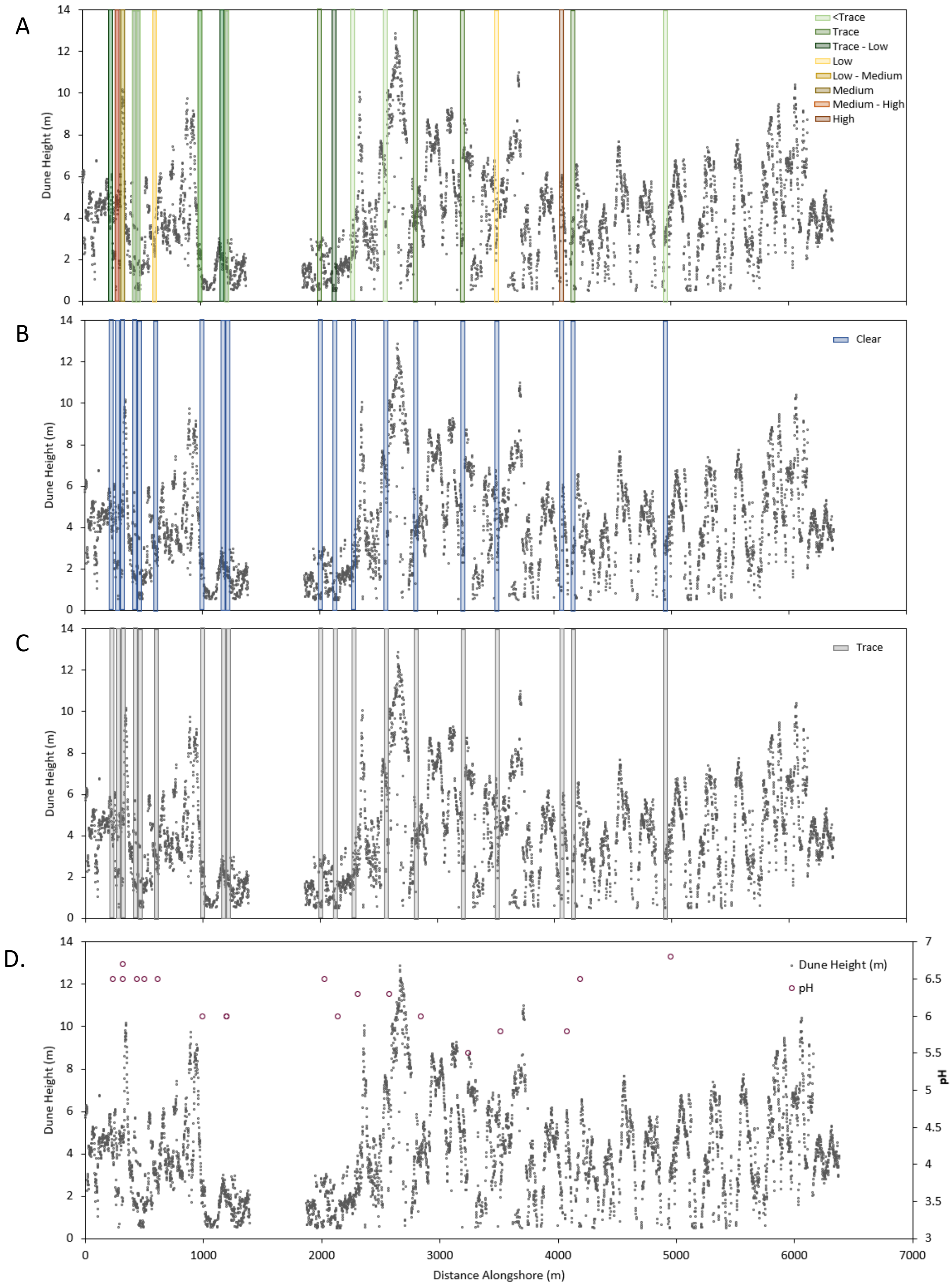


Figure 50. Cavendish nutrient soil sampling A. Nitrogen B. Phosphorus C. Potassium D. pH

