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Vegetation control allows autocyclic formation of multiple dunes on prograding coasts

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ABSTRACT

We investigate the formation of multiple dunes using a >15 yr record of dune growth from Long Beach Peninsula, Washington State (USA), and a recently published coastal dune model modified to include a feedback between vegetation growth and local dune slope. In the presence of shoreline progradation, we find that multiple dune ridge formation can be autocyclic, arising purely from internal dune dynamics rather than requiring variations in external conditions. Our results suggest that the ratio of the shoreline progradation rate and the lateral dune growth rate is critical in determining the height, number, and form of multiple dunes, allowing the development of testable predictions. Our findings are consistent with observations and imply that caution is required when using dune ridges as proxies for past changes in climate, sea level, land use, and tectonic activity because the relationship between external events and the formation of multiple dunes may not be one to one as previously thought.

INTRODUCTION

Multiple dunes and dune ridges, such as those found along much of the coast of Oregon and Washington (USA), have fascinated scientists for more than half a century (e.g., Cooper, 1958). It has long been recognized that multiple dune ridges—both modern and relict—form along prograding coasts in association with recognized variations in beach and dune sediment supply (e.g., Hesp, 1984; Psuty, 1986), local tectonic activity (e.g., Goff et al., 2008), and/or sea level (e.g., Orford et al., 2000). As such, they have been heralded, by some, as valuable indicators of local and regional changes in climate, sea level, and earthquake activity (e.g., Wells and Goff, 2007; Goff et al., 2008). In addition, the characteristics of a multiple dune ridge system, such as the number, spacing, and height of dunes, are important in predicting storm impacts (Sallenger, 2000), recovery following storms, and the effects of sea-level rise. However, the present lack of a process-based understanding of dune formation on prograding coasts limits the scope and quality of information we can extract from the characteristics of multiple dunes. It also limits our ability to make predictions about dune growth and response to external environmental changes.

Early work cites evidence for the formation of secondary incipient foredunes along a prograding coast in response to the colonization by vegetation of new areas seaward of an established foredune (e.g., Hesp, 1984). The conceptual model of beach-dune interactions presented by Psuty (e.g., 1986, 1988) assumes that sediment supply, both to the beach and to the dune, is the driving factor for the formation of multiple dune ridges. Psuty (1986) hypothesized that rapid beach progradation leads to a series of low foredune ridges whereas slower rates of progradation allow for the development of a single, larger foredune.

Here, we study the formation of multiple dunes using a high-resolution longitudinal data set characterizing dune development on the southwest Washington State coast (Fig. 1) and a modified version of a previously published coastal dune model (Durán and Moore, 2013; Durán Vinent and Moore, 2015) that includes a key assumption: a negative feedback between rhizome growth and local dune slope in which steeper slopes slow the lateral growth of rhizomes as they propagate from higher to lower areas. In the model, this feedback leads to the formation of multiple dunes, as it allows the colonization of vegetation by propagules (seeds or rhizome fragments) seaward of the foredune crest to give rise to an incipient dune (consistent with observations; e.g., Hesp, 1984), perhaps identifying a mechanism that can more fully explain the formation of multiple dune ridge systems. Here, our results suggest that multiple dunes can arise from internal dynamics alone and that the relationship between the number of dunes in a multiple dune ridge system and pulses of sand supply arising from local and regional processes may not be one to one as many previous investigations have tended to assume or conclude (e.g., Orford et al., 2000; Wells and Goff, 2007).

