Remobilizing stabilized island dunes for keeping up with sea level rise?

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Received: 1 August 2018 / Revised: 30 April 2019 / Accepted: 3 May 2019 / Published online: 17 May 2019
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Abstract

Dune spits of the island of Sylt (North Sea) persisted through millennia by mobile dunes transferring sand from exposed to sheltered shores. However, 150 years of systematic planting on washovers, blowouts and migrant dunes have almost completely stopped this sand conveyor belt. Spits lost sand until sand replenishments to the exposed side compensated for losses during the last three decades. Based on maps since 1878, aerial images from the 1930s onward as well as botanical ground surveys, we document a long-term shift from loose grass cover to dense heather dominated vegetation. Bare sand areas almost vanished and high shrubs proliferated. Only three dunes continue migrating with about 3 m a^{-1} since 1936. Mainly artificial dune stabilizations and introduced plants have facilitated succession to an almost complete plant cover. Thus, revitalization of aeolian dynamics would be desirable, and pilot projects may acquire the appropriate knowledge. For a 1.7×2.5 -km corridor across the island spit, we therefor discuss two suggested experiments: (1) intensify sand nourishments to the eroding beach and stop stabilization measures to allow excess sand blown inland and washovers entering deflation plains, and (2) examine the potential of tunnels for roads to let mobile dunes passing over. Such experiments may not only contribute to dune biodiversity but also to long-ranging adaptations of crowded barrier islands to accelerating sea level rise.

Keywords Barrier island · Dune dynamics · Habitat mapping · North Sea · Sand nourishment · Sea level rise

Introduction

Globally, more than two thirds of coastal beaches are eroding (Bird 1987), and this will exacerbate with global warming (Zhang et al. 2004). Behind eroding sandy shores, transgressive dune fields often develop (Hesp 2013). In NW-Europe, livestock grazing, introduced rabbits, clearing wood, harvesting dune vegetation and sod-cutting have facilitated aeolian activity of these dunes for centuries (Provoost et al. 2011).

However, since the nineteenth century more and more of these dunes became stable. Dune stabilization programs intended to prevent damage to and burial of arable land, hous-

es and roads. Furthermore, upcoming coastal tourism substituted for income from livestock grazing in the dunes. In addition, rabbit diseases and anthropogenic nitrogen deposition increased vegetation cover again. In combination, these effects reduced aeolian dynamics and stabilized many dunefields (Provoost et al. 2011).

Recently, a paradigm shift in coastal dune management is discussed (Arens et al. 2013; de Groot et al. 2017b; Martínez et al. 2013; Oost et al. 2012; Psuty and Silveira 2013). Restoring former morphodynamics should both reverse decreasing dune biodiversity and increase their adaptive capacity to adjust to an accelerating sea level rise in the future. However, at coasts with high real estate prices, a return to coastal dynamics constitutes a challenge (Döring and Ratter 2018; Hofstede and Stock 2018; Oost et al. 2012).

The transgressive dune field on the island of Sylt in the eastern North Sea experiences the consequences of stabilization, too. Here, Priesmeier (1970) more than 50 years ago already pointed to a long-term negative sand mass balance due to dune stabilizations, confounding attempts of coastal protection. Based on map-transformed aerial photographs from 1925 and 1965, which he combined with analyses of

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dune morphodynamics, Priesmeier proposed a qualitative sand balance model for the northern sandy hook of the island.

We here review his model because it was published in German and in a regional journal which now is difficult to access. Unlike adjacent barrier islands originating from sand bars, the position of the island of Sylt is further offshore due to a core of glacial deposits. This core is subject to permanent shoreline erosion. Longshore sand transport created two long sandy spits attached to the core, one to the south and one to the north (Fig. 1a; Ahrendt and Thiede 2002; Gripp and Simon 1940). Core and spits retreated by 1 to 2 m annually. Priesmeier (1970) assumed a partial loss of sand to the sea. The majority of the sediment, though, was blown onto the island by the prevailing westerly winds, where they form mobile parabolic dunes and large mobile dunes. These dunes migrate from west to east, until they reached sheltered tidal flats (Fig. 1b). Priesmeier measured that annual dune migration rates are about 3.75 m. This exceeded shoreline retreat, resulting in a conveyor belt transporting sand from the highly exposed North Sea beach to the more sheltered beach on the other side of the island. There, another longshore current dissipated dune sand into a tidal basin, located between island and mainland.

