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Journal of Coastal Research

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https://doi.org/10.2112/JCOASTRES-D-13-00125.1

| Journal of Coastal Research | 00 | 0 | 000–000 | Coconut Creek, Florida | Month 0000 |
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# Soft Engineering *vs.* a Dynamic Approach in Coastal Dune Management: A Case Study on the North Sea Barrier Island of Ameland, The Netherlands

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**ABSTRACT**

De Jong, B.; Keijsers, J.G.S.; Riksen, M.J.P.M.; Krol, J., and Slim, P.A., 0000. Soft engineering *vs.* a dynamic approach in coastal dune management: a case study on the North Sea barrier island of Ameland, The Netherlands. *Journal of Coastal Research,* 00(0), 000–000. Coconut Creek (Florida), ISSN 0749-0208.

Dunes act as flood defenses in coastal zones, protecting low-lying interior lands from flooding. To ensure coastal safety, insight is needed on how dunes develop under different types of management. The current study focuses on two types of coastal dune management: (1) a "soft engineering" approach, in which sand fences are placed on the seaward side of foredunes, and (2) "dynamic coastal management," with minimal or no dune maintenance. The effects of these management styles on dune formation are examined for two adjacent coastal sections of the North Sea barrier island of Ameland, The Netherlands, where dynamic coastal management was introduced in 1995 and 1999, respectively. For each section, we analyzed cross-shore profile data from 1980 until 2010, deriving dune foot position, crest position, crest height, and foredune volume for each year and analyzing the situation before and after the change in management. We further assessed the effect of the management regime on dune vegetation. Other factors that could influence dune development were also taken into account, such as beach width and shape, water levels, wave heights, and nourishments. Results show that implementation of dynamic coastal management did not directly affect the volume of the foredune. Growth was occasionally interrupted, coinciding with high-water events. In periods between erosive storms, dune growth rates did not show a significant difference between management types ($p = 0.09$ and $0.32$ for sections 1 and 2, respectively). The main effect of the change was on vegetation development. Dynamic coastal management, therefore, did not reduce coastal safety.

**ADDITIONAL INDEX WORDS:** *Coastal defense, storm surges, coastal dune development, aeolian sediment transport, vegetation development.*

## INTRODUCTION

Coastal zones are of strategic importance in Europe. Almost half of the population of the European Union (EU) live within 50 km of the oceans and seas, and many vital economic, social, environmental, and cultural activities take place there. This leads to intense competition for the limited space along Europe's estimated 89,000 km of shoreline (Ciavola and Stive, 2012). In coastal zones, dunes act as "soft" flood defenses, protecting low-lying interior lands against flooding. To ensure coastal safety in the future, insight is needed on how these soft flood defenses are likely to develop under various types of management (Bochev-Van der Burgh, Wijnberg, and Hulscher, 2009, 2011).

Dunes are of particular importance along the coast of The Netherlands. Here, in addition to coastal defense, they contribute to various ecosystem services such as drinking water supply, recreation, and nature conservation (Arens, Jungerius, and Van der Meulen, 2001; Bochev-Van der Burgh, Wijnberg, and Hulscher, 2009, 2011; Braat *et al.*, 2008; De Groot *et al.*, 2012).

The Dutch have traditionally intensively managed their coastal zones. Two main strategies are distinguishable in Dutch coastal dune management: The first is the "soft engineering" approach (hereafter referred to as "soft engineering"). This strategy involves high control of local processes to fixate, improve, or restore a predetermined dune shape and height for the purpose of coastal protection. The second is known as "building with nature," which makes use of natural processes by stimulating them in such a way as to increase coastal safety or improve ecological quality.

Often a soft engineering approach has been used that involves placement of sand fences between the sea and the foredune (defined as the first or most seaward of the dunes) along with planting of *Ammophila arenaria* (marram grass) (Arens, Jungerius, and Van der Meulen, 2001). From 1990, however, a strategy called "dynamic coastal management" has been increasingly implemented (Arens and Wiersma, 1994; De Ruig and Hillen, 1997). In 2002 the Dutch Technical Advisory Committee for Flood Defenses defined dynamic coastal management as "managing the coast in such a way that natural processes, whether stimulated or not, can take place undisturbed as far as possible, as long as the safety of the inland area is ensured" (TAW, 2002). Dynamic coastal management is

*DOI: 10.2112/JCOASTRES-D-13-00125.1 received 18 June 2013; accepted in revision 2 November 2013; corrected proofs received 7 January 2014.*
Published Pre-print online 11 February 2014.
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associated with the "building with nature" approach that is now taking root in The Netherlands (De Vriend and Van Koningsveld, 2012).

An example of building with nature is the "sand engine" created along the North Sea coast near The Hague. In this project, some 21 $Mm^3$ of sand has been added to the coastal system. The expectation is that natural processes will distribute the sand along the coastline in such a way as to increase safety against flooding in the long term (Van Dalfsen and Aarninkhof, 2009). Dutch management is thus moving away from engineering coastal-protection structures toward beach nourishment (Kabat *et al*., 2009) and eco-engineering (Van Bohemen, 2004).

With less intensive foredune management, natural processes play a greater role in flood protection, and foredunes gain a more natural appearance (De Groot *et al*., 2012). Dynamic management of foredunes could also enhance the conservation of Natura 2000 areas, which are a pillar of EU nature and biodiversity policy. Among the EU-protected coastal habitat types are "embryonic shifting dunes" (habitat type 2110), "shifting dunes along the shoreline with *Ammophila arenaria*" (white dunes, type 2120), and the priority habitat type "fixed coastal dunes with herbaceous vegetation" (gray dunes, type 2130) (De Ruig and Hillen, 1997; European Commission, 2007; Ketner-Oostra and Sýkora, 2012).

Little is known about the effect of dynamic coastal dune management on various dune functions, even though such management has already been introduced on a large spatial scale. The current study, therefore, evaluates the effect of dynamic coastal dune management on dune development (in terms of, *e.g*., dune volume and shape) by comparing foredune development before and after the introduction of dynamic coastal dune management. Two adjacent dune sections are studied on the North Sea barrier island of Ameland, The Netherlands. Dynamic coastal dune management was introduced in these two sections in 1995 and 1999, respectively. To determine the impact of dynamic coastal dune management, elevation data was analyzed to discern changes in dune shape, height, and volume for the period between 1980 and 2010. This time frame extends approximately 15 years before and after the introduction of dynamic coastal dune management. Additionally, the effect of dynamic coastal dune management on vegetation development and foredune appearance was monitored from 1995 to 2002. Because the study aims to determine the effects of the change in coastal dune management regime, other factors that could cause changes in dune development were taken into account (*e.g*., beach width and shape, vegetation, water levels, wave heights, and nourishments).

## Coastal Dune Management and Dune Development

The development of foredunes is the result of a number of factors (after Hesp, 2002): sand supply; vegetation type and density; aeolian sediment transport; occurrence, direction, and magnitude of storm erosion; and human impact and use. Coastal dune management aims to control these factors in such way as to fulfill desired ecosystem services, like coastal safety and recreation.

Several types of measures can be discerned in dune management strategies: measures that affect the availability and quality of erodible material (*e.g*., foreshore or beach nourishment); measures that affect local aeolian transport (*e.g*., planting or removing vegetation and placing sand fences); and measures that have a direct local effect on the topography of the beach or foredune (*e.g*., mechanical construction or reconstruction of dunes). The first type is characteristic of the "building with nature" strategy, whereas the last two are more closely associated with the soft engineering approach.

### Soft Engineering

For centuries the Dutch have planted *A. arenaria* and placed sand fences along the coast to trap drift sand. Dikes were first built on Ameland in the Middle Ages (Löffler, 2008). Since 1800, a succession of human interventions has influenced the very shape of the island. The last drift dike (*stuifdijk*), a human-made dune, was established in the 1960s (Provinciaal Overlegorgaan Kust Fryslân, 2000). As a result aeolian transport to the inland "gray" dunes was reduced, and high front dunes developed (Oost *et al*., 2012).

Throughout the second half of the 20th century, an extremely intensive form of management was practiced. In this period, the process of stabilization was dominant, and many mobile dunes were fixed (Arens, 2009). Throughout the 1980s, the Dutch Public Works Department (*Rijkswaterstaat*) annually erected more than 35 km of sand fences on Ameland and planted over a million specimens of *A. arenaria* (Nikkels, 2010). This resulted in stable dunes, with a dynamic zone in front of the dunes where sediment transport was controlled by sand fences, vegetation, and storm-surge events.

