Modelling foredune dynamics in response to climate change

J.G.S. Keijsers

Thesis committee

Promotor
Prof. dr C.J. Ritsema
Professor of Soil Physics and Land Management, Wageningen University

Co-promotors
Dr. M.J.P.M. Riksen
Assistant professor, Soil Physics and Land Management Group, Wageningen University

Dr A.V. De Groot
Researcher, IMARES Wageningen UR

Other members
Prof. dr. J. Wallinga, Wageningen UR, The Netherlands
Prof. dr. ir. M.J.F. Stive, TU Delft, The Netherlands
Prof. D. J. Sherman, University of Alabama, USA
Dr. A. C. W. Baas, King's College London, UK

This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

Modelling foredune dynamics in response to climate change

J.G.S. Keijsers

Thesis submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. A. P. J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 30 November 2015
at 08.30 am in the Aula

J.G.S. Keijsers
Modelling foredune dynamics in response to climate change, 191 pages.

PhD thesis, Wageningen University, Wageningen, NL (2015)
With references, with summary in English

ISBN 978-94-6257-584-4

Contents

1

Introduction

1.1 Context and research goals

Coastal dunes are prominent features along many of the world's sandy shorelines, covering 34% of the world's ice-free coasts (Hardisty, 1994) and long stretches of the European shores (Fig. 1.1A). They are the result of complex interactions between wind, waves, sand and vegetation (Klijn, 1981) and have a natural capacity to reduce storm impacts and to keep up with sea-level rise by accumulating sediments (Temmerman *et al.*, 2013). Consequently, dunes are indispensable for flood protection of the hinterland. In addition, they are considered valuable for fresh water supply, recreational hotspots and habitats for specialised plants and animals (Carter, 1990; Martinez *et al.*, 2004; Barbier *et al.*, 2011). The flood protection function is especially important for The Netherlands, as one-third of the country is below sea level (Louisse and Meulen, 1991) and the country relies on them for flood protection along most of its coastline (Fig. 1.1B).

Given their dependency on multiple natural processes, coastal dunes may be particularly sensitive to the effects of climate change, including sea-level rise. Most obviously, dunes may experience increased erosion associated with higher sea levels (Leatherman *et al.*, 2000; FitzGerald *et al.*, 2008; Ranasinghe *et al.*, 2012). However, other consequences, such as possible shifts in wind climate and wave climate and changes in temperature and precipitation regime (Van den Hurk *et al.*, 2007; KNMI, 2014) might alter the rate of dune-building processes. A change in wind patterns might lead to differences in aeolian delivery of sand, while increased summer drought might reduce vegetation cover, exposing a larger surface to eroding winds.

Under current climate and management conditions, dunes are able to cope with disturbances, e.g. storm surges or dry periods. However, if the frequency or magnitude of these

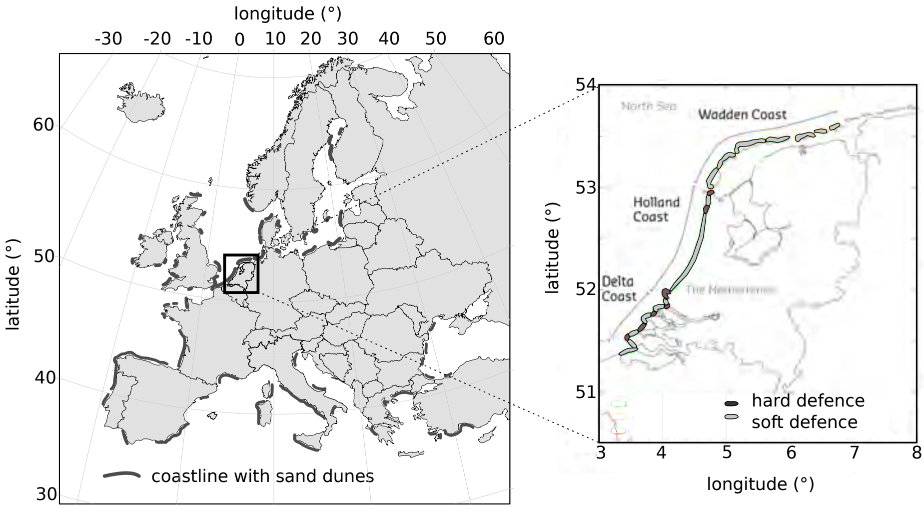

Figure 1.1: Presence of coastal dunes along the European (A) and Dutch (B) shorelines. Adapted from Géhu (1983); Klijn (1990) (Europe) and Mulder *et al.* (2011) (The Netherlands). 'Soft defence' represents section where sand dunes form the primary flood defence. 'Hard defence' indicates the presence of hard, engineered structures.

disturbances is altered and the effectiveness of dune-building processes changes, more complex responses can be expected (Carter, 1990; Martinez *et al.*, 2004). Also, sand dunes are known to exhibit threshold behaviour, with shifts between mobile and stable states (Yizhaq *et al.*, 2009; Arens *et al.*, 2013a; Tsoar, 2005). Such shifts would strongly influence flood hazards. Therefore, the first goal of this thesis is to increase our insights in climate change impacts on coastal dunes to better anticipate or prevent negative impacts on flood protection.

Before 1990, about 0.2 km^2 of dunes disappeared yearly through coastal retreat (De Ruig, 1998). Dune management at that time was aimed at dune stabilisation with vegetation plantings and sand fences, resulting in tall, static dunes and limited sand transport landward of the first ridge (Klijn, 1990; Arens and Wiersma, 1994). To halt the negative trend, the Dutch government adopted a policy of Dynamic Preservation in 1990 (Ministerie van Verkeer en Waterstaat, 1990). This policy aims to maintain the coastline at its 1990 position by applying 6 Mm^3 of sand nourishments annually. These are placed either on the shoreface, beach or dune itself. In contrast to the traditional reactive management approach, this strategy uses natural processes to redistribute sand over the beach and dune area and relies on the capacity of dunes to recover after storms, 'as long as the safety of the inland area is ensured' (TAW, 2002). However, little is known about the effect of dynamic coastal dune management on var-

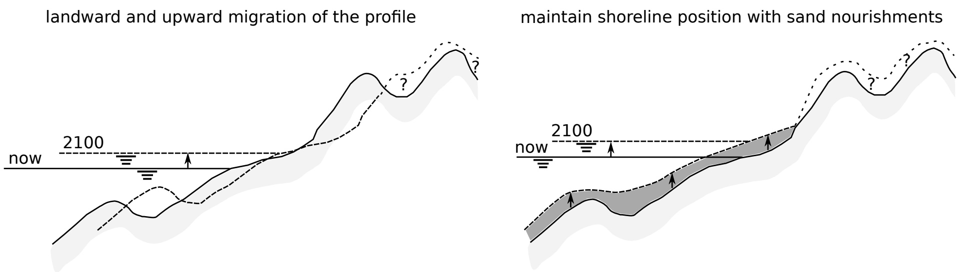

Figure 1.2: Cross-shore responses to sea-level rise: upward and landward migration expected under natural conditions (left) and upward shift expected under current sand nourishment policy (right). Adapted from MinV&W (2000).

ious dune functions, even though such management has already been introduced on a large spatial scale.

In the next decades, the nourishment regime will be intensified to raise the beach profile proportionally to the sea-level rise, expressed as 'growing with the sea' (Helmer *et al.*, 1996; MinV&W, 2000, 2009). The underlying assumption is that natural processes distribute the nourished sand over the shoreface, beach and dune zone in such a way that dunes are able to 'grow with the sea level' and maintain their height relative to the sea level (Figure 1.2). The second goal of this thesis is therefore to elucidate the effects of dynamic management on dune functions and long-term preservation of the foredune system.

1.2 Scientific background of foredune dynamics

1.2.1 Definition and formation of foredunes

This work focuses on the most seaward dune ridge, or 'foredune'. In their position on the interface between sea and land, foredunes are actively being formed and modified by aeolian, marine and biological processes. They can be separated into incipient, or newly formed, and established dunes (Hesp, 2002). Incipient dunes, with horizontal and vertical size in the order of 1-3 m, result from sand deposition within pioneer plants or other roughness elements on the beach, seaward of the larger dunes. Their formation is generally promoted on wide beaches and in periods without major storm surges, providing a window of opportunity for establishment of vegetation and dune formation. If high tides or storm surges occur, these embryonic dunes may be eradicated. Over time, incipient dunes may develop into established dunes. The latter, often between 5-20 m high, are characterised by more complex topography, greater height compared to incipient dunes and the growth of intermediate, successional vegetation species (Hesp, 2002). Once established, foredunes can become long-term features of the coastline, contributing to flood protection.

1.2.2 Overview of relevant national and international research

The spatial extent of this work is limited to the coastline of The Netherlands. Coastal dunes in The Netherlands have been the subject of a considerable amount of research. Early works include a detailed geological history of coastal dunes in the Netherlands, identifying large-scale relationships between storminess, sea-level rise and dune formation (Van Straaten, 1961; Jelgersma and Van Regteren Altena, 1969), followed by smaller-scale studies of processes contributing to dune development, e.g. sand transport by wind, dune erosion and blow-out formation (Svasek and Terwindt, 1974; Van de Graaff, 1977; Jungerius *et al.*, 1981; Kroon and Hoekstra, 1990). An inventory of foredune morphologies in the Netherlands by Arens and Wiersma (1994) provided a first classification of dune types, based on management, vegetation and topography. Following the shift towards using sand nourishments as main management strategy in 1990, detailed investigations of nourishment effects on aeolian transport and coastal dunes were made (Van der Wal, 1998b, 2004). Recently, novel management approaches such as 'Dynamic Preservation' and 'Building with Nature' have spurred coastal research in the Netherlands, leading to improved measurement techniques, better understanding of relevant processes and more effective coastal management strategies (Arens *et al.*, 2004; Bochev-Van der Burgh *et al.*, 2011; De Groot *et al.*, 2012; De Vries *et al.*, 2012a).

Also internationally, the development of foredunes has been studied extensively, as is clear from a review of foredune literature by Hesp (2002). Long-term monitoring and sand trap measurements highlight the complexity involved in predicting sand supply to foredunes (e.g. Davidson-Arnott and Stewart, 1987; Davidson-Arnott and Law, 1990, 1996; Bauer and Davidson-Arnott, 2002; Delgado-Fernandez and Davidson-Arnott, 2011). Detailed process studies by Hesp (1989, 1983, 1981) revealed intricate relationships between vegetation, sand supply and wind velocity in the formation and development of incipient dunes. Much of his conclusions can also be applied to established foredunes. Lastly, studies of vegetation patterns in a range of coastal dune environments have shown strong correlations between vegetation characteristics and dune development (Olson, 1958; Ranwell, 1972; Sarre, 1989).

1.2.3 Processes and scales involved in foredune dynamics

The beach-dune system represents a dynamic environment, where processes acting at a range of spatial and temporal scales are capable of inducing both rapid and gradual morphological changes (Figure 1.3).

Dune building takes place when sand is blown from the beach into the dune zone, where the sand is trapped by vegetation. For typical dune plant species, e.g. marram grass (*Am-*

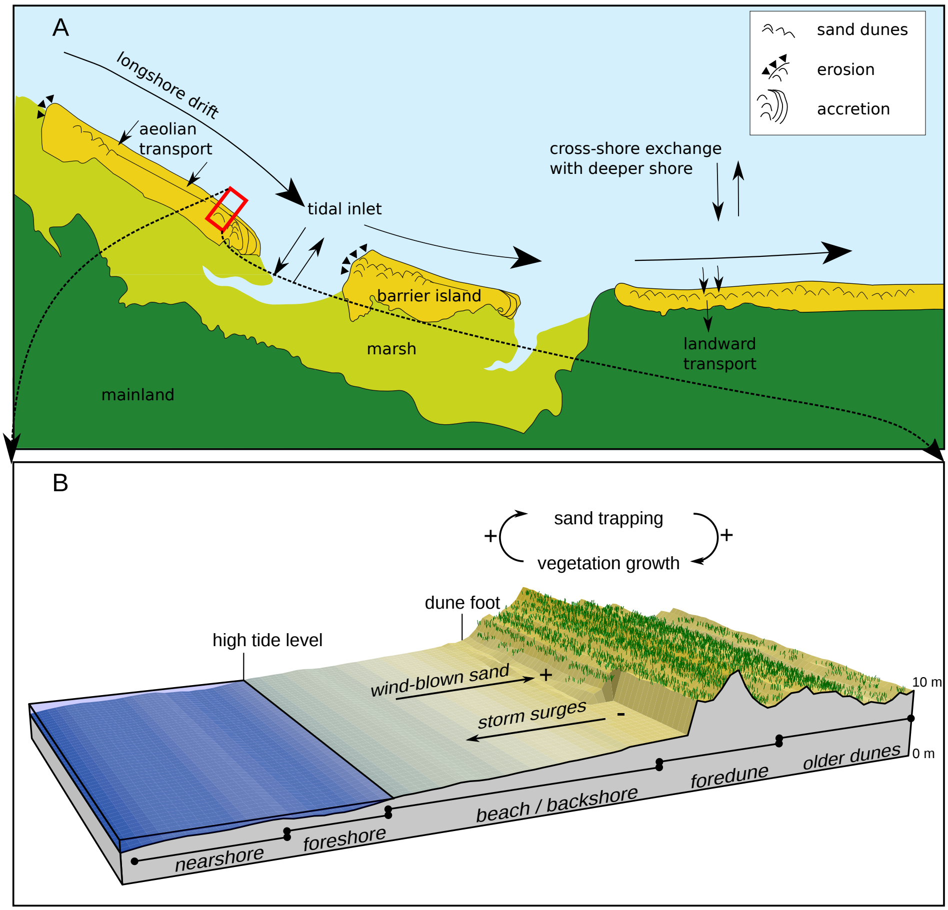

Figure 1.3: Diagram of the coastal system (A) and beach-dune system (B). Arrows indicate the main transport pathways in both systems. (A) Section of a coastline with dunes present on barrier islands and mainland coast. Alongshore currents control shoreline movements, leading to accretion at down-drift end of barrier islands and erosion on the up-drift end. Sand exchange between nearshore and offshore determines the sand budget available for the coastline. Adapted from (Masselink and Van Heteren, 2014). (B) Beach-dune system with position of high-water line, dune foot typical cross-shore zones. Processes contributing to dune building and erosion are indicated.

mophila arenaria), a certain level of burial promotes vegetation growth (Martin, 1959; Maun and Lapierre, 1984; Van der Putten *et al.*, 1993). In turn, enhanced vegetation growth stimulates sand trapping. This reinforcing feedback between sand trapping and plant growth enables rapid dune building. Over the course of a day with suitable conditions for onshore-directed aeolian transport, sediment input from the beach into the dunes can be in the order of 1 m^3 per metre along the shoreline (Delgado-Fernandez and Davidson-Arnott, 2011). Over a year, this may amount up to 10 - 50 m^3/m for the Dutch coastline (Van der Wal, 1998a). Aeolian transport also lead to sand loss to the landward side, i.e. towards the older dunes (Figure 1.3). Sand grains picked up at the foredune face may travel several tens to hundreds of metres under favourable conditions (Christiansen and Davidson-Arnott, 2004; Arens *et al.*, 2013a). However, these volumes are at least a magnitude lower than those associated with marine erosion.