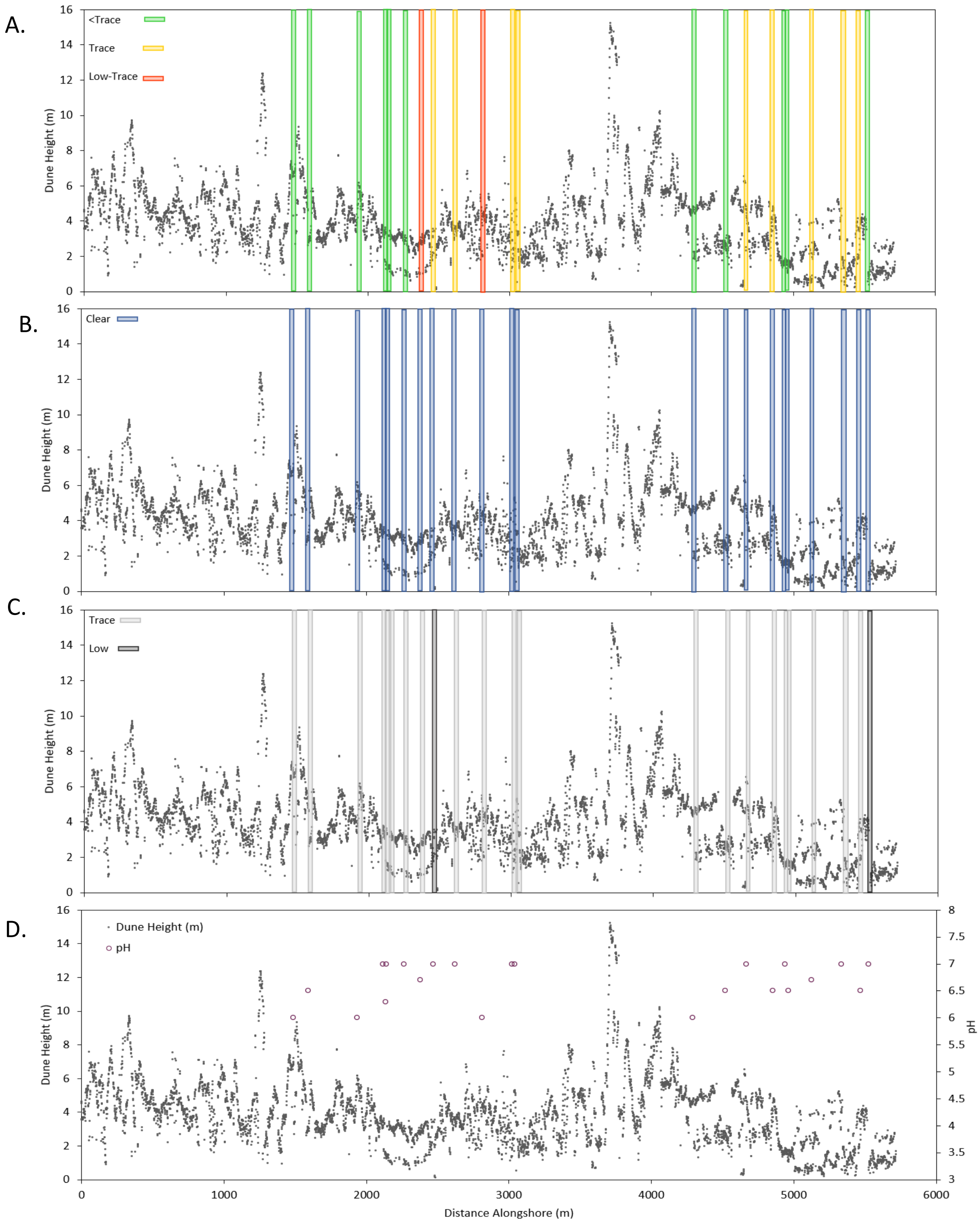


Figure 51. Brackley nutrient soil sampling A. Nitrogen B. Phosphorus C. Potassium D. pH

