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Embryo dune development drivers: beach morphology, growing season precipitation, and storms

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ABSTRACT: For development of embryo dunes on the highly dynamic land–sea boundary, summer growth and the absence of winter erosion are essential. Other than that, however, we know little about the specific conditions that favour embryo dune development. This study explores the boundary conditions for early dune development to enable better predictions of natural dune expansion. Using a 30 year time series of aerial photographs of 33 sites along the Dutch coast, we assessed the influence of beach morphology (beach width and tidal range), meteorological conditions (storm characteristics, wind speed, growing season precipitation, and temperature), and sand nourishment on early dune development. We examined the presence and area of embryo dunes in relation to beach width and tidal range, and compared changes in embryo dune area to meteorological conditions and whether sand nourishment had been applied. We found that the presence and area of embryo dunes increased with increasing beach width. Over time, embryo dune area was negatively correlated with storm intensity and frequency. Embryo dune area was positively correlated with precipitation in the growing season and sand nourishment. Embryo dune area increased in periods of low storm frequency and in wet summers, and decreased in periods of high storm frequency or intensity. We conclude that beach morphology is highly influential in determining the potential for new dune development, and wide beaches enable development of larger embryo dune fields. Sand nourishment stimulates dune development by increasing beach width. Finally, weather conditions and non-interrupted sequences of years without high-intensity storms determine whether progressive dune development will take place.

KEYWORDS: biogeomorphology; embryo dunes; *Ammophila arenaria*; *Elytrigia juncea*; beach–dune interaction; coastal dynamics; the Netherlands

Introduction

Coastal dunes occur along the sandy shores of most continents (Martínez and Psuty, 2008) and serve functions such as coastal defence, recreation, reservoirs for drinking water, and hotspots for biodiversity (European Commission, 2007; Everard *et al.*, 2010). The quality and resilience of coastal dunes is threatened, however, by climate-induced sea-level rise (Carter, 1991; Feagin *et al.*, 2005; Keijsers *et al.*, 2016). This threat may be mitigated by the spontaneous formation of new dunes on beaches where and when conditions are favourable. To predict the future of dunes and coastal evolution, knowledge about early dune development is essential. Yet, despite the obvious importance of dunes, we know surprisingly little about the mechanisms that underlie early dune development.

Embryo dunes (also referred to as incipient dunes) (Hesp, 2002; Maun, 2009) are the first stage of dune development. Embryo dunes are formed when sand is deposited within discrete clumps of vegetation or individual plants (Hesp, 2002). It starts with establishment of dune-building plant species above the high water line. Driftwood material may form a nucleus for vegetation establishment and sand deposition (Eamer and Walker, 2010; Del Vecchio *et al.*, 2017). Once vegetation becomes established on a bare beach, it serves as a roughness element that facilitates sand deposition and reduces erosion. An embryo dune is thus the result of an interaction between vegetation and aeolian processes. Embryo dunes increase in size by deposition of more sand, as a result of the reduced flow velocities caused by vegetation roughness (Hesp, 2002; Maun, 2009). In time, embryo dunes may develop into a foredune that forms the first line of coastal defence.

Previous research has focused on either the ecology of dune-building vegetation or on factors driving sediment supply to embryo dunes (Olivier and Garland, 2003; Maun, 2009; Anthony, 2013; Montreuil *et al.*, 2013). Few studies have investigated the relative importance of plant- and sand-related drivers for embryo dune development. Montreuil *et al.* (2013) found that embryo dune development has a seasonal cycle, with summer accumulation and autumn–winter erosion. Dune-building plant species become established in the summer months and are strongly influenced by soil salinity, soil moisture, and sand erosion/burial (Sykes and Wilson, 1989; Maun, 2009). The supply of sediment for development of embryo dunes depends on the transport capacity of the dominant wind direction, beach morphology and sediment availability (Olivier and Garland, 2003; Anthony, 2013; Montreuil *et al.*, 2013). Sediment supply is related to both local factors, such as surface moisture (Saye *et al.*, 2005; Delgado-Fernandez and Davidson-Arnott, 2011; de Vries *et al.*, 2012; Anthony, 2013), and to regional factors, such as the welding of intertidal bars (Aagaard *et al.*, 2004). The relative importance of these factors for embryo dune growth is nonetheless still unclear.

As, noted, embryo dunes grow mainly in summer, and erode in winter due to increased storm frequency (Montreuil *et al.*, 2013). Yet, studies of the effects of storms on embryo dune development are scarce, so impacts of storms on embryo dune development must largely be deduced from research on foredune development. Foredune erosion is influenced by storm intensity and beach morphology (Claudino-Sales *et al.*, 2008; Houser *et al.*, 2008; Haerens *et al.*, 2012; Keijsers *et al.*, 2014). Storm intensity is a product of regional characteristics and meteorological conditions, which determine surge levels, wave conditions, and storm durations (Vellinga, 1982; van de Graaff, 1986). Local factors, such as the direction of onshore winds, beach width, beach slope, and presence of intertidal bars, modify storm impact, as they co-determine wave energy and wave run-up (Ruggiero *et al.*, 2001; Anthony, 2013). Beach morphology affects dune erosion. For instance, dissipative beaches with a low and gradual beach slope are less subject to dune erosion than reflective beaches with a steep beach slope (Short and Hesp, 1982; Wright and Short, 1984). The extent that storms constrain embryo dune development, however, remains unknown.

Although embryo dune formation precedes foredune development, surprisingly little is known about the factors that determine their dynamics. In this study, we explored boundary conditions for early dune development to better predict natural dune expansion. Using a 30-year time series of aerial photographs of the Dutch coast we investigated: (1) the relation between beach morphology and presence and area of embryo dunes, (2) the effect of sand supply, storm characteristics, and other climatic factors on changes in embryo dune area.

Methods

Study area

We selected 33 sandy dissipative beach sites, each 2.5 km long, along the coast of three geographic areas in the Netherlands: the West Frisian barrier islands ($N = 20$), the Holland mainland ($N = 7$), and the south-western delta ($N = 6$) (Figure 1). The beaches on the West Frisian islands had the largest range in beach width, which is why most sites were selected there. The sites were separated by at least 2 km, to avoid spatial autocorrelation between them (de Vries *et al.*, 2012). The 33 sites represent a wide variety in beach morphology, with beach widths ranging between 50 and 1400 m. All three geographic areas contained both accreting and eroding sites. Mean tidal ranges varied between 1.6 and 2.7 m, depending on the area.