Dune erosion takes place when the water level exceeds the dune-foot level (Van de Graaff, 1977; Vellinga, 1986; Sallenger, 2000; Van Rijn, 2011). The repetitive impact of waves on the seaward dune slope removes sand and undermines the slope, which may eventually lead to avalanching. Depending on factors such as storm intensity and duration, dune erosion may amount to 50-150 m^3/m, which is the equivalent of several years of accretion (Edelman, 1967; Vellinga, 1982; Van Thiel de Vries, 2009).

Foredune dynamics can be studied on time scales of seconds to centuries. The range of scales can be divided into 3 domains: micro, meso and macro scale (Sherman and Bauer, 1993; Houser and Ellis, 2013). Other terminology has also been used, such as short, medium and long-term (Ollerhead *et al.*, 2013), events, cycles and trends (Houser and Ellis, 2013) or steady, graded and cyclic time (Schumm and Lichty, 1965).

The micro scale deals with the instantaneous processes of aeolian transport, e.g. the detachment of sand grains from the beach surface, the formation of aeolian streamers (Baas and Sherman, 2006) and the airflow over the beach and dunes (Hesp *et al.*, 2013). For a review of these processes and their importance for foredune evolution, refer to Houser and Ellis (2013). Also, the hydrodynamic processes involved in dune erosion can be studied this scale (Van de Graaff, 1977; Vellinga, 1982; Van Thiel de Vries, 2009).

On the meso scale, effects of a instantaneous processes can no longer be identified. Instead, the net effect of repeated micro scale processes is of interest. This scale typically relies on empirical data and relationships. Foredune evolution on this scale is mostly influenced by the aeolian transport potential (potential for dune building) and the degree of storminess (potential for dune erosion) (Houser and Ellis, 2013). Depending on the balance between erosion and accretion, foredunes display typical morphology (Arens and Wiersma, 1994; Hesp, 2002).

On the macro scale, i.e. time scales of centuries and longer, sea level, climate and antecedent geology determine coastal evolution and hence whether a sandy coastline and other boundary conditions for coastal dunes actually exist (Sherman and Bauer, 1993; Stive, 2004). On a slightly smaller scale decades to centuries, Van Straaten (1961) identified correlations between sustained changes in the frequency of onshore wind directions and shoreline movements. On a scale of millennia, distinct phases of dune building and erosion have been identified in The Netherlands (Pons and van Oosten, 1976). These phases can be related to changes in the rate of sea level rise, changes in the sand supply from rivers and changes in wind and wave climate (Klijn, 1981, 1990). Similarly, phases of shoreline evolution over the last millennia can be linked to changes in the balance between sea level change and sand supply (Beets and Van der Spek, 2000; Van der Meulen *et al.*, 2007; van Wesenbeeck *et al.*, 2014).

1.3 Modelling and predicting foredune evolution

1.3.1 Proposed model structure and requirements

The goal is to quantitatively model and predict the morphological evolution of dunes over a number of decades, or 1-100 years. At this scale, dune evolution can be described by interactions between the beach, dune and vegetation system (Sherman, 1995). Figure 1.4 describes the main processes and interactions between these systems. The external factors represent the macro scale boundary conditions. For sub-decadal time spans, these are often assumed to be static or changing gradually. The internal controls and interactions represent system properties and processes that can be measured at the micro or meso scale. However, the capacity to predict the rate or magnitude of these processes is limited, which hampers predictions of foredune development.

First, attempts to use process-based models for predicting sand input to the dunes are generally unsuccessful (Lynch *et al.*, 2008). Sand input is controlled by wind climate, beach morphology and surface conditions (RQ1 in Figure 1.4). Based on measurements in wind tunnels and deserts, empirical equations have been derived to link aeolian transport rate to shear velocity (e.g. Bagnold, 1941; Kawamura, 1951; Lettau and Lettau, 1978). However, the beach environment is host to a variety of transport-limiting factors, such as surface moisture (Svasek and Terwindt, 1974; Namikas and Sherman, 1995; Davidson-Arnott *et al.*, 2008), vegetation (Wolfe and Nickling, 1993) and physical or biological or crusts (Nickling, 1984; Wolfe and Nickling, 1993), which all vary greatly in time and space (e.g. Jackson and Nordstrom, 1997; Wiggs *et al.*, 2004). If accurate estimates of sand input cannot be given, adequate predictions of foredune evolution are not possible.

Second, relatively little is known of the mutually reinforcing interaction between foredune plants and sand accretion (RQ2 in Figure 1.4). It is clear that vegetation acts to trap

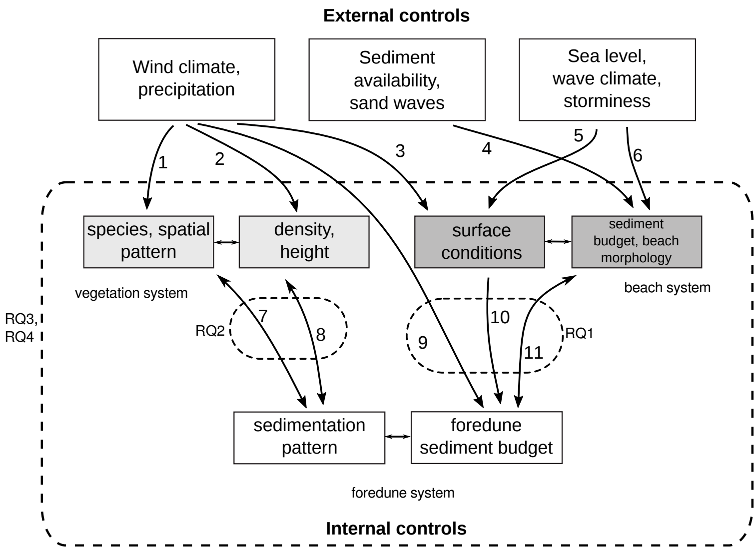

Figure 1.4: Overview of the dominant external and internal factors involved in meso scale foredune evolution. External controls are those not contained within the beach-dune system, typically related to climate, geology and sea level. Internal controls can be determined within the beach-dune zone. Arrows indicate interactions between components: (1) climatic conditions determine which plant species are able to establish and (2) at which rate plant growth takes place. (3) The wind climate controls the wind energy available for aeolian transport of sand into the dunes. (4 and 5) Precipitation, wave conditions and the tide influence the beach surface conditions, e.g. the roughness and moisture content. (6 and 7) Sediment exchange between the dry beach and nearshore is controlled by wave climate, storminess and behaviour of sand bars and sand waves. (8 and 9) The vegetation species and density influence the wind flow and hence the sedimentation pattern. In turn, sedimentation influences the growth rate of vegetation, the exact effect varying between species. (10) Beach surface conditions determine the amount of sand available for aeolian transport into the dunes. Moisture, shells and other roughness elements limit the availability. (11) Beach and dune sediment budget interact. For example, a negative beach sediment budget leads to more frequent dune erosion. Sand eroded from the dune is usually deposited on the beach, enlarging the beach volume and providing a temporary buffer against waves. Research question 1 (**RQ1**) focuses on the factors influencing the dune sediment budget. **RQ2** investigates the mutual bio-geomorphic interactions on the foredune. **RQ3** and **RQ4** study the foredune system's response to changes in external components.

sand and that a certain level of burial is required for dune vegetation species to thrive (Van der Putten *et al.*, 1993; Lancaster and Baas, 1998; Maun, 2009; Zarnetske *et al.*, 2012a). This results is a positive biogeomorphic feedback, where adequate levels of sand trapping encourage plants to grow, in turn enhancing the plant's capacity to trap sand. However, field data on plant response to burial, optimal burial levels and capacity to deal with adverse conditions are scarce. Additionally, although the effect of different vegetation densities on sedimentation has been investigated (e.g. Arens *et al.*, 2001a), our understanding of sand deposition on irregularly vegetated surfaces under different wind conditions is limited (Leenders *et al.*, 2011; Bauer *et al.*, 2013). The lack of understanding of both interactions means that our capacity to predict vegetation and sedimentation patterns on a foredune slope is limited.

Other sources of uncertainty are changes in the external controls. The climate change projections for the next decades show that there is a wide range of possibilities for most climatic and meteorological variables. While sea-level rise projections are fairly constrained, changes in wind and wave climate and storminess are less definitive (Boldingh Debernard and Petter Røed, 2008; Grabemann and Weisse, 2008; Sterl *et al.*, 2009; De Winter *et al.*, 2012). The uncertainty associated with climate change projections can be encompassed by analysing dune evolution for a number of model scenarios.

Changes in sand availability and associated shoreline movements also exert strong influence on the beach-dune system. This is especially evident on the Dutch barrier islands, with large alongshore fluctuations in beach width are found (cf. Figure 1.3A). These are related to the formation, attachment and down-drift migration of large sand bodies that temporarily enlarge beach width (Fitzgerald *et al.*, 1984; Cheung *et al.*, 2007). This clearly has repercussions for foredune dynamics. While this natural variability may not be entirely unpredictable, the sand availability is assumed to be constant in the model development. This simplifies the modelling effort and isolates climate change effects from natural variability. The consequences of this assumption will be treated further in the Synthesis chapter.

1.3.2 Existing models

Models are available to simulate different aspects of foredune evolution. These models can be divided into two categories. The first category comprises conceptual models of dune evolution, i.e. models that predict a certain direction of dune evolution for a given set of site-specific conditions. These predictions are generally qualitative in nature.

Common conceptual models link typical foredune morphologies to site-specific conditions, e.g. beach and dune sand budgets to vegetation cover (Psuty, 1988; Sherman and Bauer, 1993; Pye, 1990). These models can be used to provide a first approximation of dune development in response to changes in one of these conditions. Generally, the foredunes follow the position of the shoreline (Pye, 1990; Hesp, 2002). This means that if sea level falls or the coastline accretes, foredunes build seaward. If the coastline recedes, dunes respond by retreating landward. However, in both cases there are numerous exceptions that can be attributed to site-specific conditions.

A second category consists of computer models that simulate one or several of the morphological processes involved in dune development. Many of these focus on a single process (e.g. erosion or aeolian transport). Especially the impacts of storm surges on dune erosion have been modelled with relatively good accuracy (Larson *et al.*, 2004; Roelvink *et al.*, 2009; Van Rijn, 2009). Others have shown the development of sand dunes from a bare surface or initial shape (Werner and Fink, 1993; Werner, 1995; Herrmann, 2002; Kroy *et al.*, 2002; Lima *et al.*, 2002). Baas (2002) added vegetation to a cellular model of aeolian transport, resulting in complex interactions and realistic sand dune morphologies. Similarly, a coupled airflow-sand transport model was extended with a vegetation component to simulate vegetated 'dunescapes' (Durán and Herrmann, 2006).

However, only few of these simulation models integrate the beach, dune and vegetation subsystems. Exceptions are the SAFE model (Van Boxel *et al.*, 1999; Arens *et al.*, 2001a) and the dune model of Luna *et al.* (2011); Durán and Moore (2013). While they model airflow, transport and sedimentation over vegetated foredunes, they do not explicitly include dune erosion by marine processes. Recently, a new DUne-BEach-VEGetation (DUBEVEG) model was developed at Wageningen University (De Groot *et al.*, 2012). Still in its infancy, this model requires careful revision of the process descriptions, thorough calibration and validation. However, this tool potentially fills the hiatus identified in the array of dune models.

1.4 Research questions and outline

The research goals this thesis are (1) to predict dune evolution over a number of decades in response to climate change using the adapted DUBEVEG model and (2) to investigate the effectiveness of the proposed nourishment regime to mitigate climate-change effects on coastal dunes.

From the previous overview of dune-building processes, it is clear that predictions of dune development are hampered by an incomplete understanding of a number of processes, most importantly mesoscale aeolian transport and biogeomorphic interactions. Improved quantitative understanding of these processes is a prerequisite to answering the main goals. By formulating the main goals as research questions, we arrive at four questions and their corresponding chapters:

1. Which factors control year-to-year variations in dune growth on the Dutch coast? (Chapter 2)

2. How do biogeomorphic interactions control foredune shape? (Chapter 3)

3. What are the effects of climate change on meso-scale evolution of coastal dunes? (Chapter 4)

4. What are the effects of dynamic coastal management on the evolution coastal dunes? (Chapter 5 and 6)

Referring back to Figure 1.4, research questions 1 and 2 focus on interactions between internal components governing the foredune sediment budget (RQ1) and vegetation and sedimentation pattern (RQ2). Research questions 3 and 4 then focus on the response of the complete foredune system to changes in external factors (RQ3 and 4).

The obtained results are reflected upon in Chapter 7, including pinpointing implications and summarizing future research needs.

2

Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands

Coastal foredunes are an important part of the Dutch coastal landscape since they form a natural flood defence. Foredunes are part of the beach-dune system within which sediment is transferred by aeolian and marine processes. Aeolian sediment transport from the beach contributes to the dune volume, whereas marine processes associated with storm surges erode dune sediments thereby lowering the dune volume. Depending on the balance between erosion and accretion, dune volume and morphology change over time. The ability to model and predict such changes is still limited (Houser and Ellis, 2013; Ollerhead *et al.*, 2013). This study examines how yearly fluctuations in regional climatic variables contribute to changes in foredune volume and how the balance between these forces is influenced by beach width.

Depending on the spatio-temporal scale of investigation, different environmental variables influence sediment transfers to and from coastal dunes (Sherman and Bauer, 1993). This paper is focused on meso-scale dune development, which, is controlled by aeolian transport potential and storm intensity (Houser and Ellis, 2013).

Aeolian transport provides the primary mechanism for sediment input to the dunes. This occurs when wind velocity exceeds the sediment entrainment threshold resulting in sediment being eroded from the beach and transported downwind. The potential for aeolian transport into the dunes for a certain period can be estimated from regional wind data (Chapman, 1990; Davidson-Arnott and Law, 1990; De Vries *et al.*, 2012a). Whether the measured sediment input meets the potential depends on the presence of supply-limiting factors, such as surface

Based on: Keijsers JGS, Poortinga A, Riksen MJPM, Maroulis J (2014) Spatio-Temporal Variability in Accretion and Erosion of Coastal Foredunes in the Netherlands: Regional Climate and Local Topography. *PLoS ONE* **9**(3): e91115 moisture (Gares *et al.*, 1996; Jackson and Nordstrom, 1998; Davidson-Arnott *et al.*, 2008), crust formation (Nickling, 1984), lag deposits (Van der Wal, 1998a) and beach width.

Beach width determines the maximum fetch, which is the distance downwind where transport takes place. A minimum distance is required for transport to reach a maximum, called the critical fetch distance (Gillette *et al.*, 1996; Delgado-Fernandez, 2010). If beach width is insufficient for maximum transport to develop, aeolian transport is reduced relative to the transport potential (Nordstrom and Jackson, 1992; Bauer and Davidson-Arnott, 2002; Davidson-Arnott *et al.*, 2008). Aeolian transport is more prevalent on wide beaches, where there is a large supply of sediment for aeolian transport and unrestricted fetch length. Although the highest transport rates are expected during the highest wind velocities, such wind velocities are often accompanied by storm surges and wave run up that reduce the fetch length and increase moisture content of the beach surface and may even erode the dune. Consequently, Delgado-Fernandez (2011) concluded that most of the sediment input to the dunes actually occurs during low- to medium-magnitude wind events.