Priesmeier's model (Fig. 1b) suggests that over the past 6,000 years of spit existence, generations of migrant dunes balanced sediment loss at the western shore with accretion at the eastern shore. This has been confirmed by recent investigations (Lindhorst et al. 2008). Concerted dune stabilizations carried out on the island since the 1860s tended to interrupt the inferred sand conveyor belt. According to Priesmeier (1970), in the long-term this would be counterproductive from a coastal defence perspective. However, coastal managers either took no notice of Priesmeier's study or decided to give priority to dune stabilizations for the short-term benefit of saving infrastructures built on the dune spits. Anyway, the sand conveyor belt waned.

Since Priesmeier (1970), two developments came up which require renewed attention to his sand balance model: (1) In the wake of global warming by anthropogenic greenhouse gas emissions, sea level rises faster than before (Nerem et al. 2018), and (2), since the 1980s regular sand replenishments compensated shoreline retreat at the island of Sylt (Hofstede and Stock 2018). Therefore, we decided to extend the 1925 to 1965 comparison of the dune landscape by Priesmeier (1970) to 2012. Furthermore, we included a map from 1878. Based on this long-term comparison, we ask: (1) How has dune

Fig. 1 Schematic overview of Priesmeier's (1970) sand conveyor belt model. Beach erosion only relocates sediment into the nearshore area. The prevailing westerly winds transport the greater share as overwash and parabolic dunes across the spit. On their journey, the parabolic dunes

may merge into larger and faster mobile dunes, which eventually erode at the eastern beach. A: Island of Sylt. Red line indicates transect shown in B, where arrows refer to aeolian sand transport

migration proceeded, (2) how has vegetation cover changed, and (3) what have been the drivers affecting dune development and vegetation up to now?

Our purpose is to contribute to the challenge of adapting barrier islands to the accelerating rise of the sea and maintaining sand dune and vegetation diversity at the same time. Thus, we combine our long-term analysis with suggestions for a sustainable dune management.

Study area and methods

At the northern spit of Sylt, three transgressive dunes still migrate from west to east (Fig. 2). Migration rates are calculated by comparing positions of the steep white slip sides of migrant dunes meeting dark deflation plain vegetation in aerial photographs from 1936 to 2012, with intermediate images from 1958, 1965, 1988, 1998 and 2006. This tends to provide a rather sharp line of high contrast. In addition, topographic maps from 1878 (Königlich Preußische Landesaufnahme 1878) and 1925

(Priesmeier 1970) have been used for analysis, although their accuracy may be lower.

Our selected study area reaches from the exposed beach on the North Sea side, across a chain of primary foredunes and a transgressive dunefield comprising parabolics, static and active transgressive dunes with long trailing ridges in wide deflation plains with gegenwalle, and a sheltered beach with tidal flats on the Wadden Sea side (Figs. 1, 2 and 3). While the transgressive dune belts moved with the prevailing winds from west to east, the gegenwalle emerged during easterly winds and do not move. According to Priesmeier (1970) new belts of transgressive dunes formed about every 300 years near the western shore. Most likely, exceptional storm events had triggered their formation (Lindhorst et al. 2008). Such transgressive dune fields are common at coasts with low to variable sediment supply but are still poorly understood (Hesp 2013).

