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Geomorphology

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https://doi.org/10.1016/j.geomorph.2015.10.021

Geomorphology 253 (2016) 340–352

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Constructing notches in foredunes: Effect on sediment dynamics in the dune hinterland

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ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 15 October 2015
Accepted 24 October 2015
Available online 31 October 2015

Keywords:
Sand spray
Grey dune habitat
Coastal management

ABSTRACT

Measurements were carried out on the island of Ameland (The Netherlands) to determine whether notches cut into foredunes stimulated the supply of fresh calcareous beach and dune sand into the white and grey dune habitats behind the dunes, increasing these habitats' biological quality. Sediment characteristics and dynamics (deposition flux and grain size properties) as well as aspects of the vegetation (occurrence, composition and cover density) were studied along six transects, three behind an intact foredune and three behind a foredune with a notch cut into it. Compared to an intact foredune, the notched foredune exhibited higher deposition and accumulation behind the dune. The extra supply of sand was small, however, and for the notches studied, limited to the zone within approximately 50–60 m of the foredune's crest. Farther away from the dune, the effect of the notches became negligible. The presence of a notch did affect the grain size composition of sediment deposited behind the foredune. For intact foredunes, the grain size composition behind the dune was similar to that on the dune itself. When a notch had been cut, the sediment was finer behind the foredune, gradually coarsening away from the dune. Sand spray (deposition of sand eroded from the dune and transported in modified saltation during heavy winds) explains these granulometric results. The effect of the notches on the vegetation in the grey dune habitat behind the foredune was small and, for the notches studied, limited to the first approximately 35 m of the grey dune area, between 30 and 65 m from the foredune's crest. The notches had a greater effect on the white dune habitat but – in the opinion of the authors – this remained disproportionately small relative to the effort required for notch excavation and maintenance.

1. Introduction

Fixed coastal dunes with herbaceous vegetation ('grey dunes') commonly occur between the zone of active dunes near the shoreline and more inland dune shrub and woodland habitats. They are present in all major coastal dune areas in the Atlantic region. Across Europe, fixed dunes with herbaceous vegetation have been, and still are, the most threatened and exploited environments within these dune systems. A significant proportion of this unique coastal habitat has already been lost to tourism and residential development, and regrettably many sites have been dissected by infrastructural and coastal defence works (Houston, 2008).

From an ecological and geomorphological perspective, these habitats tend towards increasing stabilization of the topsoil, and succession from rank grasslands to heathlands, shrubs, and finally woodland (Houston, 2008). In Europe the past 50 years has seen a trend of increasing grey dune habitat, but mainly to old, stable, acidic stages, because dunes have become much more stable over this period (Houston, 2008). Newborough Warren in Wales, for example, was much more mobile in the 1950s, when mobile dunes occupied over 70% of the site, compared to just 6% today (Rhind et al., 2001). Similar trends are observed on the German Wadden Sea island of Spiekeroog, where semi-fixed grey dunes (at younger succession stages) have diminished, and heathlands, dominant grasslands, shrubs, and woodlands have expanded (Isermann and Cordes, 1992).

The main threat to the grey dune habitat comes from over-stabilization of the semi-active top layer (Houston, 2008). This stabilization may be caused by a variety of processes, such as dune management (application of techniques to prevent sand drift), diminished disturbance by animals, growth of native and non-native (introduced) shrubs, afforestation, and invasion by alien forbs. Atmospheric deposition of nutrients (such as nitrogen) is especially of concern, because of its effect on biomass production, which results in an increase of the succession rate and of soil formation. This problem is most acute on the less calcareous dune sites from The Netherlands eastward into Germany (Provoost et al., 2011).

Over-stabilization (dune management in which little or no room is allowed for sediment transport behind the foredune) has diminished the quality of several precious dune habitats. This has affected habitat

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http://dx.doi.org/10.1016/j.geomorph.2015.10.021
0169-555X/

type 2120 ('white dunes': shifting dunes along the shoreline with *Ammophila arenaria*), habitat type 2130 ('grey dunes': fixed coastal dunes with herbaceous vegetation), and habitat type 2190 (humid dune slacks) (European Commission, 2013). To counteract the deterioration of these unique habitats, a new method of coastal management, known as 'dynamic coastal management' (Arens and Wiersma, 1994; De Ruig and Hillen, 1997), was introduced in The Netherlands in the early 1990s. Dynamic coastal management aims to use natural processes (Löffler, 2010) to contribute to several goals:

- Sustainable coastal safety: giving room for wind- and water-driven sediment transport, to enable dunes and salt marshes to grow in height and follow sea level rise.
- Resilience of nature against overgrowth: regular burial with dune sand and flooding by saline water can slow or even set back natural succession, which is the process by which highly competitive plants replace the original plant species because of increasing soil fertility.
- The objectives of Natura 2000: most coastal dune areas in The Netherlands have been designated conservation areas under the European Habitats Directive, which is part of Natura 2000 (Commission of the European Communities, 2002; European Commission, 2013). This protected status requires these areas to be managed in such a way that the habitat increases (or at a minimum does not decrease) in size and quality. In dune systems, increased aeolian activity is considered an increase in quality (Arens et al., 2013).

An example of dynamic coastal management is to cut notches into foredunes along the coast, as shown by Fig. 1, at locations where this does not increase the risk of flooding. This has been done at several locations in The Netherlands. The idea is to create pathways through which wind can transport carbonate-rich beach sand towards the grey dunes behind the foredunes, thus supporting the presence of early succession stages of grey dunes.

Multiple studies have been performed to evaluate the effectiveness of this new approach for coastal management (e.g., De Ruig and Hillen, 1997; Arens et al., 2007, 2010; De Groot et al., 2012; De Jong et al., 2014). However, these studies have focused mainly on the effects of dynamic coastal management on geomorphological developments on a meso-scale, for example, at the level of a complete foredune ridge. Examples are Arens et al. (2010), which investigates the effects of nourishment on dune development, and De Jong et al. (2014), which examines the effect of dynamic dune management on dune size and position on the Dutch barrier island of Ameland. So far, little attention has been paid to the impact of dynamic coastal management on aeolian sedimentation patterns and the resulting consequences for vegetation development in the dune zone *behind* the foredunes. Nonetheless, as already noted, these zones are among the most threatened parts of the dune system, and they have suffered considerable disturbance from tourism and other human activities. It is, therefore, important to test dynamic dune management techniques that aim to conserve, or even strengthen these valuable habitats. The current study investigates whether cutting notches into a foredune stimulates the transport and deposition of fresh dune sand into the areas behind the foredunes, so that early succession stages can be restored. The aim is to determine both the amounts and patterns of sedimentation and their effects on vegetation.

2. Materials and methods

2.1. Background

Management measures were taken in 2011 on the barrier island of Ameland to stimulate sediment transport and deposition into the grey dunes. One of these measures was to cut notches through the foredune at regular intervals with the aim of creating blowouts that would remain active year-round. To evaluate the effectiveness of these artificially created blowouts in supplying fresh and calcareous sand to the grey dune area, we monitored sand deposition, soil properties, and vegetation development in transects starting at the inland foot of the foredune to approximately 100 m land inward. Our working hypothesis was that the notches would produce an extra influx of calcareous sand blown up from within the notch and/or from the beach upwind of the notch, which would nourish the acidified area behind the foredune and increase the amount of natural disturbance, thus enabling early succession stage species to successfully regenerate. Over time, the notches might develop into full-scale blowouts, and expansion of the white foredunes and the early stages of grey dunes could even be expected.

2.2. Study site

The study site is located on the barrier island of Ameland (Fig. 2), which is one of the barrier islands off the northern coast of The Netherlands and Germany. The orientation of Ameland's coastline is predominantly west–east. The longshore current direction is from west to east. The dominant wind direction is southwest, with the highest wind speeds observed in winter (Wieringa and Rijkoort, 1983).

The study site is located near the northeast fringe of the island, between 53° 27′49″ and 53° 27′58″ N and 5° 51′40″ and 5° 53′40″ E. The tidal range at the site is approximately 2 m (semi-diurnal). A single

Fig. 1. Notch cut in a foredune on the island of Ameland in 2012. The photo was taken 20 November 2012. The notch has evolved into a blowout-like structure since then.