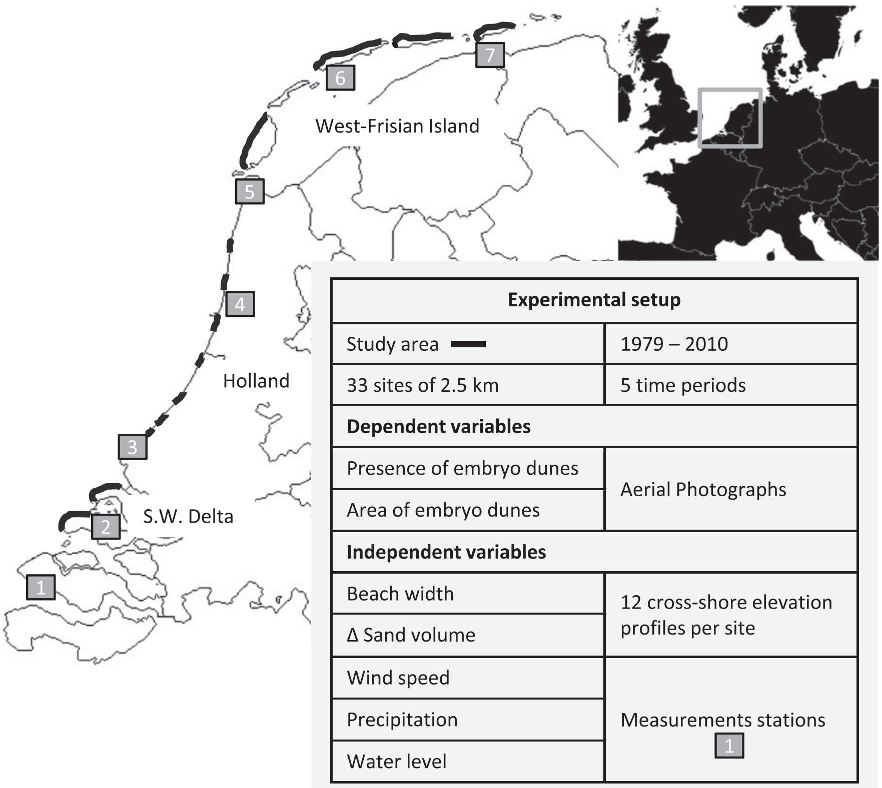

Figure 1. Study areas along the coast of the Netherlands. Each thick line represents a subset of in total 33 sites, of 2.5 km each. For the West Frisian islands and the south-western delta 2 km distance was retained between sites to avoid autocorrelation. For the data used, see tables. Squares denote measurement stations along the Dutch coast: (1) Vlissingen, (2) Brouwershavense Gat 08, (3) Hoek van Holland, (4) IJmuiden Buitenhaven, (5) Den Helder/De Kooy, (6) West Terschelling, (7) Schiermonnikoog.

Sediment mean grain size ranged between 190 and 400 µm (Arens, 1996; Stuyfzand *et al.*, 2012).

All study sites were backed by a continuous foredune ridge covered largely by the grass *Ammophila arenaria* (L.) Link (Supporting Information Appendix S1). At many sites, foredune ridges had been created, or reinforced, by vegetation plantings and sand fences. All sites had embryo dunes seaward of the foredune at one time. Embryo dunes were covered by the grass *Elytrigia juncea* (L.) Nevski with some *A. arenaria*. Some of the sites experienced intensive recreational use and tourism and were mechanically cleaned by the municipality during summer. That cleaning resulted in the removal of drift material and, potentially, seedlings or ramets of dune-building grasses (Dugan and Hubbard, 2010).

Data collection

Presence and area of embryo dunes were extracted from aerial photographs spanning the years 1979 through 2010 (Dunea, 1975; Rijkswaterstaat, 1979; PWN, 1987; AIS, 2005; Kadaster/Clyclomedia, 2010). The time interval between consecutive photographs (referred to here as the time period) depended on what photographs were available for the individual sites (Supporting Information Appendix S2, Table S2.1). The average interval was six years. Hard-copy photographs of coastal areas for the years 1978, 1979, 1982, 1983, and 1988 had a scale of 1:4000, and were scanned at 400 dpi. These digital photographs were georeferenced by matching 10 recognizable objects (e.g. beach poles, road intersections) on the beach and in the dune area to a topological map. To georeference the images we applied a spline transformation using ArcGIS software (ESRI, 2013). The resulting spatial resolution of the photographs was between 0.20 and 1 m (Table S2.2). Embryo dunes smaller than about 1 m^2 could not always be recognized, leading to conservative estimates of embryo dune area.

Embryo dune area

The outlines of individual embryo dunes were manually digitized using ArcGIS. With 2010 as the starting point, we combined information from the aerial photographs and a LiDAR-derived digital elevation model (AHN2) (Programmasecretariaat AHN, 2013). Embryo dunes could thus be identified based on their vegetation structure (aerial photographs) and height (digital elevation model) (Figure 2b). In the Netherlands, foredunes are higher than approximately 8 m NAP (NAP refers to Amsterdam Ordnance Datum, which is equal to mean sea level near Amsterdam). Patches with discrete clumps of vegetation at an elevation less than +6 m NAP in the 2010 aerial photographs were classified as embryo dunes.

Vegetation structure was used to distinguish between embryo dunes and low foredunes, which are more continuously covered with vegetation. Polygons were drawn around the vegetation patches at a standard resolution (1:600). We included no buffer around the vegetation. Subsequently, we identified embryo dunes on the photographs from the preceding years, using the 2010 embryo dunes as baseline.

For earlier years, no digital elevation model was available. We therefore used vegetation structure only to identify embryo dunes. In these earlier years some sparsely vegetated foredunes might have been falsely identified as embryo dunes, potentially increasing measurement error. After analysing all aerial photographs for a certain site, we verified the embryo dunes by comparing the most recent years with previous years. We took a conservative approach, discarding all embryo dunes that overlapped previous year's foredunes: i.e. we did not distinguish between eroding foredunes and newly developed embryo dunes in the same space. The maximum error in our assessment of the embryo dune area per site was 20% for 0.2 m resolution photographs and 5% for 1 m resolution photographs. This was determined after digitizing the same subsample of sites five times at high resolution and five times at low resolution. The area covered by embryo dunes was summed per site per year and used for the statistical analysis.