### Building with Nature

Dutch thinking about dune management changed in the 1980s. The idea gained currency that drifting sand is necessary to preserve the natural character of coastal landscapes. In 1990 this notion was embraced in The Netherlands' first policy document on coastal management, *1e Kustnota* (VWS, 1990). A major driver of this shift in thinking was the occurrence of numerous storm-surge events in the late 1980s. Moreover, continued erosion was measured in a number of places (TAW, 2002). This proved false the earlier assumption that the sum total of erosion and accretion along the Dutch coast was zero.

The government of The Netherlands committed itself to stopping any further coastal recession (De Ruig and Hillen, 1997). It established a "reference" coastline (*basiskustlijn*), which was to be maintained at its 1990 position using nourishments (De Ruig and Hillen, 1997; TAW, 2002). Nourishment is typically done by depositing sand on a beach, on a shore face, or in front of a foredune ridge (Bochev-Van der Burgh, Wijnberg, and Hulscher, 2009). Initially most nourishments were done on beaches, though later insights (from 1997) led to more sand placement on the shore face (at about the 5–6 m isobath). Since 2000 some 12 $Mm^3$ of sand has been added annually to the Dutch coast, compared to about 6 $Mm^3$ per year before 2000 (Bakker *et al*., 2012).

Nourishment changes the sediment budget of foredune systems, with negative sediment budgets in many cases reverting to positive ones (De Groot *et al*., 2012). Nourishment of beaches and foreshores changes dune morphology as well, both directly and indirectly, *via* its influence on sediment transport processes (De Vries *et al*., 2012). Bochev-Van der

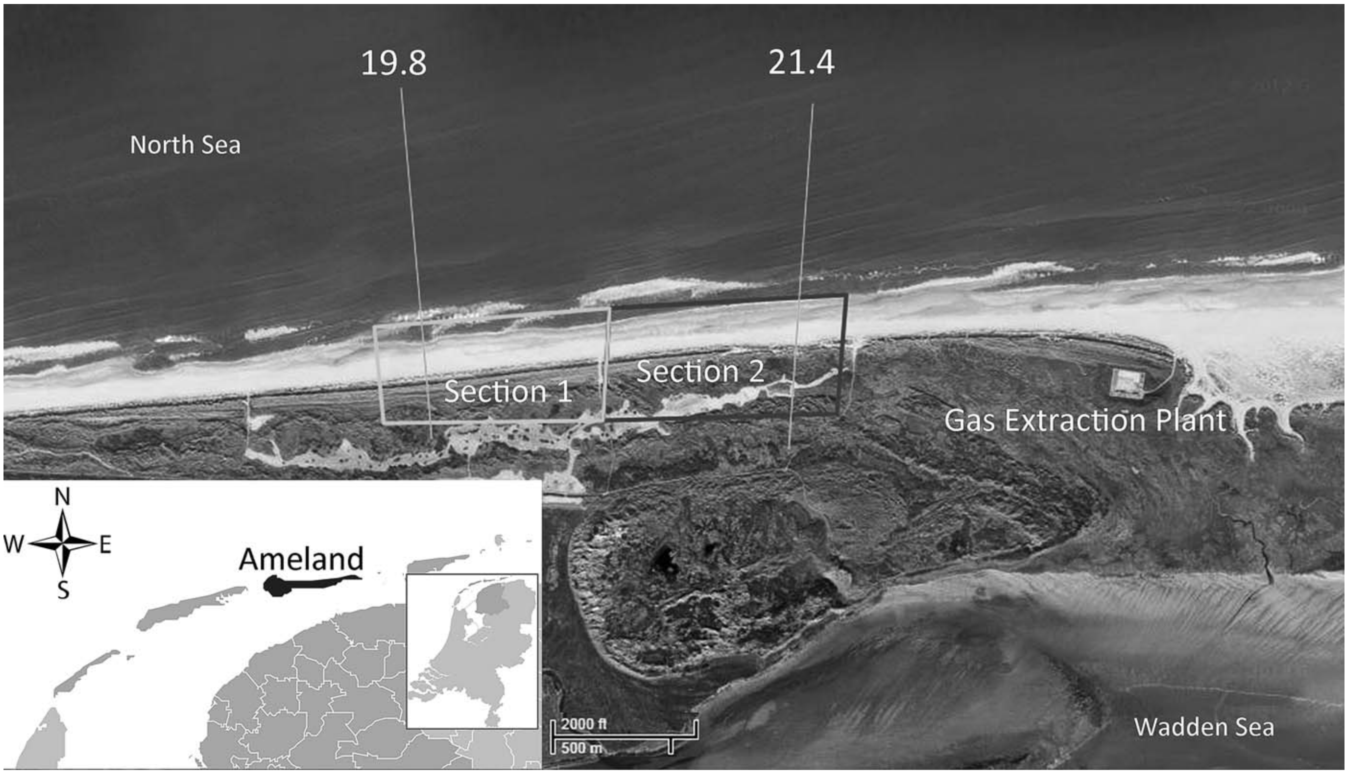


Figure 1. Location of the Dutch barrier island Ameland in relation to The Netherlands and the two research areas on the island's eastern end, labeled section 1 and section 2. JARKUS transects 19.8 and 21.4 are indicated with red lines. Transects are numbered after the state beach posts. The number represents distance in km from a point at the western end of Ameland. The location of the natural gas extraction plant is also marked (Google, 2012; Wikimedia, 2012). (Color for this figure is available in the online version of this paper.)

Burgh, Wijnberg, and Hulscher (2009) found a time delay of years (about 8 in their case) between the onset of nourishment activities and noticeable changes in foredune morphology. This is because nourished sediments take time to accumulate and cause detectable changes in dunes.

The introduction of dynamic management and nourishments to maintain the coastline of The Netherlands increased the activity of coastal dunes. Under this management regime, less strict stabilization was applied, leading to more natural dynamics in the foredunes (De Ruig and Hillen, 1997) and more sand being blown inland. Foredunes gained a more natural appearance, in some cases with an incipient foredune developing in front of the original foredunes (Arens, Löffler, and Nuijen, 2007; De Groot *et al.*, 2012). Overall, nature in the coastal dunes benefited from sand nourishments, as diminishment of dune area ceased and natural processes were allowed freer rein (Slim and Löffler, 2007).

Under dynamic management, dunes are no longer reconstructed after storm damage. Instead, dune recovery is purely the result of natural processes of aeolian sediment transport and vegetation development. The outcome of these two processes is expressed in changes in dune volume and shape: the greater the ability of plants to trap sand, the larger the dunes grow (Luna *et al.*, 2011).

Sediment supply and, in particular, beach width and fetch length, are critical factors in dune initiation and growth (Hesp, 2013). The ultimate goal is for the beach profile to remain the same after a storm; therefore the main effects of the two management types studied here will be evident in vegetation recovery time and in the subsequent sediment-trapping efficiency and thus volume growth rate of the dune.

## METHODS

To evaluate the effect of dynamic coastal dune management on dune development (in terms of, *e.g.*, dune volume and shape), two adjacent dune sections were selected on the North Sea barrier island of Ameland. Dynamic coastal dune management was introduced in these two sections in 1995 and 1999, respectively. In this section we describe the characteristics of the research area, the data collection, and the analysis methods used to determine the impact of dynamic coastal dune management. Because the study aims to determine the effects of change in coastal dune management regime, other factors that could cause changes in dune development are described and discussed here (*e.g.*, beach width and shape, vegetation, water levels, wave heights, and nourishments).

### Case Study Area

The case study was done on the coast of Ameland (53°28′ N, 5°54′ E) (Figure 1). The northern coastline of Ameland


Figure 2. View of a dune strip before (left) and after (right) introduction of dynamic coastal management. Upper photos show the situation near transect 20.2 looking to the west in 1995 (A) and 2002 (B). Photo A shows a "white dunes" habitat with *Ammophila arenaria* (marram grass) on the seaward side and sand fences. Photo B shows the same location in 2002. Here we see embryonic shifting dunes grown with *A. arenaria* and *Elytrigia juncea* (sand couch) and "gray dunes" in the hinterland. Lower photographs show details of the front of the foredune near transect 10.0 to the east with (C) and without (D) human intervention in the form of sand fence placement in 1988 and 2012, respectively. (Color for this figure is available in the online version of this paper.)

stretches over 23 km. This expanse is divided into 200 m sections separated by line transects that correspond with and are numbered after beach posts (in km from west to east). The research area consists of coastal dunes between transects 19.6 and 21.6. Here, dynamic coastal management was introduced in two foredune sections in different years (Figure 2). Section 1 is the area between transects 19.6 and 20.6, where dynamic management was initiated in 1999. Section 2 is the area between transects 20.6 and 21.6. Here a dynamic management regime was implemented earlier, in 1995. In section 1, remnants of the old sand fences can still be found.