Fig. 2. Location of the Dutch barrier island Ameland in relation to the Netherlands (inset) and the study area on the island's eastern end (large picture). Credit large photo: Digitale Kleuren Luchtfoto Nederland (DKLN) 2011, Eurosense B.V. Credit inset figure: Esri.

foredune ridge about 12 m high and 60 m in cross-section backs the beach. The dominant plant species on the foredune are *A. arenaria* (Marram Grass) and *Festuca rubra* (Red Fescue). The study site is located in the predominantly non-calcareous district of The Netherlands, but the carbonate content is about 1.3% in the beach sand and 0.5% in the older inner-dune sand (Veenstra and Winkelmolen, 1976). The sand on the beach is composed primarily of quartz grains, with some feldspar and small amounts of heavy minerals (Van der Wal, 2000). There are no active dune fields behind the foredune in the study area, which is covered by bryophytes, lichens, grasses, forbs, and small shrubs. On the north-eastern end of Ameland the sand budget is strongly positive, due to sand accretion in the foredune (Arens et al., 2010; De Jong et al., 2014).

2.3. Methodology

2.3.1. Study transects

Six transects were established for this study: three behind an intact foredune and three behind a foredune with a notch cut into it (Fig. 3).

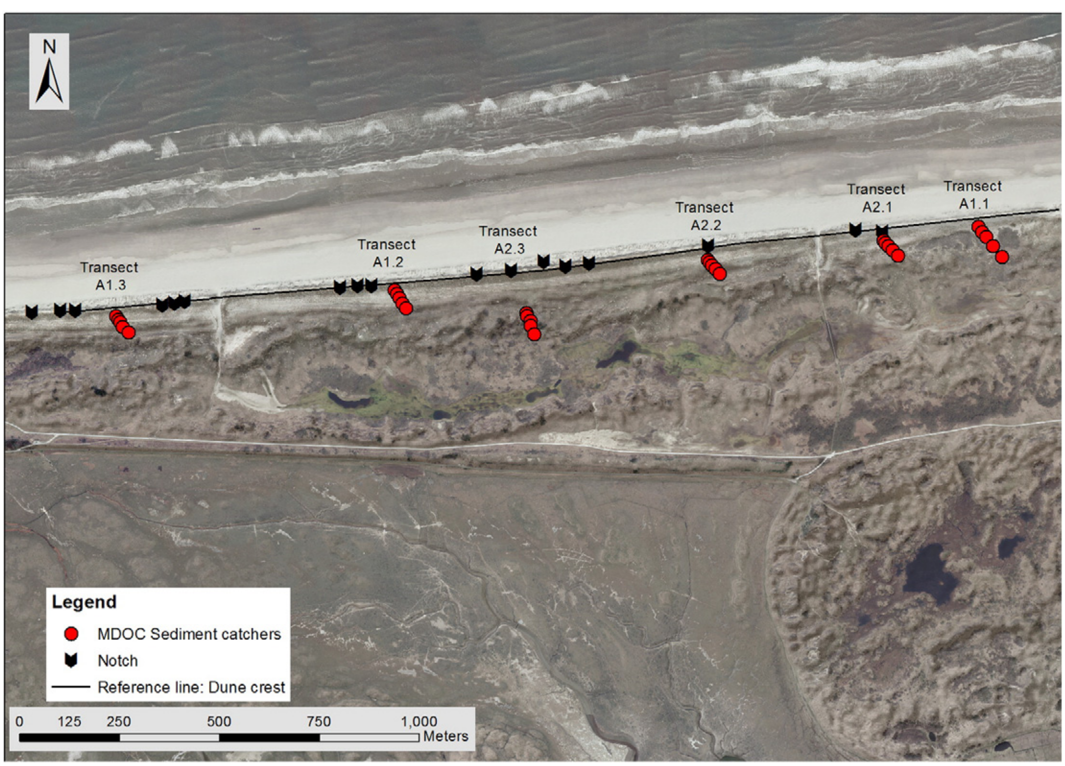

Fig. 3. Aerial photo underlain by digital elevation map of the study area with location of the six transects. Transects A1.1, A1.2, and A1.3: intact foredune. Transects A2.1, A2.2, and A2.3: foredune with a notch cut into it. MDCO = marble dust collector.
Credit aerial photo: RGB aerial photos of The Netherlands, Kadaster, Apeldoorn, The Netherlands. Credit digital elevation map: Actueel Hoogtebestand Nederland (AHN2), Waterschapshuis, Amersfoort, The Netherlands.

The notches were cut in the period from late October to December 2011. The removed sediment was spread inland, resulting in a landward shift of the dune foot of about 2–5 m for the two smallest notches. The sand of the largest notch was spread further inland, up to about 90 m from the dune, resulting in a drift-sand plain with a new dune foot approximately 100 m from the original dune crest. In November 2013, two years after completion, some maintenance was done to the notches, but for our study this affected only the largest notch (A2.3 in Fig. 3). The floor of this notch was somewhat flattened and also broadened, resulting in a drift-sand plain with a new dune foot located 90 m further inland. Table 1 summarizes the characteristics of the three notches studied.

To measure the amount of aeolian sand deposition behind the foredune, five measuring points were selected along each transect. The location of each point was measured using a differential global positioning system (DGPS). The first point was always taken at the landward dune foot; the remaining points were distributed over an approximately 75 m to 100 m segment extending landward. The orientation of all six transects was according the dominant erosive wind direction, NNW–SSE, nearly parallel to the orientation of the notches and, therefore, in the expected direction of sand transport behind the notches (see Fig. 3). Note that the measurement points for the A2.3 transect were placed further downwind because the new dune foot was located 90 m further landwards. The following parameters were measured at each point: amount of sand deposited, texture of the deposited sand, plant species composition, and vegetation cover density.

The experiment started on 18 December 2012 and terminated on 25 November 2014, lasting almost two complete years. Sediment samples were collected on 28 May 2013, 13 November 2013, 26 May 2014, and 25 November 2014, resulting in four experimental periods of comparable length (162, 169, 189, and 183 days, respectively). Meteorological data were collected for the whole experiment from the AWG-1 meteorological station, which is located off-shore only 2.5 km north of the study site. We used data for wind speed, wind direction, and precipitation, as these were the most relevant meteorological parameters for this study's purposes.

2.3.2. Sand accumulation

Accumulation was quantified by means of the vertical accumulation flux, defined here as the amount of sand accumulating on the surface per unit area per unit of time (expressed in, for example, g m^{-2} day^{-1}). It was measured using marble dust collector (MDCO) samplers. For a description of the original sampler, see Goossens et al. (2001). For the Ameland experiment, we used a modified version consisting of a circular plastic funnel with a diameter of 0.22 m (corresponding to an effective catchment area of 0.038 m^2) with a marble filter on top (Fig. 4). The filter contained two layers of marbles, 1.4 cm in diameter, which rested on a sieve on top of a plastic funnel (the diameter of the mesh openings in the sieve was 0.35 cm). Sand settled on and between the marbles and was collected in a plastic 2 liter bottle underneath the funnel. The device was buried in the soil until the marbles were level with the surface. Marbles have been found to be a more suitable catchment surface than water because they do not dry out and also because they prevent outsplash of sediment during rainfall (Goossens et al., 2001). To minimize the risk of sand insplash from the area near the sampler, a 50 cm × 50 cm permeable artificial grass mat was installed around the MDCO.

Vertical accumulation fluxes were calculated by measuring the amount of sediment caught by the sampler and dividing this by the sampling area (0.038 m^2) and the total sampling time. The flux measured by the sampler is proportional but not necessarily equal to the real vertical accumulation flux because the efficiency of the sampler for dune sand remains unknown. Previous studies (Goossens and Offer, 1994; Sow et al., 2006) have quantified the collection efficiency of marble surfaces for fine sediments such as dust, but not for dune sands. However, for relative comparisons of sites affected by the same type of sand, as in this study, this does not present a problem. The sediment was collected by removing the bottle from the trap, after which a new empty bottle was inserted. In the laboratory, the collected sediment was dried at 105 °C and weighed. The accumulation flux was then calculated.

2.3.3. Textural composition

Topsoil samples (upper 3 cm) were taken along each of the six transects to determine potential trends in grain size composition. For the five sediment trap locations, we used sediment collected from the traps themselves. By collecting additional surface samples upwind of the traps, comparisons with the sediment source (the foredune) could be made. The dune samples were taken halfway up the windward dune slope, on the dune crest, and halfway up the leeward slope. For the disturbed transects (where notches had been cut into the foredune) an additional sample was taken halfway into the notch. Thus, eight samples were taken from the three un-notched transects, and nine samples were taken from the three notched foredune transects.