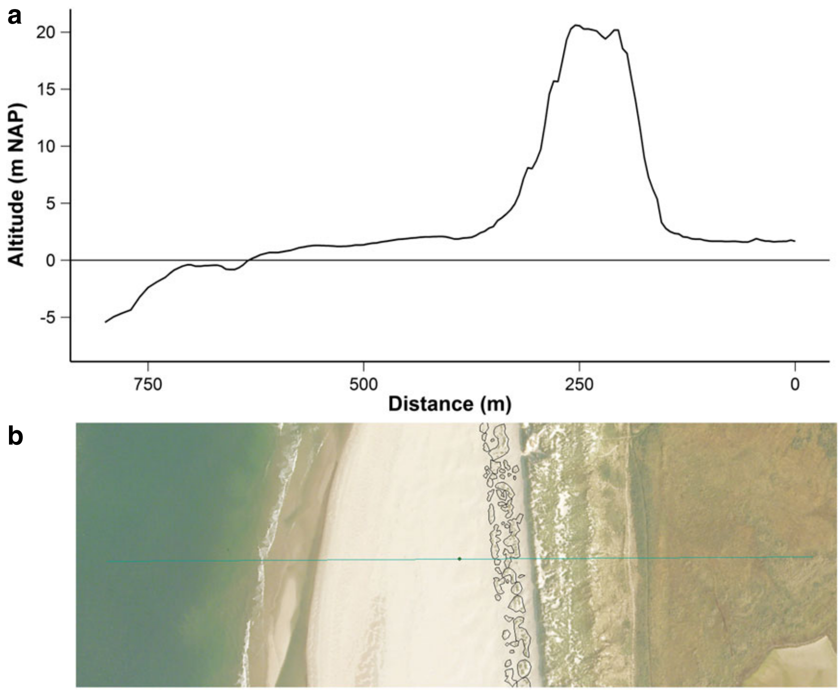

Figure 2. (a) An example cross-shore elevation profile from the JarKus database with the altitude in metres NAP (Dutch Ordnance Datum). (b) Aerial photograph with areas outlined in black representing manually assigned embryo dunes. Cross-shore line represents the location of cross-shore elevation profile shown in (a). Data from Terschelling in 2005. [Colour figure can be viewed at wileyonlinelibrary.com]

Beach morphology

Beach width (BW in metres) and beach volume (BV in m^3/m) were derived from 8 to 12 cross-shore elevation profiles for each year in which we also had photographs. Cross-shore elevation profiles from 1970 to 2010 were obtained from the JarKus database (Rijkswaterstaat, 2014a). This database contains annual elevation measurements covering dune, beach, and foreshore, and has been used in several studies addressing coastline dynamics from an annual to a decadal scale (Bochev-van der Burgh *et al.*, 2009; de Vries *et al.*, 2012; Keijsers *et al.*, 2014, 2015). The cross-shore distance between the JarKus profiles is 200 to 250 m. The distance between elevation measurements along each profile is 5 m (Figure 2a). Profile elevation was measured for the respective time periods using the following methods: levelling (1975–1977), stereo photography (1978–1995) and laser altimetry (1995–2010). The reported accuracy of the measurement techniques differed substantially, ranging from 0.01 m for levelling (Oosterwijk and Ettema, 1987), to 0.1 m for photogrammetry and laser altimetry (Minneboo, 1995; De Graaf *et al.*, 2003; Sallenger *et al.*, 2003).

Each site contained 12 profiles on average, though more profiles were available on dynamic beaches. Each profile was inspected for measurement errors and omitted if errors were found (i.e. if measurement points were missing or an unrealistically high elevation was measured). This resulted in a minimum of eight profiles per site. From the available profiles we calculated beach width (BW) and beach volume (BV). Beach volume was calculated as the area (m^3/m) under the curve of the profile to a depth of −5 m NAP. We defined beach area as the expanse between the shoreline and the dune foot (also known as the toe), i.e. between 0 and +3 m NAP (de Vries *et al.*, 2012; Keijsers *et al.*, 2014). Beach width was calculated for both the intertidal beach (between 0 and +1 m NAP, $BW_{0–1}$) and the dry beach (between +1 and +3 m NAP, $BW_{1–3}$). Beach volume was calculated for both the intertidal and dry beach, as well as for the whole beach between 0 and 3 m NAP. The change in beach volume was calculated for each time interval between consecutive photographs, again distinguishing between the intertidal beach ($\Delta BV_{0–1}$), the dry beach ($\Delta BV_{1–3}$), and the entire beach ($\Delta BV_{0–3}$). If a site had a positive change in beach volume ($\Delta BV_{0–3}$), it was classified as an accreting beach.

Meteorological conditions

Water level and storm characteristics

Dune erosion results from combination of strong onshore winds, high energy waves, high water levels, and high wave run-up were obtained (Vellinga, 1982; Haerens *et al.*, 2012). In the absence of wave height data, we used observed water levels as a proxy for storm intensity and thus potential dune erosion (Guillén *et al.*, 1999; Ruessink and Jeuken, 2002; Keijsers *et al.*, 2014). We derived hourly water level data from six tidal measurement stations along the Dutch coast (Rijkswaterstaat, 2014b): Brouwershavense Gat 08, Hoek van Holland, IJmuiden buitenhaven, Den Helder, West Terschelling and Schiermonnikoog, Figure 1). For each site we used the nearest measurement station.

We created four water level exceedance classes (i.e. storm intensity classes, I–IV), based on water level return periods from the tidal measurement stations. These were high water levels of a severity that occurs once every (I) 1–2 years, (II) 2–5 years, (III) 5–10 years, and IV) > 10 years. For each station, we calculated the number of hours per time period (between consecutive aerial photographs) that the water level fell within one of these exceedance classes. The hours for each storm intensity class were abbreviated as $T_{WLRT(1–2y)}$, $T_{WLRT(2–5y)}$, $T_{WLRT(5–10y)}$, $T_{WLRT(>10y)}$.

Additionally, we calculated the storm interval, defined as the uninterrupted time period that the water level remained below the first storm intensity class ($T_{WLRT(1-2y)}$). If a storm interval was shorter than 24 hours, we considered the event represented to be one continuous storm. Most time periods had multiple storm events. We therefore, calculated the average storm interval for each time period. Tidal range was used as an additional factor in the analysis, defined as the difference between the average high tide and low tide levels, calculated from the daily highest and lowest water levels.

Wind speed, precipitation and temperature

Data on wind speed, precipitation, and temperature were derived from two meteorological stations along the Dutch coast and operated by the Royal Dutch Meteorological Institute (KNMI, 2015). These two measurement stations (De Kooy, Vlissingen, Figure 1) were the only ones from which hourly values were available for the study period.

Wind speed was used as a proxy for potential sand supply to the dunes. We calculated the number of hours that wind speeds were equal to or greater than 7 m/s within a time period. This threshold value was based on field measurements along the Dutch coast (Arens, 1996) and corresponds to the saltation threshold of 6.6 m/s for the average grain size in our study. We did not take wind direction into account, since embryo dunes are separated features in the landscape and therefore aeolian sand transport from several directions may contribute to embryo dune growth (Montreuil *et al.*, 2013).

We calculated the total precipitation (in millimetres) in the growing season (April–September) for each time period. Since higher temperatures during the growing season may enhance plant growth, we also calculated the average temperature (in °C) in June and July for each time period.

Sand nourishment

Most of the sites had been nourished to compensate for ongoing erosion. Beach nourishment was the most common method among our study sites, although dune and nearshore nourishment had also been applied (Nordstrom, 2013). For each site we checked if sand nourishment had been applied, using the presence or absence of sand nourishment as a variable. Data on sand nourishments in the Netherlands were provided by Rijkswaterstaat (2014c).