Detailed studies of coastal foredune erosion provide a comprehensive understanding of the relevant coastal processes and interactions, resulting in the effects of storm events on dune dynamics being accurately predicted. Foredune erosion, which operates at a scale of hours to days, occurs when elevated sea level and wave run-up reach and undermine the dune foot. Storm intensity depends on the meteorological conditions that determine surge level, wave conditions and storm duration (Vellinga, 1982; Van de Graaff, 1986; Kriebel and Dean, 1985). The volume of sediment that is eroded from the foredune also depends on the angle of wave incidence and on the amount of energy dissipated traversing over sand waves, sand bars and the beach (Sallenger, 2000; Stockdon *et al.*, 2006). Therefore, the spatial variability in dune erosion under equivalent storm conditions can be related to differences in coastline orientation (Cooper *et al.*, 2004), alongshore variations in inner-shelf geology and sand bars (Houser *et al.*, 2008; Vousdoukas *et al.*, 2012), or variations in beach morphology and beach width (Davidson-Arnott and Stewart, 1987; Komar and Cary, 1976; Ruessink and Jeuken, 2002; Burroughs and Tebbens, 2008). Most eroded sediment resettles on the foreshore (Vellinga, 1982) and foredunes may recover rapidly if the sediment-transport potential and re-vegetation are sufficient (Hesp, 2002).

A critical factor in foredune development is sediment supply from the shoreface to the beach (e.g. Aagaard *et al.*, 2004a; Anthony *et al.*, 2006; Hesp, 2012). This sediment supply depends on the welding of nearshore bars (e.g. Aagaard *et al.*, 2004a; Anthony *et al.*, 2006), gradients in alongshore transport (Aagaard *et al.*, 2004b; Miot da Silva *et al.*, 2012) and other nearshore processes (e.g. Quartel *et al.*, 2008). At timescales of decades to centuries, the relative importance of sediment supply over transport potential increases (Houser and Ellis, 2013). However, the factors controlling sediment supply to the beach were not within the focus of this study. Instead, beach width was used to provide an indirect measure of sediment availability for dune building.

Temporal variability in dune volume results from fluctuations in yearly erosion and accretion. The effects of regional climate on dune volume display correlations between storminess and dune erosion (Pye and Blott, 2008; De Vries *et al.*, 2012a); however, there is little evidence linking yearly wind climate and aeolian sediment input to the dunes. Assuming a homogeneous wind and wave climate, spatial variability in dune volume is likely to be related to local beach morphology. A number of recent studies investigated foredunes in relation to beach morphology and found that foredune accretion was dominant when beaches were wider than a site-specific critical width (Saye *et al.*, 2005), when beach slopes were relatively gentle (De Vries *et al.*, 2012a), or where sand banks were welded to the shoreline (Anthony, 2013). Further identification and testing of meso-scale controls on foredune development are needed to improve predictions and modelling of environmental-change impacts and management interventions on coastal dunes.

This study investigates how the balance between erosion and accretion is controlled by regional climate and local morphology. On the basis of yearly dune volumes, hourly sea levels and wind data, we investigate (1) the temporal variability in erosion and accretion in relation to variations in storminess and aeolian transport potential; (2) the influence of beach width on dune erosion and accretion; and (3) the decadal effect of beach width on dune development.

2.1 Methods

2.1.1 Regional setting

Six sections of the Dutch coastline were selected for analysis. In a convex line from west to east, these are Noord-Holland, Texel, Vlieland, Terschelling, Ameland and Schiermonnikoog (Fig. 2.1). The sections are separated by tidal inlets, connecting the North Sea to the Wadden Sea. Except for Noord-Holland, all locations are barrier islands, and together, they cover 195 km of the Dutch coast (Fig. 2.1). Prevailing winds are from the south-west. The tidal range varies between 1.6 m in Noord-Holland and 2.1 m in Schiermonnikoog. Mean grain size of natural beach sediment is 259 μm in Noord-Holland and decreases to 202 μm on Ameland (Van der Wal, 2004) and 190 μm on Schiermonnikoog (Arens, 1996b).

Compared to the other sites, beaches of Noord-Holland and Texel are narrow (< 100 m) and show limited temporal variability. The other barrier islands feature wider beaches (> 100 m) with larger spatio-temporal variations, influenced by morphodynamics of tidal inlets (e.g. Bakker, 1968; Cheung *et al.*, 2007). Widest beaches are found on the updrift (western) heads of the islands.

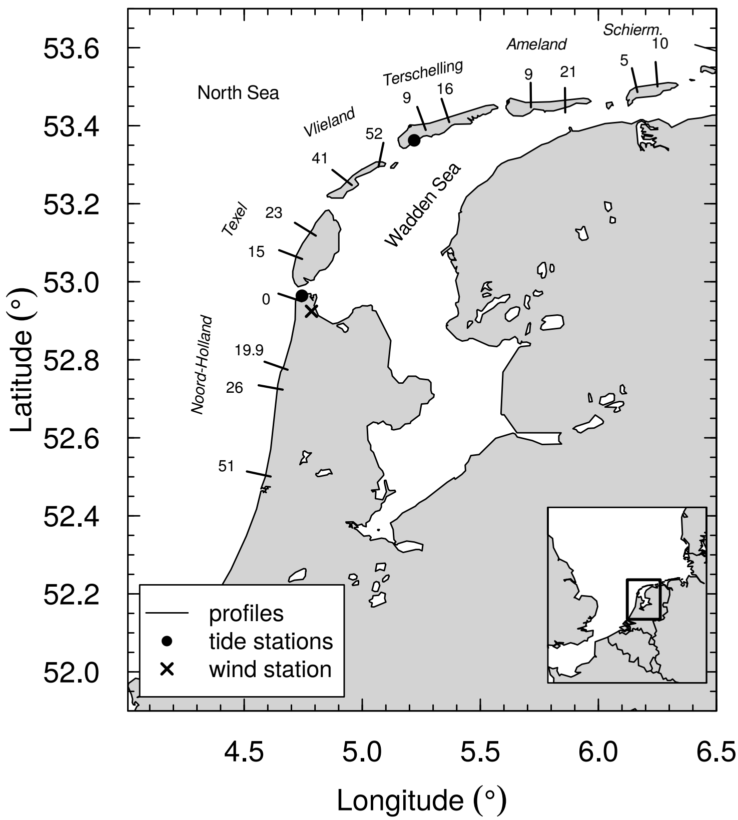

Figure 2.1: Study areas. Map shows the location of the six coastal sections used in this study within the Netherlands and identifies the location of two sea-level gauges (Den Helder and West Terschelling) and the wind gauge (KNMI station De Kooy). Positions and numbers of beach poles on the section boundaries are indicated. Inset shows the location of the study area within North-western Europe.

All sites are characterised by sandy beaches, backed by a continuous foredune ridge that is partly covered by marram grass (*Ammophila arenaria*). Average dune height ranges between 16 m +NAP (Noord-Holland) and 8 m +NAP (Schiermonnikoog), where NAP is the Dutch vertical datum approximating mean sea level. The majority of the foredunes has been influenced by vegetation plantings, sand fences or sand nourishments (Arens, 1994). Natural foredunes are found at the extremities of the islands, where beaches with mobile dune fields are present (Cheung *et al.*, 2007; Oost *et al.*, 2012).

Vegetation plantings and sand fences enhance sedimentation, but do not strongly interfere with natural foredune-development processes (Arens and Wiersma, 1994). Sand nourishment, however, can change the sediment budget of the beach and foredune, especially when nourishments are applied directly to the beach and dune, which changes the volume of available sediment and the morphology. Since 1990, the Dutch coastal policy (Ministerie van Verkeer en Waterstaat, 1990) ensures that sand nourishments are placed on the shoreface and the beach, thereby reducing any direct impact on the foredune; a process that may still influence dune development by protecting the dunes against erosion, and by changing the sediment source characteristics for aeolian sand transport (Van der Wal, 2004; Bakker *et al.*, 2012).

2.1.2 Data collection and preparation

Cross-shore elevation profiles over the period 1965 to 2012 were obtained from the JARKUS dataset. This dataset contains annual elevation measurements covering the dune, beach and foreshore and has been used in several studies addressing annual to decadal-scale behaviour of the coastline (Van der Wal, 2004; Bochev-Van der Burgh *et al.*, 2011; De Vries *et al.*, 2012a).

Profiles are spaced 200 to 250 m apart, coinciding with beach poles along the Dutch coast. Elevation measurements along the transects were taken at 5 m intervals (Van der Wal, 2004). Until 1977, the sub-aerial beach was measured by levelling, then aerial photography was used from 1978 to 1995, and since then, laser altimetry (Bochev-Van der Burgh *et al.*, 2011). The reported measurement errors (σ) of the techniques differ substantially, from 0.01 m for levelling (Oosterwijk and Ettema, 1987), to 0.1 m for photogrammetry (Bollweg and Vaessen, 1997) and laser altimetry (De Graaf *et al.*, 2003; Sallenger *et al.*, 2003).

The alongshore extent of sections in this study is constrained by the limits of a homogeneous coastline orientation. Consequently, the protruding seawall ('Hondsbossche Zeewering') near Petten was omitted, which explains the gap between profiles 20 and 26 for Noord-Holland (Table 2.1).

Two parameters were calculated from the yearly elevation profile: sub-aerial beach width (W in m) and dune volume (V in m^3/m). Beach width is defined as the distance between the

Name	Alongshore extent (km)	n observations	n discarded
Noord-Holland	0-19.9, 26-51	7564	723
Texel	15-23	1276	152
Vlieland	42-52	1743	55
Terschelling	9-16	983	12
Ameland	3-21	2644	226
Schiermonnikoog	5-10	955	92
Total:	89	15205	1260 (8%)

Table 2.1: Alongshore extent of the six coastal sections, showing the total number of profile measurements available for the section and the number of profiles discarded.

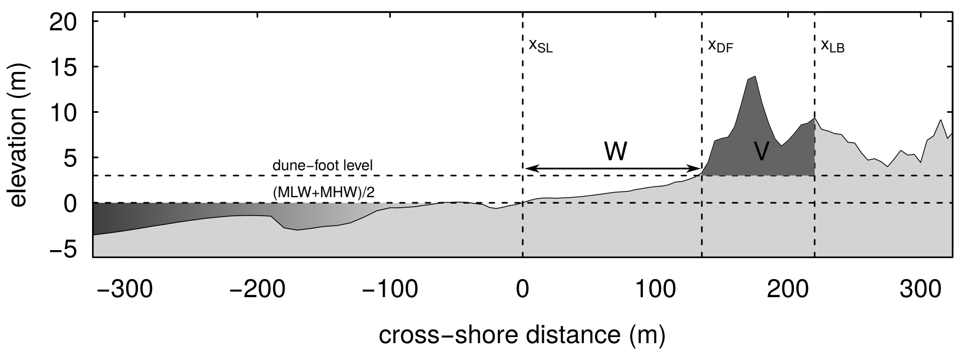

Figure 2.2: Definition of dune volume and beach width. Position of landward boundary (x_{LB}), dune-foot (x_{DF}) and shoreline (x_{SL}) are indicated. Dune volume (V) and beach width (W) are calculated on the basis of these positions.

shoreline (x_{SL}) and dune-foot (x_{DF}), while dune volume is the volume of sediment per metre alongshore above the dune-foot level, seaward of a fixed inland boundary (x_{LB}). x_{DF} is the most seaward position where dune-foot level is reached. This level is taken as 3 m + NAP, which is the elevation at which the profile slope changes significantly (Van der Wal, 2004; Bochev-Van der Burgh *et al.*, 2011). x_{LB} is the farthest-inland crest position in a profile's time series and the shoreline (x_{SL}) is the cross-shore position where elevation is equal to the mean of the average low- (MLW) and high-tide (MHW) positions (Verhagen, 1989; Ruessink and Jeuken, 2002) (Fig. 2.2). Finally, the difference between two consecutive values of V yields the change in dune volume ΔV, which represents the parameter of interest in this study.

Two filters were used to identify and eliminate outliers in calculations of dune-volume change (ΔV) that are caused by human activities and measurement errors. Firstly, the nourishment filter discards values of ΔV directly following sand nourishment. This filter includes all profiles in the zone of the sand nourishment and a buffer zone of 300 m on either side. This discards the profiles directly bordering the nourished zone, as these were found to show considerable modifications in beach morphology following the nourishment. Such modifications were not observed in profiles further away. Secondly, the dune-foot residuals filter discards any profile measurement that displays a sudden dune-foot movement > 50 m. This distance lies 3 standard deviations from the mean and movements > 50 m are therefore considered outliers, caused by measurement errors or by the formation of a short-lived incipient dune, seaward of the actual foredune. Of the 14228 available profile measurements, 1210 or 9% were discarded after these two filters were applied (Table 2.1).

2.1.3 Storminess

Storminess is a complex set of environmental conditions that may lead to dune erosion, such as powerful onshore wind, high-energy waves and high water levels. Several parameters have been defined and tested to quantify storminess on a yearly timescale (e.g. Guillén *et al.*, 1999). Assuming that the erosion impact of a storm is determined by the highest recorded water level, then the yearly storminess (S) is defined as the maximum level recorded between two profile measurements (Ruessink and Jeuken, 2002). This parameter was found to explain some of the year-to-year variability in dune-foot movement (Ruessink and Jeuken, 2002) and dune volume (De Vries *et al.*, 2012a). Yearly values of S are derived from hourly sea levels, which are measured at a number of tide stations along the coast, of which Den Helder and West Terschelling are within the study area (Fig. 2.1). Given that both the correlation between these tide stations is high (r = 0.93) and that data at West Terschelling are available from 1965 to 2012, the record from this latter station was used for all sites. Correlation between storminess and dune-volume changes was calculated using the Pearson product-momentum. The Pearson r takes a value between -1 and +1, where -1 indicates perfect negative correlation and 1 perfect positive correlation. The significance of the correlation was tested at the $p < 0.05$ level.

2.1.4 Transport potential

Transport potential is an indicator for the potential aeolian transport into the dunes based on wind velocity and wind direction. Transport potential can be calculated by applying a time series of regional wind data to aeolian transport equations (e.g. Adriani and Terwindt, 1974; Fryberger and Dean, 1979; Davidson-Arnott and Law, 1996; Kroon and Hoekstra, 1990). Transport potential is related to the cube of shear velocity; therefore, high shear velocities associated with storm winds dominate the final value for transport potential. However, this does not agree with the notion that low- to medium-magnitude winds are most important for actual aeolian input into the dunes (Delgado-Fernandez, 2011). Therefore, two time series of transport potential were calculated. The first series uses the full range of measured wind velocities (Q_{all}). The second series uses only wind velocities below a given value. As there were no local field measurements, wind velocities of 8 m/s (Q_8), 10 m/s (Q_{10}) and 12 m/s (Q_{12}) were tested as the upper limit for aeolian transport potential.