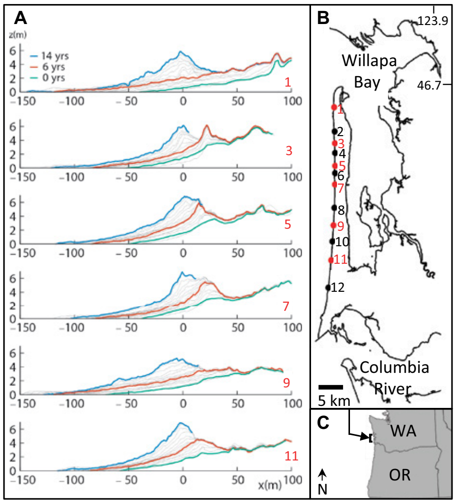

Figure 1. Representative selection of measured profiles for locations along Long Beach Peninsula, Washington State, USA. Alongshore position is given by numbers in bottom right corner of each panel, corresponding to red numbers on map. Green profiles were collected in A.D. 1998. Red profiles were collected 6 yr later (in 2004), and blue profiles were collected 14 yr later (in 2012). Elevation is relative to shoreline position (3 m contour, North American Vertical Datum of 1988). WA—Washington; OR—Oregon.

FIELD OBSERVATIONS

Topographic profiles collected across the beach and foredune quarterly since A.D. 1997 using real-time kinematic differential GPS surveying techniques (Ruggiero et al., 2005) capture the successive development of coastal foredunes along Long Beach Peninsula, Washington State (Fig. 1), over >15 yr. Profiles were measured by walking from the landward side of the primary foredune ridge, over the dune crest, to wading depth during spring low tides. This

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methodology detects vertical change greater than ~8 cm (Ruggiero et al., 2005).

A temporal analysis of 12 profiles, collected along Long Beach Peninsula and not associated with estuary entrances, indicates that a first ridge developed during an initial 6 yr time span (red profiles in Fig. 1; Fig. 2A), followed by the formation of a second ridge (blue profiles in Fig. 1; Fig. 2B), which grew seaward of the first, at which time the initial ridges stopped growing. Acknowledging minor differences in inter-site behavior (e.g., profile 3 in Fig. 1 indicates development of two new foredunes instead of one), in general both ridges aggraded vertically at a rate of ~0.5 m/yr (calculated from Fig. 2). Note that prior to becoming the site of a new foredune 6 yr into the observational period, the beach also aggraded at the rate of ~0.5 m/yr, making the appearance of the ridge indistinguishable in the plot of elevation through time and demonstrating that, despite seasonal variations in shoreline progradation, sand supply to the back beach, which then becomes dune, is fairly consistent through time and space (Fig. 2B). This is further evidenced by consistency in the seaward progradation rate of the 4 m contour (Fig. 2C) and the similar growth rates of the first and second ridges at different locations (Figs. 2A and 2B). These observations indicate that variations in sand supply (as in, e.g., Orford et al., 2000) are not a necessary ingredient to explain the formation of multiple dune ridges. Defining the shoreline as the cross-shore position of the 3 m contour relative to the North American Vertical Datum of 1988 (a datum approximately level with mean lower low water), hereafter referred to as the shoreline position and the 0 m elevation, yields average local shoreline change rates of 2–4 m/yr (Fig. 2D).

MODEL DEVELOPMENT

We developed a modified version of the coastal dune model of Durán and Moore (2013) which consists of a series of differential equations describing aeolian sand transport processes and vegetative processes involved in dune formation in the presence of a shore (see the GSA Data Repository[1] for complete model description).

In a typical simulation, aeolian transport begins at the foreshore (during low tide) at the first location where the wind shear stress is above the transport threshold. Sand flux then steadily increases to the maximum, saturated value that the wind can sustain. Under a constant onshore wind, sand blows continuously across the beach to the back beach where it is trapped by dune-building vegetation, leading to the initiation of a foredune. Once a protodune emerges, its evolution is determined by its interaction with the wind flow, and vegetation plays a secondary role as a passive roughness element anchoring the dune in place (Durán and Moore, 2013).

To explore the formation of multiple dune ridges, we allow the shoreline to move seaward at a constant imposed rate while the foreshore beach slope is held constant. We also add the possibility for vegetation to grow both from rhizomes of existing plants, as most commonly observed, and from propagules (e.g., rhizome fragments or from seeds) in unvegetated areas. In areas of existing vegetation, then, plants propagate laterally (leading to formation of linear dunes in association with grasses such as *Ammophila breviligulata*; e.g., Godfrey et al., 1979) and grow vertically at a rate that is proportional to the sand accretion rate (e.g., Maun and Perumal, 1999), except where the surface slope is steeper than a threshold value (taken here to be 15°) at which point lateral propagation of vegetation ceases. We estimate this threshold value from the field data described above, as defined by the average angle of the foredune uphill of the position where a new dune forms on the seaward side.