Statistical analyses

We explored, first, factors that influenced the presence and area of embryo dunes per site for each year in which we had aerial photographs. Second we investigated factors that influenced changes in the area of embryo dunes per site between consecutive time periods. The binominal presence/absence data of embryo dunes was analysed using a binominal linear mixed statistical model (Bolker *et al.*, 2009), with beach width ($BW_{0–1}$ and $BW_{1–3}$) and tidal range as explanatory variables. The mixed model was employed to account for variation between sites; we therefore used site as a random variable in the model (Zuur *et al.*, 2009). We analysed embryo dune area with a general linear mixed model, after log transforming embryo dune area to ensure normality of the data. For this model, we also used beach width ($BW_{0–1}$ and

$BW_{1–3}$) and tidal range as explanatory variables and site as a random variable. Both models were simplified to include only the variables with a statistically significant contribution using a backward selection method with either Akaike Information Criterion (AIC) or a Bayesian Information Criterion (BIC). The total data set contained 188 replicates (observations). For both models we calculated the marginal and conditional R^2 (Nakagawa and Schielzeth, 2013). The marginal R^2 is the variance explained by the explanatory variables and the conditional R^2 is the variance explained by the entire model (including the random variables).

We calculated the change in embryo dune area as a relative value. All the variables in the models were corrected for the number of years between the time periods. The increase or decrease of embryo dune area between consecutive photographs was tested with a binominal linear model, using as explanatory variables changes in beach volume ($\Delta BV_{0–3}$, $\Delta BV_{0–1}$, $\Delta BV_{1–3}$), hours wind speed ($WS \geq 7$ m/s), temperature in summer, precipitation in the growing season, storm intensity ($T_{WLRT(1–2y)}$, $T_{WLRT(2–5y)}$, $T_{WLRT(5–10y)}$, $T_{WLRT(>10y)}$), storm interval, beach width ($BW_{1–3}$), and the occurrence of sand nourishment. No random variables were included in the model, because we did not have enough replicates ($n = 150$), compared to the number of random effects levels. For the binominal linear model we calculated the Nagelkerke R^2 (Nagelkerke, 1991).

The relative change in embryo dune area was calculated as $\ln(t) - \ln(t-1)$ and analysed with a linear model using as explanatory variables beach volume ($\Delta BV_{0–3}$, $\Delta BV_{0–1}$, $\Delta BV_{1–3}$), hours wind speed ($WS \geq 7$ m/s), temperature in summer, precipitation in the growing season, storm intensity ($T_{WLRT(1–2y)}$, $T_{WLRT(2–5y)}$, $T_{WLRT(5–10y)}$, $T_{WLRT(>10y)}$), storm interval, beach width ($BW_{1–3}$), and the occurrence of sand nourishment. No random variable was included. Model complexity reduced by forward or backward selection with AIC or BIC. We were mainly interested in the relative importance of the variables and therefore calculated the standardized estimates for all the models (Gelman, 2008). The normality and homogeneity of variance of the data was visually checked. All statistical analyses were done in the statistical program R (R Core Team, 2016).

Results

Presence and area of embryo dunes

All sites contained embryo dunes in one or more years between 1970 and 2010. On only 30 of the 188 aerial photographs (16%) we did not find any embryo dunes. The embryo dune area per site differed significantly between geographic area and year ($F_{185} = 11.5$, $p < 0.001$; $F_{185} = 18.9$, $p < 0.001$, respectively). The West Frisian islands had on average the most embryo dunes with 11 ± 2 m^2/km [mean ± standard error (SE)], and the Holland mainland coast had the lowest embryo dune area with 2 ± 0.5 m^2/km. The south-western delta took an intermediate position with 4 ± 1 m^2/km. The differences found could be due to the corresponding significant differences in beach widths in the three geographic areas (West Frisian island: 182 ± 15 m, south-western delta: 125 ± 17 m, Holland mainland coast: 45 ± 3 m; $F_{185} = 17.1$, $p < 0.001$). Indeed, embryo dune area and presence were positively related to beach width at between 1 and 3 m NAP (Table I), with the largest dune fields occurring when the width of the dry beach ($BW_{1–3}$) exceeded 300 m or more (Figure 3). Neither beach width at between 0 and 1 m NAP ($BW_{0–1}$) nor tidal range had a significant effect on the presence or area of embryo dunes (Table I).

Table I. Statistical models for the presence or absence of embryo dunes and total embryo dune area

Factors	Full model	AIC backward	BIC backward
Presence/absence of embryo dunes, n = 188			
$BW_{1–3}$	1.85$^\bullet$	1.63$^\bullet$	
$BW_{0–1}$	−0.52		
Tidal range (m)	0.18		
Marginal R^2	0.11	0.10	—
Conditional R^2	0.46	0.49	—
Total area of embryo dunes, n = 188			
$BW_{1–3}$	2.87***	2.70***	2.70***
$BW_{0–1}$	−0.19		
Tidal range	−0.62		
Marginal R^2	0.14	0.14	0.14
Conditional R^2	0.39	0.39	0.39

Note: All time periods are included and the 33 sites were used as a random factor. The standardized estimates are shown for the models. Next to the full model, two additional methods were used for model selection: backward model selection with Akaike Information Criterion (AIC) and a backward model selection with Bayesian Information Criterion (BIC). The best BIC model for the presence or absence of embryo dunes did not select any explanatory factors. BW, beach width. Levels of significance: $^\bullet p < 0.1$, $^*p < 0.05$, $^{**}p < 0.005$, $^{***}p < 0.001$.

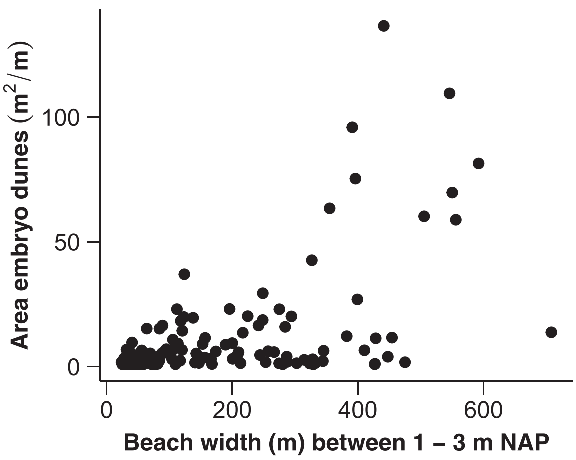

Figure 3. Relation between beach width (in metres) at between 1 and 3 m NAP (horizontal axis) and area of embryo dunes alongshore (in m^2/m) (vertical axis).