To remove shell fragments and coarse organic matter, all samples were first sieved at 500 μm. The remaining sediment was then analysed for grain size composition using a Malvern Mastersizer S laser particle size analyser (Malvern Instruments Ltd., Malvern, UK). In this study we present data for the median diameter (as an indicator for the sample as a whole), the fine sediment fraction (taken here as the fraction <125 μm), and the coarse sediment fraction (taken here as the fraction >300 μm). All grain size data are for the fourth experimental period (25 May to 25 November 2014) because the particle size analyser was only available at the end of the project and at that time the samples of the other three periods had already been exhausted in other analyses.

2.3.4. Vegetation

Vegetation along the six transects was studied using relevés (a list of plants found in a delimited plot, with information on species cover and substrate and other abiotic features of the plot). At each sediment sampling location a 4 m^2 circular area was described, directly surrounding the MDCO sampler. Within each area, the present phanerogams and cryptogams were recorded and their cover density estimated. Readings were taken twice during the project, in May 2013 and May 2014. Because the vegetation data per plot differed only very slightly between these two years, only one vegetation description was used for each relevé. This was done as follows: based on the two sampling years a species list per plot was created; if a species was recorded in both years, the maximum ground cover was used in the further analyses.

Some phanerogams and cryptogams are well adapted to harsh environments. These are called pioneer species (Runhaar et al., 2004) and are the first to respond when new habitats emerge. Because in the study area the sampled parts of the dune environment were dry and

Table 1
Characteristics of the three notches studied.

Transect ID	Cross-section	Depth of incision (m)	Width (at dune crest) (m)	Elevation of adjacent dune (m asl)	
				West	East
A2.1	Triangular	5.9	21.5	14.1	15.3
A2.2	Triangular	5.5	16.6	16.1	16.3
A2.3	Trapezoidal	8.2	90.5	16.2	15.2

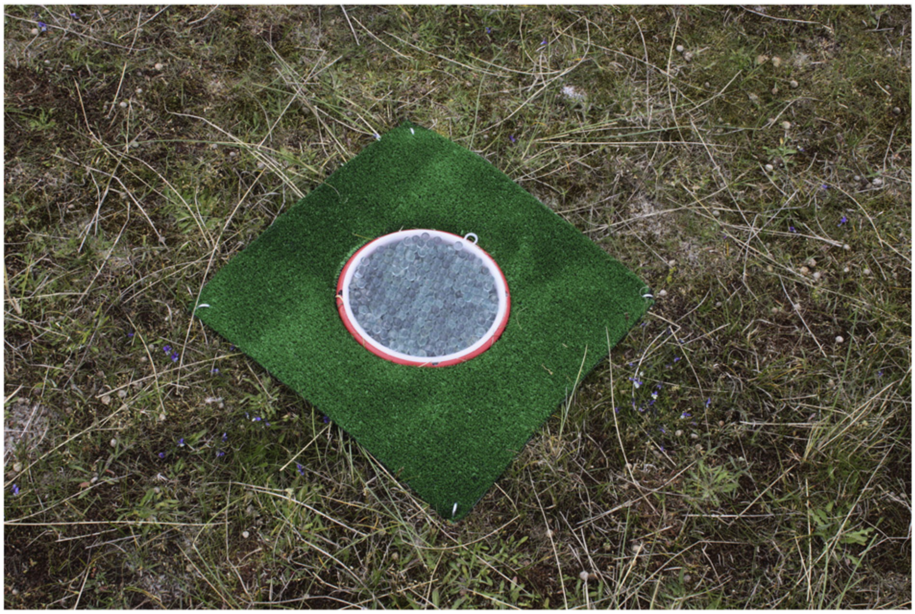

Fig. 4. Modified MDCO sampler used in the Ameland experiment.

not acidic, the following species were taken as indicators of active sand dynamics (Runhaar et al., 2004):

- Phanerogams:
  Aira praecox (Early Hair-grass).
  Ammophila arenaria (Marram Grass).
  Erophila verna (Common Whitlowgrass).
  Myosotis ramosissima (Early Forget-me-not).
  Veronica arvensis (Wall Speedwell).
  Corynephorus canescens (Grey Hair-grass).
  Phleum arenarium (Sand Cat's-tail).
  Sedum acre (Biting Stonecrop).
  Erodium cicutarium (Common Stork's-bill).
  Cerastium semidecandrum (Little Mouse-ear).
  Saxifraga tridactylites (Rue-leaved Saxifrage)
- Cryptogams:
  Syntrigia ruralis (Great Hairy Screw-moss).

In addition to the transects behind the dune, vegetation cover was also determined on the seaward slope of the foredune because this part of the dune is, together with the beach, the source area of the sand that accumulates behind the foredune. Vegetation is often seen as one of the main factors controlling wind erosion (Lancaster and Baas, 1998; Provoost et al., 2011). However, there is inconsistency in the literature as to the effect of vegetation cover on sand mobilization (see further Section 3.1.2). We tested that relationship for the Ameland case. Photos were taken of the windward slope of the foredune at each transect. The area pictured with and without vegetation was determined based on the pixel characteristics using Definiens Professional software version 5.0 (Definiens AG, Munich, Germany).

3. Results and discussion

3.1. Wind and sediment dynamics

3.1.1. Wind regime and erosion episodes

To get an idea of the potential aeolian activity in each of the four experimental periods, wind speed data (30 min average) were plotted (Fig. 5). In the figure, episodes with wind erosion are indicated in black (print version of this article) or red (online version). Ideally, erosion episodes would be identified by recording the presence of particles in the air using electronic sensors such as saltiphones, sensits, saphires, or similar devices. Using an electronic sensor was not possible in the Ameland study, however, because of the absence of electricity in the test field. Solar panels were not considered an option due to the risk of vandalism and contamination of the measuring sites by bird droppings. Therefore, we reconstructed the periods during which wind erosion was likely to have occurred from three criteria: (1) wind speed in the AWG-1 meteorological data base greater than 7 m s^{-1}; (2) wind direction NW, NNW, N, NNE or NE; and (3) dry surface. Justification of these criteria is as follows:

- Criterion 1. For dry dune sand, as in this study, the critical wind speed (at 10 m) at which wind erosion starts is of the order of 6.2 m s^{-1} (Fryberger, 1979; Al-Awadhi et al., 2005; Riksen and Goossens, 2007). The altitude of the off-shore AWG-1 meteorological station is 26 m above sea level (asl). The wind erosion threshold at 26 m can be calculated from the power law wind velocity profile: $u_{26} = u_{10} \cdot (26/10)^{\alpha}$, where u_{26} is the wind speed at 26 m, u_{10} is the wind speed at 10 m, and α is the power law exponent. Above water the value of α is between 0.10 and 0.12, dependent on the roughness of the sea surface; detailed measurements by Hsu et al. (1994) produced a value of 0.11 $\pm$ 0.03. Using this value, the erosion threshold at 26 m is 6.9 m s^{-1}, which justifies criterion 1.
- Criterion 2. Vegetation covers the area to the west, south, and east of the experimental transects. Since there is no sediment source, no sand supply will occur when the wind is blowing from these directions. This justifies the condition that wind should blow from the NW–NE sector.
- Criterion 3. Repeated field observations by the authors revealed that the sand surfaces dried very quickly, and that wind erosion restarted very shortly (<30 min) after rainfall. That the surface should be dry was implemented by removing all episodes of rainfall from the data.

Wind erosion occurred year-round during the study (Fig. 5). There were no preferential seasons or months with enhanced aeolian activity. The period from mid-December 2014 to mid-March 2014 was not very active, although the winds were rather strong; but no similar pattern of low aeolian activity was observed for the same period in 2013.