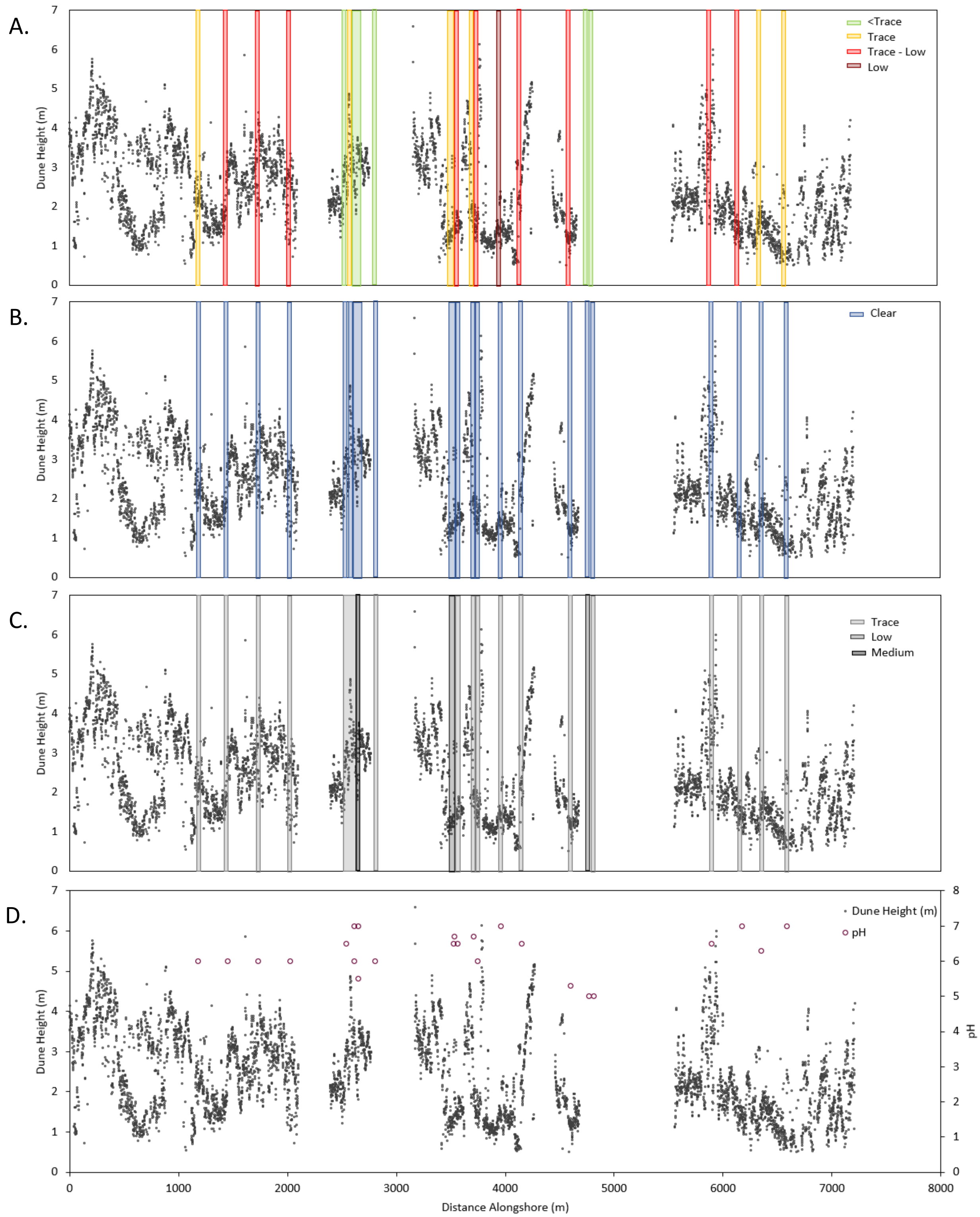


Figure 52. Stanhope nutrient soil sampling A. Nitrogen B. Phosphorus C. Potassium D. pH

8 Discussion

Coastal dunes are the first line of defence on coastal barriers and their development and evolution is an important area of research. Using a processed-based model, Duran and Moore (2013) argued that foredunes are scale invariant landforms, with heights that depend on the distance of the vegetation line from the shoreline (L_{veg}). Their model is based on the assumption that initial foredune growth is caused by a sudden decrease in sediment transport due to vegetation trapping. The evolution of a foredune is then determined by the interaction with the wind flow where vegetation plays a secondary role increasing surface roughness and anchoring the dune crest preventing dune motion. This interaction between dune topography and wind flow is the stagnation zone. They state that as the foredune continues to grow it produces a deceleration of wind flow, reducing surface shear stress and sand flux. The foredune will be able to grow vertically until this stagnation zone extends to the shoreline where the shear stress of sediment transport is below the threshold of sediment transport. The authors present limited field data to support their model results and note a lack of field measurements for L_{veg} to test their scale-invariant dune model.

Other studies suggest that dune height is not scale invariant and will continue to grow so long as there is sufficient availability of sediment. Early work by Davidson-Arnott and Law (1990), suggest that sediment supply is the primary control on dune height. The Duran and Moore (2013) model assumes sustained, on-shore winds that Davidson-Arnott et al., (2018) argue is unusual based on numerous field studies showing intermittent and supply dependent transport events. They also note that most transport into the dune is associated with oblique and alongshore winds (Arens, 1996; Bauer and Davidson-Arnott, 2003; Delgado-Fernandez, 2010; Walker et al., 2017; Davidson-Arnott et al., 2018), which means that dune height is dependent on supply consistent with the earlier work of Short and Hesp (1982). An oblique wind would also mean that the stagnation zone at the base of the dune is not pronounced or even present to influence the deposition of sediment.

The purpose of this study was to examine alongshore variation in vegetation zonation in order to test the model of Duran and Moore (2013). A total of 19km of shoreline was mapped in this study, corresponding to 38,000 transects, 118 plants sampled, and 72 soil samples, to examine the relationship between vegetation and the morphology of the beach and dune. This study found no evidence for scale-invariance within and across three beaches along the North Shore of Prince Edward Island (PEI). Rather than a constant relationship, an overall negative (decreasing) relationship between the ratio of crest elevation and crest distance from shore (L_{crest} ratio), and L_{veg} was observed. Specifically, the L_{crest} ratio decreased as L_{veg} increased. The data from this study are compared to the model results of Duran and Moore (2013) and previously published data in Figure 53. Consistent with the results presented in Figure 3, the data collected in this study suggests that the L_{crest} ratio decreases towards a possible constant of ~0.05 with increasing L_{veg}. These results support a companion study (Houser et al., in review) that found no evidence for a representative scale-invariant beach-dune profile in previously