A railway track built in 1908 traversed the dune field and became a bike trail after 1970 (crossing the main road and then running south of it; Fig. 2). Since 1935, a road runs parallel to

Fig. 2 Location and study area (orange frame) at the northern spit of the island of Sylt, between exposed shore (left) and the Wadden Sea (right). Superimposed colour coding is for dune types, and dark shading

within the orange rectangle comprises deflation plains. Inset shows the region of the northern Wadden Sea located in Germany and Denmark, and arrow points to the study area

Fig. 3 Aerial view of study area from North Sea (foreground) to Wadden Sea (upper right). At the upper beach, brushwood fences occur in front of foredunes with *Ammophila arenaria* (light green) and *Rosa rugosa* (bright green). Dark brown-green indicates heather vegetation of

Calluna vulgaris and *Empetrum nigrum*. Moist parts of deflation plains appear in rose (*Erica tetralix*). White migrant dunes originated near the beach 400 to 500 years ago. Two roads now traverse the transgressive dune area. Photographed by Alex S. MacLean in August 2017

the beach through the second deflation plain, and since 1965 the present main road branched off eastward, cutting a dune ridge and then running across the third deflation plain (Figs. 2 and 3).

We examined six aerial images from 1936 to 2012 using ArcGIS (ESRI) 10.4.1 for desktop (Table 1). On these images, dune morphology and vegetation types were mapped. The timeline could be partially enlarged by a detailed topographic map from the Prussian mapping programme (Königlich Preußische Landesaufnahme 1878). The dune migration rates were calculated based on the position of the lee slope edge of the migrating dunes in different years with the Digital

Shoreline Analysis System (DSAS) version 4.4 using linear regression (Thieler et al. 2017).

We distinguished 5 categories of coverage comprising the succession stages from bare sand to dune grasses (mainly marram grass, *Ammophila arenaria*), heathland (mainly *Empetrum nigrum* and *Calluna vulgaris*), scrub or small trees (mainly *Rosa rugosa*, and species of *Populus*, *Betula*, *Sorbus*, *Pinus* and *Picea*) as well as anthropogenic infrastructure.

Dunes were mapped as geomorphological units. Besides the basic dune types (foredune, parabolic dune, transgressive dune and gegenwalle), we focused on erosional features like blow-outs, dune cliffs and overwash relics. Embryo dunes hardly

Table 1 Maps and aerial images used for analysing dune morphodynamics and change in vegetation cover. Maps for 1925 and 1965 are from Priesmeier (1970)

Year	1878	1925	27.08.1936	Summer 1958	1965	11.05. 1988	22.11.1998	12.09.2006	27.08.2012
Colour			BW	BW		IR	RGB	RGB	RGB
Spatial Resolution	2,1 m	1,1 m	0,64 m	0,40 m	1,1 m	0,40 m	0,53 m	0,50 m	0,30 m
Coordinate system used	Bessel 1841	DHDN	DHDN	DHDN	DHDN	UTM	UTM	UTM	UTM
Scale	1:25.000	1:15.000			1:15.000				

BW Black-White; IR False coloured, including infra-red information; RGB Red-Green-Blue; DHDN, Deutsches Haupt-Höhennetz (old system in 1925); UTM, Universal Transverse Mercator

occur in the area, except as ephemeral Kupsten on active transgressive dunes, which were not considered in the analysis. Single dunes were identified and mapped by transmitting their edges and crests to vector-based GIS shapefiles. For reasons of comparability and orientation during the mapping process, we also adjusted the topographic map from 1878, and the geomorphological maps of 1925 and 1965 provided by Priesmeier (1970). Further information on dunes and dune vegetation in the survey area by Jessen (1914), Kolumbe (1928), Straka (1963), Heykena (1965), Voigt (1992), Beinker (1996), Panten (2003), and Leguan (2013) were also used in this study.

Results

Migrant dunes

Bare sand areas, particularly with large mobile dunes, were dominant at the northern spit of Sylt in 1878 and 1936 (Fig. 4) and presumably in the centuries before. Since the Middle Ages, several villages, including List, have been buried by migrating dunes (Bartels 2013). Since 1878, though, we

detected a continuous decrease in bare sand areas, which was most prominent between 1936 and 1988, after which it slowed down, but continued until 2012.