Temporal variation in environmental factors

The environmental variables into our models – hours wind speed ($\geq$ 7 m/s), temperature, precipitation, storm intensity, beach volume changes, and sand nourishment – showed considerable temporal variation in the 30-year period covered by our study. Temperatures in June and July increased steadily over the years, ranging from 14.0 to 19.2°C ($F_{39} = 13.91$, $p = < 0.001$) (Figure 4b). Precipitation during the growing season also showed a steady rise over the years, ranging from 154 to 490 mm/yr ($F_{39} = 4.27$, $p = 0.045$) (Figure 4c). Storm intensity varied from year-to-year, showing no consistent pattern over time, unlike precipitation and temperature. The time periods with the most severe storms were 1988–1996 and 2005–2010 (Figure 4d). The highest storm intensity ($T_{WLRT(>10y)}$) occurred three times in our dataset. Precipitation during the growing season and a high storm intensity ($T_{WLRT(5–10y)}$) were auto-correlated (Pearson correlation: −0.32, t-value = −4.53, p-value $\leq$0.001). As the correlation was not very

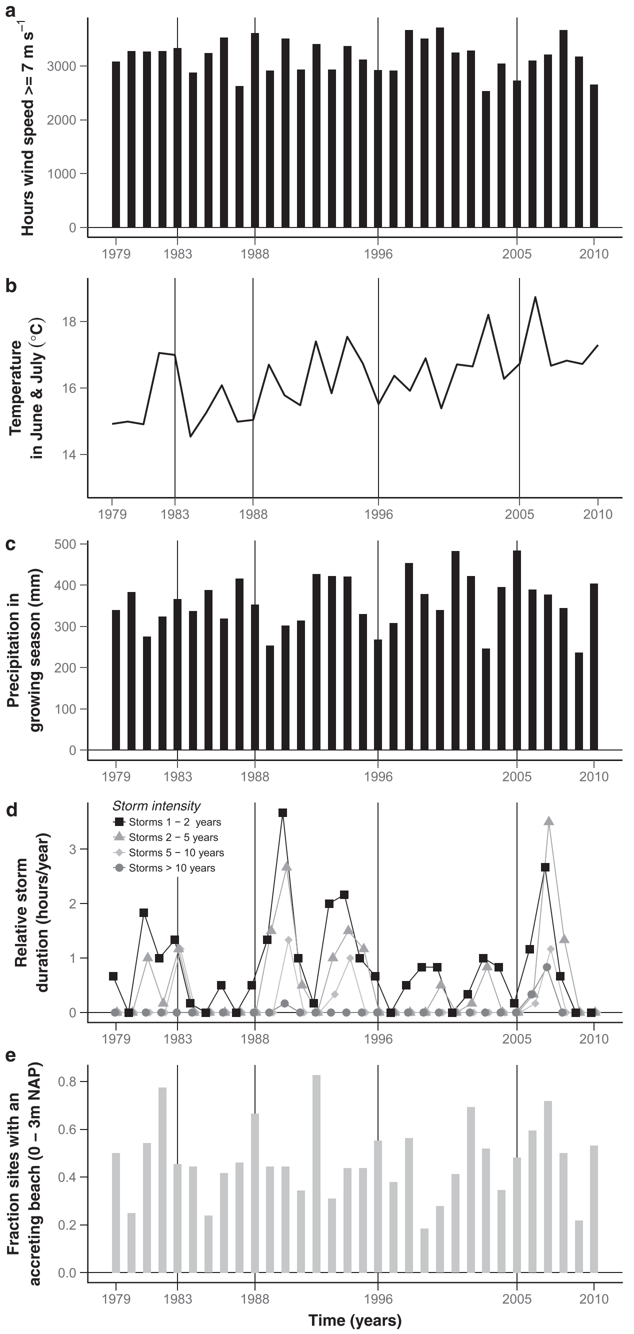

Figure 4. Environmental conditions over the study period. The vertical line represents the time points of the aerial photographs. The weather data is the mean of the two weather stations. (a) Hours that the wind speed was equal to or greater than 7 m/s. (b) Average temperature in June and July (°C). (c) Total precipitation during the growing period (in millimetres). (d) Occurrence of storm intensity (based on water levels, averaged over six tide stations), where the different shades and shapes represent the different storm intensity classes. (e) Fraction of sites with an accreting beach (0–3 m NAP).

strong, we used both variables in our statistical analyses (see Methods section). Wind speed did not change significantly over the years ($F_{39} = 0.031$, $p = 0.85$) (Figure 4a), wind speeds equal to or above the 7 m/s threshold were quite common, occurring between 2300 and 3900 h/yr. The most common wind direction was south-southwesterly (onshore) to westerly (alongshore), ranging between 195° and 285° (Supporting Information Appendix S3, Figure S3.1).

Changes in beach volume (ΔBV_{0-3}, ΔBV_{0-1}, ΔBV_{1-3}) did not vary significantly over time (Figure 4e) and ranged between −209 and +180 m^3/(m yr). The number of nourished sites increased after 1990 as a result of changes in coastal management, rising from five between 1979 and 1983 to 14 between 2005 and 2010. Nourishment was applied more often on narrow beaches than on wide beaches. The average beach width where sand nourishment was applied was 68 m [±7 (SE)], whereas the average beach width without sand nourishment was 180 m [±16 (SE)].

Changes in embryo dunes over time

Embryo dune area changed significantly over time ($F_{134} = 2.01$, $p = 0.02$). During the first time period (1979–1983) embryo dune area decreased on most sites (Figure 5). This was followed by a steady increase over the next three time periods (1983–1988, 1988–1996, 1996–2005), with a decrease in the last time period (2005–2010). Despite large differences between the sites in embryo dune area, we found no significant effect of sites on embryo dune area and development ($F_{117} = 0.34$, $p = 1.00$).

Periods with an increase in embryo dune area had relatively high precipitation during the growing season and a low frequency of high-intensity storms ($T_{WLRT(>10y)}$). We included both these variables in all four binomial models using either BIC or AIC as selection criteria (Table II). Sand nourishment and storm intensity $T_{WLRT(5-10y)}$ were included only in the models with AIC as selection criteria. Embryo dune area increased more on beaches with sand nourishment than on beaches where no sand nourishment had taken place (Figure 6a). An increase in the area of embryo dunes was positively correlated to growing season precipitation (Figure 6b), whereas decreasing embryo dune area was correlated with high-intensity storms ($T_{WLRT(5-10y)}$ and $T_{WLRT(>10y)}$) (Figures 6c and 6d). Changes in sand volume, hours wind speed (WS ≥ 7 m/s), temperature, storm interval, and beach width (BW_{1-3}) did not significantly affect the change in embryo dune area.