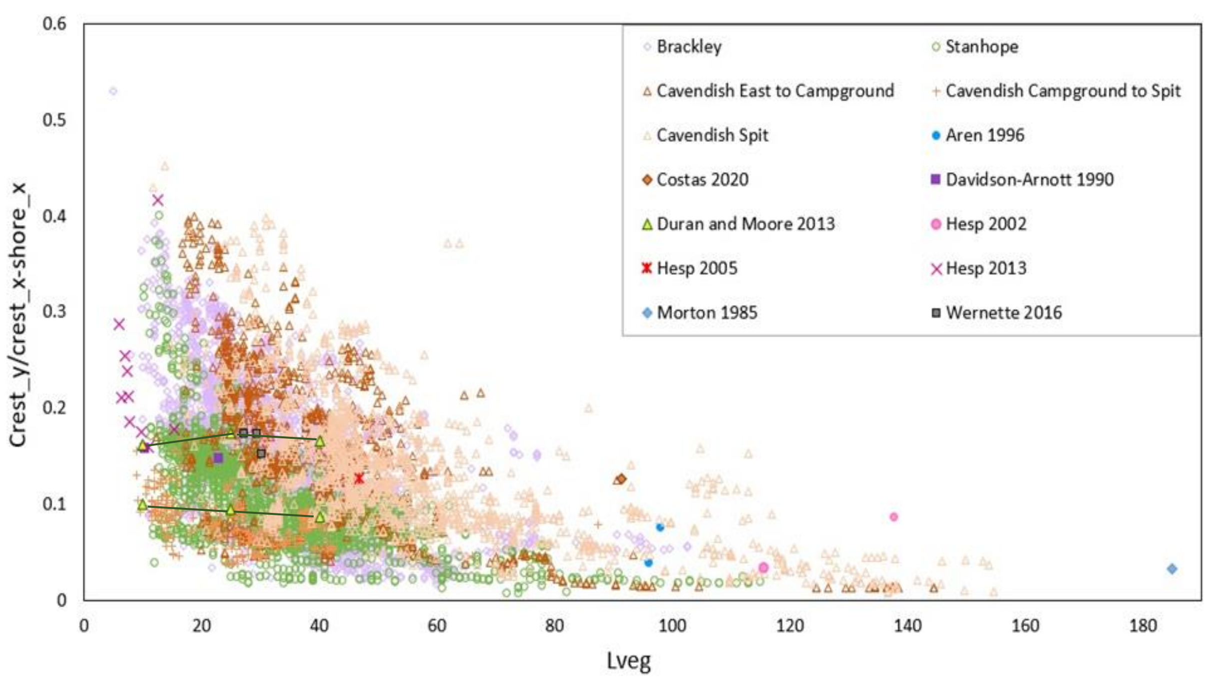


Figure 53. L_{veg} and L_{crest} ratio for empirical PEI data at Cavendish, Brackley, and Stanhope plotted with Duran and Moore (2013) simulated scale-invariant profiles (green triangles) and other empirical data. The lower of the two Duran and Moore sets was simulated with low sediment transport and the set upper set was simulated with high sediment transport.

The steepest dunes (L_{crest} ratio >0.2) are found in areas where there is evidence of beach erosion and dune scarping. For example, profile 844m at Cavendish Beach has a tall dune close to the shoreline in which vegetation is only able to persist high on the dune face close to the crest (Figure 54). At this particular site L_{veg} value is 18.6m, the L_{crest} ratio value is 0.4 and the dune crest is 8.7m above the shoreline. In contrast, dunes with L_{crest} between 0.1 and 0.2 appear to be more stable and lack significant scarping or evidence of erosion. An example from Stanhope beach (profile 1426m, L_{crest} ratio is 0.1, crest height is 4.3m, L_{veg} value is 28.7m), exhibits a wider more stable beach that supports the establishment of vegetation on the beach seaward of the dune toe (Figure 55). In areas with L_{crest} <0.1, the dunes are low profile and set back relatively far from the shoreline, with some sites associated with washover and blowouts. An example from Brackley beach (5403m, L_{veg} =53.3m, L_{crest} =0.041, and crest elevation of 2.7m) exhibits a low-profile dune with vegetation extending a considerable distance seaward of the dune crest (Figure 56). Washover channels and berm at Cavendish Beach (profile 1088m, L_{veg} =138.0m, L_{crest} ratio is 0.016, and the crest elevation is 2.8m) exhibit similar characteristics (Figure 57).