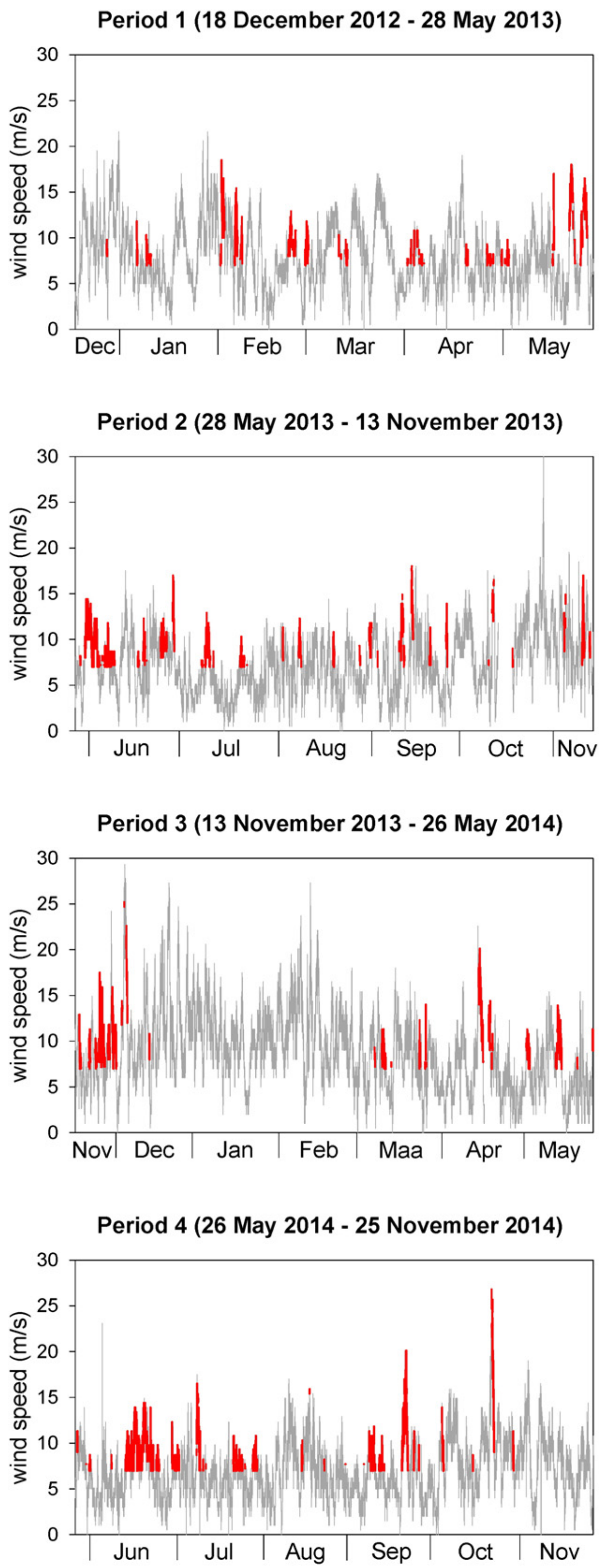

Fig. 5. Wind speed during the four experimental periods. Wind erosion episodes are shown in black (print version of this article) or red (online version).

For the four experimental periods, the percentage of time that wind erosion occurred (based on the data in Fig. 5) was 8.6% (period 1), 11.6% (period 2), 6.8% (period 3), and 11.9% (period 4), or 9.7% on average for the entire two-year experiment. Long-term data on wind erosion are sparse in the literature, but some have been reported. De Ploey (1980) collected annual data for a dune in Kalmthout (Belgium) from October 1973 to October 1977 with a psammograph and measured percentages between 0.9% and 1.5%, with a four-year average of 1.1%. Riksen and Goossens (2007) measured aeolian activity in the inland dune area of Kootwijkerzand (The Netherlands) with saltiphones and found that 82% of all registered wind erosion transport took place during a few sand storms with a total duration of 9.3 days, or 4.2% of the total measuring period. Goossens and Buck (2011) measured aeolian activity in the Nellis Dunes (a very active dune field in Nevada, USA). They found that, for the year 2008, wind erosion occurred 12.2% of the time. The Ameland percentages are only slightly lower, which can be explained by the type of fetch (open sea), which promotes the occurrence of high-speed winds and wind erosion.

3.1.2. Sand drift potential

Although the data in Fig. 5 situate the episodes of wind erosion, they provide no information about each episode's contribution to total erosion and deposition in the sand traps. Certain wind directions may be more powerful and generate more erosion and deposition than others. Because the objective of this study was to investigate the effect of notches cut into the foredune on sediment transport and vegetation development landward of the dune, it is crucial that the orientation of the experimental transects be chosen such that these effects are optimally captured by the measurement data. Ideally, transects should be oriented parallel to the direction of the most erosive winds. Because no electronic sensors could be used to document wind erosion activity (see Section 3.1.1) we calculated the sand drift potential (DP), which should provide similar information. We used the method of Fryberger (1979), which is based on Lettau and Lettau's (1978) equation for sand drift:

$$q = C \cdot (\rho/g) \cdot (u_*)^2 \cdot (u_* - u_{*_t}) \tag{1}$$

where q = rate of sand drift, C = a dimensionless constant, ρ = mass density of air, g = gravitational acceleration, u_* = friction velocity, and u_{*_t} = impact threshold friction velocity.

From this equation Fryberger (1979) derived the DP as follows:

$$Q \propto u^2 \cdot (u - u_t) \cdot T \tag{2}$$

where Q = proportionate amount of sand drift, u = average wind velocity at 10 m height, u_t = impact threshold wind velocity at 10 m height, and T = amount of time (in %) the wind blows above the threshold velocity.

Values derived from this formula reflect the sand-moving capacity of the wind for the total time period considered. They are numerically expressed in vector units. The combination $u^2 \cdot (u - u_t)$ can be seen as a weighing factor, in which strong winds are given a higher weight than weaker winds (Al-Awadhi et al., 2005). To lower the value of the vector unit and facilitate the plotting of sand drift roses, the value of $u^2 \cdot (u - u_t)$ is divided by 100.

It should be noted that Fryberger's method must be applied with some care because the final result depends on the input parameters available. One problem is that the numerical value of the DP, which is expressed in vector units, depends on the units of the wind speed, for example, m s^{-1}, km h^{-1}, or mph (Bullard, 1997). However, because values of DP are usually recognized as being relative to one another, the actual magnitude of the value is unimportant provided that all data have been standardized in the same units (Bullard, 1997, p. 500), which is the case in our study.

Another problem is the so-called frequency (or directional) bias: the values of the vector units depend on the number of sectors in the wind rose. For example, 16 sectors of 22.5° each (N, NNE, NE, ENE, E, and so on) will produce a different drift potential result than 36 sectors of 10°

each. To minimize the influence of systematic frequency bias, Pearce and Walker (2005, p. 53) recommend that "unprocessed" wind data (i.e., precise wind speed values measured to-the-degree) when available should be categorized into 16 equal direction sectors. Our wind data from the AWG-1 meteorological station are available for 16 sectors (N, NNE, NE, etc.) This will result in a small but systematic frequency bias towards the cardinal directions (see Pearce and Walker, 2005), but the bias will remain small (in Pearce and Walker's test, the bias was less than 3%).

A third problem with the Fryberger method is the so-called magnitude bias, which results from taking the mid-point wind speed value for each sector. DP values derived using wind speed mid-point values versus other statistical measures of central tendency (mean, median) for positively skewed wind speed distributions, which is the case for most wind speed datasets, will over-estimate actual DP (Pearce and Walker, 2005, p. 45). In Pearce and Walker's test the bias was as large as 34%, but the overall pattern of the sand rose did not substantially change, and the shift in the resultant DP was only 3–5°.

This study used the drift potential for two purposes. First, it was used to determine whether the amount of wind erosion on the Ameland foredune was mainly a factor of the wind regime itself, or of the presence of vegetation on the dune. Dunes with different vegetation cover densities will demonstrate different degrees of aeolian activity, even if the wind regime is identical. Sedimentation and DP were found to be strongly positively correlated (Fig. 6). Moreover, a correlation between sedimentation and vegetation cover was also observed, though negative this time (Fig. 7). We therefore conclude that on Ameland both the wind regime and vegetation should be taken into account when interpreting sand dynamics. These findings differ from results obtained by Jungerius and Van der Meulen (1997), who found no consistent relationship between sand accumulation and vegetation cover in the Meijendel dunes (Dutch west coast). They concluded that "in the relationship between aeolian dynamics and vegetation, the former appears to be the independent variable" (p. 63). Other studies have demonstrated that a decrease in vegetation cover commonly results in an increased aeolian sand flux (Lancaster and Baas, 1998; Allgaier, 2008).

Our second purpose for calculating the drift potential was to determine the importance of each wind direction in the aeolian activity (see Fig. 8). The pattern found is similar in the four sand drift roses and shows that by far most of the sediment was eroded, transported, and deposited when the wind blew from the N-NW sector. The contribution of NNE and NE winds was very small. Therefore, the orientation of the transects in this study, NNW–SSE, should adequately capture any effect the notches may have on sedimentation behind the foredune. While winds from oblique directions may be steered into a trough blowout or notch (Hesp and Pringle, 2001), thereby widening the potential sand source area, given the very narrow width of the two smallest Ameland notches the effect on landward sand transport is expected to be small. The large Ameland notch, being more than 90 m wide, is expected to hardly exhibit any such steering effect.