The relative change in embryo dune area (m^2/m^2 per site) responded to similar environmental drivers as the absolute change in embryo dune area (Table II; Figure 7). The relative change in embryo dune area was overall positive when the interval between storms was 100 weeks or longer. The explained variance in these linear models with relative change in embryo dune area (13–16%) was much smaller than the variance explained in the binomial models with change in embryo dune area (25–30%). It is possible that the long time periods between consecutive photographs, combined with the high stochasticity of the dune ecosystem, masked any

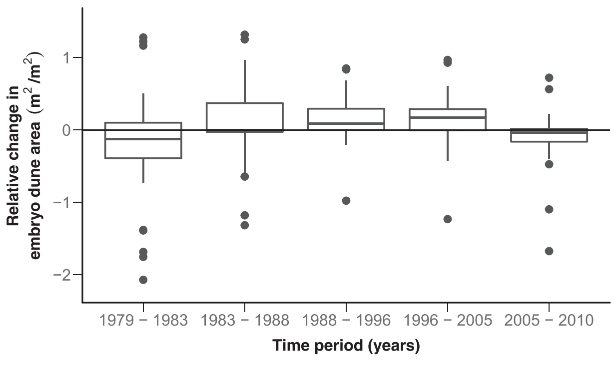

Figure 5. Boxplots showing relative change in embryo dune area (in m^2/m^2) over five time periods. The middle line in the boxplot is the median, whereas the lower and upper hinges represent the 25% and 75% quartiles. The upper whisker extends from the hinge to the highest value that is within 1.5 × the interquartile range of the hinge. The dots represent the values outside the 1.5 × interquartile range.

Table II. Model selection for the increase or decrease in embryo dune area (binomial model) and the relative change in embryo dune area (linear model)

Factors	Full model	AIC forward	AIC backward	BIC forward	BIC backward
Increase/decrease in embryo dune area over time period, n = 150					
$\Delta BV_{1–3}$	0.27				
$\Delta BV_{0–1}$	−0.01				
$\Delta BV_{0–3}$	0.16				
Hours WS ≥ 7 m/s	−0.79				
Temperature	0.37				
Precipitation	0.98	0.92*	0.92*	1.40***	1.40***
$T_{WLRT(1–2y)}$	0.50				
$T_{WLRT(2–5y)}$	0.25				
$T_{WLRT(5–10y)}$	−1.16	−0.94*	−0.94*		
$T_{WLRT(>10y)}$	−1.70	−1.80*	−1.80*	−1.90*	−1.90*
Storm interval	1.07				
Sand nourishment	1.07*	1.02*	1.02*		
$BW_{1–3}$	0.82	0.83•	0.83•		
Nagelkerke R^2	0.32	0.29	0.29	0.25	0.25
Change in embryo dune area over time period, n = 150					
$\Delta BV_{1–3}$	0.23•	0.15•	0.18*		
$\Delta BV_{0–1}$	0.06				
$\Delta BV_{0–3}$	−0.08				
Hours WS ≥ 7 m/s	−0.20•		−0.14		
Temperature	0.16				
Precipitation	0.24•	0.31***	0.31***	0.29**	0.29**
$T_{WLRT(1-2y)}$	0.05				
$T_{WLRT(2-5y)}$	0.06				
$T_{WLRT(5-10y)}$	−0.11				
$T_{WLRT(>10y)}$	−0.18		−0.13		
Storm interval	0.37*	0.26**	0.28**	0.26**	0.26**
Sand nourishment	0.03				
$BW_{1–3}$	0.04				
R^2	0.19	0.15	0.17	0.13	0.13
Adjusted R^2	0.10	0.13	0.14	0.12	0.12

Note: All time periods were included in the models; the standardized estimates are shown. Four methods were used for model selection: a forward and backward model selection with Akaike Information Criterion (AIC) and a forward and backward model selection with Bayesian Information Criterion (BIC). ΔBV, change in beach sand volume; WS, wind speed; T_{WLRT}, hours between water level return time, indicates storm intensity; BW, beach width. Levels of significance: •$p < 0.1$, *$p < 0.05$, **$p < 0.005$, ***$p < 0.001$.

relationship between the initial area of embryo dunes at the start of a period and the change in area observed over that period.

Discussion

Embryo dune development and environmental factors

This study explored boundary conditions for early dune development with the aim of enabling better prediction of natural dune expansion. Our results show a positive relationship between embryo dune area and beach width. Growth of embryo dune area was negatively correlated with storm frequency and intensity, and positively correlated with growing season precipitation and sand nourishment.

Beach morphology

We found embryo dune area to be most closely related to beach width. Among our study sites, large embryo dune complexes developed on beaches wider than 300 m, suggesting a high potential for the development of a new foredune ridge. There were a few locations where this was not the case, including sites having a small embryo dune area on a wide beach. Yet, these beach widths had only recently increased and vegetation had not had enough time to become established thus not enough time for the formation of embryo dunes to begin.

The positive relationship found between beach width and embryo dune development points to several conclusions. First, the fact that only beach widths at between 1 and 3 m NAP had an effect on embryo dune development suggests that the space available for embryo dunes to develop, the accommodation space, is a key factor. Second, a minimum beach width, or fetch length, may be needed for maximum aeolian transport. On narrow beaches, the fetch length is shorter than on wide beaches, resulting in less aeolian transport (Nordstrom and Jackson, 1992; Davidson-Arnott *et al.*, 2008) and less sand available for dune development. Previous research has shown the critical fetch distance for maximum aeolian transport to lie between 10 and 50 m (Shao and Raupach, 1992; Dong *et al.*, 2004; Delgado-Fernandez, 2010). This distance is much smaller than the beach width that we found necessary for maximum embryo dune development, suggesting that the fetch length was not the limiting factor in our study areas. Third, increased in beach width could protect embryo dunes against storms, for example, by attenuating wave energy (Ruggiero *et al.*, 2001). In our study it was not possible to separate these three factors. It is, however, clear that in the areas we investigated beach width strongly determined the potential for embryo dunes to develop.

Recent work by Durán and Moore (2013) suggests a relationship between beach width and foredune height, with wide beaches generally having higher foredunes than narrow beaches. Interestingly, we found an opposite relationship for our sites: wide beaches had lower foredunes than narrow beaches. This discrepancy may be related to beach morphology, as our study covered only dissipative beaches, whereas Durán and Moore (2013) examined a mix of dissipative and reflective beaches. An alternative explanation for the relationship we found between foredune height and beach width is the presence of embryo dunes. Embryo dune fields may constrain the height of foredunes by starving them of sand (Hesp, 1989; Montreuil *et al.*, 2013). We explored whether using the width/height ratio might improve the fit of our statistical models. We found that large embryo dune fields occurred on beaches with a width to foredune height ratio of 10 m/m and larger. However, the relationship between this ratio and the area of embryo dunes was weaker than the relationship between beach width and embryo dune area, indicating that beach width is the better explanatory variable for our study region.