The orientation of the coast is west-east, with northerly winds blowing perpendicular to the shore. The longshore current direction is also west to east. The dominant wind direction is SW, with highest wind speeds in autumn. The tidal range at Ameland is approximately 2 m (semidiurnal), and a single foredune ridge about 10 m above NAP backs the beach (NAP refers to Amsterdam Ordnance Datum, which is more or less equal to mean sea level). The dominant plant species on the foredune are *A. Arenaria* and *Calammophila baltica* (Baltic marram grass). The study site is located in the predominantly noncalcareous district of The Netherlands, but lime content is about 1.3% in the beach sand and 0.5% in the older inner-dune sand. The sand on the beach is primarily composed of quartz grains, with some feldspar and small amounts of heavy minerals (Van der Wal, 2000). In the research area there are no (active) dune fields behind the foredune. According to Arens, Van Puijvelde, and Brière (2010), the sand budget on the eastern end of Ameland is slightly positive, at some 5 $m^3$/m annually (measured from 1975). Between transects 15 and 23, the sand budget is strongly positive, due to sand accretion in the foredune. In the storm season 2006–2007, there was erosion due to storms.

Extraction of natural gas at the study site has caused soil subsidence. This amounted to 0.22 m at transect 19.8 and 0.33 m at transect 21.4 from 1986 to 2011. Total subsidence is expected to reach 0.38 m in 2050 after extraction ends in 2035 (Eysink *et al*., 2000; Ketelaar, Van der Veen, and Doornhof, 2011). Progressive subsidence has been used as a model for relative sea level rise, as applied by Van Dobben and Slim (2012). According to predictions of the Intergovernmental

Table 1. *Months with extremely high water and/or extreme wave-height events. Extremely high water is defined as a water level greater than 250 cm. Extreme wave height is defined as a wave height above 660 cm. "High-water event?" (final column) indicates months with both an extremely high water level and an extreme wave height. An exception was made for February 1990; no extreme wave height was recorded in this month, but the water level measured was the highest in the period examined. Data derived from Rijkswaterstaat (2010).*

| Date | Water Level (cm) | Wave Height (cm) | High-Water Event? |
|---|---|---|---|
| November 1981 | 275 | 710 | Yes |
| February 1983 | 273 | 663 | Yes |
| February 1989 | | 686 | |
| February 1990 | 297 | | Yes |
| December 1990 | 253 | 814 | Yes |
| December 1991 | 255 | | |
| February 1993 | | 758 | |
| January 1994 | 269 | 725 | Yes |
| February 1999 | 251 | 756 | Yes |
| December 1999 | | 669 | |
| January 2000 | 266 | 723 | Yes |
| November 2006 | 272 | 880 | Yes |
| January 2007 | 253 | | |
| March 2007 | 271 | | |
| November 2007 | 281 | 841 | Yes |
| March 2008 | | 680 | |
| October 2009 | | 693 | |

Panel on Climate Change (Church *et al.*, 2001), a sea level rise of 0.44 m can be expected by 2100.

## Other Factors besides Dune Management Influencing Dune Formation

In order to evaluate the effect of dune management, other factors (*e.g.*, high-water events, wind climate, beach width and shape, and sand nourishments) that could cause a change in dune development were examined as well.

### High-Water Events

High-water events indicate storm surges that could potentially cause erosion of the foredune (Ruessink and Jeuken, 2002; Van Rijn, 2009; Zhang, Douglas, and Leatherman, 2002). Yet they are just that, an indication, because other factors, like wind force and wind direction, are important as well (*e.g.*, Morton, 2002). Rijkswaterstaat measures water level and wave height and makes these data available *via* its Web site (Rijkswaterstaat, 2010). For water level, this study uses data taken from the Wierumergronden measurement station located offshore NE of Ameland (53°31′ N, 5°58′ E). While there is a station on the island itself, it is located on the Wadden Sea side where impoundment occurs. Its data are therefore less representative of the coast on the eastern side of the island (Krol, 2011). For wave height, the station Schiermonnikoog Noord was chosen (53°35′ N, 6°10′ E).

Because no data from earlier than 1981 were available, water levels were analyzed for the period after 1981. For each month in the study period, the highest water level and wave height were selected. Only maximum values were used and not the frequency or duration of a high-water event. This is because the maximum value is most indicative of the impact of such an event (following Ruessink and Jeuken, 2002). Water levels exceeding 250 cm and wave heights above 660 cm were classified as extreme (Table 1).

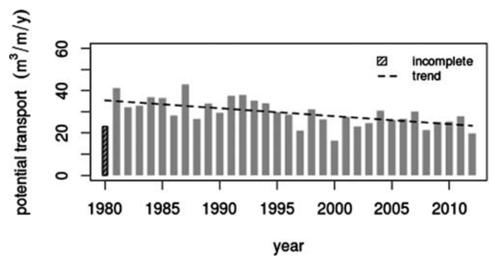


Figure 3. Yearly potential sediment transport based on climate data from the meteorological station of De Kooy, Den Helder, The Netherlands (52°56′ N, 4°47′ E).

High-water and high-wave events coincided in eight of the months studied (see column "High-Water Event" in Table 1). In these months, both water level and wave height were extreme near Ameland, indicating the possible occurrence of a storm surge. In February 1990, only water level was classified as extreme; however, because this level is the highest recorded in the study period, the authors elected to add February 1990 to the months in which a high-water event was recorded.

### Wind Climate

Wind climate can be calculated from hourly wind measurements. The meteorological station of Terschelling is closest to the study area but has data starting only in 1994. To study the wind climate from 1980 to 2010, another station had to be selected. The meteorological station of De Kooy provides data from 1980 and has the best correlation with station Terschelling for the 1994–2010 range (r = 0.93). As variation in wind climate is of interest rather than actual values of potential transport, wind measurements from De Kooy were used to calculate yearly values of transport potential.

The average yearly transport potential is about 30 $m^3$/m/y (Figure 3). However, the potential seems to decrease from 1980 to 2010. Assuming a linear trend, a least-squares linear regression indicates that the decrease is 0.3 $m^3$/m/y per year ($R^2 = 0.31$).

### Beach Width and Shape

To investigate if changes in beach morphology could account for changes in dune growth rate, the positions of the shoreline (where elevation is 0 m +NAP) and dune foot (where elevation is 3 m +NAP) were calculated. Furthermore, time sequences of profiles were examined to explore changes in the height of the beach (Figure 4).

Transects 19.6 to 20.4 show that the height of the beach increased from 1980 to 2010. This coincides with the seaward movement of the dune foot while the shoreline position remained constant, causing a reduction in the width of the dry beach from 200 m in 1980 to 150 m in 2010. In transects 20.6 to 21, there was little change in beach morphology, and both the dune foot and shoreline position were constant. Profiles east of 21 show dune foot retreat relative to the 1980 position, widening the dry beach from 120 m in 1980 to 150 m in 2010. From this we can conclude that changes in beach width and shape were minimal during the research period.