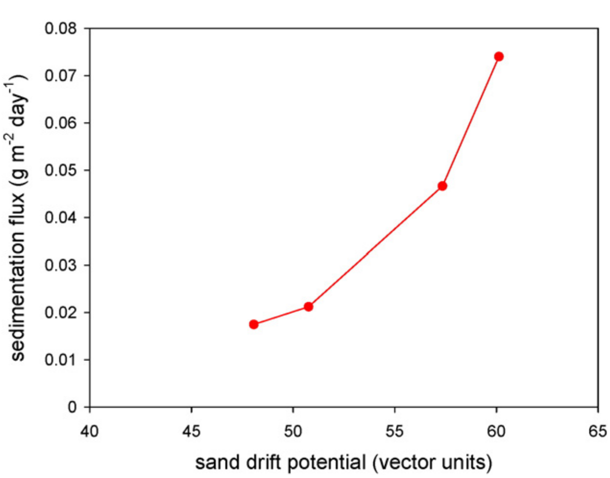

Fig. 6. Relationship between sand drift potential (DP) and sedimentation flux.

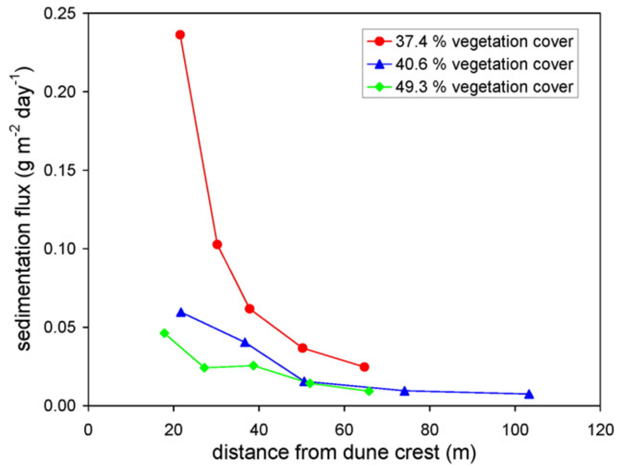

Fig. 7. Relationship between vegetation cover (windward dune slope) and sedimentation flux.

3.1.3. Sedimentation flux

To investigate whether a notch cut into a foredune affects the inland deposition and accumulation of sand in the grey dune area, we plotted the sedimentation flux as a function of the distance from the foredune (Fig. 9). The data in the figure are averages for the four experimental periods and shown separately for the transects with a notch and those without a notch. As expected, deposition decreases exponentially with the distance from the dune, due to the gradual fallout of sand as the airborne sand cloud moves landward. However, the data show greater deposition along the transects with a notch, compared to the transects without a notch, up to a distance of approximately 50 to 60 m from the crest of the foredune. There appears to be a decline in deposition along the transects with a notch compared to those without a notch (see Fig. 9). For distances greater than 50–60 m, the difference between the two types of transects diminishes to become very slight.

It can be concluded that, despite the increased wind acceleration caused on the windward slope of the foredune (see Wiggs et al., 1996), cutting a notch into a foredune results in greater deposition and accumulation in the grey dunes behind the white foredune, but only up to a limited distance from the crest of the foredune: 50–60 m in the case of the Ameland dunes. At greater distances, the effect of notches diminishes to insignificance, in part because deposition is reduced to very low amounts. This confirms observations by Stuyfzand et al. (2010) that, on the Dutch west coast, sand transport and deposition is limited to a zone 50–160 m landward from the foredune's crest. It also corroborates the results of Petersen et al. (2011), who measured small amounts of sand transport up to approximately 100 m past the foredune crest during seasonal high wind events on the windward west coast of New Zealand, and those of Hesp and Hyde (1996), who attributed the effect to rapid expansion and deceleration of the flow past the depositional lobe marking the downwind end of the incision (in their case: a blowout).

3.1.4. Grain size

We first discuss the grain size pattern for the six transects separately (Fig. 10). The figure shows data for the median diameter (an indicator pertaining to the sediment as a whole), the fine sediment fraction (taken here as the fraction <125 μm), and the coarse sediment fraction (taken here as the fraction >300 μm). Looking at the transects without a notch, no systematic changes in grain size are evident along the transects. A slight increase in fine sediment (<125 μm) was measured for transects A1.1 and A1.3, but this remains negligible. For the transects

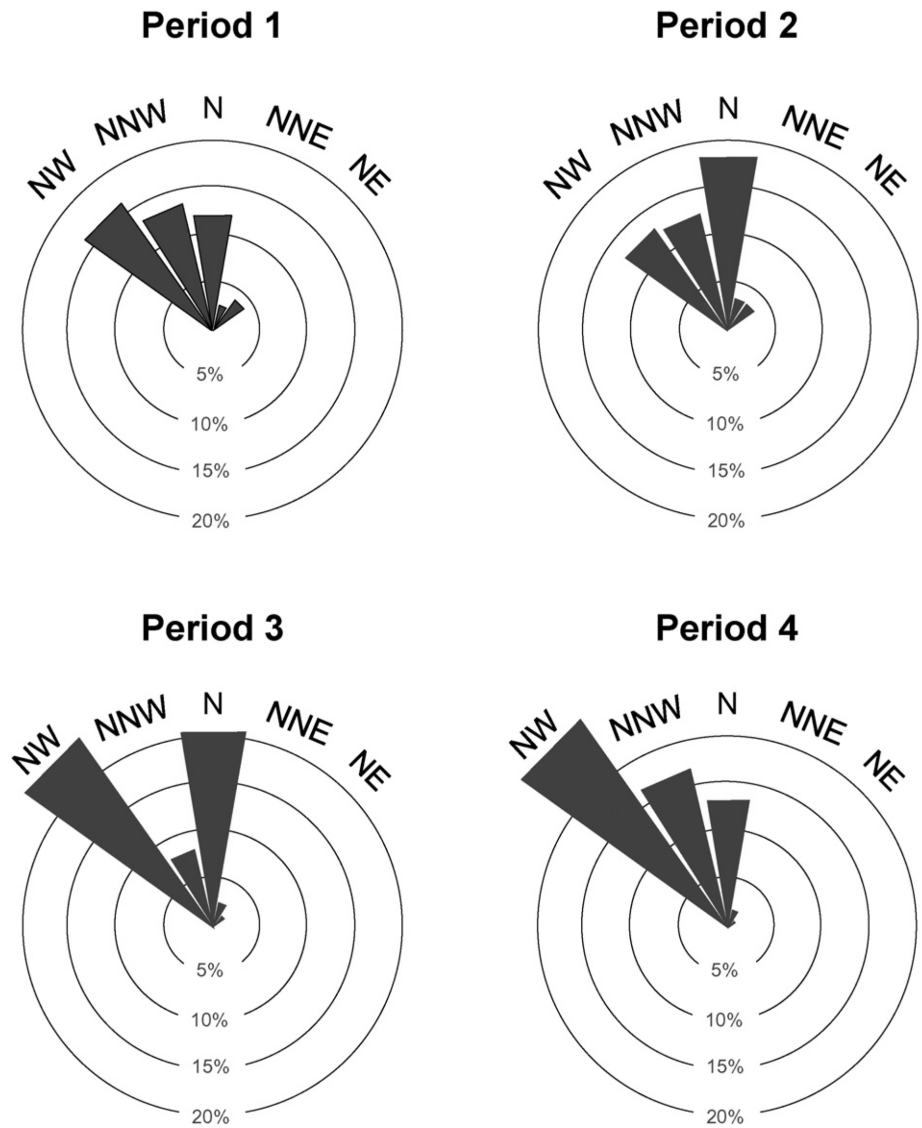

Fig. 8. Sand drift roses for the four experimental periods. Note that no sediment was supplied from the southern sector because these surfaces were covered by vegetation.

with a notch the pattern is different: here the proportion of the fine fraction increases sharply with the distance from the foredune; but somewhat unexpectedly, the same is true for the coarse sediment. The overall result is that the median diameter increases with the distance from the foredune. These trends are evident for all of the transects with a notch. Because both the finest (<125 μm) and the coarsest (>300 μm) fractions become more important, the proportion consisting of intermediate particles (125–300 μm) in the sample decreases with the distance from the foredune. The sediment thus becomes less well sorted landward for transects with a notch.