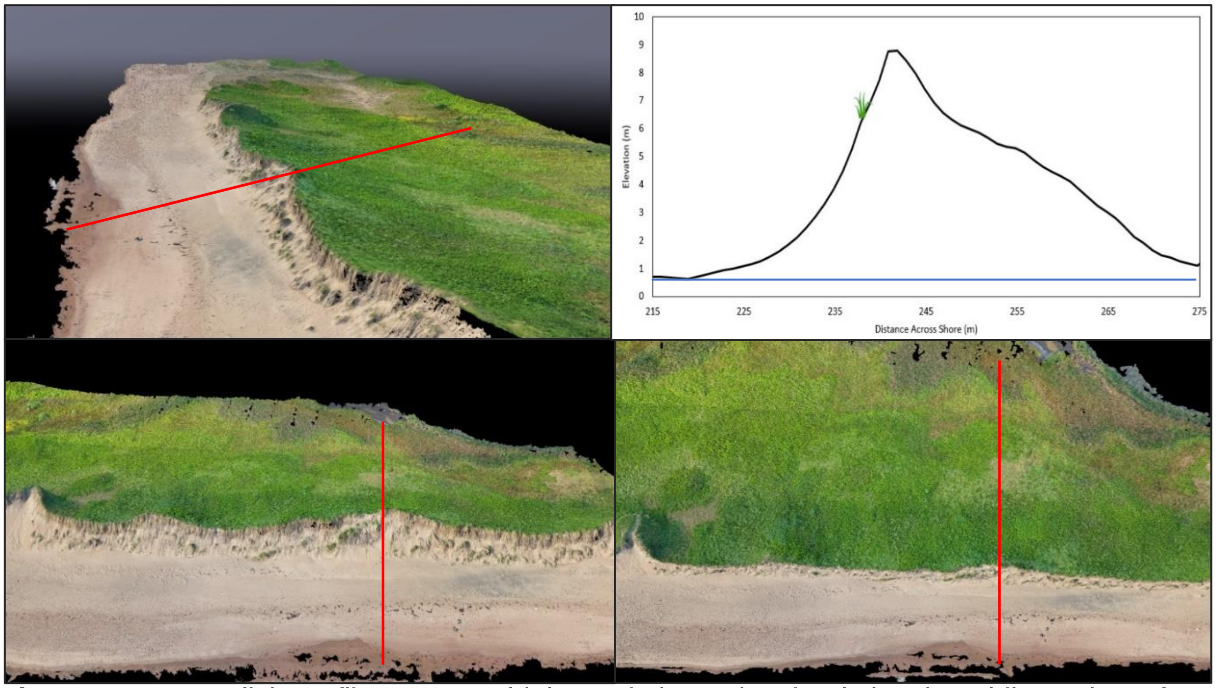


Figure 54. Cavendish profile 844m, A. high resolution point cloud showing oblique view of profile, B. across shore profile indicating shoreline (blue) and L_{veg} relative to beach-dune morphometry. C and D. frontal and aerial view of the profile, respectively.

