Sediment Budget Controls on Foredune Height: Comparing Simulation Model Results with Field Data

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Abstract

The form, height and volume of coastal foredunes reflects the long-term interaction of a suite of nearshore and aeolian processes that control the amount of sand delivered to the foredune from the beach versus the amount removed or carried inland. In this paper, the morphological evolution of foredune profiles from Greenwich Dunes, Prince Edward Island over a period of 80 years is used to inform the development of a simple computer model that simulates foredune growth. The suggestion by others that increased steepness of the seaward slope will retard sediment supply from the beach to the foredune due to development of a flow stagnation zone in front of the foredune, hence limiting foredune growth, was examined. Our long-term data demonstrate that sediment can be transferred from the beach to the foredune, even with a steep foredune stoss slope, primarily because much of the sediment transfer takes place under oblique rather than onshore winds. During such conditions, the apparent aspect ratio of the dune to the oncoming flow is less steep and conditions are not favourable for the formation of a stagnation zone. The model shows that the rate of growth in foredune height varies as a function of sediment input from the beach and erosion due to storm events, as expected, but it also demonstrates that the rate of growth in foredune height per unit volume increase will decrease over time, which gives the perception of an equilibrium height having been reached asymptotically. As the foredune grows in size, an increasing volume of sediment is needed to yield a unit increase in height, therefore the apparent growth rate appears to slow.

Keywords: Foredune evolution; beach/dune interaction; computer simulation; limits to foredune height

Introduction

Coastal foredunes form where sand transported landward from the foreshore by wind is deposited on the backshore, usually within vegetation that has established above the high-water line. Growth of the foredune over time is controlled by the relative rates of sediment supply from the beach by wind action and removal from the foredune toe due to storm wave action (Davidson-Arnott and Law, 1990, 1996; Hesp, 2002). A sediment mass balance approach therefore provides the mechanism by which dynamic changes in the height and width of the foredune can be determined. On a decadal scale, these changes are of interest to coastal scientists because they are diagnostic of the coastal nearshore context in which the foredunes evolve (Bauer and Sherman, 1999; Walker *et al.*, 2017), but also because of the role played by foredunes in providing protection to the area landward of the foredune from erosion and flooding from storm events. There is now considerable interest in enhancing understanding of the controls on foredune growth and using these insights to improve morphological models that can be used to test ideas about foredune evolution (Baas and Nield, 2007; Durán and Moore, 2013; Hounhout and de Vries, 2016), to predict the vulnerability of natural dunes to scarping and overwash during storms (Claudino-Sales *et al.*, 2008; Brodie *et al.*, 2017), to assess the impact of invasive species such as non-native marram grass (e.g., Hilton *et al.*,), and to improve the management and restoration of protective dune systems in developed settings (Elko et al. 2016). While sediment budget approaches are conceptually simple, it has long been recognised that the actual controls on sediment supply to and from the foredune are numerous and complex (de Vries *et al.*, 2014; Walker *et al.*, 2017). Conceptual models of foredune evolution have sought to relate morphological response to gradients in specific controls such as sediment supply and littoral drift (Psuty, 1988, 2004; Davidson-Arnott and Law, 1990; Miot da Silva and Hesp, 2010; Heathfield and Walker, 2015), beach morphodynamics (Short and Hesp, 1982; Sherman and Lyons, 1994; Hesp and Smyth, 2016), storm frequency and magnitude (Sallenger, 2000; Houser and Hamilton, 2009; Splinter and Palmsten, 2012), vegetation type and cover (Hesp, 1991, 2002; Hilton *et al.*, 2005; Baas and Nield, 2007; Darke *et al.*, 2015), and changes in sea level (Olson, 1958; Sherman and Bauer, 1993; Davidson-Arnott, 2005). An increasing number of computer simulation models have been proposed that incorporate some of these controls, but typically they focus on equilibrium transport systems and the feedback that the evolving morphology exerts on the wind and transport dynamics (e.g., Andreotti, 2004; Durán and Moore, 2013; Goldstein and Moore, 2016).

In this paper we explore the way in which the sediment budget of a coastal foredune will control the morphological evolution, specifically dune height and width. Ultimately, we aim to assess whether there is an equlibrium limit to the height of a foredune, as proposed by Durán and Moore (2013). A data set showing the evolution of foredune profiles at Greenwich Dunes, Prince Edward Island, Canada over a period of more than six decades, based on photographic records, is integrated with recent field measurements of profile change spanning almost two decades (Ollerhead *et al.,* 2013) to inform the development of a simple 2-D morphodynamic model. Annual sediment inputs by aeolian transport from the beach and losses generated by wave erosion during storm events are simulated. The model is used to explore the effects of varying sediment input and varying storm frequency and magnitude on the growth of a simple triangular foredune over runs extending over 400 years. The validity of the model assumptions and results of the modelling exercise are examined in light of the field measurements of profile morphodynamics and of key controlling processes, in order to assess the temporal evolution of foredune profiles and the limits, if any, to the growth in foredune height and width. This is followed by a comparison of the results of our modelling exercise, which shows very few limits to foredune growth over time, with the model of Durán and Moore (2013) that, in contrast, shows that foredune height has predictable limits that are controlled by the steepness of the stoss slope, which limits inland transport during onshore winds.