Storm characteristics

We found that high-intensity storms, occurring no more than once every five years, constrained embryo dune development, whereas low-intensity storms had no effect on embryo dune development. This suggests that the erosion caused by low-intensity storms was rapidly offset by aeolian sand caught by the vegetation in the following growing seasons. Additionally, we found that the storm interval influenced embryo dune development, as the erosion caused by storms occurring in rapid succession might be much greater than that from a single, larger storm (Lee *et al.*, 1998; Forbes *et al.*, 2004; Ferreira, 2006; Dissanayake *et al.*, 2015). The effect of storm interval on embryo dunes indicates that recovery time is very important

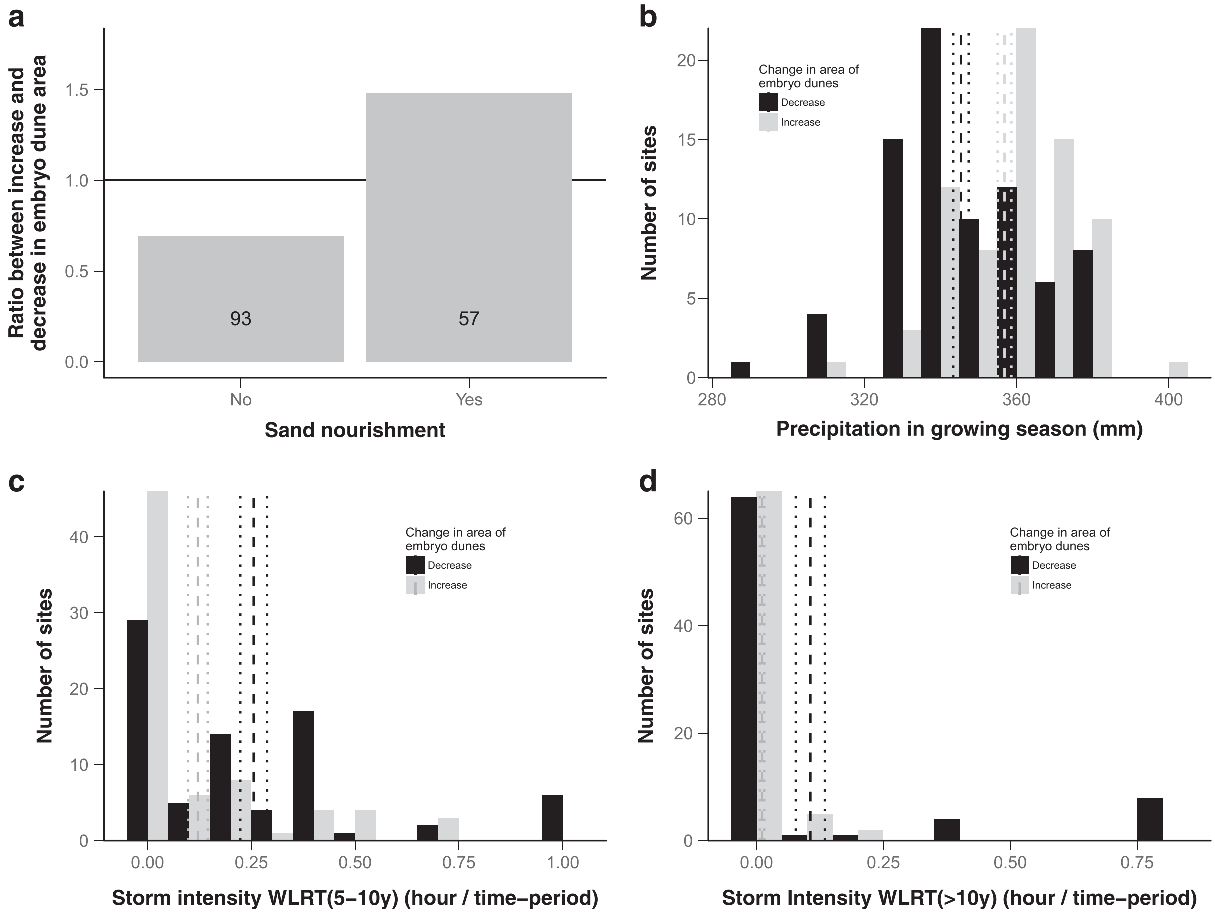

Figure 6. (a) Ratio between increase and decrease in embryo dune area, for sites without (no) and with (yes) sand nourishment. Values above one indicate a net increase in embryo dune area. Values below one indicate a net decrease in embryo dune area in the time period analysed. The numbers indicate the quantity of replicates. (b) Precipitation (in millimetres) during the growing season for either an increase or decrease in embryo dune area. Dashed line indicates the mean and the dotted line the standard error. (c) Storm of an intensity that occurs every 5–10 years (hours/time period $T_{WLRT(5–10y)}$) for either an increase or a decrease in embryo dune area. WLRT, water level return time. (d) Storm of an intensity that occurs less than once every 10 years (hours/time period $T_{WLRT(>10y)}$) for either an increase or decrease in embryo dune area.

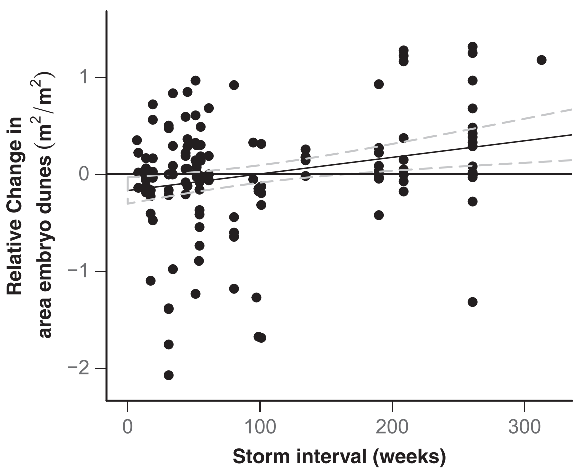

Figure 7. Relative change in embryo dune area (in m^2/m^2) as a function of storm interval in weeks. The solid line represents the predicted values from a model with the storm interval as explanatory variable, the grey dashed line is the 95% confidence interval. $Y = 0.0017\times + 0.165$, $p = 0.001$, $R^2 = 0.06$.

for the coastal system. Of course, recovery time cannot be seen independently of the regional storm climate of our study sites. For example, recovery times are likely to be far longer for hurricane-impacted coastlines, where embryo dune fields are likely to be completely eroded (Claudino-Sales *et al.*, 2008).

Meteorological conditions

We found precipitation to stimulate embryo dune development, presumably because of its positive effect on the growth of dune-building plant species. Sandy beaches can become very dry during summer (Lichter, 1998), precipitation increases soil moisture, water availability, and reduce soil salinity (Gooding, 1947). This benefits the growth of dune-building species, such as the grasses *A. arenaria* and *E. juncea*, and may even act as a trigger for germination (Sallenger *et al.*, 2003; Maun, 2009).