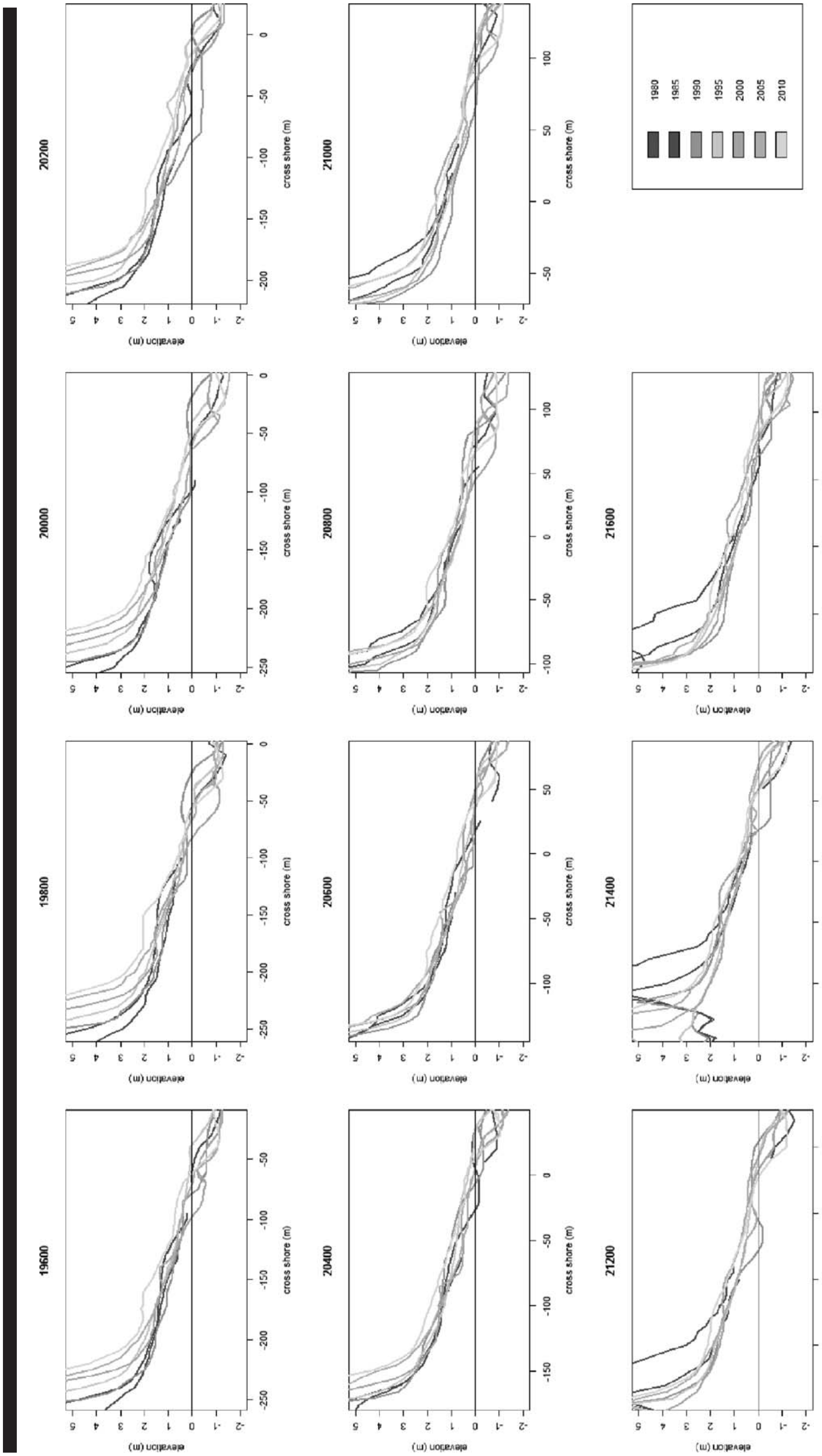


Figure 4. Cross-shore profiles of the dry beach for all transects in the study area (19,600 = 19.6, *etc.*). For clarity, only one measurement per 5 y is given. Cross-shore extent was limited to show only the dry beach and dune foot. Distances were measured from the beach post, with negative values being landward from the beach post. (Color for this figure is available in the online version of this paper.)

Table 2. *Foredune, beach, and foreshore nourishments on the northern coast of Ameland from 1980 to 2010. Data derived from Deltares (2012).*

| Year | Position | Amount ($m^3$/m) | Location (beach posts, km) |
|---|---|---|---|
| 1980 | Foredune | 367 | 10.0–16.0 |
| 1990 | Foredune | 202 | 12.4–17.0 |
| 1992 | Beach | 178 | 11.4–19.6[a] |
| 1996 | Beach | 388 | 7.2–11.2 |
| 1998 | Foreshore | 312 | 13.0–21.0 |
| 2003 | Foreshore | 332 | 9.4–13.6 |
| 2006 | Beach | 220 | 11.0–16.0 |
| | Foreshore | 300 | 12.0–17.0 |
| 2010 | Foreshore | 539 | 11.0–14.6 |
| | Foreshore | 562 | 14.8–16.8 |

[a] Nourishment stopped at the border of the study area.

### Nourishments

The "reference" coastline referred to in government policy has been maintained on Ameland since 1990. Where structural deviations have occurred, nourishments were undertaken (for temporary deviations no such intervention was deemed necessary). Table 2 lists the nourishments applied, both on the beach as well as in front of the dune and near the shore. Research shows the ratio between sand accretion and the amount of nourished sand to be 17% (Arens, Van Puijvelde, and Brière, 2010).

On the eastern stretch of the North Sea coast (east of transect 17), coastal safety is less of an issue than ecological quality because of the absence of human habitation in this area. A relatively flexible approach to maintenance of the coastline can therefore be taken (Provinciaal Overlegorgaan Kust Fryslân, 2000). For the study area, this means that a foreshore nourishment was applied only in 1998.

## Data and Data Analysis

To evaluate the shift in dune management, we looked at dune morphology and volume and dune ecology and appearance.

### Dune Morphology and Volume

To estimate the effect of the change in management on dune development, we made use of JAaRlijkse KUStmetingen (JARKUS), a database of cross-shore profiles of the Dutch coast maintained by Rijkswaterstaat since 1964 (*cf*. Arens and Wiersma, 1994). These coastal profiles (following the transects described above) are recorded annually after the storm season, which is from September to March. They extend from 200 m landward of the foredune some 800 m seaward. The distance between measurement points in a transect (horizontal resolution) is 5 m. Elevation is measured relative to NAP. Methods used to record the profiles have evolved over the years: leveling was used from 1964, followed by (aerial) stereophotogrammetry from 1977, and finally laser altimetry from 1996 (Minneboo, 1995; Bochev-Van der Burgh, Wijnberg, and Hulscher, 2011). The accuracies of these methods are estimated to be 0.01 m for leveling (Oosterwijk and Ettema, 1987), 0.1 m for stereophotogrammetry (Veugen, 1984), and 0.1 m for laser altimetry (De Graaf *et al*., 2003). Rijkswaterstaat considers an average deviation of ±0.04 m to be normal, which makes these data unsuitable for year-to-year comparisons (Rijkswaterstaat, 2010). Because of the scale of the changes (decimeters per year) and the number of years available, the JARKUS data are suitable for investigating trends over a longer period.

The foredune in this study is defined by the dune foot as its seaward border and the edge of the first dune as its inland border. The dune foot was set at 3 m +NAP following Van der Wal (2004), Bochev-Van der Burgh, Wijnberg, and Hulscher (2011), and De Vries *et al*. (2012). The yearly position of the foredune was derived by linearly interpolating the distance to the beach post from the spot where the foredune height is equal to the dune foot. The relative position is derived by comparing this yearly position to the position in 1980. Maximum dune crest height and crest position were extracted from the foredune profile. The volume of the foredune was calculated using the following formula:

$$V = \sum_{i=1}^{n} ((Av(H_i, H_{i+1}) - 3) \times D_{i,i+1}), \tag{1}$$

where $V$ is the volume of the foredune and $Av(H_i,H_{i+1})$ is the average of the height at point $i$ (landward side) and the height at point $i$+1 (5 m seaward). The factor –3 is a correction to the actual height, since the dune foot is set at +3 m and only the volume above this base is accounted for. $D_{i,i+1}$ is the distance between $i$ and $i$+1 (5 m in this case).

This equation gives the volume of the foredune for a transect that is 1 m in width. Years with incomplete records were omitted. Total volume of the foredune was derived by summing the volumes of the individual transects. The results were extrapolated by multiplying the volume of the transect by 200 m to cover the whole area represented by these transects (except for transects on the edges, which were multiplied by 100 m).

The growth rate was determined per transect and per section by calculating the difference in volume between each year and the previous year. For both sections, the changes in dune foot position, crest position, crest height, and foredune volume were tested for significance by an independent-samples t test using IBM© SPSS® Statistics.

### Dune Ecology and Appearance

To analyze the effect of the change in coastal dune management, we made use of existing monitoring data. Vegetation cover, vegetation composition, and foredune appearance were monitored between 1995 and 2002. Detailed results can be found in Krol (2006). For vegetation monitoring, each section was divided into 10 plots with a length of 100 m along the shore and the width of the foredune (50–70 m). The frequency of each vascular plant species was estimated annually in June/July. This was done visually using the scale of Tansley (1965) for frequency of occurrence. For vitality of *A. arenaria* an estimation scale was used with three classes: languishing (light green leaves, >70% dead biomass), dense (green leaves, 30–70% dead biomass), and thriving (dark green leaves, <30% dead biomass). Plant species were identified according to Stace (2010).