Thus, in the model, foredunes accrete vertically as the shoreline progrades in association with rhizomes which grow seaward until the foredune becomes sufficiently mature (steep) to reach the threshold slope. At this point, lateral propagation of dune-building vegetation ceases and the dune grows vertically while keeping a constant slope, as long as there is sand influx from the beach to the dune. Following this, colonization of the previously unvegetated prograding beach by seedlings or vegetative fragments triggers formation of a new incipient foredune, which eventually captures sand flux from the beach, thus preventing further growth of the established foredune. Hesp (1984) observed this cycle of dune initiation driven by vegetation growing from propagules alternating with growth of established dunes in association with lateral propagation of rhizomes.

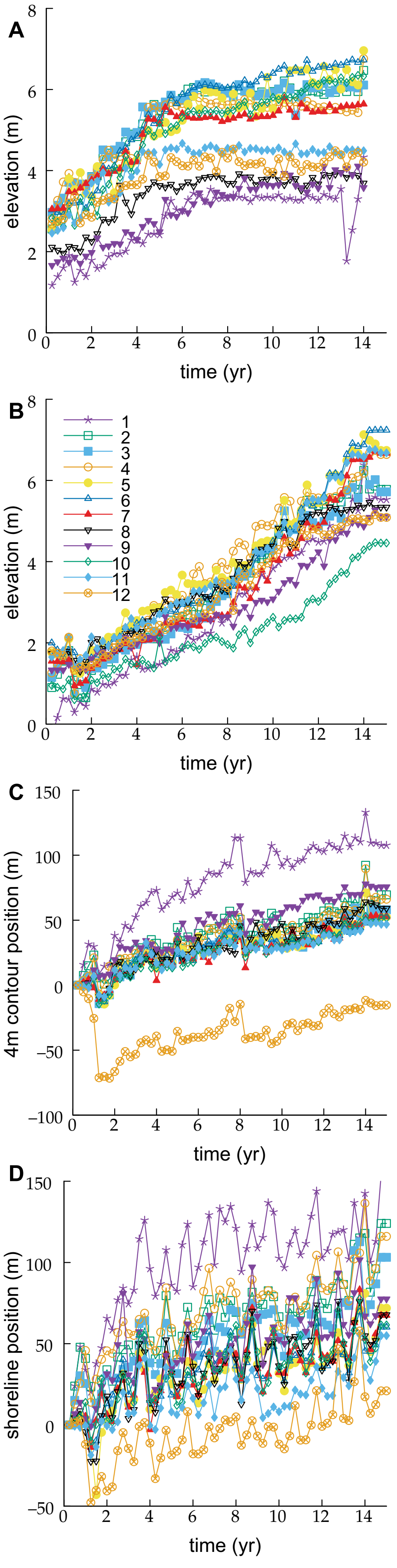

Figure 2. A,B: Change in elevation relative to 3 m contour (North American Vertical Datum of 1988) (shoreline) at two cross-shore positions identified approximately as crest of first (A) and second (B) ridge given by red and blue profiles in Figure 1, respectively, for locations 1–12 as shown in Figure 1B. Time $t = 0$ is A.D. 1997, and $t = 15$ is 2012. At approximately $t = 6$ yr, several locations in B become a ridge, which aggrades at a rate similar to the beach prior to ridge formation. C: Change in 4 m contour position from its value at $t = 0$. D: Horizontal change in shoreline position (relative to the initial shoreline position) throughout the 15 yr of observation measured from each profile.