Conceptual Background

The simplest sediment budget approach for modelling dune growth is based on the aeolian sand drift potential proposed by Fryberger and Dean (1979) for desert environments, with the assumption that all sediment delivered to the dune is deposited in the dune. Following this approach, the sediment supply to coastal foredunes has been predicted using hourly mean wind speed as the primary variable driving one or more aeolian sediment transport models (Chapman, 1990; Davidson-Arnott and Law, 1990, 1996; Miot da Silva and Hesp, 2010). However, in the coastal zone many factors limit the actual sediment supply, including moisture, fetch distance, lag gravels and shells, snow and ice, and textural variations (e.g., Carter, 1976; Nickling and Davidson-Arnott, 1990; Bauer and Davidson-Arnott 2003; Delgado-Fernandez, 2010; Hoonhout and de Vries, 2016). In addition, spatial and temporal variations in the morphology of the inner nearshore and foreshore zones will affect the potential sediment supply to the aeolian system and the protection provided to the foredune to the secondary backdunes or critical human infrastructure(Aagaard *et al.*, 2004; Houser, 2009; Bochev-van der Burgh *et al.*, 2011; Walker *et al.*, 2017). Several researchers have sought to isolate the role of a small number of controls and to investigate the possible limits that they impose on the evolution of the foredune and dune field complexes (e.g., Short and Hesp, 1982; Bauer and Davidson-Arnott, 2003; Baas and Nield, 2007, Durán and Moore, 2013; Goldstein and Moore, 2016). Models have also been developed to predict the extent of dune erosion due to wave run-up during individual storm events (e.g., Kriebel and Dean, 1993; Roelvink *et al.*, 2009; Houser and Mathew, 2011; Splinter and Palmsten, 2012; Amaroli *et al.*, 2013; Dissanayake *et al.*, 2014; de Winter *et al.*, 2015; Castelle *et al.*, 2017; Berard *et al.*, 2017).

Within the range of morphological models of beach/dune interaction and foredune growth, group of models can be identified wherein the primary objective is to reproduce, as far as possible, the complexities of the major controls on sediment erosion, transport and deposition and to enable real world prediction (e.g., van Dijk et al., 1999; Roelvink et al., 2009; Hounhout and de Vries, 2016; Berard et al., 2017). The primary aim of another group of morphological models is to isolate the effects of one or more key variables using a number of simplifying assumptions (e.g., Andreotti et al, 2010; Baas and Nield, 2007; Durán and Moore, 2013; Keijsers et al., 2016). These exploratory models serve a useful function because the simplifying assumptions allow for the exploration of morphodynamic reactions across time and/or the full range of the variables, thus permitting the identification of end member states as well as the potential for some form of morphodynamic equilibrium response (e.g. Zhou *et al.*, 2017). However, as Zhou *et al.* (2017, p. 259) note, the virtual world of computer models may allow for the development of morphodynamic equilibria that may not exist in the complex world of natural systems.

Zhou et al. (2017) focus on assessing morphodynamic equilibrium in terms of sediment flux equilibria which can be expressed using a form of the Exner equation (Paola and Voller, 2005; Bauer et al., 2015):

$$(1-\rho)\frac{\partial\eta}{\partial t}+\nabla.\mathrm{qs}=\sigma$$

where η is elevation of the bed, t is time, ρ is sediment porosity, q_s is sediment (volume) flux, and σ is an undefined sediment source or sink. Using this approach, they recognise three forms of morphodynamic equilibrium. First, static equilibrium occurs where there is no import or export of sediment and qs and σ are both 0, thus there can be no morphologic change. Next, there are two forms of dynamic equilibrium. Type I dynamic equilibrium occurs where $qs \neq 0$ $\nabla.qs = \sigma$ and σ = constant. If $\sigma = 0$, then the sediment flux divergence must also be zero, which also implies no net morphologic change. Note, however, that sediment transport is active in this situation, but there is no spatial difference in transport rate. If $\sigma \neq 0$, the sediment flux divergence is balanced by some constant source/sink term such as sediment consolidation or tectonic uplift (Zhou et al. 2017 p.260). Type II dynamic equilibrium is defined by $qs \neq 0$, $\nabla.qs = \sigma(t)$ and σ(t) is a function of time. This type of equilibrium is the most complex to model, although it is likely the most realistic when considering long time frames. The response of the beach and dune profile on a sandy beach to relative sea-level fluctuations (driven by a combination of eustatic and regional tectonic interactions) illustrates one form of this where the profile is translated transgressively through time (Bruun, 1962; Davidson-Arnott, 2005).