## RESULTS

To analyze the influence of dynamic coastal management on the foredune, a comparison was made between section 1 and section 2 before, during, and after the reference period (1995–1999). During the reference period, the traditional soft engineering approach to management was applied in section

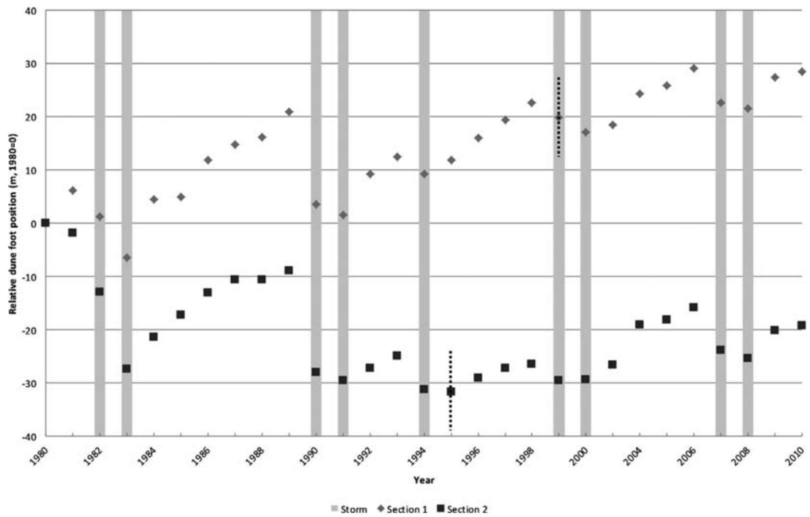


Figure 5. Relative position of the dune foot (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section, with positive values indicating a seaward shift of the dune foot position. Vertical lines indicate the introduction of dynamic coastal management. High-water events (storm) are indicated by high bars.

1 (transects 19.6 to 20.6), while in section 2 (transects 20.6 to 21.6) dynamic management was implemented, replacing the soft engineering approach.

## Dune Morphology and Volume

### Dune Foot Position

The position of the dune foot varied over time in both sections (Figure 5). Periods of seaward movement were followed by quick retrogradation at certain points. Adding the high-water events to the graph, we see that these points coincide with high-water events. On average, the dune foot in section 1 moved seaward (30 m), whereas the dune foot in section 2 moved landward (20 m). After introduction of dynamic coastal management, the position of the dune foot showed similar patterns.

### Crest Position

The relative crest position at first moved seaward in section 1 and landward in section 2 (Figure 6), ceasing in 1994 for section 1 and in 1998 for section 2 with no marked changes observed thereafter. After the introduction of dynamic coastal management, crest position remained fairly stable in both sections. In section 1, however, stabilization started in 1994, before dynamic management was introduced.

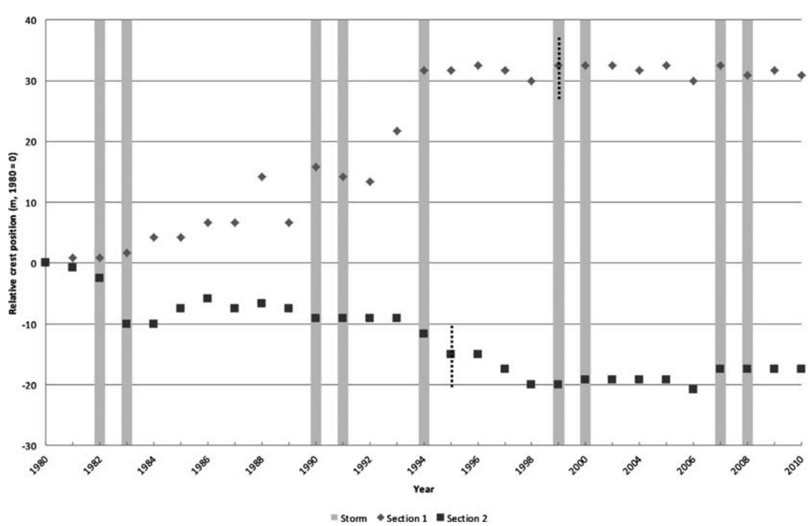


Figure 6. Relative position of the dune crest (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section, with positive values indicating a seaward shift in crest position. Vertical lines indicate the introduction of dynamic coastal management. High-water events (storm) are indicated by high bars.

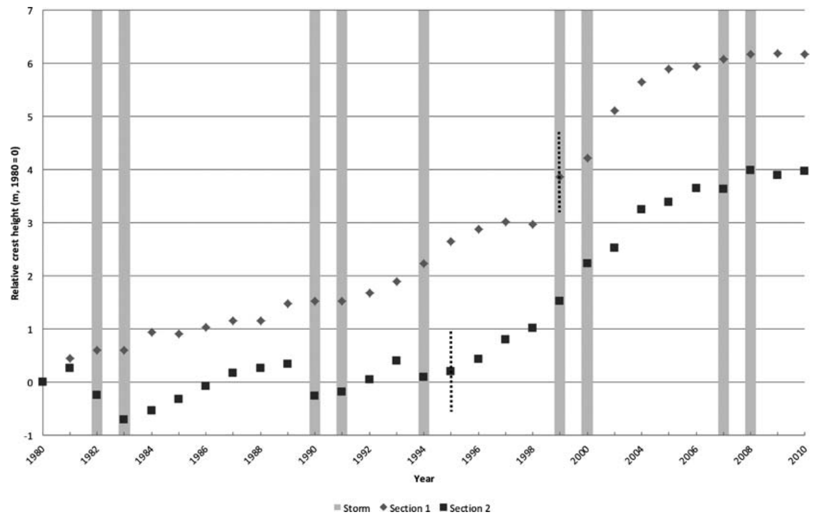


Figure 7. Relative height of the crest (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section. Vertical lines indicate the introduction of dynamic coastal management. High-water events (storm) are indicated by high bars.

### Crest Height

Crest height increased steadily in section 1 but stabilized at about 6 m after 2004 (Figure 7). Section 2 showed periods of growth and decline in crest height until 1995. After that its height was comparable to that of section 1 (which showed growth followed by stabilization). In section 2, this stabilization almost coincides with the shift to dynamic management.

### Foredune Volume

The volume of the foredune is a measure of dune development. Our data show a fairly steady increase, though interrupted by two periods of considerable decrease (1982–1983 and 1990–1991) (Figure 8). These periods coincide with high-water events (storms). Outside these periods, growth followed a nearly linear trend, with rates of increase for the whole foredune in the study area (transects 19.6 to 21.6) of 24,823 $m^3$/y between 1983 and 1989, and 19,173 $m^3$/y between 1991 and 2008. Even including the years of decrease, the total volume of the foredune rose from 264,140 $m^3$ in 1980 to 597,460 $m^3$ in 2008, an average growth of 11,904 $m^3$/y. Between 1997 and 2006 the trend lines for the two sections were almost parallel (slope of 11,051 $m^3$/y for section 1 *vs.* 10,343 $m^3$/y for section 2). In the earlier period, growth was slower in section 2 (2,611 $m^3$/y between 1990 and 1996) due to a washover event.

### Statistical Analysis

To see how the foredunes recover after a storm surge under both management types, we compared the growth rate and other parameters in the years between these events (Table 3).

Before the introduction of dynamic management, the growth rate was much higher in section 1 than in section 2. After the shift in management regime, the average annual change in volume was almost equal for the two sections.

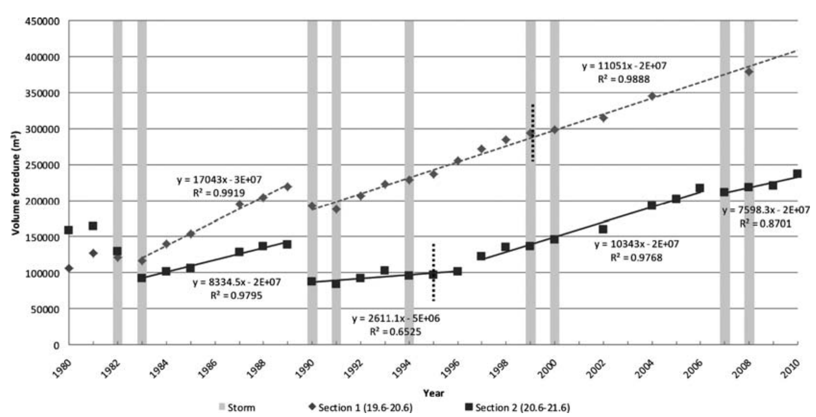


Figure 8. Foredune volume in sections 1 and 2 between 1980 and 2010. Two and three linear trend lines with corresponding breaks are shown for section 1 and section 2, respectively. Vertical lines indicate the introduction of dynamic coastal management. High-water events (storm) are indicated by high bars.