The map from 1878 was merely helpful for descriptive purposes. It did not allow exact calculations of migration rates, though, as dune fronts are represented only very imprecise. From the aerial images from 1936 up to 2012 we were capable to measure a mean migration rate of 2.9 m a^{-1} (standard deviation 1.2; dune 1: 2.7 m a^{-1} , $\text{SD} \pm 1.4$; dune 3: 3.2 m a^{-1} , $\text{SD} \pm 1.3$; dune 4: 3.0 m a^{-1} , $\text{SD} \pm 0.7$; Fig. 5 and for dune numbers see Fig. 2). Considering also maps from 1878 and 1925, the overall migration rate is estimated to only $2.2 \pm 1.0 \text{ m a}^{-1}$.

Dune morphology

Close to the exposed western beach, the decrease of bare sand areas went along with the gradual disappearance of washovers and blowouts (Fig. 6). Apparently, stabilizations of washovers resulted in the formation of a coherent foredune ridge with a retreating dune cliff on the seaward side. Parabolic dunes behind foredunes moved landwards somewhat faster than the

Fig. 4 Maps (1878 and 1925) and aerial photographs (1936 and 2012) of the northern spit of Sylt (named Listland)

Fig. 5 Annual migration rates of the three remaining mobile dunes between 1878 and 2012

Fig. 6 Change of dune morphology (1878 to 2012) from highly intersected, regressing dunes to a straight cliff and then on to an artificial foredune ridge bolstering the old cliff at the exposed side of the island

cliff retreated. However, during the second half of the twentieth century, these parabolics ceased to move. At the same time, the dune cliffs shrunk in size, providing less sediment for aeolian transport into the hinterland. Since 1998, a new foredune ridge accumulated in front of the older. A small cliff at the seaward side of the new foredune ridge emerged temporarily within intervals of artificial sand supply. Foredunes behind the passive old cliff continue to move slowly landward, partly covering parabolics on their way.

Vegetation cover

Bare sand and marram grass cover decreased over time, while heath and high shrubs increased (Fig. 7). The nineteenth century map provides only rough information on the proportions of sand and vegetation. Bare sand areas were apparently dominant in the dune field as a whole. Due to insufficient spectral variations, the image of 1936 only allows an estimate of the extent of bare sand areas. From 1958 onward, quantitative data on all five coverage categories are derived from aerial images. Until 2012, bare sand areas declined from 21% in 1936 and 12% in 1958 to 4%. Whereas marram grass declined from 41% to 13%, heather vegetation increased from 46% to 77%. Tall shrubs and trees became apparent only in the late twentieth century; in 2012, they covered 4% of the area.

Around 1880 and 1936, migrating dunes appeared almost completely uncovered. Of these, dunes 2 and 5 as well as others adjacent to the study area (see Figs. 2 and 4) were planted with marram grass in the 1930–40s. Dune 4 had been cut through and stabilized for the railway track early in the twentieth century at the southern trailing ridge, and again after 1965 for a road (Straka and Straka 1984). In that second phase, also the central part of dune 4 was treated with fertilizer, brushwood fences and marram grass planting. However, this had only lasting success close to the new road (Fig. 8). At present, marram grass and crowberry are encroaching this dune (own observation). Thereby, the bare sand area of the mobile dune decreased from 21.6 ha in 1988 to 13.6 ha in 2012. Decreasing bare sand and marram grass gave way to dune heath (mainly *Empetrum nigrum* and *Calluna vulgaris*).

Discussion

About 150 years of dune stabilizations have degenerated a sand conveyor belt of a transgressive dune spit and its potential for adjusting barrier island geomorphology to an accelerating sea level rise. We first discuss the processes of dune aging and its implications, and then add suggestions for the rejuvenation back to a dynamic dune landscape.