In the virtual world of morphodynamic models, especially exploratory models, equilibrium conditions are frequently invoked to make the numerical simulations viable. However, as Zhou et al., (2017) point out, in the real world, “variability in the environmental drivers and landscape settings often precludes the system from reaching an equilibrium condition” (p. 265). Therefore, it is critical to assess the results of computer models in light of our understanding of real world dynamics and to test the degree to which the identification of key controls and the assumptions behind the model development are sound.

Study Area and Methodology

Greenwich Dunes field site

Greenwich Dunes is situated on the NE coast of Prince Edward Island, Canada, and is part of Prince Edward Island National Park, facing the Gulf of St. Lawrence (Figure 1a, b). Prevailing winds are from the SW and W, but dominant storm winds resulting from the passage of mid-latitude cyclones are from the NW, N and NE blowing over fetches that exceed 300 km. These storms typically generate waves with a significant wave height of 3-7 m and storm surge of up to 2 m (Manson *et al.*, 2015). Tides are mixed semi-diurnal with a spring tidal range of 1.1 m. Sea level is rising at a rate of about 0.25-0.3 m per century (Walker *et al.*, 2017).

The study area includes about 5 km of the exposed north-facing shoreline stretching eastward from the entrance to the St. Peters estuary to just beyond the Park boundary

(Figure 1c, d). The shoreline is characterised by a sandy nearshore and beach, which are backed by a continuous foredune ranging in height from 4-12 metres with the sand deposit extending offshore as a wedge overlying sandstone bedrock (Walker *et al.*, 2017). Bedrock outcrops about 300-500 m offshore and locally is close to the surface near the beach in a few areas. Net littoral drift is from east to west. The shoreline is divided into two reaches based on observed sediment budget dynamics (Figure 1d). Reach 1 is about 2 km long and has a net negative littoral sediment budget. The beach here is 20-40 m wide, the foredune ranges from 4-10 m in height, and the shoreline is retreating at an average rate of about 0.5 ma^{-1}. In Reach 2 the littoral budget transitions from slightly negative at the updrift end near Line 5 to neutral or slightly positive at the estuary entrance. The beach is generally 35-50 m wide. The foredune ranges from 6-11 m in height and its position is essentially stable over the western two kilometres (Ollerhead et al. 2013).

Long-term foredune evolution

An intense storm on October 1, 1923 affected much of the NE coast of PEI leading to the complete erosion (i.e., removal) of the foredune within the study area and elsewhere along the coast (Simmons, 1982; Mathew *et al.*, 2010). Interpretation of the remnant morphology evident in the historical aerial photographs suggests that erosion of the foredune was likely in response to an extreme storm surge that led to inundation overwash (Sallenger, 2000; Morton, 2002; Donelly *et al.*, 2006). Re-establishment of the foredune took many decades because of the almost complete removal of pioneering dune species, especially marram grass (*Ammophila breviligulata*), along the whole shoreline (Mathew *et al.*, 2010). Aerial photographs from 1936 show the shoreline still consisting of overwash flats and fans and small, mobile transgressive dunes. By 1953 foredunes had established at the back of the beach over large sections of the shoreline, and by 1971 a continuous foredune was in place (Mathew *et al.*, 2010). Of critical importance for this study is that the exact age of the various stages of foredune growth is known because the beach-dune system was completely removed by the 1923 storm. The subsequent development and evolution of the foredune since 1936 is easily reconstructed through the aerial photography.

Surveyed foredune profiles and evolution

In 2002, eight profile lines were established along reaches 1 and 2 (Ollerhead *et al.*, 2013 – see Figure 1d). The profiles were surveyed annually between 2002 and 2011 and again in 2016, and a complete photographic record was taken for both the cross-shore and alongshore directions. Deposition along the profiles was measured seasonally between 2002 and 2008 together with vegetation height and density (Ollerhead *et al.*, 2013). Additional insight into the evolution of the foredune system was obtained from orthorectified mosaics and DEMs constructed from vertical aerial photography taken in 1936, 1953, 1971 and1997 (Mathew *et al.*, 2010), which permitted extraction of topographic data for profiles 4-9 (Figure 1d). Field experiments designed to measure the controls on aeolian sediment transport on the beach and foredune were carried out in 2002, 2004, 2007 and 2010 in the vicinity of profile 7 (e.g., Hesp *et al.*, 2005; Davidson-Arnott *et al.*, 2008; Bauer *et al.*, 2009; Walker *et al*., 2017) and continuous monitoring using a remote camera system was carried out from September, 2007 to May, 2008 (Delgado-Fernandez *et al.*, 2010, Delgado-Fernandez, 2011). The field research provides insights into the foredune sediment budget, including the mechanisms and volumes of the transfer of sand from the beach to the foredune, sand movement on the foredune itself, and the impact of foredune erosion during major storm events. The primary focus here is on profiles 5-8 in Reach 2 where the position of the foredune has been very stable over the past two decades. These data and insights are key to the development of the exploratory simulation model described in the next section.