The yearly transport potential (Q) was calculated as a measure of aeolian forcing (Adriani and Terwindt, 1974; Kroon and Hoekstra, 1990). Hourly values of wind velocity at 10 m above the surface were measured and provided by the Royal Dutch Meteorological Institute (KNMI). Hourly values of wind direction and velocity from the KNMI station De Kooy (Fig. 2.1) were converted to shear-velocity values using the law of the wall:

$$u_z = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \tag{2.1}$$

where u_z is the wind speed (m/s) at elevation z above the bed (m), u_* is the shear velocity (m/s), κ the von Kármán constant (0.4) and z_0 the roughness length, taken as 0.001 m (Van der Wal, 1998a).

The threshold shear velocity for transport is then calculated as

$$u_{*t} = A \sqrt{g\, d\, \frac{\rho_s - \rho}{\rho}} \tag{2.2}$$

where u_{*t} is the threshold shear velocity (m/s), A is a dimensionless constant (0.1 for the impact threshold), g is the gravitational acceleration (m/s^2), d is median grain size in the field, ρ_s?s is the density of the sediment (kg/m^3) and ρ is the density of air (kg/m^3). As differences in grain sizes were relatively small, a median grain size of 0.25 mm was used for all sections.

Hourly potential transport q_j (kg/m/h) was computed whenever hourly $u_* > u_{*t}$ using the Bagnold equation (Bagnold, 1941):

$$q_j = 3600\, C \sqrt{\frac{d}{D}} \frac{\rho}{g} u_*^3 \tag{2.3}$$

where C is a dimensionless empirical constant (1.8), and D the grain diameter of a standard sand (0.25 mm).

Fluxes were summed over all directions i (10° bins) and wind velocities j (0.1 m/s bins) to yield the total amount of sediment that potentially crosses the dune foot in one year (Q):

$$Q = \sum_i - \sin \alpha_i \sum_j f_{ij}\, q_j \tag{2.4}$$

where α_i is the angle of incidence of the wind, f_{ij} frequency of wind direction i and wind velocity j (hours) and q_j is the potential aeolian transport for velocity j.

Lastly, potential aeolian transport into the dunes was converted from kg/m to m^3/m (bulk density of 1590 kg/m^3) to ensure values are comparable with calculated dune volumes.

As wind measurements are available from 1981 onwards, correlations between transport potential and dune-volume change only concern data from 1981 to 2012. Correlation between the time series of potential transport and dune-volume changes were calculated as the Pearson product-momentum correlation coefficient. The significance of the Pearson product-momentum correlation coefficient was tested at the $p < 0.05$ level.

2.2 Results

2.2.1 Temporal variability in dune-volume changes, erosional and accretionary forces

Dune-volume changes (ΔV) for all sites are generally between -50 and +50 m^3/m, with average values ranging from -2 at Ameland to +13 m^3/m at Terschelling. Within any year, there is significant alongshore variability in ΔV, as indicated by the size of the boxes (Fig. 2.3). The interquartile distance commonly exceeds 20 m^3/m and tends to be larger when the median of ΔV values is negative (e.g. 1974, 1976, 1990).

Between years, there are also large differences in ΔV. This temporal (year-to-year) variability in ΔV is apparent from the strongly different median and quartiles of ΔV (Fig. 2.3). For Noord-Holland, alongshore average ΔV ranges from -35 to 31 m^3/m. The lowest value, for 1976, corresponds to a 1-in-20 years storm (De Vries *et al.*, 2012a). In most years, however, average ΔV is positive, which indicates dune growth. Temporal variability is lowest on Schiermonnikoog (Fig. 2.3), Vlieland and Terschelling (not shown).

The indicator for storminess (S) shows considerable temporal variation (Fig. 2.4). The highest sea levels were recorded in 1976, 1990 and 2008 and caused significant dune erosion (e.g. Rijkswaterstaat, 1990). Values of $S < 2$ m occurred in 1973, 1977, 1979 and 2009, causing minor dune erosion only in 1973 (Rijkswaterstaat, 1973). Note that the years listed here do not refer to calendar years, but to profile-to-profile cycles.

Dune accretion is expected to be related to aeolian transport potential (Q), which also shows considerable temporal variability for all sites, caused by the year-to-year variations in wind climate (Fig. 2.5). The average transport potential is highest in Noord-Holland (125 m^3/m) and decreases, as the shoreline orientation changes from west to north, to 40 m^3/m at Ameland and Schiermonnikoog (Table 2.2). This decrease in transport potential reflects the changing orientation relative to the dominant south-west wind direction. Potential sediment input calculated from only those hours with wind velocities below 8, 10 or 12 m/s (Q_8, Q_{10},

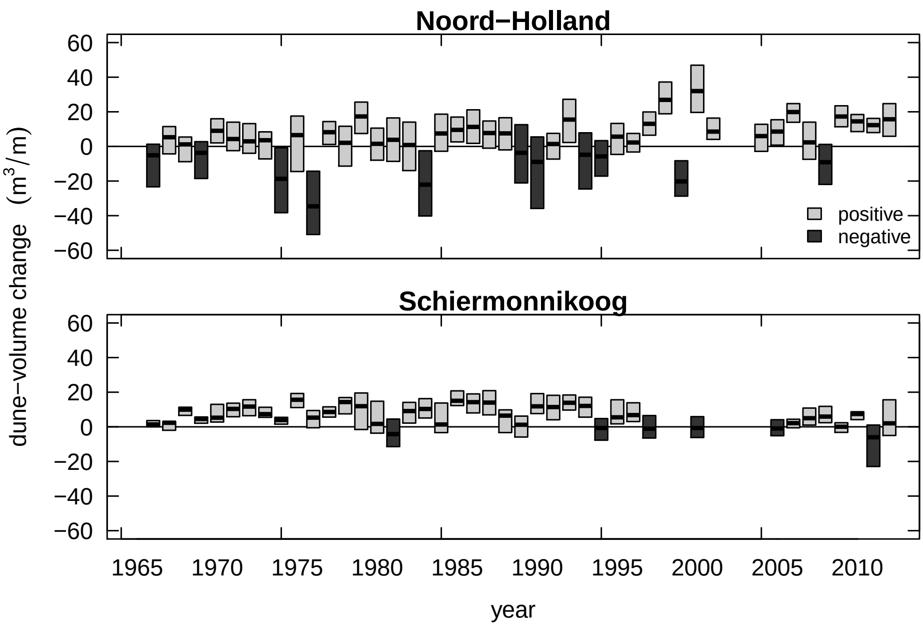

Figure 2.3: Temporal variability in dune-volume changes. Range of dune-volume changes (ΔV) per year, calculated for Noord-Holland (top) and Schiermonnikoog (bottom). Each boxplot represents the upper and lower quartile and median of dune-volume changes for a single year. Differences among years indicate temporal variability in dune-volume changes. The height of the boxes indicates spatial variability in dune-volume changes. Boxes with a positive median are light grey, boxes with a negative median are dark grey.

Q_{12}) displayed similar variability. However, the mean values were reduced relative to Q_{all} as the latter includes all wind velocities.

2.2.2 Influence of erosional and accretionary forces on dune volume

Dune erosion (negative ΔV) is linked with high values of S (Fig. 2.6). For Noord-Holland, ΔV is mainly negative when $S > 2.5$ m, which indicates that the eroded sediment volume is larger than the accreted volume. When S is between 2.0 and 2.5 m, ΔV can be both positive and negative. When $S < 2.0$ m, positive values for ΔV dominate (Fig. 2.6). Similar links exist between S and alongshore-averaged ΔV for Texel, Vlieland and Ameland. Both Terschelling and Schiermonnikoog show a lower occurrence of negative ΔV and no obvious relationship between S and ΔV (Fig. 2.6).

Time series of both ΔV and S were correlated in Figure 2.7, showing the strongest correlations for locations where beaches were narrow; with 35% of the correlations being signif-

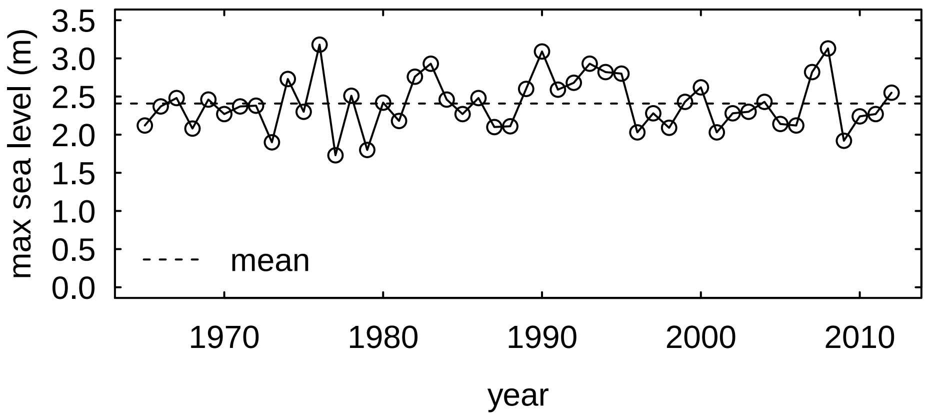

Figure 2.4: Yearly maximum sea level as an indicator for storminess, with a mean of 2.4 m. Measurements from the tide station of West-Terschelling (1965-2012).

Location	Shoreline orientation (°)	Transport potential (m^3/m)	
		mean	st. dev.
Noord-Holland	190	127	34
Texel	215	83	25
Vlieland	235	61	18
Terschelling	255	45	11
Ameland	265	40	9
Schiermonnikoog	265	40	9

Table 2.2: Average and standard deviation of yearly transport potential, calculated from 1980-2012 data.

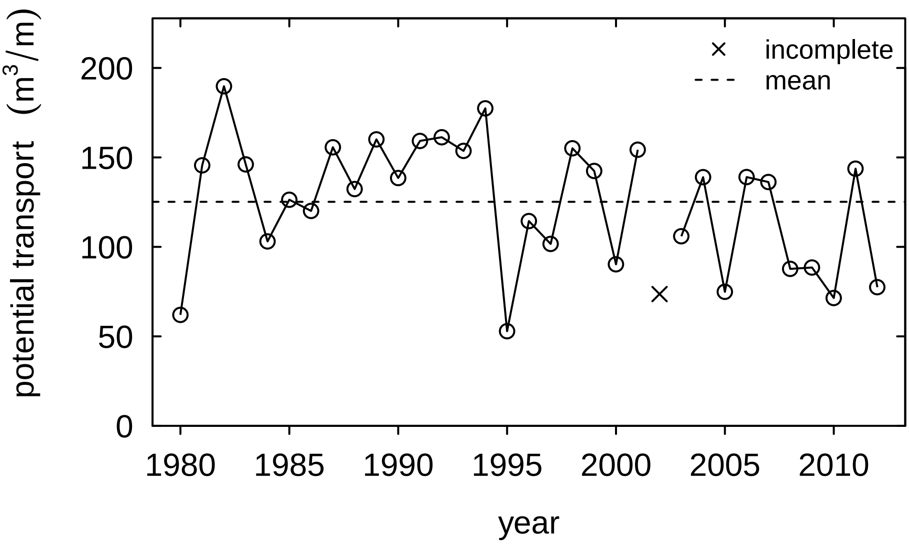

Figure 2.5: Yearly transport potential for location Noord-Holland. The measurements of 2002 are incomplete, with 22 hours of missing data. This hiatus seems unrelated to storm conditions. The mean transport potential is 125 m^3/m.

icant. Negative correlations imply that higher values of S are associated with lower values of ΔV. In contrast, correlations are weakly positive on the wide beaches of Terschelling and Schiermonnikoog.

Dune accretion is not linked with transport potential (Fig. 2.8). Values of ΔV are generally below the potential sediment input, indicating an overestimation of Q relative to the actual volume gain.

Time series of ΔV show a weak correlation with yearly values of Q. For most of the alongshore positions, the correlation coefficient is negative (9% were significant), suggesting that increasing Q is associated with decreasing ΔV. Positive correlations are associated primarily with wider beaches, e.g. positive correlations were evident for parts of Vlieland and Ameland and for the islands of Terschelling and Schiermonnikoog. These are, however, very weak ($r < 0.4$) and in only 3% of the cases, a positive correlation is significant.

The low number of significant correlations between Q and ΔV is most probably caused by two different effects. Firstly, strong winds associated with storm surges were included in the analysis. Secondly, within a given year, both dune erosion and dune accretion can occur. Even if aeolian transport is high, a single dune-erosion event may offset or undo any dune accretion. To limit the effect of co-occurring dune accretion and erosion, correlations were re-tested after discarding the years in which $S > 2.5$ m (13 years discarded, 20 remaining). This is the value of S above which erosion dominates accretion (Fig. 2.6). Discarding these

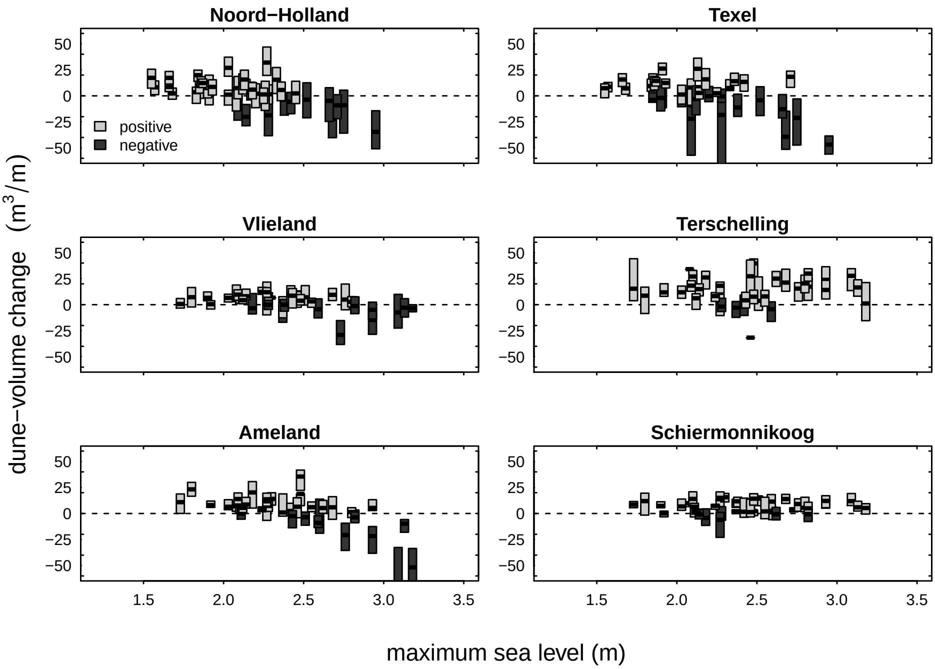

Figure 2.6: Dune-volume changes (ΔV) as a function of maximum sea level (S) for all sites. Each boxplot represents the alongshore variation for a single year. Boxplots with a positive median are light grey, with a negative median are dark grey.

years significantly improved the results, especially for Terschelling, Ameland and Schiermonnikoog. The results did not differ significantly between Q_{all} Q_8, Q_{10} and Q_{12}. However, compared to the correlations between storminess and ΔV, the explanatory value of Q is still low, with only 5% of the profiles having a significant positive correlation.