Fig. 7 Change in vegetation cover. 1878: Bare sand in 1878 presumably includes sparse grass cover (shaded area). 1965: Data are from Priesmeier (1970). Deflation planes are not included

Fig. 8 Mobile dune approaching a road. Dune stabilizations after 1965 were only successful near the road, where succession replaced the planted marram grass by heath (*Empetrum* and *Calluna*). The remaining mobile

dune is now burying its stabilized part and is heading towards the road again. Photographed by Alex S. MacLean in August 2017

Historical change

As reviewed by Provoost et al. (2011) for coastal dunes in NW-Europe, a phase of increased dune mobility by overgrazing with livestock and introduced rabbits, wood clearance, harvesting marram grass and cutting sods preceded a reverse phase of increasing dune stability. At many sites, the Little Ice Age supported the trend of general aeolian activity. Since then, aeolian sediment dynamics at many sites have decreased, because of a phasing out of grazing and other uses of dune vegetation, epidemic diseases in rabbits, introducing exotic plants, atmospheric nitrogen deposition, and measures of coastal defence like planting marram grass and pine forests.

A similar environmental history applies to the dune spits of the island of Sylt. A royal decree for dune protection issued already in 1539, repeat lawsuits over grazing rights, introduction of rabbits in 1732, harvesting of marram grass for fodder and thatching (Fischer 1938; Jessen 1914; Panten 2003) together indicate reduction of dune vegetation until the nineteenth century. Concomitant dune mobility prevailed. Due to nutrient poor acidic soil and dune migrations, no woodland could develop. After the war of conquest by German armies against Denmark in 1864, a war against dune dynamics commenced. Almost all grazing and marram grass harvesting stopped, and washovers and blowouts became precluded by organized plantings of marram grass. Sprawl of military and

touristic infrastructures in the dunes were another incentive to stop dune dynamics after 1914.

Our analysis of dune migration and vegetation cover is concerned with the latter phase. Bare dunes near the exposed western shore became stable by building brushwood fences and planting marram grass since the 1860s as a measure of coastal defence. Where military infrastructures and residential areas were built near mobile dunes, these have been similarly stabilized in the 1930s and 1940s, and occasionally thereafter. These stabilizations account for most of the decrease of bare sand between 1936 and 1958. The subsequent loss of bare sand areas occurred until the 2000s with less direct human interference, like the succession of dune vegetation, its increase in terms of area and, especially, introduced plants.

Large migrant dunes not subjected to planting campaigns continued to move at variable speed. Previous estimates on shorter intervals (Priesmeier 1970; Straka and Straka 1984) are somewhat higher than our averages of 2.2 to 2.9 m a⁻¹, with or without including old maps, respectively. Comparing the migration rates with other mobile dunes around the North Sea and the Baltic Sea unravels a rather irregular pattern. For the large Danish mobile dune ‘Råbjerg Mile’ Anthonsen et al. (1996) have calculated higher annual migration rates of 11 to 13 m. On the other hand, Labuz et al. (2018) mention that the Polish mobile dune ‘Lacka’ close to Leba merely proceeds with 1 to 2 m annually. Besides methodological differences,

arguably, each transgressive dune field has its own distinct characteristics. Hesp (2013) considers a complex interplay of multiple factors, which in turn determine the migration speed of single dunes. Furthermore, individual dune migration may vary in multi-annual cycles: Years of slow migration occur when westerly winds primarily increase dune height. This gradually creates steep slip faces, which advance fast by sand avalanches (Priesmeier 1970; Jakob 2014). These avalanches eventually decrease dune height again and dune migration slows down. Length of phases may depend on storms and precipitation (own observations).

Washovers and blowouts in the vicinity to the exposed beach gradually disappeared. We attribute this to stabilization efforts of coastal engineering. In addition, the building of access paths to the beach, fences and information signs helped preventing people from trampling on dune vegetation from the 1970s onward (Klug and Klug 1998; own observations).