Decadal scale evolution of the profiles is illustrated for profiles 5-8 in Figure 2. No vegetated foredunes were evident in the 1936 air photos, 13 years after the overwash event. By 1953, small, vegetated dunes had become established on the backshore along parts of the shoreline, and these are evident on lines 5, 6 and 7 (Figure 2a, b, c). There were no vegetated dunes in the vicinity of Line 8 (Figure 2d). In 1971, vegetated foredunes were present along the whole shoreline in the study area, with maximum heights up to 7 m along Lines 5-7 and about 3.5 m on Line 8. Foredune evolution along these four lines and also Line 4 (not shown) can be characterised by the development of a relatively low, broad foredune in the early stages, sloping gently down to the backshore and with the highest point located some 30-60 m inland from the vegetation line. Between 1971 and 1997 the foredune prograded seaward and a distinct crest was developed close to the beach with a steep stoss slope on all lines (Figure 2). A new lee slope developed, terminating on the older dune deposits landward. In the immediate vicinity of Line 7, the originall foredune crest was about 10 m high and the seaward dune crest was about the same height as the older crest. Between 1997 and 2016 the toe of the stoss slope of the foredune remained essentially in place along Lines 6, 7 and 8 while there was small retreat at Line 5.

The change in maximum height of the foredune crest over the period 1953-2016 is shown in Figure 3a for Lines 5-8. In 1953 there were only incipient dunes present, whereas by 1971, as noted above, the dune crest was established at quite some distance from the shoreline. By 1997 a new active foredune crest developed out of the low dune complex at a location much closer to the current back beach (Figure 2) and the crest height measurements from then on are for this location. The change in measurement location likely accounts for the discontinuity between 1971 and 1997 evident in Figure 3a. At all four locations there was a substantial increase in foredune volume over the period 1953-1971 and then a rapid increase in dune height between 1971 and 1997. On Lines 6, 7 and 8 foredune height continued to increase from 1997-2016 (Figure 3b) though there are indications that the rate of height increase was diminishing. On Line 5, where some recession of the profile occurred, dune height was stable to increasing slightly.

Based on detailed profile surveys from 2002-2016, the crest position migrated slowly landward, ranging from 0.26 m at Line 7 to nearly 8 m at Line 5 (Figure 4, Table 1). This is in contrast to the long period of crest progradation beginning in 1971 after establishment of the foredune in 1950s and 1960s. A major storm on December 21, 2010 resulted in scarping of the foredune as well as a landward shift in the position of the toe of the stoss slope by about 4-6 m along the entire length of Reach 2. This is evident in the 2011 profiles on all four lines (Figure 4). Subsequent landward movement of the crest has resulted from slumping of the over-steepened scarp and wind erosion of the top of the scarp, while the lower portion of the profile has been rebuilt by the formation of a dune ramp and the re-establishment of vegetation on it (Figure 5, 6).

Mean stoss slope angles for the period 2002–2016 are about 20° and are similar for all four lines (Table 1). There was more variability from year to year than for the lee slope angles, as a result of the periodic scarping of the stoss slope during storm events, and this is reflected in the maximum stoss slope angle for each of the years of survey (Figure 5). Lee slope angles are 15-17° for Lines 6-8 but only about 8° for Line 5. The lee slopes are generally well vegetated (Figure 5) and bare avalanche slopes are only found occasionally where a blowout has developed near the crest (Hesp and Walker, 2012) or when discrete lobes of sediment develop over the crest during fall and winter when vegetation cover is sparse due to seasonal phenology (see Ollerhead et al. 2013: Fig. 9) .

Measured mean annual sediment deposition at Greenwich Dunes over the period 2002-08 ranged from 1.98 to 3.22 m^3m^{-1} (Table 1) with the minimum annual value being slightly negative after a dune erosion event and a maximum of about 6 m^3m^{-1} (Ollerhead et al, 2013). Similar mean values were reported for foredunes located on Long Point spit on Lake Erie, Canada by Davidson-Arnott and Law (1996) with a maximum annual value of 10 m^3m^{-1}. Average annual values of about 5 m^3m^{-1} were measured at Skallingen spit, Denmark with maximum deposition of about 9 m^3m^{-1} (Aagaard *et al.*, 2004; Christiansen and Davidson-Arnott, 2004).