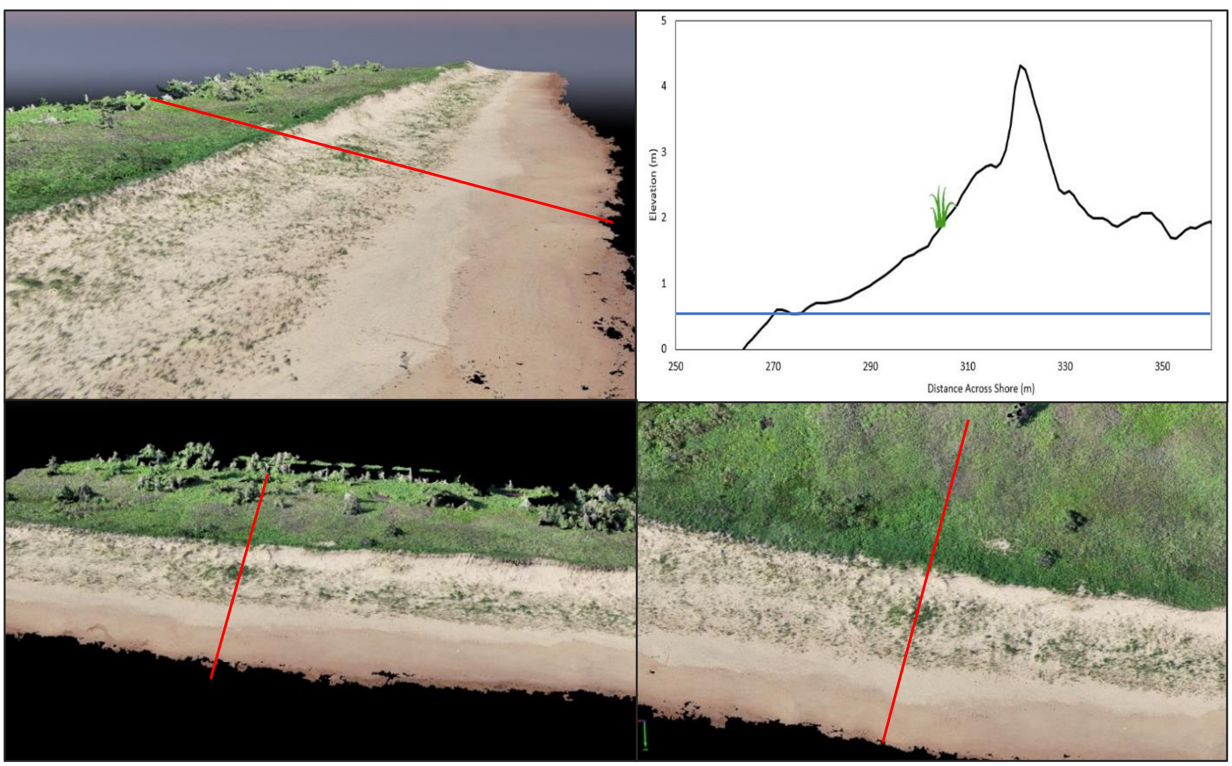


Figure 55. Stanhope profile 1426m. A. high resolution point cloud showing oblique view of the profile indicated in red. B. across shore profile graph indicating shoreline (blue) and L_{veg} relative to beach-dune morphometry. C and D. frontal and aerial view of the profile, respectively.

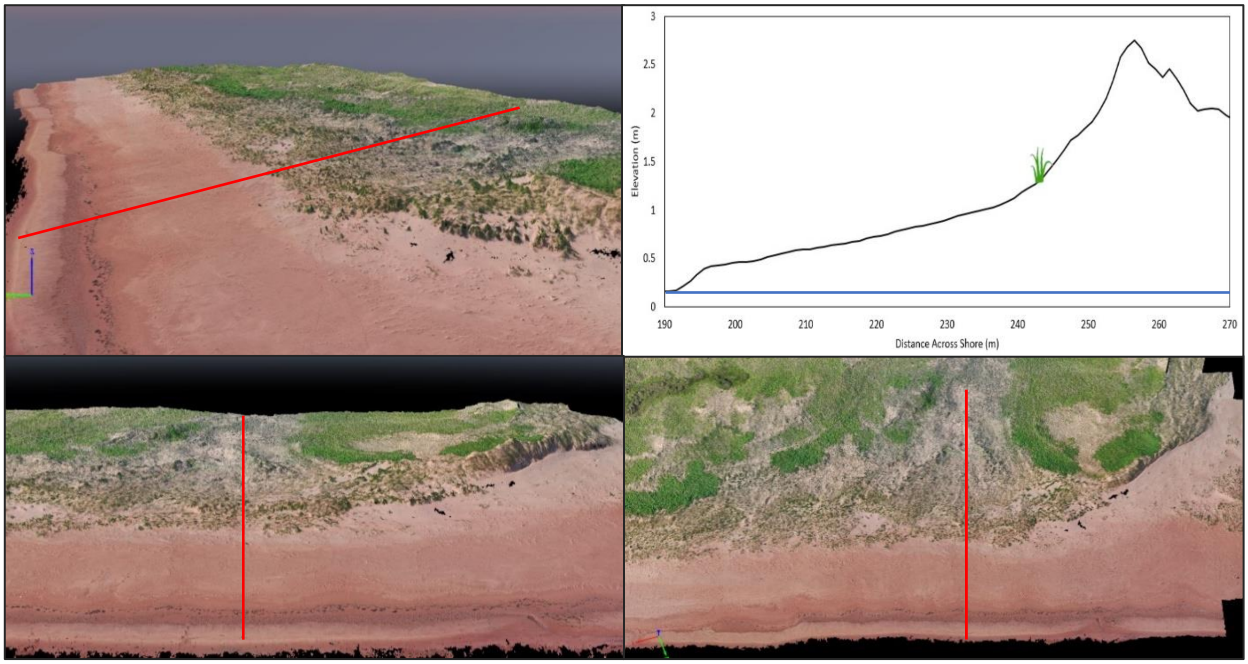


Figure 56. Brackley profile 5403m. A. high resolution point cloud showing oblique view of the profile indicated in red. B. across shore profile graph with shoreline represented in blue and L_{veg} shown. C and D. frontal and aerial view of the point cloud, respectively.