2.2.3 Influence of beach width on dune-volume changes

Alongshore variations in correlations between the climatic variables and ΔV indicate alongshore differences in the balance between erosion and accretion. To investigate how these variations are related to beach width, values of ΔV were correlated with beach width for: (1) erosion-dominated years and (2) accretion-dominated years (Fig. 2.10).

When major storms are absent ($S \approx 2.0$ m, nearly all dunes experience net growth, with average rates similar across beach widths. In years with high storminess ($S \approx 3.0$ m), erosion occurs dominantly where $W < 100$. The amount of erosion decreases and changes into net growth towards higher values of W, indicating that the dunes are better protected against storms and may grow despite major storms.

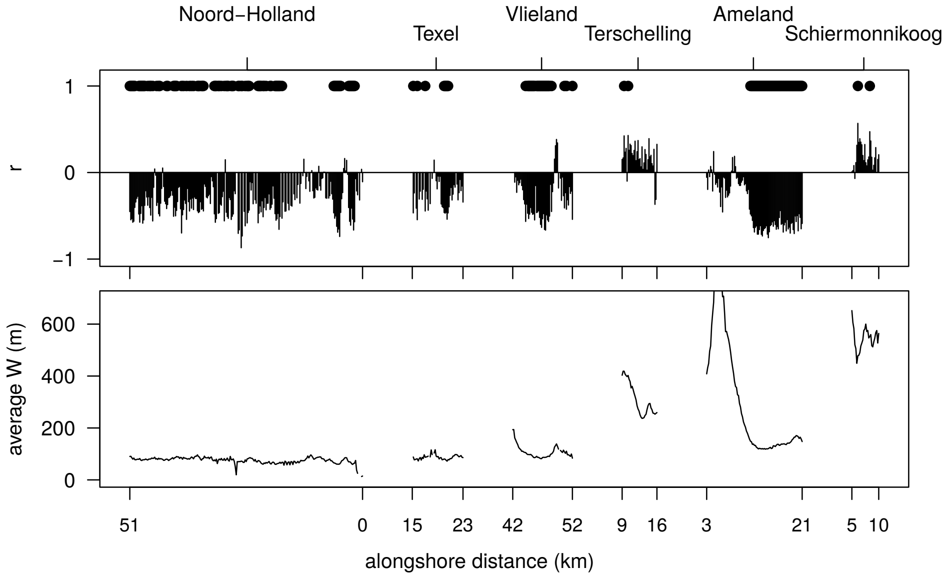

Figure 2.7: Temporal correlation of dune-volume changes (ΔV) and storminess (S). Upper panel: correlation between dune-volume changes (ΔV) and storminess (S). Correlation was calculated as the Pearson product-moment coefficient r. Correlations significant at $p < 0.05$ level are indicated with 'o'. Lower panel: time-averaged beach width (W) for each profile. The numbers on the x-axis refer to the boundaries of each location.

These patterns imply that, if beaches are narrow, dune growth depends strongly on the yearly maximum storm, resulting in alternating growth and decline. In contrast, where W exceeds 100 m, dune growth is relatively constant regardless of storminess, allowing more continuous, steady development.

Dune-volume changes over 5-year time windows (i.e. differences between dune volume in 1970 and 1975, 1975 and 1980 etc.) integrate the effects of accretion and erosion. At this scale, ΔV trends upwards between $W = 50$ m and $W = 200$ m (Fig. 2.11). Where $W > 200$ m, these positive effect of beach width disappears, which implies that similar levels of dune growth take place regardless of beach width.

2.3 Discussion

2.3.1 Temporal variability in erosion and accretion

Temporal variability in ΔV is best explained by the variation in erosive forces rather than aeolian transport potential, as identified by De Vries *et al.* (2012a). However, the results presented here show that relationships between climatic variables and ΔV fluctuate alongshore.

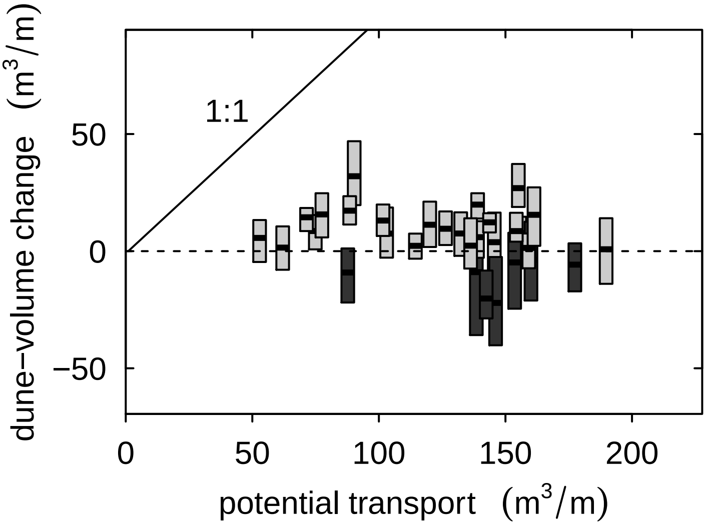

Figure 2.8: Dune-volume changes (ΔV) as function of transport potential for Noord-Holland. Each boxplot represents the alongshore variation of a single year. Boxplots with a positive median in a lighter shade, boxplots with a negative median in darker shade. The solid line indicates the 1:1 line, where potential transport equals ΔV.

Significant negative correlations between storminess and ΔV were found dominantly on beaches less than 200 m in width. Hence, the temporal variability in ΔV on the associated profiles is controlled by variations in storminess. On wider beaches, no significant correlation was found.

Correlations between time series of ΔV and aeolian transport potential are weak compared to the correlations with storminess. Also, except for a few profiles on wide beaches, the correlations are dominantly negative whereas positive correlations would be expected considering the positive dependence of aeolian transport on wind velocity. The negative correlations can be explained by the high impact of storm winds associated with storm surges. As transport potential is related to the cube of shear velocity, strong winds contribute exponentially to the yearly sum of potential transport. However, although these winds are theoretically capable of transporting large volumes of sand, they also generate high sea levels that reduce fetch distance, increase surface moisture and possibly erode the dune-foot. Hence, actual aeolian transport is reduced and erosion might occur instead (Ruz and Meur-Ferec, 2004; Delgado-Fernandez, 2011). Recalculations of transport potential with an upper limit on wind velocity decreased the proportion of negative correlations, in support of this proposition. Best results were obtained after discarding years with high water levels (higher likelihood of dune erosion). Hence, when the influence of dune erosion is low, aeolian transport potential can

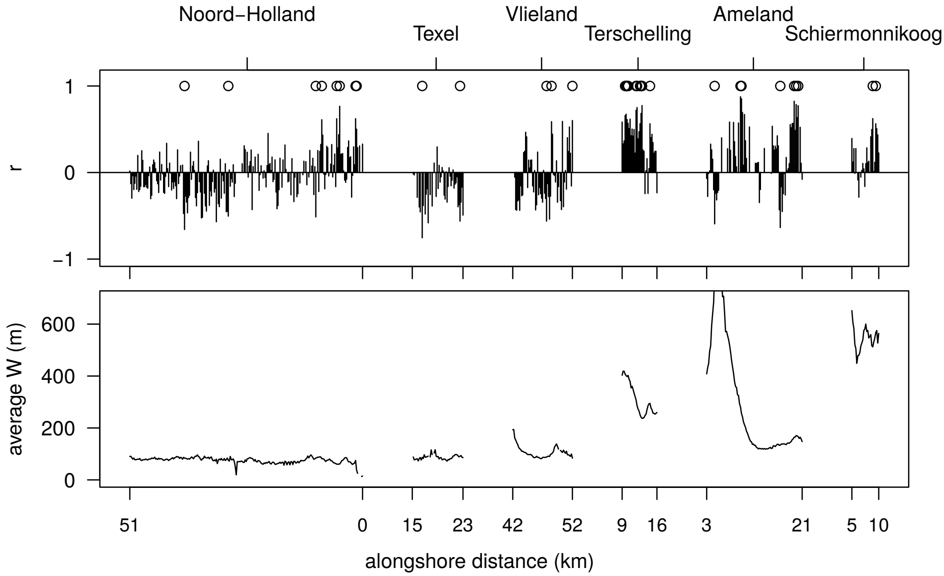

Figure 2.9: Correlation between time-series of dune-volume changes (ΔV) and transport potential (Q). Upper panel: correlation between ΔV and Q, after discarding years with $S > 2.5$ m. Correlation was calculated as the Pearson product-moment coefficient r. Correlations significant at $p < 0.05$ level are indicated with 'o'. Lower panel: time-averaged beach width (W) for each profile. The numbers on the x-axis refer to the boundaries of each location.

explain some of the year-to-year variability in dune-volume changes.

Further work as done by Delgado-Fernandez (2011) is needed to identify aeolian transport activity in relation to wind velocity and sea levels at a timescale of days to months. Such higher-resolution records will enable better distinction between storm and fair-weather circumstances, recognition of the influence of bar-welding, and identification of spring versus neap conditions. On the basis of hourly values of wind velocity and sea levels, aeolian transport events can be discriminated from non-transport events, leading to better predictions of meso-scale sediment input to the dunes.

2.3.2 The effect of beach width

On a scale of decades, there is a considerable positive effect of beach width on dune growth, up to $W \approx 200$. In a study on dune dynamics on the Holland Coast (beach widths of 80-90 m), De Vries *et al.* (2012a) found a similar correlation between beach slope and ΔV and suggest this is related to the limiting effect of beach slope on aeolian transport. Additionally, Davidson-Arnott and Stewart (1987) found that sand waves associated with bar welding offered both better protection against dune erosion and larger sediment input to the foredunes

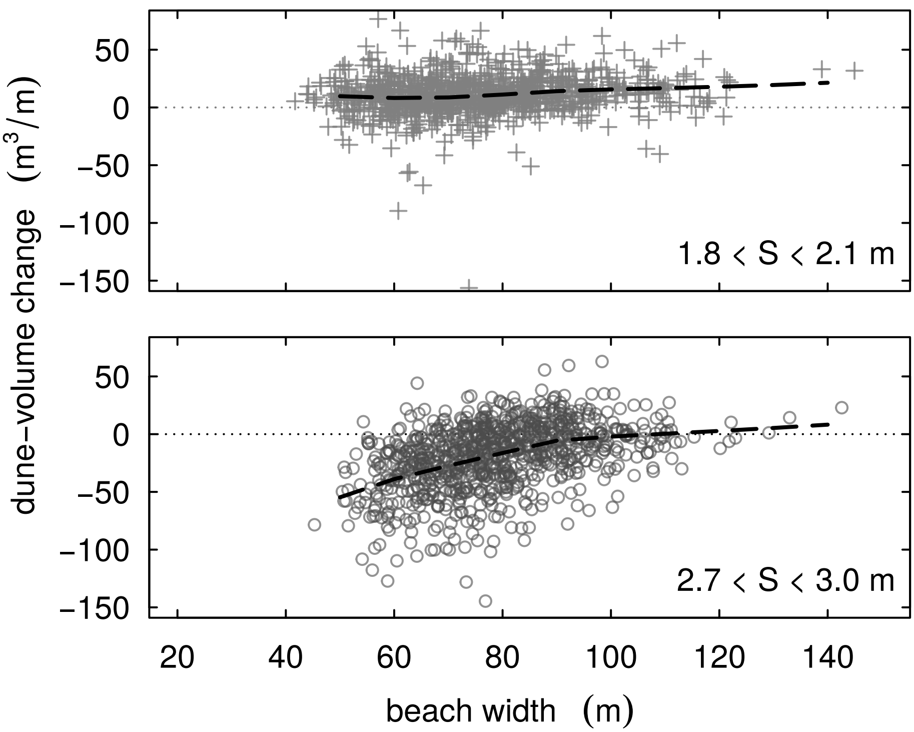

Figure 2.10: Dune-volume change (ΔV) as a function of beach width (W) for low storminess (S between 1.8 and 2.1 m) and high storminess (S between 2.9 and 3.2 m). Data from section Noord-Holland. The dashed lines represent locally-weighted polynomial regression.

(beach widths < 40 – 90 m).

However, on the basis of results presented here we suggest that higher dune growth on wider beaches is related to a reduction in erosion, not to higher sand input. In stormy years, alongshore variation in dune growth is explained by fluctuations in beach width: considerable erosion at narrow beaches, little or no erosion at wider beaches (Figure 2.10). In years without erosion however, alongshore variability is less and ΔV is roughly independent of W (Figure 2.10). Therefore, we propose that the 5-year scale correlation between ΔV and W represents an effect of beach-width dependent dune erosion rather than any effects on dune accretion.

The absence of a correlation between W and ΔV in calm years indicates that there is little impact of W on sediment supply to the dunes. Especially where W exceeds 200 m, yearly dune growth is relatively constant. A small positive effect can be identified (Figure 2.10), but the effects are weak compared to those in erosion dominated years. Even on relatively narrow beaches, dune growth in the order of 20 m^3/m can be achieved, similar to that at very wide

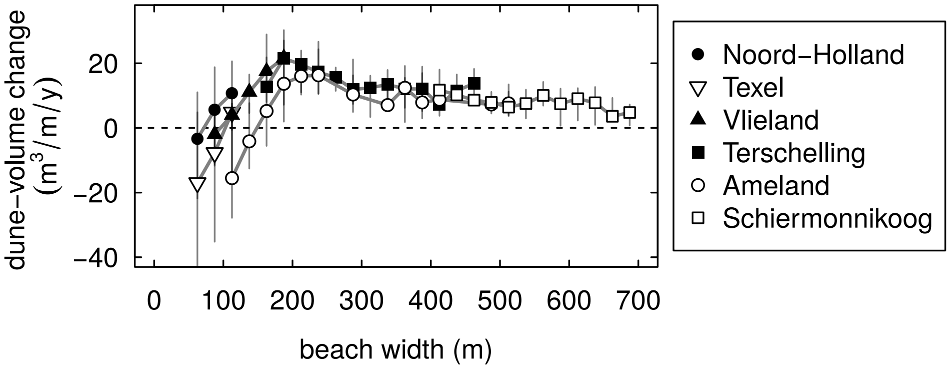

Figure 2.11: Correlations between dune-volume changes (ΔV) and beach width (W), calculated over 5-year periods after grouping into 10 m W intervals. Symbols indicate median ΔV for a given group, vertical lines indicate range between 10^{th} and 90^{th} percentile. Values representing a profile with nourishment activity within the specific time window were discarded.

beaches. This suggests that fetch-limitation is relatively unimportant in controlling yearly dune-growth rates along the Dutch coast.