Computer model of foredune development

Informed by the data set described above, a simple model of foredune evolution was developed and executed in an Excel spreadsheet to explore the effects of the dune sediment budget on foredune growth. The model uses a 2-D profile oriented normal to the shoreline, and therefore it ignores alongshore variability. It is assumed that net sediment transfers to the foredune are balanced by littoral inputs from alongshore or offshore (i.e., wind and wave climates are in dynamic equilibrium so as to maintain the sediment balance). Further, it is assumed that there is no long-term change in relative sea-level rise due to variations in eustatic, tectonic or isostatic setting. Under these simplifying assumptions, the upper portions of the stoss slope can be considered to be fixed in space and used as the reference plane to evaluate long-term dune evolution, Critically, however, the toe region (lower stoss slope) is allowed to vary as a consequence of wave scarping events followed by sand ramp re-building processes that 'heal' the scarp. Thus, the model constrains the most seaward location of the toe of the stoss slope and the mean position of the foredune (i.e., no net migration) while allowing temporal variations in dune form. It therefore reproduces the two key elements of beach/dune interaction, namely deposition by aeolian processes and erosion by wave action during storm events (Houser and Ellis, 2013). It would be straightforward to add a translation component in the model to simulate dune form migration, if needed, but the drivers of dune migration are not immediately obvious and would require an additional level of complexity that is unnecessary for our immediate purpose.

The foredune is assumed to be covered by pioneering vegetation such as marram grass (*Ammophila breviligulata*) at a sufficient density to trap all the sand supplied from the beach such that no sand by-passes the lee slope of the foredune. Clearly, this assumption is not valid for unstable blowout sections leading to transgressive parabolic dunes in the hinterland, but it is reasonable for very stable, vegetated foredune systems similar to those in PEI. However, it is also assumed that vegetation on the stoss slope permits sediment to be transported to the dune crest and distributed evenly across the lee slope through one or more mechanisms such as seasonal phenology, which results in a reduction in plant height and density in winter, the existence of bare areas between vegetation clumps (Okin, 2008), and the building of a bare sand ramp following major wave scarping episodes (Christiansen and Davidson-Arnott, 2004). This assumption of transport through the vegetation but no sand by-passing of the foredune is essential if sediment accumulation on the lee slope is to be simulated.

For simplicity, the stoss and lee slopes are assumed to have fixed angles; 30° for the stoss slope and 20° for the lee slope. The lee slope is thus slightly steeper than the long-term average measurements for the PEI foredune (Table 1), while the stoss slope angle lies between the average slope and the values for the steepest slope for the foredune transects measured at the study site. These are admittedly somewhat arbitrary choices for the model, but the fixed slope values are convenient because they facilitate easy calculations of the volume of sand stored in the foredune. A more complex model might allow for unequal deposition of sediment across the dune form, and hence varying slope angles, but the general outcome would be similar in terms of overall morphodynamic evolution of the dune form. In this regard, it should be noted that the model is not driven by wind but simply by sediment inputs, and therefore there is no feedback between the evolving form and wind acceleration or steering through time (Hesp et al., 2015). The initial foredune height was set at 3 m, which is reasonable for an established foredune and allows for the depiction of the triangular form.

Net annual sediment supply from the beach by aeolian processes is held constant during any simulation run, all of which have durations of 400 years. A range of sediment fluxes from 1.5-10.0 m^3 m^{-1} per year were simulated in different runs to reflect differences in major controlling variables such as incident winds (speed, approach angle), beach width, and other supply limiting variables (moisture, surface crusts, snow cover, fetch distance, etc.).

Erosional events are simulated by removing sediment from the lower stoss slope of the foredune for a horizontal distance landward from the toe of 2.5, 5.0 or 7.5 m along the base of the dune using an annual frequency of 0.09, 0.03 and 0.01, respectively, based roughly on evidence from the site. Non-erosive events therefore occur with a frequency of 0.87. A random number sequence is used to determine which type of scarping event will occur in any given year, but only one event is allowed. The volume of sand removed from the dune during the event is a function of the event magnitude (i.e., horizontal distance eroded) as well as the dune height, which dictates the volume of the eroded wedge. Erosion by the larger events may be less than the maximum possible if the dune has not yet reached the critical height or if there has been insufficient time between storm events to replenish the sediment eroded by a previous event or events. Aeolian deposition in the following year(s) is directed first to replacing the volume eroded from the toe region in previous year(s). No deposition on the dune crest or on the lee slope is possible until the stoss slope is fully rebuilt and the eroded volume from the previous event has been replaced. If the annual aeolian sediment supply is relatively small, the process of scarp infilling may take more than one year, while a close succession of erosional events could result in no increase in dune height for a decade or more.