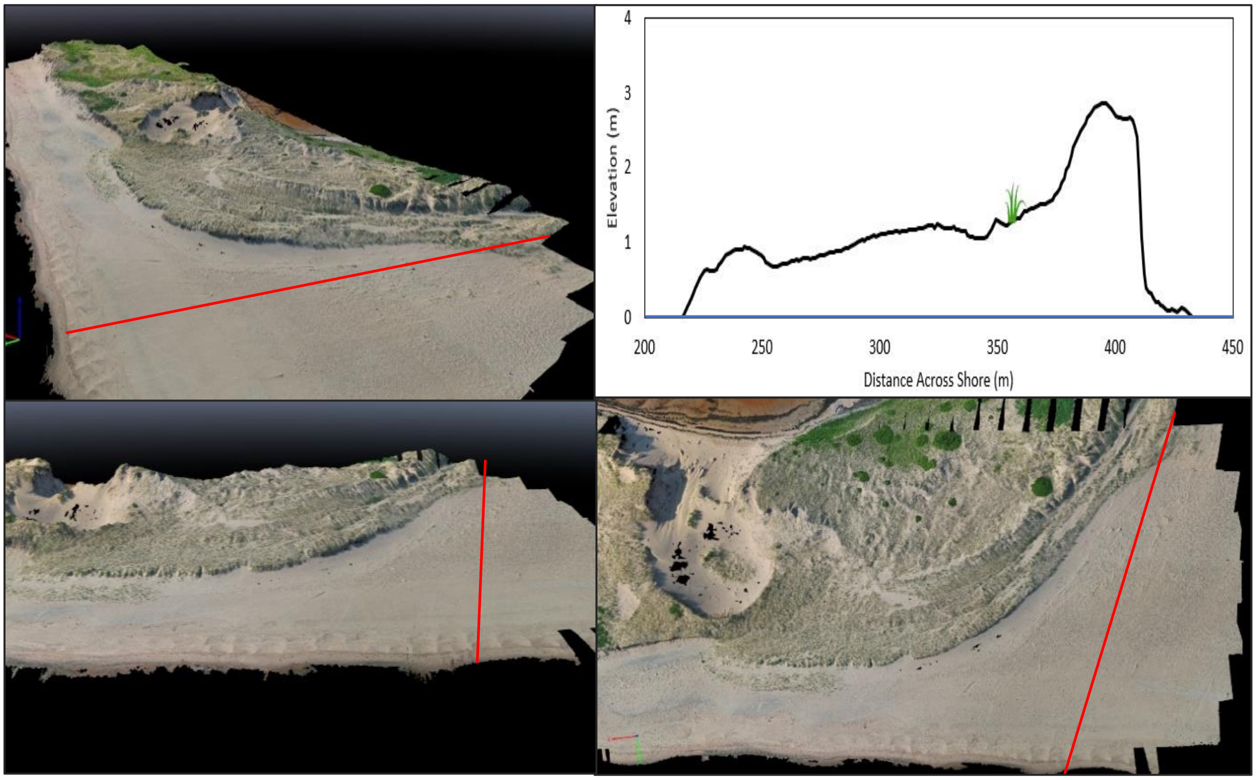


Figure 57. Cavendish profile 1088m. A. high resolution point cloud showing profile indicated in red at oblique view. B. across shore graph of profile indicating shoreline (blue) and L_{veg}. C and D. frontal and aerial view of profile, respectively.

As noted, the results of this study suggest that the dunes along the North Shore of PEI and extracted from previously published studies are not scale-invariant. The only evidence for scale invariance is for the largest L_{veg} (>60m) which is associated with low dune profiles and washover channels. With decreasing L_{veg} the beach width also decreases, and the beach slope increases. The narrow steep beaches are susceptible to erosion by storm waves, which limits the establishment of vegetation and increases the potential for dune scarping. The relationships observed at PEI are not unique, the previously published data appears to follow the same relationship (Figure 53). This would suggest that the morphology of a dune is dependent on the cycle/history of beach and dune erosion and recovery, and that the dunes at this and other sites may not be in a dynamic steady-state equilibrium with the wind and wave activity that control the nearshore and beach morphology.

The areas that show the greatest deviation from scale-invariance are in areas where the beach is narrow and there are prominent dune scarps, which are not considered in the Duran and Moore (2013) model. Although vegetation is needed to trap sediment and initiate the dune building processes, these results further suggest that vegetation is not the primary control on dune height; it is an emergent result of the complex feedback amongst nearshore, beach, and dune.

If the assumptions of the Duran and Moore (2013) model were correct, we would expect that the horizontal and vertical position of the vegetation would vary alongshore in response to the nearshore and beach morphology. However, cross correlations of the horizontal and vertical vegetation position did not show a significant relationship within and between sites. Although there was no consistent relationship, minimum distances and elevations were observed. Across all sites, the L_{veg} had a minimum of 10m and the elevation of L_{veg} did not fall below 1m, except for areas where disturbance was relatively recent, and the vegetation may not have yet responded. These minimum thresholds and the lack of a relationship to dune morphology suggest that the vegetation is controlled by the morphology and behaviour of the beach. The lack of scale invariant dune morphology with L_{veg} further suggests that there is no feedback between L_{veg} and dune height through the development of a stagnation zone as suggested by Duran and Moore (2013). This is not unreasonable given that a stagnation zone does not develop with oblique winds that are associated with the greatest input of sediment to the dune.