Later, repeated sand nourishments (4 times between 1992 and 2016; www.schleswig-holstein.de) at this beach generated a new foredune ridge in front of the cliff, bolstering it and turning it passive. Sand nourishments reversed former beach and dune erosion into dune aggradation, as they substantially increased sediment availability. However, a higher sediment flux from the beach to the hinterland did not occur. Instead, the added sand formed ephemeral embryonic dunes and brushwood trapped sand to form a new foredune ridge, further stabilized by planted marram grass. Therefore, the artificial sand supply does not reach the transgressive dune field in the hinterland. Similar observations have been made at the so-called sand motor at the Dutch coast, where a new foredune acted as a sediment trap (Arens 2015).

Natural succession versus anthropogenic decline in dune dynamics

Our result, that bare sand and marram grassland areas declined while heath became dominant in the dunes, may be the outcome of natural succession in nutrient poor and acidic dune sand (de Groot et al. 2017a). Also Hesp (2013) describes a large-scale overall trend of transgressive dune fields to stabilize. However, in transgressive dune fields, frequent natural disturbances by waves (washover) and wind (blowouts, migrating dunes) tend to set back plant succession from heath to bare sand. Dunes overgrown with marram grass hold an intermediate position between bare sand and heath. They are still mobile to some extent, driven by wind, and their resilience to wind disturbances is high. Dunes overgrown by heath have become immobile. However, their resilience is low if disturbance initiates a blowout. The deflation widens and on sand deposits at the leeward side marram grass takes over (see Hesp et al. 2017). Especially beach erosion and foredune retreat initiate aeolian sediment redistribution (Psuty 2004). Early maps of Sylt support this tendency. Thus, without human interference,

dynamic processes with washovers, blowouts and parabolic dune formation near the beach would have prevailed.

We have found, though, that this was not the case (Fig. 9). For dunes on Sylt, there is ample evidence of direct human interference by stabilizing dunes for coastal and infrastructural protection, culminating in the 1940s and still lingering on (see above). This may explain most of the loss of bare sand area and the eventual dominance of heath. However, this does not exclude the role of other facilitating or confounding factors. Grazing by domestic animals stopped around 1970 in our study area but continued in the adjacent dune area to the north. Surprisingly, no difference in vegetation on either side of a fence could be detected (Beinker 1996) and is still not apparent after 40 years (own observation). An explanation may be that sheep in this area can choose between grazing on dune and salt marsh vegetation, and clearly prefer the latter. Variable grazing by rabbits could have had an effect too. Since 1927, a causeway connects the island with the mainland, and a fox population established subsequently. We assume, this excludes rabbits from most dunes and relegates them to residential areas. Due to this timing, vegetation changes that occurred after 1958 (as shown in Fig. 6) cannot be attributed to fading effects of rabbits.

Also there has been no remarkable shift within the regional water regime. The consequences of ongoing climate change such as slightly increasing winter precipitation (DWD 2016) may interact with eutrophication and then facilitate scrub proliferation and grasses (Bakker et al. 2016). This may drive future change in dune vegetation but may not account for changes in the past. Groundwater extraction by wells in the dune field adjacent to our study area occurred from 1936 until 2006 (Petersen 1982; B. König, pers. communication). This might have led to lower groundwater level, while sea level rise would cause it to rise again (Lindhorst et al. 2008). It is unlikely that this affected the vegetation categories in our study.

Instead, increased eutrophication (N-deposition in Fig. 9) accelerates plant succession in nutrient poor and acidic coarse dune sand, where it often results in grass encroachment (Provoost et al. 2011; Veer and Kooijman 1997). In the Wadden Sea region, atmospheric nitrogen deposition increased in the twentieth century until it reached a peak of up to 40 kg N ha⁻¹ y⁻¹ in the 1980s and then decreased again. Current values for atmospheric nitrogen deposition in Germany are within a range of 9–12 kg N ha⁻¹ y⁻¹ (de Groot et al. 2017a; Lammerts et al. 2009). Nevertheless, these values still have an impact on dune vegetation. Based on studies from dunes at the Baltic coast, Remke et al. (2009) conclude, that even nutrient inputs as low as 5–8 kg N ha⁻¹ y⁻¹ result in grass encroachment. However, we observed no encroachment with *Carex arenaria* in our study area (Leguan 2013, own observation).