Model results

The simple, yet empirically grounded, simulation model presented here allows us to explore aspects of beach-dune interaction, specifically the interplay between sediment supply from the beach to foredune growth and the return of sediment through erosional storm events. Growth of a prototype foredune over the first 100 years is shown in Figure 7 for an annual sediment input of 5 $m^3 a^{-1}$. Because of the assumption that the stoss slope is fixed in position and in slope angle, net deposition occurs only on the lee slope and crest (i.e., seaward progradation or landward migration are not simulated in this non-translational model). As the dune grows in height and volume, the length of the lee slope increases, with the result that a greater volume of sediment is required to produce an increment in height in subsequent years. This is illustrated first for a simulation run without any wave-scarping events (Figure 7a), which shows decreasing thickness of the deposition layer as well as the gradual reduction in dune height growth for progressive decades. A more complex evolution is shown in Figure 7b for a simulation run that includes erosional events determined by random selection and weighted probabilities. This produces variations in the thickness of depositional layers from decade to decade depending on the frequency and intensity of the erosional events while maintaining constant sediment supply from the nearshore.

The growth rate of the dune is determined by the relative magnitude of the erosional event and the net annual sediment supply (Figure 8). The change in foredune sediment volume and height over 400 years is shown in Figure 8a with sediment input set at 5 m^3a^{-1}, and with a random sequence of storm events superimposed over the simulation period. The annual sediment supply is greater than the volume eroded for the smallest event, but not so for the two larger events. Thus, it takes more than one year for the stoss slope volume to be replaced and deposition on the lee slope to resume. When the dune height is still relatively small, or when there is a sequence of events in close succession, there may be insufficient time to replace the volume eroded by previous events and so the actual erosion (shown in purple in Figure 8a) is less than the potential erosion (shown in green). This is a realistic reproduction of what field measurements show at Greenwich Dunes as outlined above and shown in Ollerhead *et al.* (2013).

When the annual sediment input by aeolian processes is reduced, storm events and dune erosion have a greater control on the transfer of sediment to the lee slope and thus on the increase in volume and height of the foredune. The simulations demonstrate that, with an input of 1.5 m^3a^{-1} and the same erosional event regime used to create the dune in Figure 7b, there is very little increase in dune height over the 400-year period (Figure 8b). It is possible to map out combinations of sediment supply and event frequency and magnitude under which the growth of dune volume and height is effectively limited, thereby approximating a state of dynamic equilibrium over the short term.

The change in foredune height in the model is dependent on the stoss and lee slope angles that define the volume associated with a given height. The model was therefore tested with a stoss slope angle of 20° and lee slope angle of 15º, values that are closer to the average at Greenwich Dunes. The reduced lee slope angle requires a larger volume increment for each unit increase in height. However, the reduced stoss slope angle generates erosional events that yield smaller volume losses and the overall magnitude of changes to dune height are very similar to those presented in Figure 8.

The foredune geometry requires an increasing volume of deposition on the lee slope to produce a unit increment in height as the foredune grows; thus, with a constant sediment input, there is a corresponding increase in the time this takes (Figure 7a). The actual growth rate over a period of decades will also vary as a function of the volume of sediment input and the magnitude and frequency of the erosional events (Figure 7b; 8c, d; Table 2). Assuming that the net sediment input in Reach 2 at Greenwich is between 4.5 and 5 $m^3m^{-1}a^{-1}$ (Table 1) the simulation model predicts that, after 60-70 years of growth, the foredune will develop to a height on the order of 8-10 m at a growth rate of about 1 m in height every 20 years. These are similar to the actual values measured at Greenwich for Lines 5-8. Importantly, while the model shows continuing growth in foredune height after 400 years, when the dune has reached a height of about 10 metres it takes another two decades to add an additional one metre to the height with a constant rate of sediment input. Thus, unless sediment supply is extremely large or progressively increasing, the rate of increase in foredune height becomes relatively small once it has attained an elevation of 10-12 metres under the scenario represented in the model.

Model Assessment

To test the validity of this simple dune growth model (as well as other more complex models), it is necessary to compare the simulation results to real-world data and identify the restricted set of conditions for which the model is valid. The focus here is on the general evolution of the foredune under a range of sediment inputs and erosional storm events, and particularly on the conditions under which some form of static or dynamic equilibrium might be attained. The more sophisticated model of Durán and Moore

(2013), for example, predicts that the growth in dune height is limited because steepening of the stoss slope via sediment contributions from the nearshore will cause deceleration of wind flow at the seaward base of the foredune. Shear stress at the dune toe is therefore reduced below the threshold for transport, and sand supply to the stoss slope and crest of the foredune is cut off. In their model, a static equilibrium dune height H_{max} is developed (Durán and Moore, 2013: p. 17219 and their Figure 3) due to form-flow feedback, whereas in our model there is no such limitation on dune height because sediment transport to the dune is continuous, consistent with long-term measurements at the Greenwich Dunes.