On beaches that are steep and narrow, the dunes are closer to the shoreline and subject to a greater frequency of storm surge, salt spray, and wave erosion compared to wide and low angle beaches. Steep reflective beaches are ‘out of equilibrium’ during storms and there is a greater chance that vegetation on these beaches will be eroded as the shoreline retreats. It is reasonable to expect that the frequency of beachface erosion would set the seaward limit that the vegetation could establish. Using the concept of the beach change envelope (BCE; Brenner et al., 2017), coastal species also inhabit areas based on ecological envelopes where the disturbances are too high within the envelope and ideal conditions exists outside or at some threshold within the boundary (Dugan et al., 2013). Further study is needed to determine how the vegetation line varies within the BCE for sites that are in equilibrium and for sites that are either eroding or depositing.

At the other end of the range of beach states, large L_{veg} values were observed in areas where the beach slope was lower, which means that BCE would not be a likely influence on vegetation position. Although these beaches have a larger fetch length and presumably would provide a greater amount of sediment to the dune (Davidson-Arnott and Law, 1990; Davidson-Arnott et al., 2018), the height of the dunes were relatively smaller relative to $L_{veg.}$ On these beaches, the L_{veg} is most likely controlled by the frequency of storm surge and the threshold elevation is at or close to the distribution of high-water elevations. Gently sloping beaches would also reduce drainage and increasing moisture content on the surface that would prevent sediment transport (Turner, 1993; Houser and Ellis, 2013). It would follow that these dunes were supply limited, which is supported by the observation that the smallest dunes were associated with the largest beach widths. This is consistent with Houser and Mathew (2013) who found that dunes along South Padre Island were transport limited and exhibited an inverse relationship to the conceptual model developed by Short and Hesp (1982). For example, the larger and lower sloped beach widths of Stanhope should result in larger dunes (Psuty, 1988; Davidson-Arnott et al., 2018), but this beach had the smallest dunes. The relationship is, however, opposite to the observations of Houser et al. (2015) from Santa Rose Island in northwest Florida and support the idea that dune height is a combination of transport and supply and not either one alone as suggested by Short and Hesp (1982) or Psuty (1988) respectively. While the controls on dune height are still not clear, this study has shown that scale-invariant dunes are not likely to be seen in the real-world and that the Duran and Moore (2013) model was based on incorrect assumptions about the role of vegetation controlling dune morphology.

Zonation as described by Maun (2009) is the spatial distribution of vegetation forming belt-like zones based on species specific tolerances to environmental conditions. Although this study focuses on *A. breviligulata,* there are multiple coastal vegetation species found beyond the crest of these dune systems. Throughout the study site, the vegetation changed from predominantly *A. breviligulata* seaward and over the dune to established bushes and woody shrubs landward of the crest (Figure 58). Duran and Moore (2013) suggest that vegetation characteristics (e.g. density and species type) and evolution are irrelevant to the growing foredune as long as the maximum plant height and growth rate is higher than maximum erosion. While vegetation height aids in sediment trapping and increasing surface roughness there are multiple characteristics which influence foredune development. Interestingly, results of this study suggest that there is not a clear relationship amongst the density gradients and the dune morphology. Specifically, the density at L_{veg} varied from 5-75% and there was no consistent density gradient from L_{veg} to the dune crest. The vegetation-density locations appear to be dependent on the presence of inlets, blowouts and hotspots of erosion.

No clear relationship was observed between beach and dune morphology and the manual (in-field) measurements of *A. breviligulata* on the dune and on the beach. This suggests that individual plant metrics like height, stock width, and root strength do not have a strong control on or are not influenced by beach-dune morphology. It is also noted that average vegetation height did not vary greatly at each site despite varying levels of disturbance and erosion at the different sites (Table 10). The lack of variation in vegetation height cannot be used to explain the variation in dune heights alongshore. However, it is important to note that vegetation could only be sampled in approved areas with low levels of erosion, low slopes, and could not be in areas of endangered species, and further studies are required to ascertain whether vegetation is an active or passive participant in this system.

Figure 58. Back barrier of Cavendish beach with areas of different vegetation species indicated in red outlines. *A. breviligulata* is seen closest to the shoreline and after the crest the diversity increases with the introduction of shrubs and woody species.

9 Conclusion

This study is the first to characterize the alongshore variation in vegetation on coastal barriers and to determine whether it is a control on dune height within and between sites. Results suggest that the scale-invariant model of Duran and Moore (2013) is not appropriate in the real-world, and that future models of barrier dune development need to consider the transport and supply limitations on dune development associated with beach and nearshore morphology. More importantly, this study was based on the accepted idea that vegetation is a primary and active control on dune development, but the results suggest that it is secondary and controlled by the nearshore and beach morphology. In this respect, it appears to be an emergent feature not a control.

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