Table 3. *Average changes per section in dune foot position, crest position, crest height, and volume with results of independent-samples t test (p). The period of traditional management using a soft engineering approach (Eng.) is 1980–1998 for section 1 and 1980–1994 for section 2. The period of dynamic coastal management (Dyn.) is 1999–2010 for section 1 and 1995–2010 for section 2. For calculating p in section 1, 6 years in the period 1990–1998 (engineering) versus 6 years in the period 1999–2010 (dynamic) were compared in order to have two equal data series (n is the same). Years with incomplete data and years with high-water events (storms) were excluded when calculating the average values.*

| | Section 1 | | | Section 2 | | |
|---|---|---|---|---|---|---|
| Management Type | Eng. | Dyn. | *p* | Eng. | Dyn. | *p* |
| Dune foot position change (m/y) | 4.4 | 2.5 | 0.01 | 2.4 | 1.9 | 0.43 |
| Crest position change (m/y) | 0.9 | −0.3 | 0.24 | 0.2 | −1.0 | 0.05 |
| Crest height change (m/y) | 0.2 | 0.2 | 0.30 | 0.2 | 0.2 | 0.75 |
| Volume change per transect ($m^3$/y) | 3302 | 2453 | 0.09 | 1695 | 2052 | 0.32 |

Movement of the dune foot position was reduced for both sections after the introduction of dynamic management, whereas the evolution of the crest position reversed, from a seaward movement to a slight landward shift. For crest height, no influence of management type was observed.

In most cases there was no significant difference between the situation before and after change in dune management. Only the dune foot position in section 1 showed a significant difference.

## Characteristic Profiles

Characteristics of two of the transects, transect 19.8 and transect 21.4, are described in more detail here.

### Transect 19.8

The profile in Figure 9 is characteristic of transect 19.6 to 20.6. The red line (dune foot) marks the part of the foredune that was used to calculate the volume. After 1980 the foredune developed rapidly in height and in a seaward direction. No changes were found in the first years of dynamic coastal management, but after 2004 a new incipient dune became established, which had reached a significant height and volume by 2010.

### Transect 21.4

This transect marks the location where a washover event occurred in 1994 (between transect 21.0 and 21.6). In 1980 there was a foredune at about the position of the beach post (0 m). After a decline and brief increase in the following years, in 1992 just a small foredune was observed. That foredune had disappeared in 1995, at which point a new foredune developed (at about –40 m) (Figure 10).

Between 1998 and 2010, a new foredune developed. The top of this foredune moved from –40 m to –30 m during those 12 years, and the foot of the foredune slowly moved seaward. Contrary to the more westward section 1 (described above under “Transect 19.8”), no incipient dune had yet developed here. Because the washover event occurred at about the same

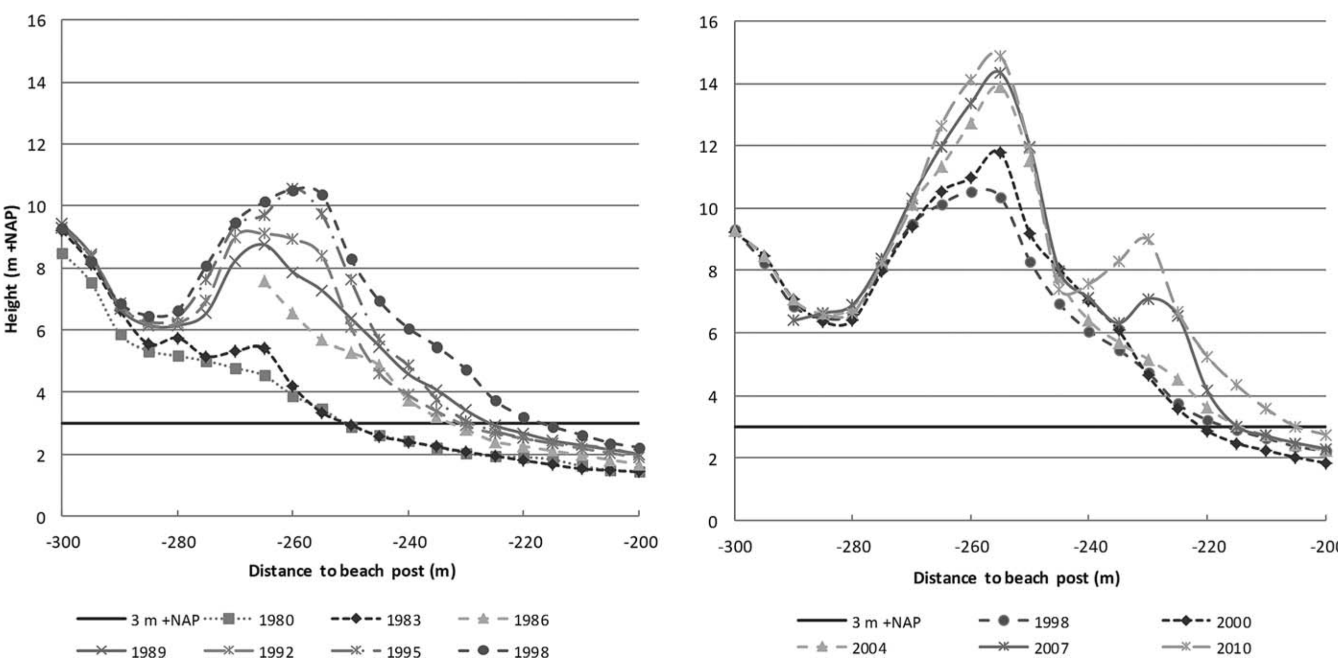


Figure 9. Cross-shore profile of the foredune at transect 19.8 for the period of traditional soft engineering management (left) and dynamic management (right). Distances are measured from the beach post, with negative values being landward from the beach post. (Color for this figure is available in the online version of this paper.)

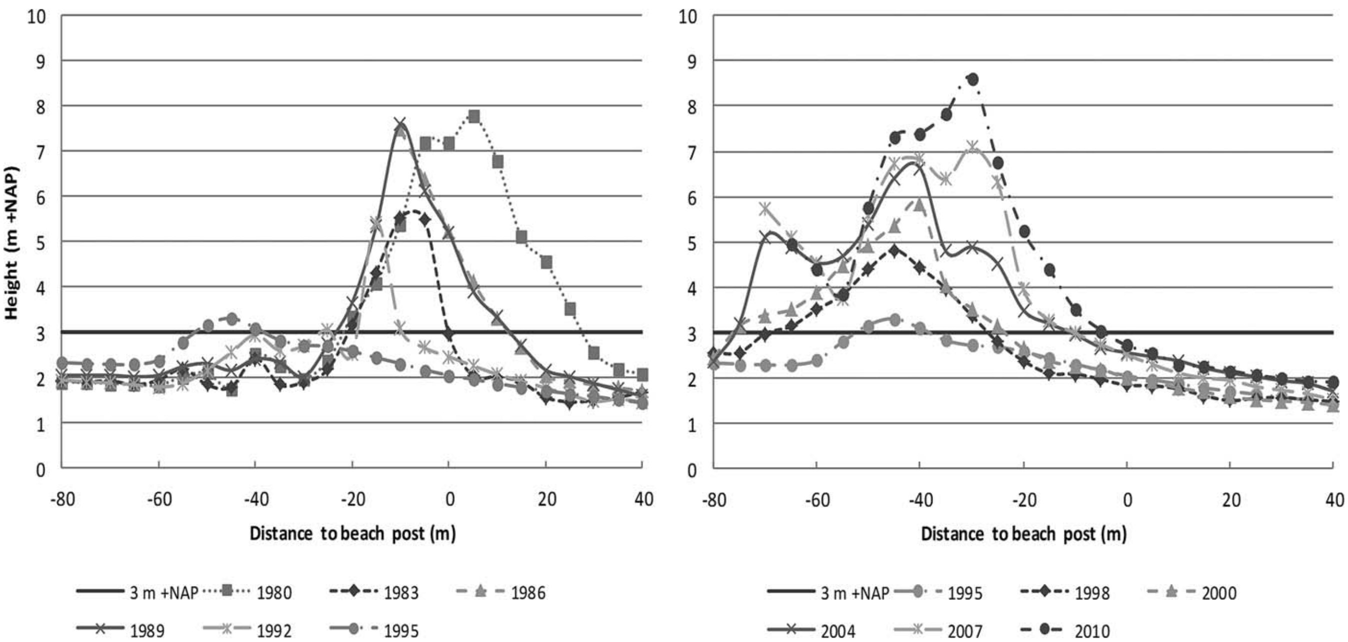


Figure 10. Cross-shore profile of the foredune at transect 21.4 for the period of traditional soft engineering management (left) and dynamic management (right). Distances are measured from the beach post, with negative values being landward from the beach post. (Color for this figure is available in the online version of this paper.)

time as the change in management type, it is difficult to compare the periods before and after this shift.