Four important results can be derived from our simulation modelling. First, with small sediment input annually and relatively large but infrequent storm erosion, the long-term sediment budget for the foredune is essentially balanced, producing a Type I dynamic equilibrium for which foredune heights cannot increase above the initial conditions. Most of the sediment supply goes to healing the large wave-cut scarps that the infrequent storms produce. Dune growth only occurs if, by random chance, a long series of years contains few large storms, thereby allowing the dune ramp to heal and sediment to be transported to the lee of the foredune. High foredune crests do not develop under such sediment budget conditions. Second, if annual sediment inputs are greater than losses due to storm erosion on a decadal scale, the foredune will grow progressively in volume. There is no limit to growth in foredune height under this scenario. Third, even though the simulation model treats the average position of the mid-to-upper stoss slope as fixed, the position of the foredune crest and the lee slope can migrate landward over time as the dune grows in size. This is not a translational migration of dune form, but a net increase in foredune volume that is accommodated (in our model) by lee expansion. The seaward toe of the dune is able to shift depending on wave scarping and ramp healing events, but the most seaward position of the stoss toe (when fully healed) is always fixed relative to the mean shoreline position Fourth, the rate of increase in dune crest height is small once the foredune exceeds 10-12 m, within the range of sediment supply scenarios tested. Thus, over periods of years to decades, a condition of equilibrium could be incorrectly inferred from field data, but crest height is in fact still increasing along with dune volume. The challenge for short-term monitoring projects on large dunes is that measurement uncertainty and seasonal fluctuations in dune volume are likely of the same order of magnitude or greater than the long-term dune growth signal.

Discussion

Given the simplistic nature of our model, it is reasonable to ask whether a more sophisticated model such as that of Durán and Moore (2013) has better predictive power. Specifically, their assumption regarding an inherent limit to the sediment supply to the foredune--due to the reduction in wind speed and transport potential at the base of a steep dune--requires assessment. As Durán and Moore (2013) show, this condition arises only under sustained, onshore-directed winds that are perpendicular to an extensive two-dimensional foredune system. Our experience at Greenwich Dunes, as well as observations at many other coastal foredune systems, suggests that this conditions is unusual (and the assumption generally invalid) for two reasons. First, flow deceleration upwind of the foredune in the Durán and Moore (2013) model is developed for steady flow and saturated sand transport. Over the past two decades a number of studies have shown that unsteady, non-uniform flow conditions prevail on beach-dune systems, and that even when a positive pressure gradient develops in front of the dune toe, sediment transport onto the stoss slope and crest can be sustained, perhaps by the enhanced turbulence intensity (e.g., Wiggs *et al.*, 1996, McKenna Neuman *et al.*, 1997, 2000; Walker and Nickling, 2003; Chapman *et al.*, 2012; Walker and Hesp, 2013; Walker *et al.*, 2017). A time-invariant cessation of transport seaward of the dune toe after a critical dune steepness threshold has been reached is unusual, as has been shown on coastal dunes (Hesp *et al.*, 2015) and on desert dunes (Wiggs *et al.*, 1996; McKenna Neuman *et al.*, 1997, 2000; Baddock *et al.*, 2011; Weaver and Wiggs, 2011, Wiggs and Weaver, 2012). We note in passing that Durán and Moore (2013) incorrectly cite one of our papers (Bauer *et al.*, 2012) as supporting their assumption of no transport from the beach into the dune during an onshore wind event. During the event that they refer to, the wind speed was consistently below the threshold for sediment transport across the entire beach, so sediment transport was not active at all for that event.

The second, and more significant, reason to question the applicability of the Durán and Moore (2013) model is that a very large proportion of annual total transport into most foredunes takes place under oblique and alongshore winds., Under oblique wind approach angles, adverse pressure gradients on the windward side are not extreme, and it is unlikely that there will any significant reduction in sand transport onto the stoss slope (Arens, 1996, 1997; Davidson-Arnott *et al.*, 2005; Hesp *et al.*, 2015; Walker *et al.*, 2017). While sand transport per metre alongshore is reduced by the cosine effect, the actual transport may be greater than for onshore winds because of the fetch effect on relatively narrow beaches (Arens, 1996; Bauer and Davidson-Arnott 2003; Delgado-Fernandez, 2010???; Walker *et al.*, 2017). Transport on the stoss slope is also favoured by the reduction in the apparent slope effect with oblique winds. This is certainly the case at Greenwich Dunes as the data on deposition and the profiles in Figure 4 and Table 1 show that there is ongoing sediment supply from the beach to the steep, high foredunes – precisely the conditions that should produce no sediment delivery to the foredune stoss slope under the assumptions of the Durán and Moore model.