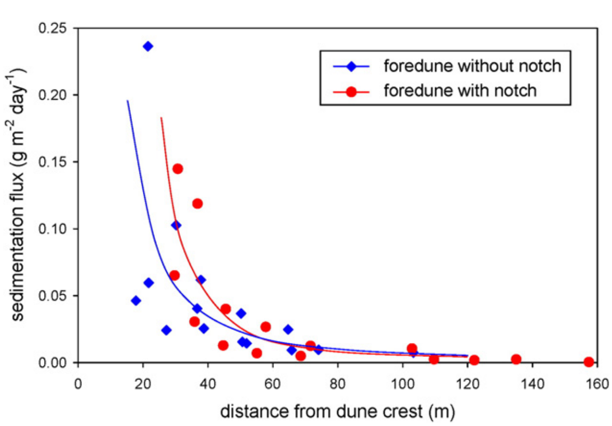

Fig. 9. Sedimentation flux as a function of the distance from the dune crest.

Compared to the foredune itself, no substantial differences in grain size characteristics occur for transects without a notch: the grain size composition in the foredune is similar to that in the transect behind the dune (Fig. 11). This is not true for transects with a notch. For these, the sediment is clearly finer just behind the foredune, then gradually coarsens away from the dune, even if the proportion of the fine fraction (<125 μm) increases (see Fig. 11).

The results for transects without a notch agree with observations by Stuyfzand et al. (2010), who measured six transects near the Dutch west coast. In four of the six transects no changes in the mean grain diameter were found, and in the remaining two transects only a very slight decrease in mean grain diameter occurred with increasing distance from the high-water line. They also found that the proportion of the finest fraction (<2 μm) increased with the distance from the high-water line. The Ameland sediment did not contain particles less than 2 μm, but there was an increase in the proportion of the fine fraction (<125 μm in this case) away from the dune.

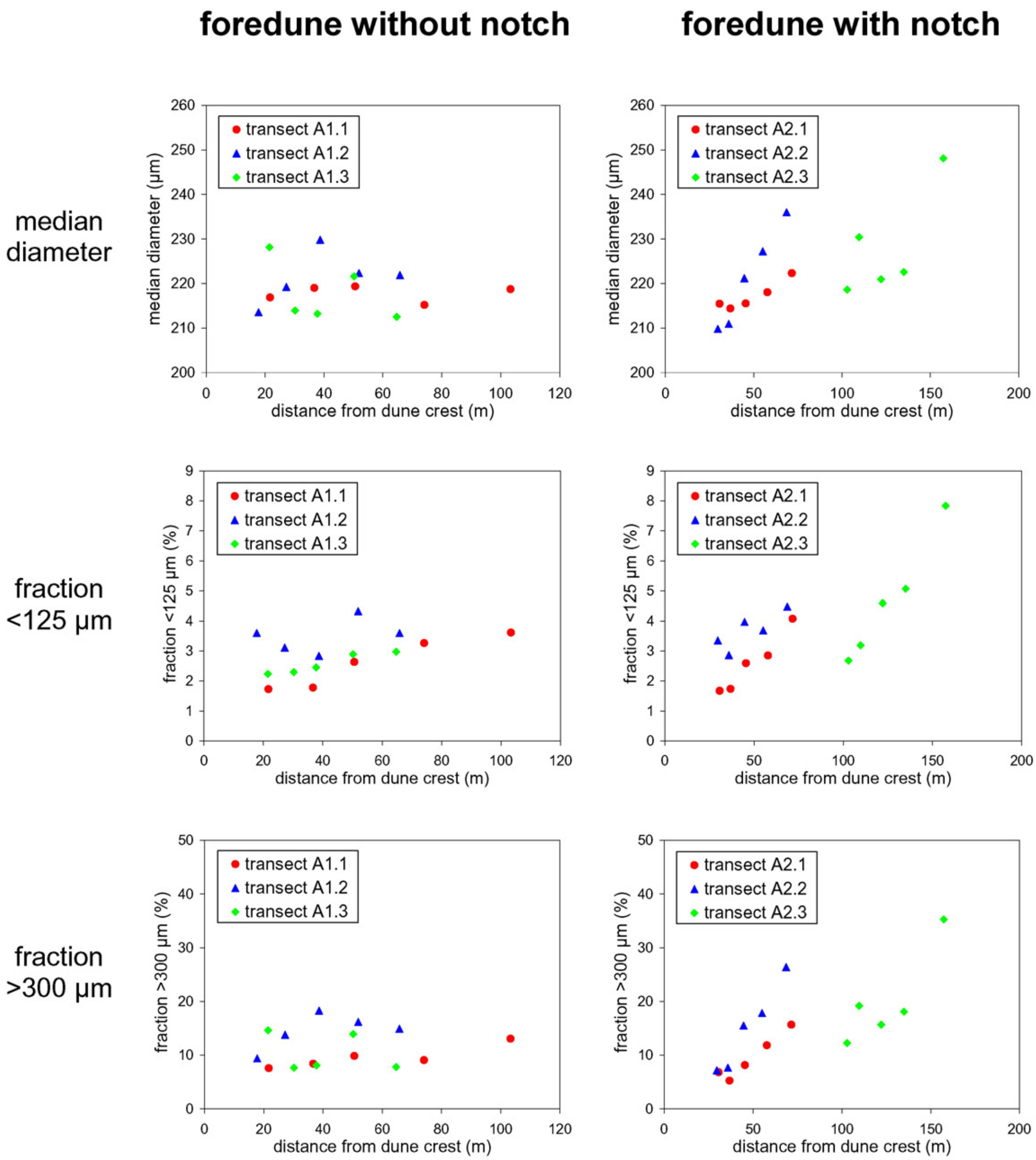

Fig. 10. Median diameter, proportion of fine sediment (<125 μm), and proportion of coarse sediment (>300 μm) in the transects behind the foredune.

For transects with a notch the proportion of the coarse fraction (>300 μm) did not decrease, but instead increased away from the foredune. For transects without a notch, the coarse fraction remained constant. These observations conflict with the widely accepted principle of aeolian selection, which states that aeolian sediment becomes finer as the distance from the source increases.

A possible explanation is the sand spray effect. During normal winds, sand eroded from the windward slope and crest of a foredune is transported only a short distance downwind and settles on the leeward slope or only shortly thereafter. During very strong winds, however, even coarse particles may be transported much farther downwind, sometimes several tens of metres or more (Fig. 12). Petersen et al. (2011) measured small amounts of sand transport up to nearly 100 m past the foredune crest during very high wind speeds. Under such conditions many particles are no longer transported in saltation but in modified saltation or even short-term suspension. Arens et al. (2002) confirms that turbulent flow over vegetated foredunes may cause a change from saltation on the beach to modified saltation and suspension on the foredunes. Hesp (2002), Christiansen and Davidson-Arnott (2004), Hesp et al. (2005), and Petersen et al. (2011) also describe the occurrence of modified saltation and suspension above foredunes during heavy wind storms. On Ameland, sand spray events such as the one pictured in Fig. 12 are not uncommon.

In the case of a flat surface (no dune present) the principle of aeolian selection does apply: aeolian sediment becomes finer with increasing distance from the source. If there is sand spray behind a dune, then it is mainly the dynamics of the coarse particles that are affected. During normal winds these particles settle on the leeward slope of the dune or shortly thereafter, as indicated above; but in a sand spray event they are transported over much larger distances before settling. This means that, at greater distances, proportionally more coarse grains will be found in the aeolian sediment for a dune than for a flat surface. The proportion of coarse grains in the sediment will even increase with increasing distance away from the dune because the sedimentation quantities decrease rapidly away from the dune (see Fig. 9), and coarse particles affect the grain size distribution more than fine particles because of their larger volume. Since a grain size spectrum is a closed system, an increased proportion of coarse particles is automatically