## Morphologically Distinct Zones

Based on these cross-shore profiles, three morphologically distinct zones can be distinguished between transects 19.6 and 21.6:

(1) Expanding dune: transects 19.6 to 20.6 are characterized by structural growth, seaward development, and establishment of an incipient dune.
(2) Transition zone: transects 20.6 to 21.0 make up a transition zone where no incipient dune has formed. Initially the foredune receded, but no washover took place.
(3) Washover: transects 21.0 to 21.6 were influenced by a washover event in 1994. At this location, the foredune is lower, and after the washover event the position of the foredune shifted landward.

## Ecological Effects of Dynamic Coastal Management

Table 4 shows the plant species present in both sections. Section 2 has fewer species than section 1, but species richness increased over the years in both sections (after a dip in 1999).

According to Table 4, the characteristic (vascular) plant species are clearly increasing. Three typical "white dune"

Table 4. *Presence of characteristic plant species in sections 1 and 2. Values indicate number of plots where species were found (*n = 10*). The table shows the three years in which vegetation was monitored between 1995 and 2002. Species are ordered according to their zonation in a landward direction, starting at the beach. The bottom two rows indicate vitality of* Ammophila arenaria *using the estimation scale (0 = languishing [light green leaves, >70% dead biomass], 1 = dense [green leaves, 30–70% dead biomass], 2 = thriving [dark green leaves, <30% dead biomass]) and the total number of vascular plant species found.*

| | Section 1 ($n$ = 10) | | | Section 2 ($n$ = 10) | | |
|---|---|---|---|---|---|---|
| | 1995 | 1999 | 2002 | 1995 | 1999 | 2002 |
| Characteristic species | | | | | | |
| *Elytrigia juncea* | 0 | 0 | 10 | 0 | 0 | 10 |
| *Leymus arenarius* | 0 | 1 | 10 | 0 | 1 | 7 |
| *Cakile maritima* | 2 | 2 | 10 | 2 | 5 | 10 |
| *Ammophila arenaria* | 10 | 10 | 10 | 10 | 10 | 10 |
| *Sedum acre* | 0 | 5 | 10 | 7 | 6 | 5 |
| *Taraxacum* sect. *Erythrosperma* | 5 | 7 | 9 | 4 | 4 | 5 |
| *Cerastium semidecandrum* | 5 | 10 | 10 | 0 | 1 | 5 |
| *Calamagrostis epigejos* | 10 | 10 | 7 | 6 | 5 | 2 |
| Vitality of *Ammophila arenaria* | 1 | 1 | 2 | 2 | 2 | 2 |
| Number of vascular plant species | 28 | 23 | 38 | 23 | 20 | 32 |

species—*Elytrigia juncea* (sand couch), *Leymus arenarius* (lyme grass), and *Cakile maritima* (sea rocket)—became more dense on the seaward side of the dune. On the landward side, increases were recorded of *Sedum acre* (biting stonecrop), *Taraxacum* sect. *Erythrosperma* (dandelion), and *Cerastium semidecandrum* (little mouse ear), while *Calamagrostis epigejos* (wood small reed) diminished. *Ammophila arenaria*, which is characteristic of the foredune in between these zones, showed no change. It was present on every plot during the whole period.

### Section 1 (Transects 19.6 to 20.6), 1995–2002

The seaward part of section 1 consists of a slope covered with thriving *A. arenaria*. The landward part is steeply sloped, with similar vegetation cover. The vitality of *A. arenaria* clearly increased between 1995 and 2002. Sand is trapped by *A. arenaria*, preventing large-scale blowing of sand over the dune. The vegetation cover varies around 30% and does not appear to have changed between 1995 and 2002, despite increased sand drift. The absence of sand fences did not lead to erosion. The previously bare squares between the fences seem to have been covered by plants of the community *Elytrigia juncea*, possibly pointing to establishment of a more natural dune foot (trapping more sand than before). No erosion of the dune foot was observed after 1995; rather there was mainly sedimentation. Further, variation across the foredune increased, giving the dune a more natural appearance. Variety in relief of the dune surface increased as well. The less intense management regime thus did not result in greater erosion of the foredune, and the natural quality of the area was reinforced.

### Section 2 (Transects 20.6 to 21.6), 1995–2002

The seaward part of section 2 consists of a steep and bare slope. Due to the absence of fences, sand is blown directly to the crest of the foredune, which grew high and steep as a result. Thriving *A. arenaria* grew on the narrow crest. Some of the sand is blown from the crest to the vegetation behind the foredune. The landward side of the foredune is also steeply sloped and covered with *A. arenaria*. This section is very dynamic, which is the reason why few species are found. The vitality of *A. arenaria* was optimal during the entire period, leading to a considerable increase in the height of the foredune. No change in vegetation cover was observed.

At about transect 21.4, a large washover event took place in 1994, allowing seawater to enter the dunes. In 1995 the original foredune was hardly evident here: Just a single tussock of *A. arenaria* marked its location. Further, only a low ridge of drift sand, 20 m wide, was present. From 1995, the washover opening was closed by drift sand, and a new foredune rose up 30 m landward from the original foredune. Variation between erosion and sedimentation due to thriving tussocks of *A. arenaria* in the foredune led to development of a more natural foredune. A number of spots of erosion were observed in 2002. The sand fences had, by that time, been replaced by a more natural transition from dune to beach that was still in full development. Refraining from placing sand fences, thus, did not lead to degradation of the foredune but to a more natural development without erosion. The crest is very dynamic with some bare spots, but *A. arenaria* persists, trapping drift sand.

## DISCUSSION

The traditional soft engineering approach to management was to catch sediment in front of the foredune by placing sand fences and planting a dense pattern of *A. arenaria*. In periods between major storms (*e.g.*, from 1983 to 1989), this resulted in a seaward shift of the dune foot position (Figure 5). After introduction of dynamic coastal management, the dune foot position also showed a similar seaward shift.

The seaward movement of the crest position in section 1 corresponds with the accumulation of sediment in front of the dune under soft engineering management (Figure 6). In section 2 we see a small landward shift. Looking at the individual profiles (Figure 10), we observe a greater impact of storm surge events in this section.

In section 1, crest height increased both before and after the introduction of dynamic coastal management (Figure 7). Arens (2007) also found increases in foredune height as well as width. This indicates substantial sediment transport to the crest, despite the large amount of sand trapped at the dune foot (Figure 9). The differences in dune development between sections 1 and 2 cannot be explained by management type.

The changes in foredune volume (Figure 8, Table 3) indicate little or no influence of the two types of coastal dune management investigated. In section 2 the growth rate was greater after introduction of dynamic management, but this seems to be related more to the washover event in 1994 than to the change in management. Smaller dunes are relatively more dynamic and exhibit greater erosion, so they present lower net growth.

Although the aforementioned data do not indicate an effect of dynamic coastal management on dune foot position, crest position, crest height, or dune volume, the appearance of the foredune and its ecological quality did clearly change. The increase of plant species that are characteristic of dynamic circumstances on both the seaward and the landward side of the foredune confirms greater sand movement under dynamic management.

Visual inspections between 1995 and 2002 found increased vitality of *A. arenaria*. This effect is also described by Van der Stoel, Van der Putten, and Duyts (2002) and is related to regular sediment deposition on the vegetation. This points to higher and more frequent sediment transport and deposition on the foredune. The less regular vegetation cover observed indicates a larger spatial variety in these processes.