We found no effect of wind speed on embryo dune development. A number of possible factors may explain the absence of a correlation. First, aeolian sand transport may not be the limiting factor in the growth of embryo dunes. The amount of sand that vegetation can capture is determined by vegetation density and height (Zarnetske *et al.*, 2012). If vegetation density and height do not change between consecutive transport events, the vegetation cannot capture more sand. The embryo dune is then in an equilibrium condition, and does not increase in size. Second, the effect of storms may have overshadowed the effect of aeolian transport over our time periods. Third, the 7 m/s threshold proxy we used for aeolian sand transport may not have described the actual transport at our sites, as it did not consider local conditions such as surface moisture and lag deposits (Davidson-Arnott *et al.*, 2008; van der Wal, 1998). Furthermore, the effectiveness of vegetation at capturing sand depends on the wind speed

(Buckley, 1987; Zarnetske *et al.*, 2012). The effectiveness decreases at higher wind speeds, and at very high wind speeds, during storm events, erosion can occur. Our study used only a single threshold. Obtaining, data to create multiple wind speed categories could yield different results for the effect of wind speed on embryo dune development. This would be a worthwhile avenue for future research.

Sand nourishment

Sites with sand nourishment had an overall net increase in embryo dune area over the study period, whereas sites without sand nourishment had an overall net decrease. This pattern suggests that sand nourishment reduces erosion or promotes growth of embryo dunes. Sand nourishment is known to increase or stabilize beach width (van Duin *et al.*, 2004; Grunnet and Ruessink, 2005; Arens *et al.*, 2013). The wider beach, in turn, provides more accommodation space for embryo dune development, while perhaps also attenuating wave energy during storms and reducing wave erosion of embryo dunes (Ruggiero *et al.*, 2001). Sand nourishment was primarily applied to the narrow beaches in our dataset. Although sand nourishment increases beach width, it does not create the very wide beaches that, our findings show, allow for large increases in embryo dune area. Still, sand nourishment on average increased dune development on narrow beaches.

The net effect of sand nourishment on embryo dune development likely depends on the type of nourishment applied. Beach nourishment was the most common type of nourishment in the period of our study. Beach nourishment generally results in an immediate increase in beach width. In contrast, nearshore nourishment has a more diffuse effect on beach width: beach width might merely be stabilized or might increase slowly over time (Hamm *et al.*, 2002). Consequently the effect of such nourishment on the development of embryo dunes would likely be less strong than that observed in our study.

(Dis)similarities between embryo dune and foredune development

We found that embryo dune development was determined by beach morphology, storm intensity and interval, and precipitation during the growing season. These factors have been reported as drivers of foredune development too. The biggest differences between findings on foredunes and our results lies in the strength of the relationships, as we found embryo dunes to generally be more sensitive particularly to storms. Moreover, precipitation effects on foredune growth have not been reported, although moisture plays an important role in dune vegetation growth (Seeliger *et al.*, 2000; Maun, 2009; Greaver and Sternberg, 2010).

The positive relationship found in our study between beach width and dune development has also been reported in studies on foredunes (Saye *et al.*, 2005; Anthony, 2013; Keijsers *et al.*, 2014), but the nature of the relationship differs. We found a linear relationship between beach width and embryo dune area for beaches wider than 300 m. However, Keijsers *et al.* (2014) found that for foredunes the positive relationship between beach width and foredune development was no longer significant for beaches wider than 200 m. This suggests that embryo dunes are more sensitive to storm erosion than foredunes.

Windows of opportunity for embryo dune development

Our study suggests that embryo dune development depends on embryo dune survival over the storm season. Dune development is limited by storms, since small dunes can be completely eroded by wave run-up and storm surge. Bigger dunes, stand a better chance of surviving storm events (Claudino-Sales *et al.*, 2008). This indicates that storm-free periods represent windows of opportunity (Balke *et al.*, 2014; Durán Vinent and Moore, 2015) for embryo dune development, enabling new dunes to form and existing dunes to grow large enough to survive storm erosion. The required length of this window of opportunity depends on the lag time between storm erosion and the rebuilding of embryo dunes. Our results suggest that frequent precipitation during the growing season may reduce this lag time, as high precipitation stimulates plant growth and therefore embryo dune development.

The window of opportunity represents a useful concept for understanding embryo dune development in a changing climate. To take the next step, to predict embryo dune development according to climatic variables (e.g. storm interval and intensity, precipitation), we need to further examine the relationships between climatic variables and plant establishment, as well as the relationships between characteristics of embryo dunes and dune fields (e.g. volume and height) and their responses to dune erosion by wave run-up and storm surge. For example, we know very little about the effect of wave run-up and storm surge on different embryo dune sizes and whether such effects may be modified by plant species due to their wave attenuation effects, which reduce the wave energy (Koch *et al.*, 2009).

Management implications

Sand nourishment is often applied locally on severely eroding coasts and has to be repeated frequently. With accelerated sea-level rise due to climate change, sand nourishment is likely to become more prevalent in the future. In the Netherlands, a large-scale 'mega-nourishment' pilot project is under way that mimics the onshore migration of a large intertidal bar (the project is called the 'sandmotor') (Stive *et al.*, 2013; Temmerman *et al.*, 2013). Such mega-nourishments create very wide beaches and thus accommodation space for dune development, possibly leading to development of a new foredune ridge. The effect of beach morphology on embryo dune area can be applied to predict how embryo dunes will develop in large mega nourishment projects.

Climate change will have a substantial impact on coastal areas (McGranahan *et al.*, 2007; Nicholls and Cazenave, 2010). Climate change-induced sea-level rise combined with strong storms could lead to severe erosion of dunes [Intergovernmental Panel on Climate Change (IPCC), 2014]. Altered precipitation patterns may affect the lag period needed for dunes to recover from storm erosion, as precipitation during the growing season stimulates embryo dune growth and rebuilding after storms. Embryo dune development might be constrained in areas where precipitation is expected to decrease, whereas embryo dune development might increase where precipitation is expected to rise. Coastal managers may thus be able to anticipate changes in embryo dune regeneration times by monitoring projected precipitation patterns in their region.

Conclusions

The purpose of this study was to explore the boundary conditions for embryo dune development. Our results show that, first, beach widths at between 1 and 3 m NAP correlate positively with embryo dune development, suggesting that accommodation space is a key development factor. Second, beach nourishment stimulates embryo dune development by increasing beach width. Third, precipitation in the growing season enhances embryo dune development by increasing vegetation growth. Fourth, low frequency and high magnitude storms constrain embryo dune development by increasing recovery time. These results indicate that on wide beaches progressive dune development depends on precipitation and non-interrupted sequences of years without heavy storms.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.