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[1] GSA Data Repository item 2016186, full model description, profile measurements, and Figure DR1, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

SIMULATION RESULTS AND COMPARISON WITH OBSERVATIONS

Simulations of dune formation under the simplifying condition of constant onshore winds and a range of constant shoreline progradation rates successfully produce a range of multiple dune ridge patterns (Fig. 3). In the presence of a stable shoreline that is neither eroding nor prograding, a single, steady-state dune forms (Fig. 3A; Durán and Moore, 2013). For moderate rates of shoreline progradation, more complex dune shapes emerge (Figs. 3B–3D). Qualitatively, these complex overlapping dune forms closely resemble the measured dune profiles shown in Fig. 1 for Long Beach Peninsula. Simulations having relatively higher rates of shoreline progradation give rise to multiple dunes having more consistency of shape, wider spacing, and similar or lower heights than the steady-state case (Figs. 3E and 3F). The predicted dune profiles for rapidly prograding shorelines are more similar in form to observed dune profiles from the cuspate foreland at Cervantes in Western Australia observed by Hesp (1984). A comparison between the change in elevation through time of three simulated ridges for a moderate shoreline progradation rate (as in Fig. 3D) with observations for the two ridges at locations 2 and 3 (four ridges total) near the northern end of Long Beach Peninsula (Fig. 1) reveals growth rate curves of similar shape (see Fig. DR1 in the Data Repository).

Dune shapes arising in the model depend on the ratio between the shoreline progradation rate and the rate at which the dune ridge propagates seaward due to vertical dune growth. Defining the lateral dune growth rate as the vertical dune growth rate divided by the typical seaward dune slope (tangent of the angle measured from the actual and simulated dune profiles), the model suggests two regimes (Fig. 4). When shoreline progradation rates are slower than the lateral dune growth rate, dunes are taller than the equilibrium size achieved under stable shoreline conditions, ridges tend to be aperiodic and can overlap (i.e., Fig. 3A–3D, and most profiles in Fig. 1), the typical ridge formation time decreases with increasing shoreline progradation rate, and the distance between ridges, rescaled by the typical dune length, is relatively constant. In contrast, when progradation rates are faster than the lateral dune growth rate, dunes are smaller than their equilibrium size, ridges tend to be periodic (Figs. 3E and 3F; and as in Hesp, 1984), and the rescaled ridge formation time is relatively constant. This implies that the rescaled distance between ridges is proportional to the shoreline progradation rate (Fig. 4C).

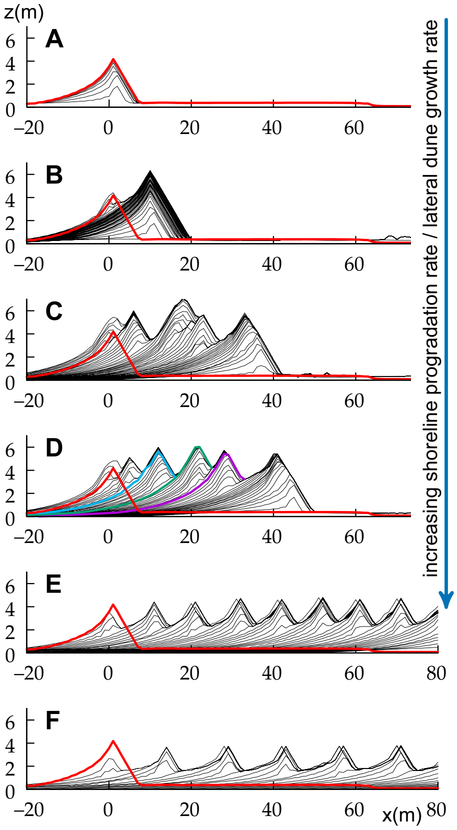

Figure 3. Evolution of dune profiles in association with shorelines prograding at different rates. For comparison, steady-state dune profile for stable shore is highlighted in red with its crest centered at $x = 0$. Progradation occurs to left as in Figure 1, and $x = 0$ corresponds to position of crest of newest foredune. Growth rates of colored ridges shown in D are plotted in Figure DR1 (see footnote 1). Mean sea level corresponds to $z = 0$.