Bringing together the results presented in this paper, effects of storminess and beach width can be integrated and summarised graphically, linking spatio-temporal variability in ΔV to variations in S and W (Fig. 2.12). This diagram synthesises observations from all sites and years, going from narrow to wider beaches and calm to stormy years. First, ΔV was found to be positive and relatively constant across all W in calm years (low S, solid line). In stormy years (high S), ΔV is negative at narrow beaches and increases with W (dashed lines). Foredunes backing beaches wider than 200 m (e.g. Terschelling, Schiermonnikoog) rarely experience erosion and ΔV is therefore positive, irrespective of S (cf. Figure 2.11).

2.4 Conclusions

Using a dataset of yearly beach-dune elevation profiles, temporal and spatial variability in dune-volume changes (ΔV) were calculated for six sections along the Dutch coast. Comparison of monitoring records shows that:

- Where beach width (W) is less than 200 m, temporal variability in ΔV is significantly correlated with yearly maximum sea levels; a proxy for storminess. Correlations between ΔV and aeolian transport potential are weak at best.

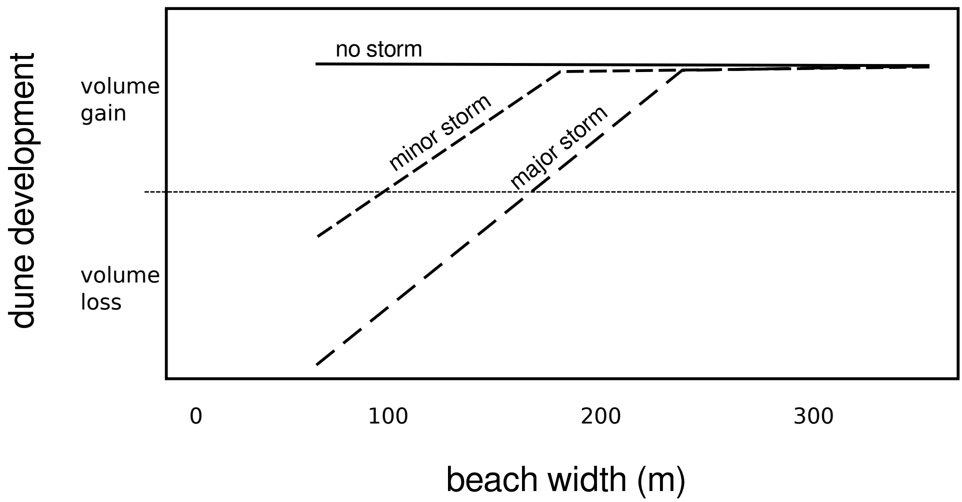

Figure 2.12: Schematic illustration of the influence of storminess and beach width on foredune volume. When beach widths are less than 200 m, ΔV depends on storminess. When beach width is over 200 m, as occurs e.g. on Terschelling and Schiermonnikoog, ΔV is no longer dependent on storminess or beach width.

- Dunes backing narrow beaches experience erosion more frequently than those near wide beaches. For a given storm, the erosion volume decreases with increasing beach width. Such a correlation is absent in years dominated by dune accretion, suggesting similar rates of aeolian sand input across all beach widths.
- Over periods of 5 to 10 years, dune growth is highest where W approaches 200 m.
- Along the Dutch coast, alongshore variability in dune-volume changes is related more to dune erosion than dune accretion.

3

Vegetation and sedimentation on coastal foredunes

3.1 Introduction

Foredunes grow as sand is transported from the beach to the dunes by the wind, where it is trapped and fixed by vegetation. During onshore winds, sediment is eroded from the beach and moves towards the foredunes. The spatial pattern of deposition in the foredunes is largely controlled by wind velocity, dune topography and vegetation cover (Hesp, 2002).

Airflow over a foredune is modified by the topography and vegetation. During onshore winds, wind is topographically accelerated due to flow compression over the seaward slope (Arens *et al.*, 1995; Arens, 1996a; Walker *et al.*, 2009). At the same time, vegetation roughness slows down the airflow, counteracting the topographic acceleration. This leads to a speed-up above the vegetation and slow-down within the canopy (Hesp *et al.*, 2005). However, during gale-force winds acceleration can occur both above and within the canopy (Hesp *et al.*, 2013).

These airflow patterns strongly determine patterns of aeolian transport across foredunes. During onshore winds, sand is eroded from the beach and moves towards the foredunes mainly in saltation. The increased vegetation cover near the dune foot reduces wind velocity, blocks incoming grains and reduces the erodibility of the surface below it (Wolfe and Nickling, 1993). As a result, saltation usually ceases within a short distance from the first vegetation, leading to sedimentation over a width determined by wind velocity and vegetation density (Hesp, 1983, 1988; Sarre, 1989; Arens, 1996a; Arens *et al.*, 2001a). The turbulence induced by vegetation and the upward velocities caused by the dune slope may also initiate transport of grains in suspension (Arens, 1996a; Arens *et al.*, 2002). These grains may

Based on: Keijsers JGS, De Groot JGS and Riksen MJPM (2015). Vegetation and sedimentation on coastal foredunes. *Geomorphology* **228**: 723-734

travel farther up the dune as they pass over the vegetation canopy, leading to deposition farther up the slope and near the crest (Arens *et al.*, 1995; Arens, 1996a; Hesp, 2002; Petersen *et al.*, 2011; Ollerhead *et al.*, 2013). Additionally, storm winds may bend the foliage into their streamlines, reducing roughness and creating a secondary surface for saltation, allowing sand grains to proceed considerable distances downwind in 'modified saltation' (Hesp *et al.*, 2009; Petersen *et al.*, 2011).

Although progress has been made in estimating transport patterns on vegetated surfaces (e.g. Lancaster and Baas, 1998; Van Dijk *et al.*, 1999; Arens *et al.*, 2001a; Dong *et al.*, 2008; Okin, 2008; Leenders *et al.*, 2011; Dupont *et al.*, 2014; Luo *et al.*, 2014), it remains difficult to predict patterns of erosion and deposition for varying wind conditions and on irregularly vegetated surfaces, such as foredunes (Leenders *et al.*, 2011; Bauer *et al.*, 2013). However, such predictions are a prerequisite for modelling foredune development, as erosion and sedimentation patterns eventually determine foredune morphology and evolution (Hesp, 1988). General profiles of sedimentation have been obtained from measurements of daily to monthly elevation change on vegetated foredunes (e.g Sarre, 1989; Arens, 1996a; Christiansen and Davidson-Arnott, 2004; Ollerhead *et al.*, 2013). These show that maximum sand deposition occurs near the seaward edge of vegetation, decreasing with distance upslope. Compared to sedimentation on the seaward slope, relatively little reaches the crest and landward slope.

In turn, sedimentation may influence vegetation patterns. Typical foredune vegetation species require a certain amount of burial to thrive (Martin, 1959; Maun and Lapierre, 1984; Van der Putten *et al.*, 1993) and have an upper limit to the amount of burial they can cope with (e.g. Ranwell, 1958; Maun and Lapierre, 1984; Maun and Perumal, 1999). Plant growth on the foredune is consequently stimulated where an adequate amount of sand is deposited, while vegetation declines where tolerance limits are exceeded in either sedimentation or erosion. Hence, the pattern of sedimentation may determine where vegetation thrives and where it declines. Furthermore, variations in the tolerance to burial and exposure between species may contribute to spatial distribution of plant species (Levin *et al.*, 2008; Maun, 2009).

Although the relationships outlined here are understood in concept, there is relatively little detailed empirical information to quantify the positively reinforcing interaction between vegetation growth and progressive sedimentation, especially over timescales of more than a year. Also, both the optimum and the erosion and burial limits of foredune vegetation in a field setting are not well known. This chapter investigates the interaction between vegetation and aeolian processes in shaping the foredune, by examining observed sedimentation and vegetation patterns over a period of 10 years.

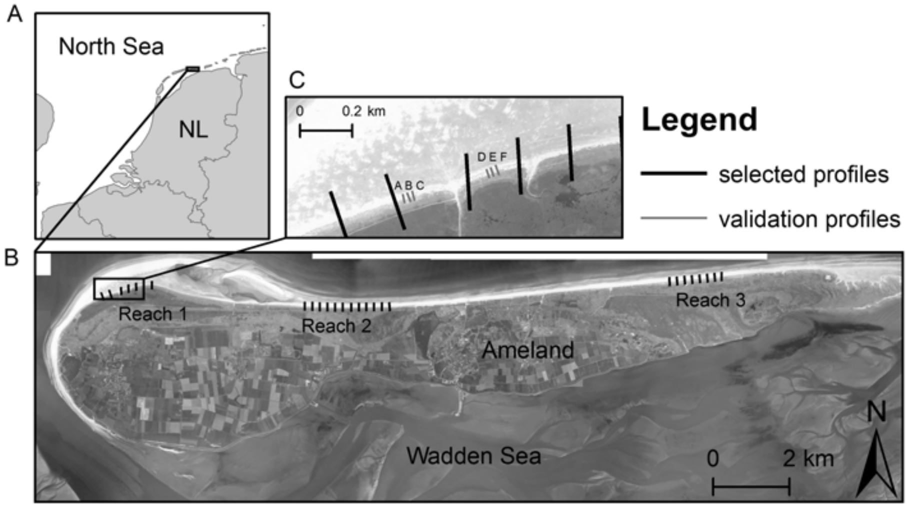

Figure 3.1: Location of the three selected reaches in Ameland. Upper left panel shows location of Ameland relative to the Netherlands. Photo copyright Aerodata Int. Surveys, aeroGRID NL2003.

3.2 Methodology

3.2.1 Regional setting

The study site is the on the Dutch barrier island of Ameland (Figure 3.1). The island is oriented approximately west-east with the largest part of the foredunes facing north towards the North Sea. The island has a semi-diurnal tide with a mean tidal range of 2.2 m (mesotidal, Rijkswaterstaat (2014a)). The dominant wind direction is from the south-west (KNMI, 2014). Perpendicular onshore winds, i.e. from the north, are less frequent. Water levels are strongly influenced by wind force and direction.

The Ameland foredunes are between 9 to 15 m in height and are vegetated by Marram grass (*Ammophila arenaria*), Sand couch (*Elytrigia juncea*), Baltic marram grass (*Calammophila baltica*) and Lyme grass (*Leymus arenarius*). Most of the foredunes on Ameland have been created and fixed by sand fences and vegetation plantings (Arens *et al.*, 2001b), leading to dunes that are fairly stable in place. Since 1990, management strategy has changed to from using stabilising measures to using sand nourishments to maintain shoreline position. This new strategy allows marine and aeolian processes to distribute sand over the beach-dune profile and has led to a more natural appearance of the foredunes (Arens, 2007; De Jong *et al.*, 2014). For the analyses in this chapter, we make use of certain stretches of coastline, based on trends in the data (see section 2.3).

3.2.2 Elevation data

Elevation data are obtained from the JARKUS dataset of the Dutch Department of Public Works (Rijkswaterstaat). The dataset contains yearly elevation profiles across beach and foredune, covering almost the entire Dutch coastline. Profiles are 200 m apart alongshore and elevation is given every 5 m cross-shore at fixed positions. The dataset has been used in several studies on beach and dune morphodynamics (Arens and Wiersma, 1994; Bochev-Van der Burgh *et al.*, 2011; De Vries *et al.*, 2012a; De Jong *et al.*, 2014). This study uses elevation data from 2002 to 2012 from Ameland, which are derived from LiDAR measurements. Vertical accuracy (σ) of this technique is estimated at 0.10 - 0.15 m (De Graaf *et al.*, 2003).

The elevation data are used to calculate yearly elevation changes across the profile. The cross-shore extent of elevation data is limited to the zone between 25 m seaward and 100 m landward of the dune foot in 2002. The dune foot is defined as the most seaward point where elevation is below + 3 m NAP (NAP is the Dutch ordnance datum, and lies approximately at Mean Sea Level). In this study area, this is generally the same as the height at which there is a change in slope, separating the backshore from the foredune (Ruessink and Jeuken, 2002; Bochev-Van der Burgh *et al.*, 2011; De Jong *et al.*, 2014). The dune crest is defined as the highest point within 50 m of the dune foot, which makes sure the crest is set at the foremost established dune ridge and avoids other local maxima to be designated as crest.

The position of the dune foot varies in time, moving seaward between 5 and 40 m relative to the initial (2002) position. The position of the initial crest does not change, although new, lower crests may form seaward. This analysis is focused on the seaward slope of the foredune, as this is where most of the sediment settles. The cross-shore extent of the elevation profiles is limited to the dune foot and crest, plus 50 m seaward and landward of the foot and crest, respectively, to account for sand deposition near the dune foot or on the landward slope.

3.2.3 Site selection

The status of the Ameland foredunes ranges from slightly eroding to accreting (Figure 3.2). As the main interest of this study is aeolian sedimentation as opposed to sea erosion, only those profiles that show clear accretion are used. This selection reduces the influence of hydrodynamic processes on foredune development, while the interaction between aeolian transport and vegetation is more prominent. Three reaches of accreting foredunes are identified, based on linear trends of dune volume over time. High R^2 indicates a constant growth, whereas low R^2 indicates irregular dune development. Alongshore differences are likely related to variations in beach width and the offshore bar configuration, controlling the impact of storm surges. Where impacts are large or frequent, dune volume does not increase linearly,

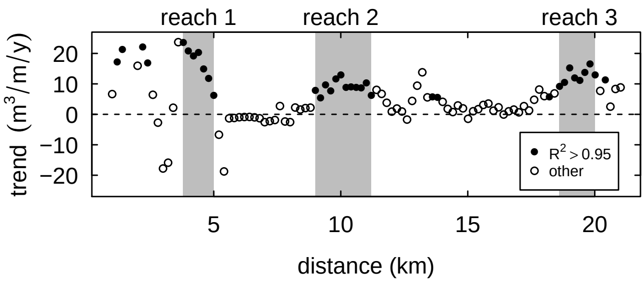

Figure 3.2: Linear trends in foredune volume over time (2002-2012), calculated for each transect. Shaded zones indicate extent of reaches with relatively rapid and constant growth (high R^2).

but shows an irregular development instead (Keijsers *et al.*, 2014b). The first selected reach lies between km 3.8 and 5.0, on the west of Ameland. The second reach runs from km 9.0 to 11.2 and the third reach from 18.6 to 20.0. This selection resulted in 25 transects.

In all reaches, foredunes are partially covered by vegetation (Figure 3.3). Beaches are relatively wide, from 100 m in reach 2 to over 500 m in reach 1. In reach 1, foredunes are low and relatively steep. In reaches 2 and 3, foredunes are higher than in reach 1, where reach 2 has the most gentle slopes.

The coast of Ameland receives regular beach and shoreface nourishments (Rijkswaterstaat, 2014c). Shoreface nourishments have been applied to reach 2 in 2003 and to reach 3 in 2010 and a beach nourishment was applied to reach 3 in 2011. Both shoreface and beach nourishments are intended to increase local sediment budget and reduce erosion. This often promotes foredune growth (Van der Wal, 2004; Bakker *et al.*, 2012; Keijsers *et al.*, 2014a). In contrast to dune reinforcements, these nourishments do not instantaneously alter foredune morphology, as water and wind are still needed to transport the nourished sand into the foredune (Arens and Wiersma, 1994). Inspection of the dune profiles before and after nourishments showed no abrupt morphological changes, making the data suitable for the analyses. The change in sediment availability does however influence foredune morphology on the longer term, as without a regular addition of sand, the majority of Dutch foredunes would be in an erosional state (Hesp, 2002).