Arguably, introduced plants constitute a severe indirect human effect on dune succession on Sylt, too (Beinker 1996;

Fig. 9 Varying intensity of anthropogenic effects since the nineteenth century supporting (red) and lowering (green) the natural dune dynamics on the island of Sylt, resulting in declining bare sand area and dominance

of heath cover. See also the comment on Fig. 7 regarding the bare sand area from 1870 and the text

Leguan 2013). Particularly from residential areas there is a sprawl of high shrub and trees into the adjacent dunes which is detectable on aerial images. However, most trees (mainly species of *Pinus*, *Picea*, *Populus*, *Betula* and *Sorbus*) remain

small and scattered in the dunes up to now. Most prominent are shrubs of *Rosa rugosa*, occurring at roads and residential areas, at former military infrastructures and on the leese of foredunes. The latter may be due to beach visitors relieving

themselves and thus increasing the nitrogen supply for this exotic plant. *R. rugosa* is generally invading dune islands in the Wadden Sea region (Isermann 2008), and on Sylt may cover at least 3% of total dune area (H. Hoffmann, pers. communication). Another important invader is the heath star moss *Campylopus introflexus*. In our study area it spread since in the late 1980s and became particularly abundant within grey dune vegetation (Skowronek et al. 2017) and on bare sand areas at the transition between marram grass and heather vegetation (own observation). It contributes to the decline of bare sand, and may facilitate dune stabilization (Essl et al. 2014; Skowronek et al. 2017). We conclude that next to the direct human efforts of dune stabilization, the spread of introduced plants has contributed most to the decline of bare sand and marram grass areas. The overall effect is diminishing habitat diversity and increasing dominance of a few plants at the expense of pioneer species (see also de Groot et al. 2017a, b). The encroachment by high shrubs and trees from residential areas is still at an early stage but is expected to displace characteristic dune vegetation in the long run. Reviving dune dynamics would roll back these long-term trends.

Reviving dune dynamics

Priesmeier (1970) has documented the wane of the aeolian sediment conveyor belt. Our findings demonstrate that this process has exacerbated since the 1960s. For reasons of nature conservation (de Groot et al. 2017a, b) and long term coastal safety (Oost et al. 2012) this development is detrimental. In the face of accelerating sea level rise in the wake of global warming (Clark et al. 2016; Nerem et al. 2018), traditional strategies for coastal protection require revision. Hofstede and Stock (2018) have outlined a support strategy for tidal flats and salt marshes in the northern Wadden Sea growing with the sea. Similar to coastal wetlands, dune islands should be able again to grow as sea level rises. Pioneering experiments for dune revitalization have already been conducted in The Netherlands (Arens et al. 2013) and in Wales (Pye et al. 2014).

Currently, however, vertical accretion of dune areas is largely impossible due to all the former coastal protection measures still in place (Oost et al. 2012). Gateways for aeolian sand transport across barrier islands will be necessary for stimulating aggradation and resilience in response to an accelerating sea level rise. On crowded recreational islands such as Sylt, dune dynamics adjusting deflation plains to a rising sea and the build-up of new massive dunes surely will cause conflicts with existing infrastructures including residential areas and roads. Furthermore, debates will emerge that may resemble those on managed coastal realignment (i.e., Ahlhorn 2018; Schemewski et al. 2018). New strategies in dune management would constitute a substantial policy change. To gain experience and knowledge, Huitema et al. (2011) stress the importance of pilot experiments. Furthermore, the success

should become visible locally before a general paradigm shift is ripe for acceptance.