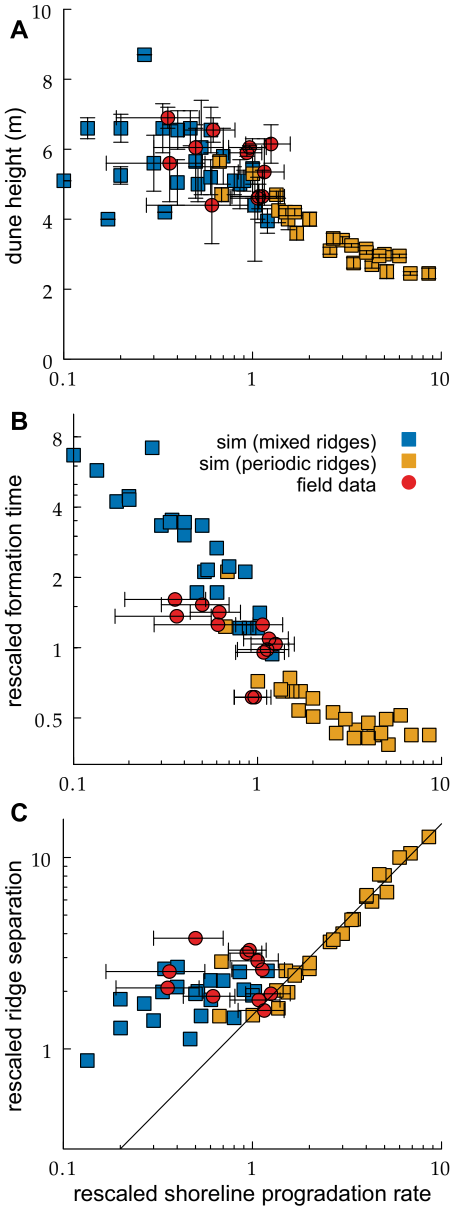

Figure 4. Model predictions as function of the re-scaled shoreline progradation rate. A: Dune height (vertical bars represent range of elevation for different ridges). B: Rescaled ridge formation time (total time divided by number of individual ridges, and rescaled by characteristic dune formation time, which is defined for simulations as the ratio of equilibrium height achieved under stable shoreline conditions and vertical dune growth rate, and for field data as ratio of average dune height [5.5 m] and vertical dune growth rate). C: Rescaled distance between consecutive ridges (rescaled by elevation of highest ridge in that location). Simulations were performed for three different wind intensities and progradation rates in range 0–15 m/yr. Shoreline progradation rate is rescaled by lateral dune growth rate, defined as ratio of measured vertical dune growth rate (calculated from the growth rate curves for simulations and field data; see Fig. 2 and Fig. DR1 [see footnote 1]) and characteristic stoss slope (average value of 0.14 and 0.36 for field data and simulations, respectively). For field data, shoreline progradation rates were calculated from shoreline positions during period of formation of second ridge (years 5–13). Measured quantities are listed in Table DR1 (see footnote 1).

DISCUSSION AND CONCLUSIONS

One might hypothesize temporal changes in the rate of sediment supply to the beach as a potential source of variation (annual or longer-term, as in Wells and Goff, 2007) that gives rise to the formation of multiple dune fields—with each sediment burst resulting in the formation of a single new dune. However, whereas shoreline progradation rates, and therefore sediment supply to the beach, along Long Beach Peninsula vary annually (Fig. 2D), these variations are dampened at the higher-level elevation contours (e.g., 4 m) where dunes form: at these higher elevations the beach accretes vertically and progrades seaward at rates that are relatively consistent through time (Fig. 2C). Further, observations of dune formation are not consistent with the formation of one dune per year in association with seasonal variations in the shoreline progradation rate or vegetation growth. Rather, the transition from a first to a second ridge occurs after 5–6 yr and is not precipitated by external factors or events (e.g., storms), and dune formation appears to be uncoupled to the short-term dynamics of the shoreline and seasonality in vegetation growth. Thus, we agree with Goff et al., (2008) that sea-level fluctuations, land-use changes, and climatic shifts are not necessary to initiate dune ridge formation. Indeed, simulations suggest that periods of sustained progradation at higher-elevation contours—regardless of the original cause of, or variations in, increases in sediment supply to the beach—in combination with the internal dynamics of the dune formation process are sufficient to give rise to multiple ridges (within the course of a decade, in the case of Long Beach Peninsula). Simultaneous future monitoring of vegetation metrics and dune morphometrics are needed to quantify lateral rates of vegetation growth relative to the formation of new ridges, as well as to test the relationship between dune slope and lateral growth of vegetation.