3.2.4 Vegetation data

Vegetation patterns are derived from aerial photographs. Suitable photographs, taken in spring or summer, i.e. during the growing season of the vegetation, with low amounts of shadow and relatively dry beach sediment are available for 2003, 2006, 2009 and 2011 (Table 3.1). These requirements guarantee clear differences between bare surface and vegetation. Prior to classification, photos are aligned to ground control points (n=16). The root

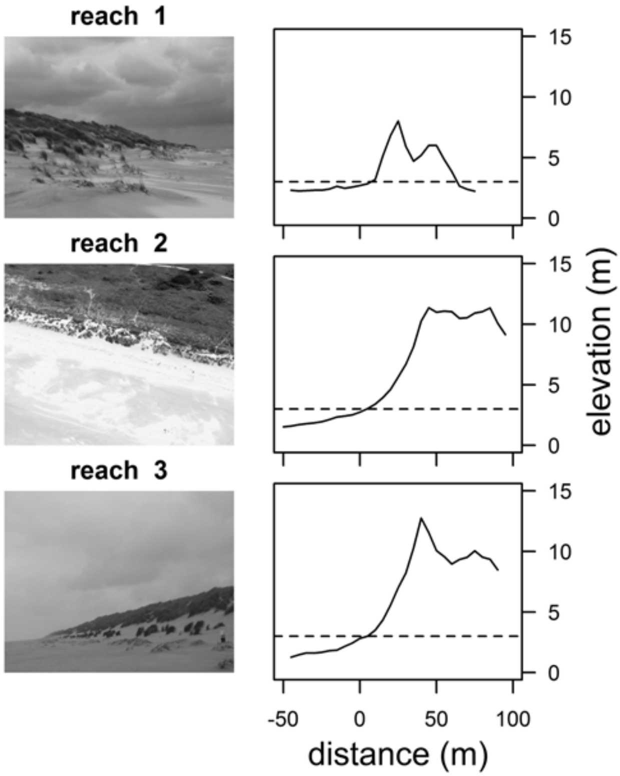

Figure 3.3: Foredunes at reach 1, 2 and 3. Right panels show examples of initial (2002) elevation profiles within the reach. The dashed line indicates the elevation of the dune foot. Distance is relative to the dune foot position, where positive is landward. Photo 1 and 3 by AdG, photo 2 by `https://beeldbank.rws.nl`, Rijkswaterstaat / Joop van Houdt.

mean square error after aligning is between 0.6 and 1.3 m (Table 3.1).

As tests showed little difference in classification results between using colour images and grayscale images, all colour images are converted to grayscale to reduce computation time. Classification of the greyscale images into ‘bare’ and ‘vegetated’ pixels is done with Maximum Likelihood Classification in ArcGIS (ESRI, 2011). Clusters of pixels of both bare and vegetated sites (training pixels) are manually selected approximately every km along the coast, yielding between 332 and 2991 pixels per training class, depending on the image resolution (Figure 3.4A). A mask is applied to the beach to avoid wet surface or surface water being classified as vegetation.

For each elevation data point, average vegetation cover is determined for a circular zone surrounding it (Figure 3.4B). A 2.5 m zone radius is used to avoid overlap between adjacent zones. Classification results are validated with field measurements from May 2011. Vegetation height was measured at every 0.5 m along 6 transects crossing the foredune. The pres-

year	date	resolution (m)	root mean square error (m)
2003	29 May 2003	0.5	1.6
2006	3 July 2006	0.5	0.5
2009	Summer 2009	0.4	0.9
2011	25 April 2011	0.25	0.4

Table 3.1: Characteristics of the aerial photos used for vegetation analysis.

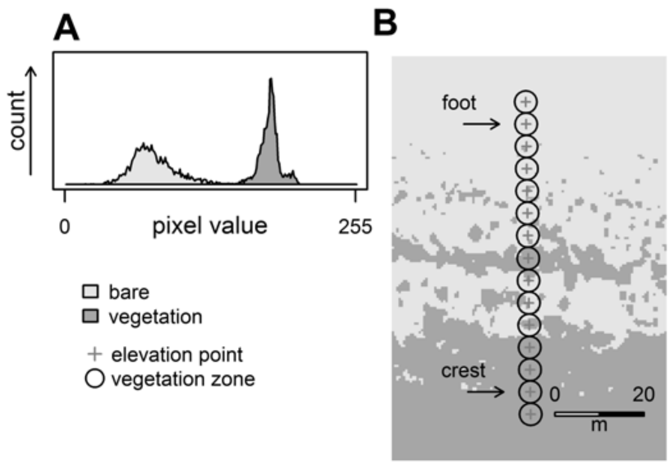

Figure 3.4: Methodology for extraction vegetation cover from aerial photos (A) Value of training pixels for vegetation and bare sand in the 2011 aerial image. (B) Plan view of a beach and foredune profile, after classification. Average vegetation cover is extracted from the circular zone surrounding each elevation measurement.

ence of vegetation along these measured transects is compared with the pixel-scale presence of vegetation in the 2011 aerial photograph classification. Success rate of the classification is calculated as percentage of pixels that is classified correctly.

With this methodology, the distribution of vegetation over the foredune slope can be extracted. It does however not provide information on the height or density of vegetation within pixels, two aspects which may also be important for aeolian transport (Olson, 1958; Bressolier and Thomas, 1977; Hesp, 1983; Arens *et al.*, 2001a; Hesp, 2002).

3.2.5 Combining sedimentation and vegetation

To investigate correlations between sedimentation and vegetation profiles across foredunes, the time series of elevation data is cut in four sub series, each corresponding to a particular aerial photo (Table 3.2). Each sub series starts one year before the photo and ends one year before the next photo. As no elevation data are available for 2013, the elevation data for the 2011 starts two years before and ends one year after.

subseries	elevation data	photo
1	2002-2005	2003
2	2005-2008	2006
3	2008-2011	2009
4	2009-2012	2011

Table 3.2: Subsets of time series.

As measurement uncertainty of elevation data is in the same order of magnitude as yearly elevation changes on a foredune, morphological developments calculated over short periods are unreliable. Therefore, elevation changes Δz over year t are calculated as the average change in 2 periods of 2 years: $\Delta z_t = ((z_{t+1} z_{t-1}) + (z_{t+2} z_t))/4$.

3.3 Results

General patterns of vegetation and sedimentation

The general pattern of sedimentation is obtained by averaging sedimentation data of all profiles from all three reaches (Figure 3.5). Sedimentation increases from the beach to the seaward slope, reaching a maximum between the foot and crest of around 0.4 m/year, then decreasing towards the crest and farther landward. The sedimentation rate beyond the crest decreases from 0.15 m/year to 0 m/year within approximately 30 m.

Variation in sedimentation among profiles is low on the beach and landward of the crest, while large differences occur on the seaward slope. Highest rates of deposition over the entire period are between 0.5 and 0.7 m/year, although yearly values may be much higher.

Three different vegetation patterns can be identified (Figure 3.6B): (1) a continuously vegetated slope without patches near the foot; (2) a vegetated slope, with a laterally continuous line of vegetation near the dune foot, i.e. incipient dune type 2 in Hesp (1989); and (3) a vegetated slope with a zone of sparse patchy vegetation near the dune foot, i.e. incipient dune

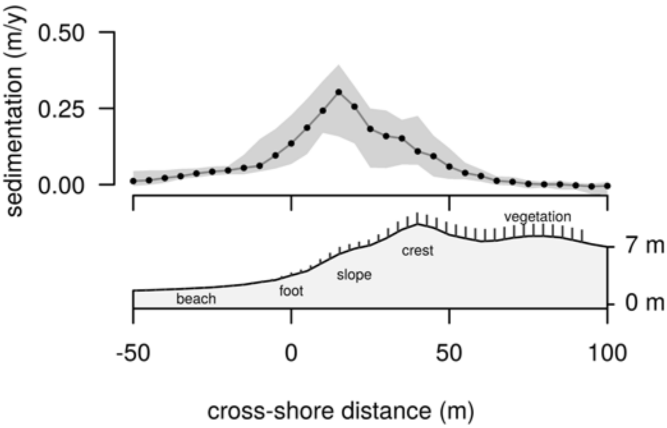

Figure 3.5: Sedimentation across a foredune from 2002-2012 as a function of distance from the 2003 dune foot. Mean values (line) and first to third quartile (shaded area) are indicated. Bottom half shows average dune profile and vegetation cover for reference, with height of vegetation lines indicating relative vegetation cover. Vegetation classification from the aerial photographs shows a good agreement with field measurements, with classification success for the six measured transects between 73% and 90%. On the beach, vegetation is generally absent, although occasionally patches of vegetation are found. In general, vegetation cover increases with distance from the dune foot, although there are considerable differences between sites and years (Figure 3.6A).

type 1 in Hesp (1989). Throughout the observation period, reach 1 shows type 1 and type 2 vegetation profiles. Although the average vegetation profile does not change much in time, the seaward vegetation limit moves seaward considerably. Vegetation profiles in reach 2 are of type 2 initially, but gradually change to type 3 as the bare zone is increasingly covered. Foredunes in reach 3 show a change from a type 1 vegetation cover into type 2, which represents the formation of a new vegetation line near the dune foot. In some cases, distinction between types is difficult. Clearly, the given types only represent end members of a range of possible patterns and actual patterns may be a mix of different types.

A combination of sedimentation and vegetation patterns is shown in Figure 3.7. Highest sedimentation rates occur between foot and crest. In most cases, correlation between vegetation cover and sedimentation pattern is evident, with sedimentation increasing upon crossing the seaward vegetation limit.

3.3.1 Vegetation effects on sedimentation

Effect of seaward vegetation limit

Sedimentation is low on the beach and strongly increases after encountering the seaward limit of vegetation. The lower limit of vegetation could be defined as the furthest seaward point

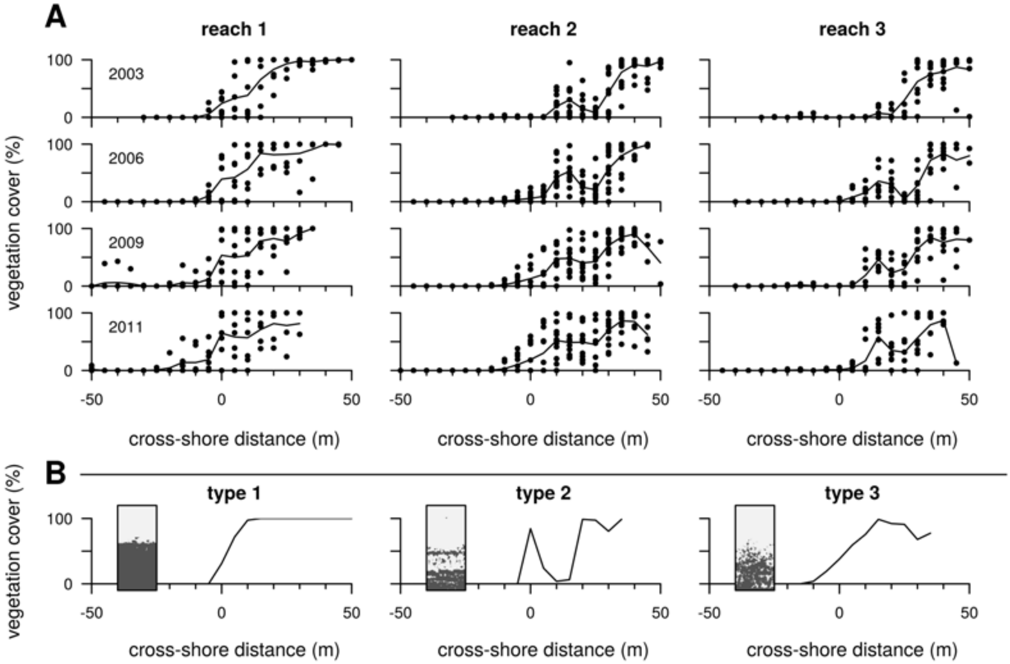

Figure 3.6: Vegetation profiles across the beach and foredune, with distance relative to the dune foot in 2003. (A) Vegetation cover data for the three reaches (left to right) in 2003, 2006, 2009 and 2011 (top to bottom), showing all point observations (circles) and the averaged vegetation profile (line). (B) The main vegetation patterns found alongshore the study site. Type 1 is profile 5.0 in 2003, type 2 is profile 11.2 in 2006 and type 3 is profile 9.4 in 2011. Insets show a vegetation cover map of the corresponding sites.

where vegetation occurs on a profile. However, whether this is a single culm of vegetation or a laterally continuous ridge is likely to have important effect on sedimentation. Therefore, we defined seaward limits as the most seaward points where vegetation cover is above a given percentage. Taking this percentage as a series from 5% to 85% and comparing the positions of the respective vegetation limits with the position of maximum sedimentation, allows a critical cover for sedimentation to be established (Figure 3.8A).

Generally, the position of maximum sedimentation (x_{sed}) follows the alongshore fluctuations of the 5%-vegetation limit (x_{veg}). In reach 3, there are some cases where sedimentation is maximum seaward of the vegetation. These are likely related to nourishments in 2010 and 2011. The actual vegetation cover on the position of maximum sedimentation can be any value between 5% and 85%.

In 71% of the cases, the distance between the 5%-vegetation line and point of maximum sedimentation is between 5 and 20 m (Figure 3.8B). While variation is considerable within sites, no obvious differences are found between sites or between years.