We note that H_{max} has been incorporated in two other papers that simulate foredune height and apparent stability regimes on barrier islands (Durán and Moore, 2015; Goldstein and Moore, 2016) and, thus, the results of those modelling efforts should be re-appraised.

Conclusions

The controls on foredune establishment and evolution in nature are highly varied and complex. Ultimately a comprehensive simulation model must incorporate the beach and foredune sediment budgets (e.g., Psuty, 1988, 2004; Arens, 1997; Bauer and Sherman,, 1999) as well as the effects of progradation, stability, or retrogradation (Hesp, 2002); sea level rise or fall (Sherman and Bauer, 1993; Ruz and Hesp, 2014; Keisjers *et al.*, 2016); the magnitude, frequency and sequencing of storm events (Sénéchal *et al.*, 2017; Walker *et al.*, 2017); the presence of seasonal snow and ice cover (Delgado-Fernandez and Davidson-Arnott, 2011; Kilibarda and Kilibarda, 2016); the characteristics of dune vegetation, including growth form, density and cover, ability to withstand burial, and seasonal growth variations (e.g., Maun, 2004; Hesp and Hilton 2013; Darke *et al.*, 2016), and the impact of human activities (e.g., Jackson and Nordstrom, 2011, Kaplan *et al.*, 2016). The challenge of utilizing highly simplified models such as the one presented here, as well as that of Durán and Moore (2013), is to assess whether the virtual results accurately emulate real world processes that characterize the morphologies of interest.

In this regard, we conclude the following:

1) Under conditions of stable sea level and fixed position of the foredune, the data from our field studies at Greenwich Dunes, Prince Edward Island, coupled with the results of a simple simulation model show that sediment supply can be delivered continuously to a foredune and that the dune will increase in height and volume over periods of decades to hundreds of years;

2) The concept of a natural limit to foredune height because of form-flow feedback, as proposed by Durán and Moore (2013), is an artefact of the assumptions in their model, particularly that of shore perpendicular flow against a two-dimensional foredune. In the real world, oblique wind approach angles are prevalent and sediment supply to the foredune by aeolian processes can continue indefinitely as long as the littoral sediment budget can supply it, and assuming that changes in other controls (e.g., sea level, beach progradation, vegetation cover) do not exceed some critical limit;

3) Because of the complexity of the controls on foredune dynamics and evolution (e.g., Walker et al., 2017) it is essential that any form of static or dynamic equilibrium that

arises within a simulation model be assessed critically against empirical evidence. Models are very useful in providing insights into complex processes that take place over long time frames or are difficult to measure due to technological limitations, but rarely do they yield insights into fundamentally new modes of system behaviour. In these instances, the range of assumptions that underpin the model should be evaluated to assess validity with respect to process controls at larger and smaller spatial-temporal scales.

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Table 1

Line No.	5	6	7	8
Crest height change (m)	1.33	1.24	0.50	1.55
Crest position change (m)	-7.68	-2.00	-0.26	-1.68
Stoss slope (°)	20.87	20.39	18.88	18.63
Max stoss slope (°)	35.32	30.67	35.01	36.75
Lee slope (°)	8.21	15.50	17.34	15.66
Annual net deposition	2.74	3.22	1.98	2.38
Maximum net deposition	4.60	4.83	4.64	6.31

Table 1: Morphometric properties of the foredune in Reach 2 based on profile measurements 2002-2016. Net change in the crest height and position are given for the period between 2002 and 2016. Negative values for the crest position indicate landward movement. Stoss and lee slope angles (degrees) are averaged for all the years of profile surveys from the crest to the toe of the slope. The maximum stoss slope angle is determined for the steepest portion of the stoss profile over a vertical distance of at least 2m. Average annual net deposition (m^3m^{-1}) between 2002-03 and 2007-08 is based on measurements using a bedframe at stations along each line (Ollerhead *et al.*, 2013). The maximum annual net deposition is the largest annual volume measured.

Table 2

Input (m^3a^{-1})	**1.5**	**2.5**	**5**	**7.5**	**10**
Height 50 years	4.1	6.2	9.6	12.1	14.1
Height 100 years	4.4	7.3	12.8	16.5	19.5
Height 400 years	7.1	13.5	25	32.7	38.9
Growth rate 5m	71	14	8	4	3
Growth rate 10m	NA	23	17	7	5

Table 2: Values for the height of the simulated foredune at three times as a function of the annual sediment input and the rate of growth in height expressed as the number of years needed to produce an increase in height from 5 to 6 metres, and from 10 to 11 metres.