Importantly, by introducing the ratio of the shoreline progradation rate and lateral dune growth rate as a new control parameter, we provide a means for predicting the height, number, and spacing of multiple dunes under different conditions. For example, in places where the sand flux is low (e.g., where winds are weak, tide range is large, or the beach is often wet), well-defined multiple dune ridges may form even at relatively slow rates of shoreline progradation. At another extreme, if the rate of shoreline progradation is comparable to or slower than the rate of lateral dune growth, new ridges typically become superimposed on one another to form large complex foredunes, regardless of how rapid the shoreline progradation rate is. This latter scenario may explain the formation of especially large modern and relict foredunes such as those found in the Outer Banks of North Carolina (i.e., the famous Jockey's Ridge) and Clatsop Plains, Oregon (Ruggiero et al., 2005), United States, and at Saint Pierre and Miquelon archipelago, France (Billy et al., 2014). Overall, our findings suggest that internal interactions between abiotic and biotic factors are sufficient to give rise to multiple dune fields having a morphology characterized by the ratio of the rate of shoreline progradation and the rate of lateral dune growth. Field data appear to be consistent with this idea.

Simulation results suggest testable explanations for observed patterns in dune morphology across sites. For example, the range of shoreline progradation rates observed along the cuspate foreland at Cervantes in Western Australia by Hesp (1984) and at Long Beach Peninsula are similar (~2–5 m/yr and 2–4 m/yr, respectively), yet dune morphology is markedly different (similar to Figs. 3D and 3E versus Figs. 3B and 3C, respectively). Although addressing them here is beyond the scope of our study, two testable explanations are suggested by the model. One possible explanation is that the dune ridges of Cervantes may be steeper than those of Long Beach Peninsula and therefore propagate seaward more slowly; coarse measurements of dune slope from profiles of Hesp (1984) are qualitatively consistent with this prediction. Alternatively, observed differences in dune morphology between the two sites could have arisen from faster rates of vertical dune growth at Long Beach Peninsula than at Cervantes (e.g., due to stronger winds, finer grain size, or dryer conditions and thus increased sand flux), leading to a lower value for the ratio between the shoreline progradation rate and the lateral dune growth rate (because a higher vertical growth rate results in a faster rate of lateral dune growth).

Finally, our findings have significant implications for the use of dune ridges as proxies for changes in local conditions and tectonic activity. For example, in anticipating the formation of a single dune ridge in association with a single earthquake (where each earthquake delivers sediment to rivers, and thus to the coast, via landslides), Wells and Goff (2007) suggested that one of their observed dune ridges, which appears to be an "extra" ridge not associated with a previously documented earthquake event, is in itself evidence for an event that was otherwise missed in proxy records. In demonstrating that in the presence of sustained shoreline progradation, dune ridges can arise from internal dune dynamics rather than variations in external factors, our results suggest a potential alternative interpretation for this aspect of the dune sequences studied by Wells and Goff (2007)—that the occurrence of multiple earthquakes across an 800 yr time span led to a long-term increase in sediment delivery and thus long-term shoreline progradation giving rise to the formation of multiple dunes throughout this time. In this case, the age of each dune may well be independent of a particular earthquake event. At a minimum, our results suggest that a single, large tectonic event that produces a prolonged period of shoreline progradation has the potential to result in the formation of more than one dune ridge, confounding the use of dune ridges as proxies for paleoevents.

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