In section 1, *E. juncea* benefited from the remnants of the sand fences. Development of *E. juncea* led to increased sediment trapped in this zone, which was also indicated by the seaward shift of the dune foot (Figure 5). In section 2, the sand fences disappeared during the washover event. The lack of vegetation development provided room for sediment transport and development of a new dune inland of the old location. The landward movement of the dune continued until vegetation cover was high enough to hold it stable (Figure 6).

Reducing the intensity of management did not lead to increased erosion of the foredune, while its natural quality was reinforced. Similar observations were made by Arens, Löffler, and Nuijen (2007) of other locations along the Dutch coast where a dynamic management regime was introduced.

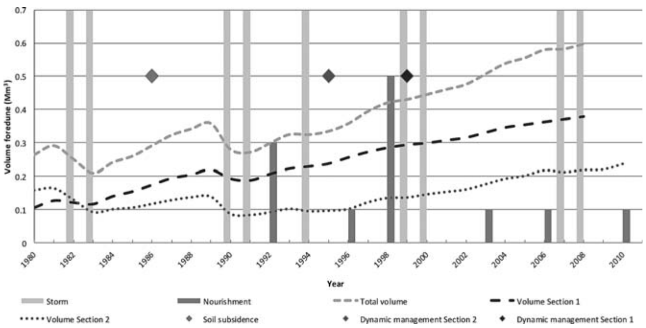


Figure 11. Total foredune volume (transects 19.6 to 21.6) and volumes of sections 1 and 2 between 1980 and 2010, with markers for high-water events (storm), beach nourishments on the north coast of Ameland, introduction of dynamic coastal management, and the start of soil subsidence. High-water events and nourishments have a different temporal scale and are therefore not represented on the y-axis. High-water events are indicated by high bars. For sand nourishments, a distinction is made between nourishments within the investigated foredune and those to the west of this area. The former are represented by high bars, with the nourishment of 1992 reaching to transect 19.6 and that in 1998 reaching to transect 21.0. Low bars indicate nourishments farther west (up to transect 17). Foredune nourishments outside the study area (1980 and 1990) are not displayed. Dynamic coastal management was introduced in section 2 in 1995 and in 1999 for the rest of the foredune. Natural gas extraction started in 1985, with soil subsidence starting in 1986. (Color for this figure is available in the online version of this paper.)

To look at the results of the different management regimes under the impact of storms, nourishments, and soil subsidence, we combined these factors with volume development in Figure 11. The change in volume is given for both the whole foredune (sum of section 1 and section 2) as well as individually for the two sections investigated. Most of the nourishments were applied west of the research area. In 1992 the beach was nourished up to transect 19.6; only in 1998 was the research area itself nourished on the foreshore (and then just until transect 21.0). Natural gas extraction began in 1985, with the first soil subsidence recorded in 1986.

Volume increase (Figure 11) is continual but interrupted. The largest interruptions (in 1981, 1990, and to a lesser extent 1994) coincide with storms. Nonetheless, the storm events of 2006 and 2007 demonstrate that this relationship is not a given, as no decrease in volume was observed in those years. Van der Wal (2004) suggests that a higher foreshore or beach in 2006 and 2007 absorbed the erosive force of the storm, leaving the dune intact. Or a larger buffer might have been present at the dune foot, which was resupplied relatively quickly after the storms. Observations in the dunes support this latter suggestion. At Ameland we observed in 2006, for example, that a foredune with a cliff, created by storm surge, was soon restored by aeolian sediment supply. Arens (2007) found that incipient dunes that formed in front of the foredune absorbed most of the erosive force of the storm in 2006.

The effect of major storm surges on dune volume is in line with the findings of Zhang, Douglas, and Leatherman (2002) and Bakker *et al*. (2012). Development of the foredune was interrupted, but not reversed, by erosive events. After some time the foredune recovered, and the volume growth rate returned to the long-term trend. The growth rate in the period between two erosive storm events seems not to be affected by the storms but controlled by other factors, like beach width and available sand budget (Ruessink and Jeuken, 2002).

No direct effect of nourishments was observed on the foredune volume growth rate. As mentioned earlier, a time delay is sometimes observed between nourishments and noticeable changes in foredune volume (Bochev-Van der Burgh, Wijnberg, and Hulscher, 2009). The period of the delay depends on the time interval between applications, the location of the applications (*e.g*., on the beach, on the shore face, or against the dune front), distance to the coast, and the quality of the nourishment. However, no such delay was observed for the dune sections in this study.

Soil subsidence, which started in 1986 due to gas extraction, did not affect dune development in the sections analyzed. It can even be concluded that the average growth rate over the whole period easily compensated for subsidence, given that the research area is situated very near the center of subsidence, where up to 0.34 m subsidence has been measured (see Ketelaar, Van der Veen, and Doornhof, 2011).

## Limitations of the Methods Used

In general, the transects can be assumed to give a representative picture of the behavior of the foredune. But if few transects are included, a single transect representing an atypical area could have a large influence on the averages. This might be the case for the transects in the washover area of section 2. Furthermore, it might be questioned whether the foredune was correctly depicted. On the seaward side, the delineation is uniform and comparable for the different transects. But on the landward side the transects are delineated differently, meaning that the lengths of the transects vary.

Inaccuracies were also revealed in determining the crest position because of the spatial resolution (of 5 m) of the JARKUS database. Additionally, the emergence of a new foredune at some transects caused a sudden shift in average crest position, especially when both the "old" and "new" crests had about the same height during a "transition" period of some years.

The different temporal scales of the mechanisms under study might have influenced our comparisons of the factors investigated. For example, nourishments act on a larger temporal scale (years to decades), whereas storms have a direct on-site effect. Moreover, because of the uncontrolled and *ex post facto* character of this study, no replications could be made. Furthermore, storms are analyzed per month, while JARKUS has a temporal resolution of one year (see Bakker *et al*., 2012). For this reason, the influence of storms in the last months of one year are included in the volume measurements of the next year.

Finally, it is unclear whether the two coastal sections used in this study are in fact comparable on a one-to-one basis. Section 1 started with a much larger volume of the foredune in 1990. Section 2 was influenced by the washover event, which greatly affected the development of the foredune. Furthermore, section 1 is located to the west of section 2. The direction of sand supply is from west to east, and the sand nourishments were to the west as well; this might have produced a larger sand supply for section 1.

## CONCLUSIONS

The goal of dynamic coastal management can be formulated "to restore natural processes along the coastline and in the accompanying habitats while maintaining safety" (RIKZ, 2003). Yet, until recently, little was known about the short-term effects of dynamic coastal management or about the medium-term impact of this new management regime on the development of foredunes. From this study, four conclusions can be drawn.

First, the introduction of dynamic coastal management did not negatively affect volume growth of the foredune in the investigated sections of the Dutch coast of Ameland.

Second, dynamic coastal management resulted in the establishment of a more natural foredune and corresponding dune foot. It further led to an increase in characteristic plant species, indicating enhancement of the natural quality of both the "embryonic dunes" and "white dunes" habitat types.

Third, high-water events, which interrupted the nearly linear volume growth of the foredune, appear to be the main factor affecting the volume growth of the foredune. But they did not affect the growth rates in the period between the erosive storms.

Finally, the relatively small impact of the 2006 and 2007 storms on dune volume suggests a better protection of the dune front by natural vegetation. Without knowing the exact force of the different storms on the dunes, however, this is merely conjecture. Further research is needed on the development of vegetation (*e.g.*, density of cover, patterns, and rooting depth) and its ability to withstand an erosive storm event.

The introduction of dynamic coastal management appears to have been a positive step. It had no negative effect on the volume of the foredune, while it did enhance the foredune's natural quality. As long as the foredune volume continues to grow and nature profits from a dynamic coast, we recommend abstaining from nourishments on the island of Ameland east of transect 17.

Lastly, we would like to stress the importance of the JARKUS database and recommend continuation of this annual measurement of the coast. The availability of such databases makes it possible to investigate the effects of management in both the short term and the long term. From this perspective, it is recommended that the complete foredune be covered annually, instead of focusing on a smaller zone as was done in some previous years.

## ACKNOWLEDGMENTS

This research is part of the Kennis Basis IV (KBIV) strategic research program "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 Rijkswaterstaat for collecting and providing the data used, especially Tonnie Overdiep for facilitating the research on sections 1 and 2 and It Fryske Gea for permission to enter the research area. The authors also thank Michelle Luijben and several anonymous reviewers for their comments, which helped to improve this manuscript.

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