Suggestion for two pilot experiments

As a pilot site, we suggest the investigated transgressive dune field which is merely dissected by two roads (Figs. 2 and 3). The residential areas in the vicinity would remain unaffected by reviving dune dynamics. Successful aeolian sand transfer from the exposed beach to the backshore dunes will depend (1) on the amount and frequency of nourished sand to the beach, (2) on local dune topography, and (3) the vagaries of wind, rain and other weather conditions, storm surges in particular.

The aim of the experiment is to initiate parabolic dunes moving inland from the beach with the prevailing wind. Formation and landward migration of parabolics will depend on perpetual supply of sand from the shoreface. This also requires repeated sand nourishments to the beach. In the selected corridor, these parabolics could migrate for two to three centuries before approaching the first road. They would probably fuse with formerly stabilized dunes on their route (see Fig. 3), and then could form a new migrant dune in the far future, progressing with higher speed across the island. The deflation plain left behind it would increase in elevation as groundwater level rises in concert with sea level rise (Lindhorst et al. 2013). Besides preventing nourished sand from being washed back to the sea again, mobile dunes thus raise the elevation of barrier islands, adjusting them to the level of the sea.

At the selected corridor, safety is not at risk and stabilizations of dunes are possible at any time if that would deem necessary. Nourishments have already occurred since the 1990s at this site. However, we endorse shortening intervals and increasing the supply of sand in an effort to initiate substantial aeolian sand movement in backshore direction. Therefore, existing brushwood fencing and planting of marram grass in the foredunes should stop. If storm surges cause washovers, this would facilitate landward sand transport and thus be appreciated. Nevertheless, an immediate success is not certain, and the experimentally increased sand nourishments should continue over a decade or more.

Secondly, we suggest examining to what extent migrating dunes can be reconciled with existing infrastructure. Our study site offers a suitable location for that purpose, too. Since 1965, a main road runs alongside one of the last migrating dunes (Fig. 8). Next to that road the dune (No. 4 in Fig. 2) was stabilized for protecting the nearby road. In the meantime, the still mobile part has been overtaking the formerly stabilized part. Thereby the dune gained in height and now is turning towards the road. Instead of (partially) stabilizing this dune once more, we now suggest to examine another solution in detail: A tunnel for the traffic could allow the dune to pass over the road and proceed to the sheltered beach. Maybe that would be the first time of building a tunnel before a mountain appears.

For a long-term adjustment of the barrier spit to the expected sea level rise, more than a narrow corridor would be necessary. In the meantime, this pilot project could provide experience with proper management, and then could serve as a vivid example needed for societal choices. This will not only concern financial implications when dunes approach roads or even residential areas but also trade-offs between e.g. short-term benefits and long-term debts.

Conclusions

During the last 150 years, dune dynamics have rapidly faded on the island on Sylt. We attribute the long-term increase of heather and other shrub vegetation typical for aging dunes at the expense of bare sand and marram grass areas typical for dune mobility on a barrier island in NW-Europe to dune stabilization measures aggravated by introduced plants. Additionally, the sediment conveyor belt of migrating dunes has been waning. For the sake of nature conservation and long-term coastal safety this state is undesirable. To revert this habitat degeneration and to adapt a barrier island to accelerating sea level rise, we recommend a revitalization of dune dynamics rather than continuing with a static protection strategy. To gain experience with dynamic forms of dune management we suggest two pilot experiments: Finding ways of initiating new parabolic dunes at the exposed western beach, and reconciling migrating dunes with human infrastructure on a crowded tourist island.

Acknowledgements First of all, we thank the anonymous reviewer for the valuable and helpful comments. We express our gratitude to the Coastal Protection Board of Schleswig-Holstein (Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz des Landes Schleswig-Holstein) for providing the aerial images from 1936 and 1958. We thank Alex S. MacLean for his photographs (Figs. 3 and 8). Our special thank goes to Martin Stock who supported this study with data on current vegetation. Furthermore, we should like to thank Bernd König from the Environmental Protection Agency (Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein) who contributed valuable information about the history of groundwater extraction on Sylt.

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