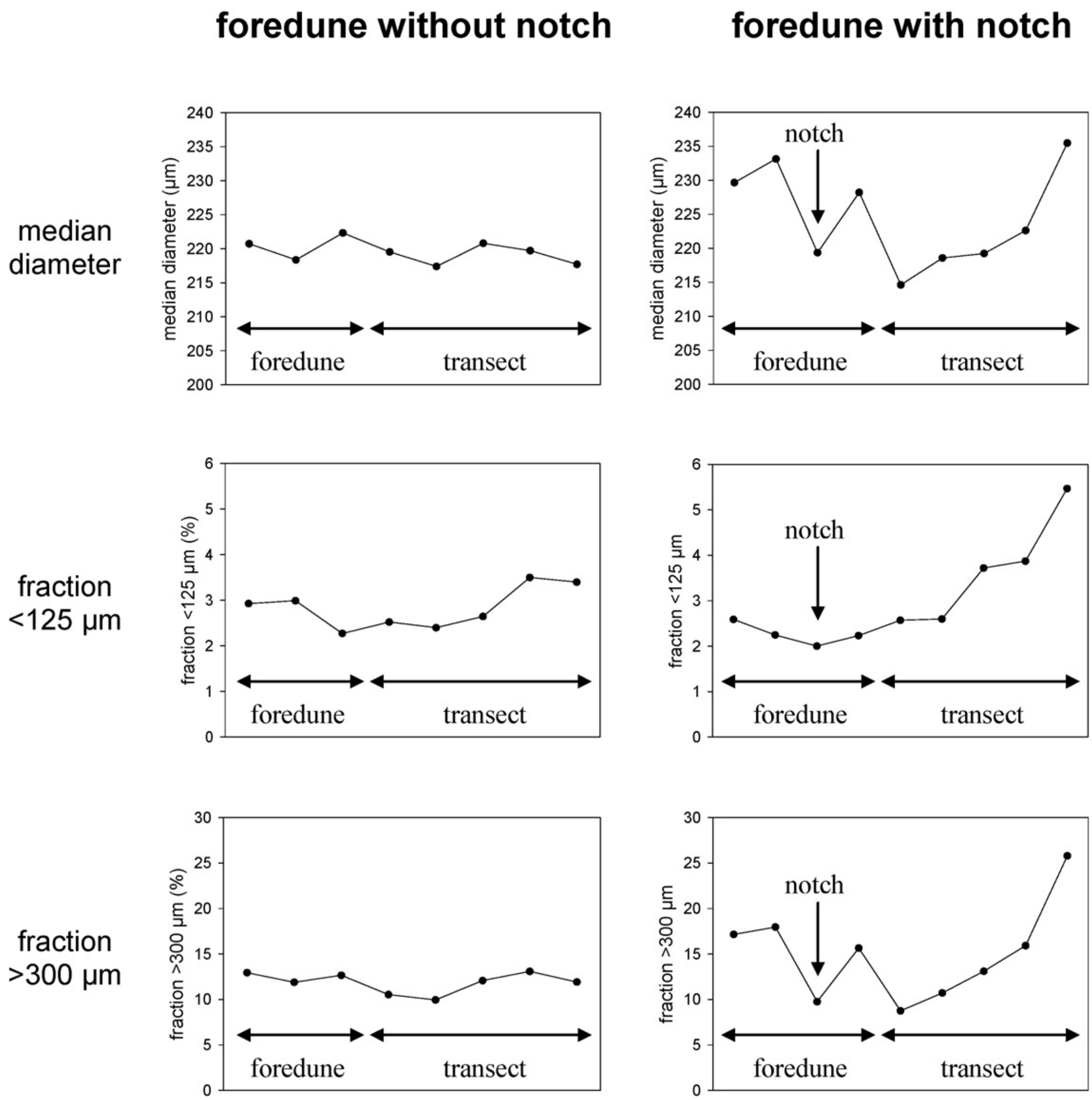

Fig. 11. Median diameter, proportion of fine sediment (<125 µm), and proportion of coarse sediment (>300 µm) in the transects compared to the foredune. Data for the transects are the averages of the three homologous transects that were measured. Since the distances between the deposition plots may differ slightly between transects (see Fig. 10) the x-axis is functional; the location of the foredune and the deposition transect is indicated with double arrows.

associated with a reduced proportion of fine particles. The increase in the proportion of fine particles away from the source, typical of a flat surface, is therefore counteracted when sand spray occurs, as this dampens or may even eliminate any such increase. This effect is nicely illustrated by the Ameland transects without a notch: the increase in the fine fraction is still visible but has become very slight in transects A1.1 and A1.3; in transect A1.2 it has disappeared. Sand spray, therefore, provides a plausible explanation for the patterns found in transects without a notch, as shown in Figs. 10 and 11.

Sand spray also explains the granulometric patterns found in the notched transects. As an incision in the foredune, a notch locally creates a situation comparable to a flat surface. Looking at Figs. 10 and 11 we see that the increase in proportion of the fine fraction (<125 µm) with increasing distance from the dune is greater in the notched transects than for transects without a notch. Furthermore, immediately behind the dunes with a notch the coarse fraction (>300 µm) is indeed less than in the dune itself (outside the notch). The effect of the notch gradually disappears downwind, farther away from the dune. There, the no-notch situation is restored, and the coarse fraction again begins to increase. Indeed, Fig. 11 shows that the effect of the notch has disappeared from sedimentation plot No. 4 (second point from the right in the diagram) some 50–60 m downwind from the dune crest. Note that this is the same distance at which the differences in deposition between the transects with a notch and those without a notch disappear (see Fig. 9). Therefore, for the Ameland transects investigated in this study, it appears that a notch affects sediment dynamics up to a distance of approximately 50 to 60 m behind the foredune's crest. Note that this distance may vary according to the wind regime, the height and width of the foredune, and the size (length and width) of the notch. It may also depend on the grain size of the dune sand, however this remains unclear.

3.2. Vegetation

3.2.1. Vegetation types

Three types of vegetation occur in the studied transects:

- Marram Grass dominated vegetation. Half of the relevés are of this type, composed mainly of *A. arenaria* (Marram Grass), although other species such as *Sonchus arvensis* (Perennial Sowthistle) and *Carex arenaria* (Sand Sedge) may also occur. This vegetation is characteristic of habitat type 2120 ('white dunes': shifting dunes along the shoreline with *A. arenaria*).
- Dry dune grassland. In the studied transects, 13 of the 30 relevés are of this vegetation type, consisting of dry, moss- and lichen-rich

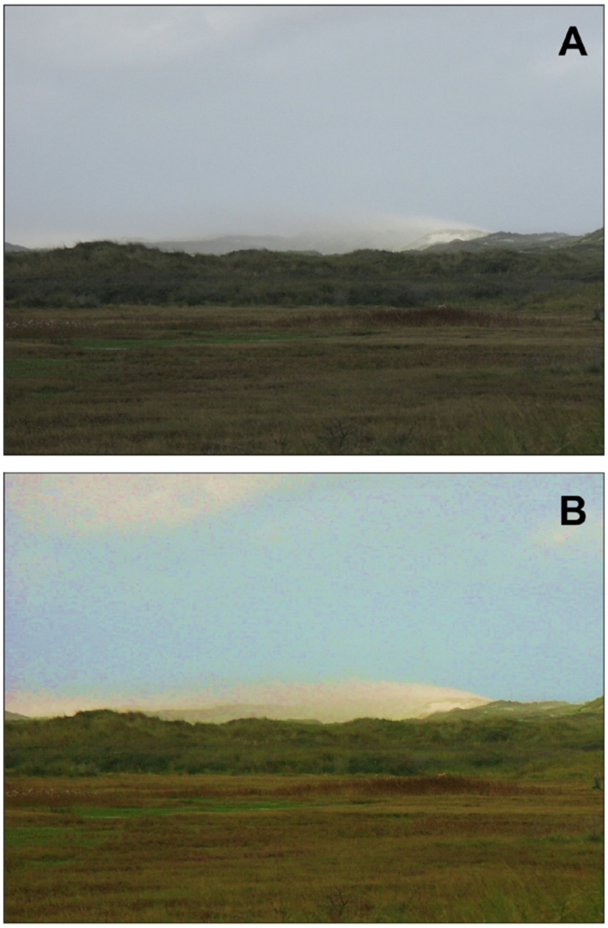

Fig. 12. Sand spray event on Ameland (20 October 2010; wind direction NW; wind speed 14 m s^{-1}). To better illustrate how far downwind the dune sand can be transported under such conditions we increased the contrast in subpanel B. The photo clearly shows that during a sand spray event many sand particles are transported in modified saltation.

grassland. Moving sand is part of the ecology of this vegetation, as it hampers the accumulation of organic matter and the formation of humus. This vegetation is characteristic of habitat type 2130 ('grey dunes': fixed coastal dunes with herbaceous vegetation).

- Shrubs. Two relevés are of this type, characterised by the presence of ruderal species like *Cirsium arvense* (Creeping Thistle), *Urtica dioica* (Common Nettle), and a cover of *Hippophae rhamnoides* (Sea-buckthorn). This vegetation is characteristic of habitat type 2160 ('dunes with *H. rhamnoides*') (European Commission, 2013).

3.2.2. Vegetation and sand supply

Looking at the spatial occurrence of the three vegetation types in the studied transects (Fig. 13) we see that all relevés characteristic of habitat type 2120 ('white dunes') are found within a distance of 65 m behind the foredune's crest. These relevés consist of pioneer vegetation that need a regular and substantial supply of fresh dune sand to sustain growth. The supply of sand is greatest just behind the foredune and is very low from a distance of approximately 60 m downwind from the dune's crest (Fig. 9); this corresponds with the occurrence of the white dune vegetation, which (behind the dune) is restricted to this same zone (Fig. 13).

The relevés characteristic of habitat type 2130 ('grey dunes') are found between approximately 30 and 160 m behind the foredune (Fig. 13). In the zone between 30 and 65 m behind the dune, both the

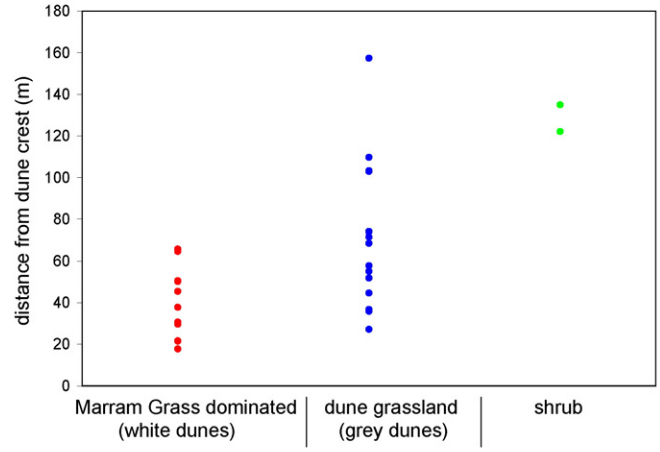

Fig. 13. Occurrence of the three vegetation types in the studied transects.

white dune and the grey dune habitats occur: this zone contains vegetation from both habitat types.

The positive effect of a notch on sand supply is restricted to a distance within approximately 60 m of the foredune (Fig. 9), which is the same distance at which the sand supply becomes too small to support the occurrence of the pioneer species typical of a white dune habitat. Therefore, if notches are constructed to restore earlier succession stages in the grey dune area (see Section 1) this will work only within the first approximately 35 m of the grey dunes, for notches of a size comparable to those investigated. The effect of a notch remains small and the spread of the points in the figure is large, but if the increased supply of sand caused by a notch does affect the percentage of open space then, according to Fig. 14, the effect again disappears approximately 60–65 m from the foredune's crest.

These data suggest that the effect of notches comparable to those investigated in this study on the grey dune habitat is small, and limited to the first approximately 35 m of the grey dunes (between 30 and 65 m from the foredune's crest). In the white dune habitat, the effect of a notch is larger, but remains disproportionately small relative to the effort involved in notch construction and maintenance.

3.3. Sand spray versus saltation

The mechanism of sand transport and deposition by sand spray is very different from the normal ('classic') saltation. In the latter, particles are transported at low altitudes, within centimetres to a maximum of a

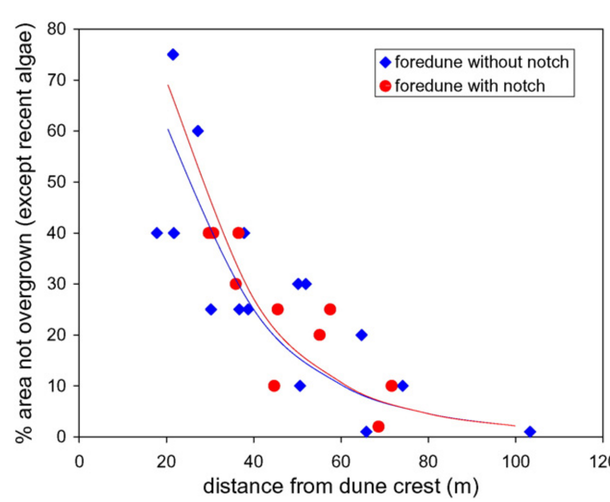

Fig. 14. Percentage of open space (area not overgrown except for litter and recent algae) as a function of the distance from the dune crest.

few decimetres from the ground. Settling happens when the particles complete their aerial saltation jumps. In contrast, sand spray lifts particles to much higher altitudes, up to several metres, due to wind acceleration near the dune crest, which acts as a springboard that ejects the grains into the air during strong winds (Arens, 1996; Hesp, 2013). Particles are then transported downwind in modified saltation to settle metres or even several tens of metres from the dune crest (see Fig. 12).

If notches remain rather narrow, the foredune is only locally disturbed and sand spray is not substantially affected. Normal transport in saltation occurs within the notches during strong winds, but the landward influence of the notch on sand dynamics is limited to only a few tens of metres (see Section 3.1), which is the same distance normally reached by sand spray. Therefore, as confirmed by the results of this study, landward transport and deposition of sand behind a foredune with only narrow notches is usually restricted to a few tens of metres.

This may change completely if the notches are much wider, 100 m or more, as illustrated by the neighbouring Wadden Island of Terschelling. Here, several notches about 100 m wide were cut into a foredune in the 1990s. They were, moreover, constructed close to one another, leaving only short segments of foredune between them. Since then, the original landscape has transformed into two large, fairly open deflation areas bordered on both sides by an intact foredune. In these deflation areas, sand transport occurs by saltation only; no sand spray can happen due to the absence of the foredune as a springboard for the particles. Because there are no important topographic obstacles in the deflation plains, the saltating sand is transported far landward, up to 300 to 400 m from the original foredune. On Ameland, the foredune was conserved and, apart from one exception, the notches cut into it were narrow. Transport and deposition of sand landward has, therefore, been limited, because of the absence of deflation plains. At the Ameland study site, sand supply occurs through sand spray (where the foredune is intact) or by saltation (in the notches and also behind the foredunes). On Terschelling, sand is transported and deposited much farther inland, but only behind the deflation areas. Behind the intact foredune it is restricted to about 80 m from the dune's crest, comparable to the situation on Ameland.

The width of a notch, and its effect on the sand transport process, should thus be considered a key parameter in dynamic coastal dune management.

4. Conclusions

Cutting notches in foredunes resulted in higher deposition and accumulation behind the dune. This can be explained by the funnelling effect (higher wind speed) and a higher degree of turbulence in the notch, leading to higher erosion rates in the notch, and also to the larger potential sand source area on the beach upwind of the notch. The extra supply of sand was small, however. For the notches studied it was limited to a zone within approximately 50–60 m of the foredune's crest. Further inland, the effect of the notches was negligible.

The presence of a notch did affect the grain size of the sediment deposited behind the foredune. Where the foredune was intact, no systematic changes were observed in median diameter or in the proportion of coarse or fine particle fractions downwind of the dune, and the grain size distribution behind the dune was similar to that on the dune itself. Where a notch had been cut, both the fine fraction (<125 μm) and the coarse fraction (>300 μm) increased with greater distance from the dune crest, whereas the intermediate fraction (125–300 μm) decreased. Furthermore, just behind the dune the sediment was distinctly finer and coarsened gradually away from the dune. Sand spray (deposition of sand eroded from the dune and subsequently transported in modified saltation during heavy winds) explains these granulometric results.

The effect of the notches studied on the current grey dune habitat behind the foredune was small, and limited to the first approximately 35 m of the grey dune area (between 30 and 65 m from the foredune's crest). In the white dune habitat the effect of the notches was larger, but in the opinion of the authors it remained disproportionately small relative to the effort required to construct and maintain the notches.

The notches investigated in this study were rather narrow, 20 m or less, except for the notch in transect A2.3, which was 90 m wide. Elsewhere on the Wadden Islands, on the island of Terschelling, notches up to 100 m wide were constructed starting in 1994. In part because these were constructed close to each other, they have merged to produce two large deflation areas where sand has been transported more than 300 m land inward by saltation. On Ameland, the notches are narrow and the foredune has remained largely intact. Sand supply to the area behind the dune occurs via sand spray and saltation, but only up to a distance of several tens of metres behind the dune crest.

Acknowledgements

This research is part of the Kennis Basis IV (KBIV) strategic research programme "Sustainable Spatial Development of Ecosystems, Landscapes, Seas and Regions", funded by the Dutch Ministry of Economic Affairs and carried out by Wageningen University & Research Centre. The authors thank It Fryske Gea, especially Henk de Vries and Sietske Rintjema for permission to enter their area to facilitate our research. The authors also thank Michelle Luijben who helped to improve this manuscript. We also like to thank the two reviewers for their constructive remarks.

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