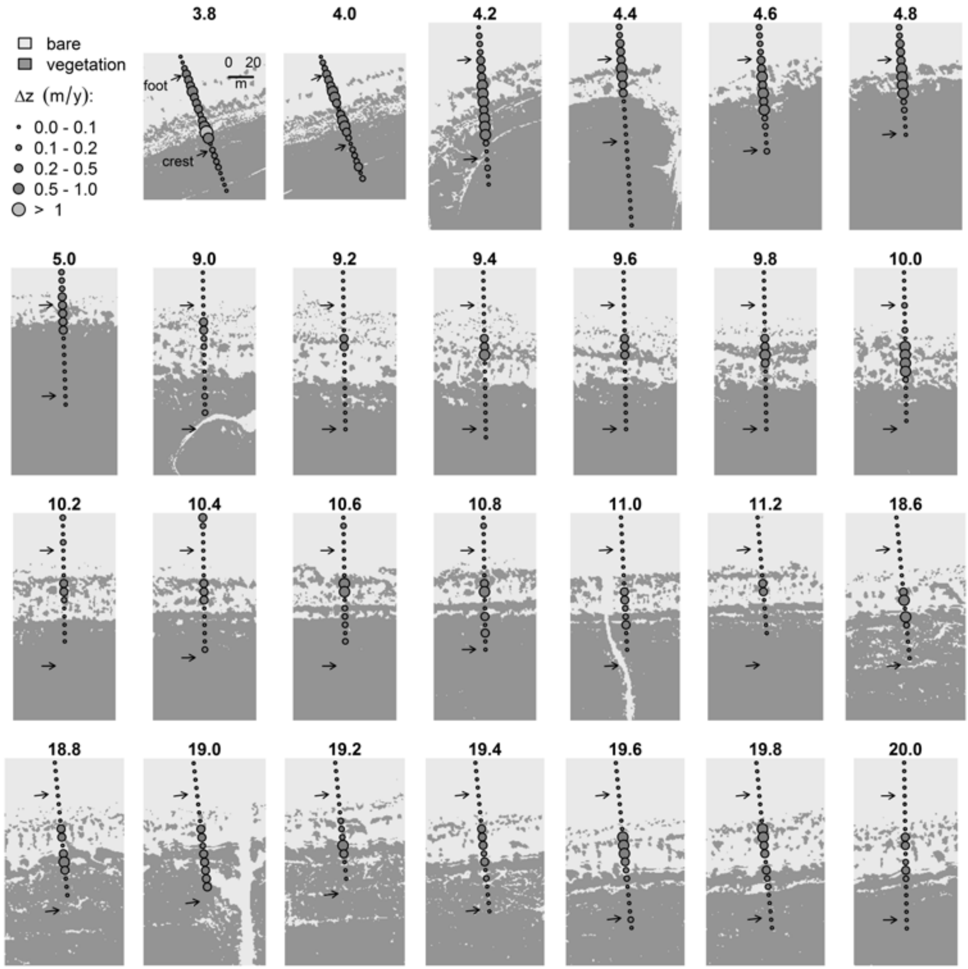

Figure 3.7: Vegetation map for each profile with indication of the amount sedimentation at each measurement point. Arrows indicate the position of the dune foot and crest. Sea is located at the top of each image. Data from the 2006 aerial photo.

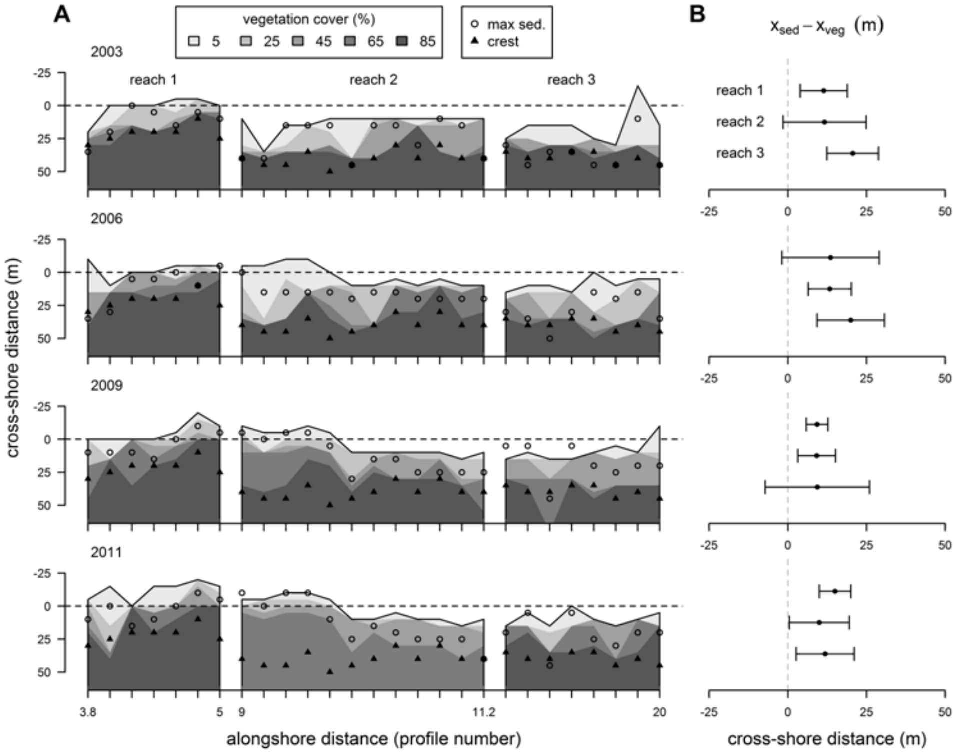

Figure 3.8: Position of maximum sedimentation relative to the vegetation line. (A) Plan view of the position of maximum sedimentation relative to isolines of vegetation cover for each photo. Cross-shore distances are relative to dune foot of 2003. (B) Distributions (mean and sd) of the distance between 5% vegetation line (x_{veg}) and position of maximum sedimentation (x_{sed}) for each year, grouped per reach.

Effect of vegetation cover

On the basis of literature, it is expected that the amount of sedimentation is positively correlated with vegetation density, because the transport-limiting effect of vegetation increases with density and because sedimentation promotes vegetation growth. However, the data show no clear relationship between vegetation cover and sedimentation when calculated for each aerial photo (i.e. $\Delta t = 2$ y, Figure 3.9A). Both erosion and sedimentation occur across the full range of cover values, although high values seem most common between 20% and 80% of vegetation cover. The upper limit of sedimentation declines cover values for above 80%. If the same relationship is calculated over longer periods of time (2002 to 2012, $\Delta t = 10$ y), the results are similar. As a consequence of averaging over a longer time period, few points experience net erosion and net maximum sedimentation values are lower. Also in this case,

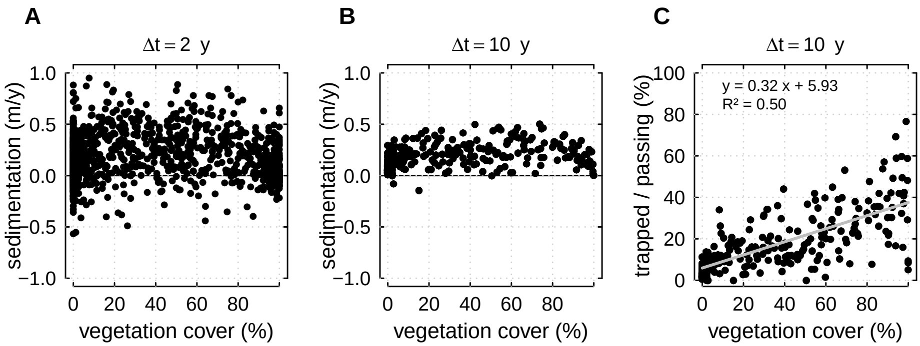

Figure 3.9: Vegetation cover and sedimentation on a point-by-point basis. (A) Calculated for each photo, with $\Delta t = 2$ y. (B) The same relationship, but calculated over the entire period, i.e. from 2002 to 2012, representing time-averaged vegetation cover and sedimentation. (C) The amount of sedimentation at each point relative to the total amount of sedimentation landwards of it. Line shows least-squares linear fit. In all plots, only points on the seaward slope were considered.

values are distributed quite evenly over the range of vegetation cover, although the upper limit seems to decrease for dense vegetation cover.

This lack of a trend and decrease with higher cover values is counter-intuitive, but may be caused by the gradual depletion of the aeolian sand load over the foredune slope. This leads to relatively low volumes of sand reaching the upper slope, where cover is generally high. To account for this effect of depletion, the amount of sedimentation (amount trapped at point x) is calculated relative to the amount of sand that passes each point (total amount trapped at points landward of x). Hence, the amount of deposition at a point is divided by the volume of sand that ends up landward of it, which can be interpreted as a measure of the trapping efficiency. The results show that average trapping efficiency increases considerably with increasing vegetation cover, although even at full cover, 100% efficiency is not attained (Figure 3.9C). Some locations with vegetation cover below 5% were related to the deposition of considerable volumes of sand (panels A and B). Figure 3.9C shows that these cases only occur when there is a large influx of sand to the entire profile, as the trapped/passing values for these vegetation densities are mostly below 10%. Thus, although large volumes of sand may be trapped at low vegetation cover, these volumes are low compared to the total amount that passes.

Effect of vegetation pattern

Three different vegetation patterns were identified (Figure 3.6B). To examine the extent to which these lead to differences in foredune sedimentation, profiles of sedimentation are anal-

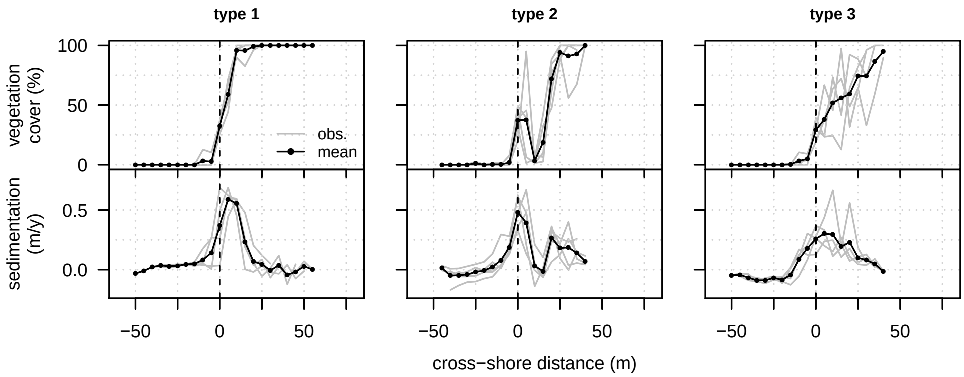

Figure 3.10: Sedimentation patterns for the three different vegetation patterns: (1) no incipient dune; (2) laterally continuous incipient dune; (3) patchy incipient dune. Lower panels show the associated sedimentation profile. Observations of type 1 and 2 are from 2003, observations of type 3 are from 2009 as this type was not present in 2003. Cross-shore distance is relative to the seaward vegetation limit.

ysed for each pattern (Figure 3.10).

Although all profiles show most sedimentation on the seaward slope, there are some marked differences. Type 1 shows a regular sedimentation profile, with a sharp increase upon passing the first vegetation and rapid decrease farther landward. The distance over which sedimentation occurs is approximately 20 m. Type 2 shows two peaks in sedimentation, coinciding with peaks in vegetation cover. Over half of the total sedimentation takes place after the first peak in vegetation cover, although cover at that point might be relatively low. In the relatively bare zone in between vegetated zones, sedimentation is considerably lower and increases again after reaching the vegetation farther upslope. Type 3 shows sedimentation over a longer distance and a lower peak value. In the two latter types, the length of the sedimentation zone is approximately 40 m, which indicates that sedimentation occurs over a longer distance.

3.3.2 Changes in vegetation cover

Trends in vegetation patterns are determined by comparing the vegetation cover in subsequent photos (Figure 3.11A). The total vegetation cover over the pictured profile has increased from 2003 to 2011. Although the vegetation cover has changed considerably, e.g. the limit moves seaward and the area of bare surface declines, initial patches are stable and can still be recognised 8 y later. Two types of growth can be observed: (1) establishment of new patches and (2) expansion of existing patches.

Establishment of new patches is dominantly found near the dune foot, seawards of the

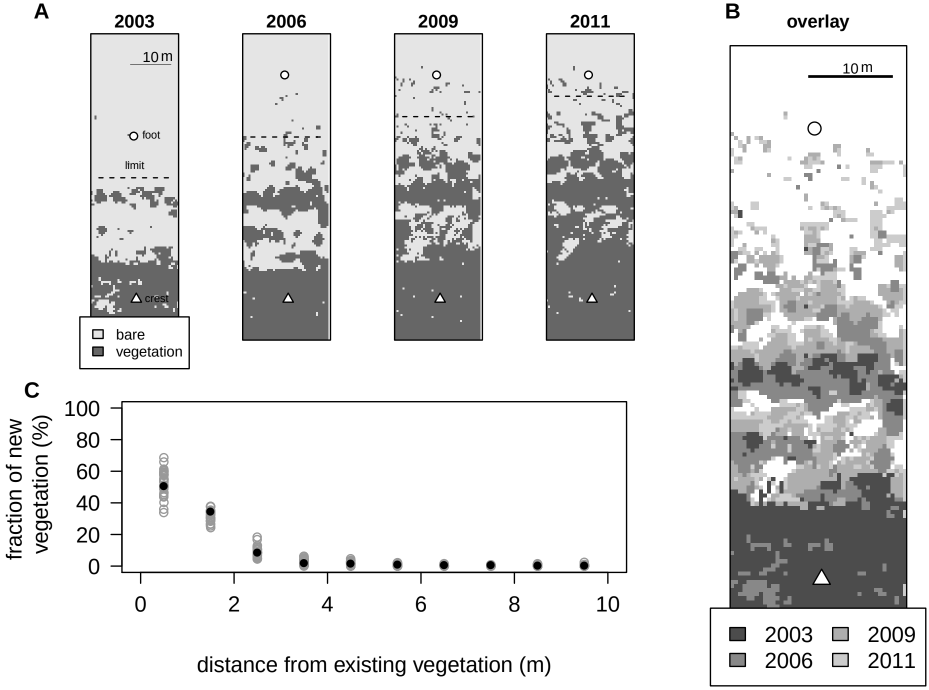

Figure 3.11: Changes in vegetation cover across a foredune. (A) Development of vegetation cover from 2003 to 2011, profile 9.6. Dashed lines indicate seaward limit of vegetation (at least 5% cover). (B) Stacked map of vegetation cover, from 2003 (top level) to 2011 (lowest level). Arrows indicate the lateral expansion of vegetation clumps. Data from profile 9.6. (C) Fraction of new vegetated pixels as a function of distance to existing vegetation, calculated per 1m bin for the three consecutive photo pairs. Black dots represent data from profile 9.6, grey dots represent data of all other profiles.

original vegetation limit. As a consequence, the seaward limit of vegetation moves seaward, up to several metres between photos (Figure 3.11A). In the pictured profile, the seaward limit moves 10 m between 2003 and 2006. In the following years, the line remains almost in place. Averaged over all profiles, the limit moves 2.5 m/year seawards between 2003 and 2006, with individual profiles showing shifts up to 10 m/year. Average changes between the later images are 0.5 and 0.6 m/year.

Landward of the original vegetation limit, lateral expansion of existing patches is the dominant method of growth (Figure 3.11B). Clumps of vegetation present in 2003 grow in size and eventually link up to form a shore-parallel line of vegetation. The rate of expansion is estimated from the stacked image, by calculating the distance between the clump edges in 2003 and 2011 along the pictured arrows. Over this period, edges have expanded between 2.1 and 4.1 m, which means an average of 0.3 to 0.5 m/year. Similar rates of expansion are found for other profiles.

Approximately half of the new vegetation develops within 1 m of an existing patch and 85% of it within 2 m (Figure 3.11C). This indicates that the gain in vegetated area is mostly due to lateral expansion of existing patches. As the upper limit of expansion between photos is between 1 and 2 m (three years at 0.5 m/year), values in classes above 2 m likely represent the establishment of new patches. The contributions of these classes to the total gain is relatively low, decreasing from approximately 10% at 2-3 m to 1% at 9-10 m.

To study the extent to which changes in vegetation cover, both loss and gain, are correlated with sedimentation profiles, the change in vegetation cover is averaged alongshore over every reach. By taking the average change over the 2003-2011 period, a pattern similar to the sedimentation profile appears, i.e. an increase in vegetation cover from the dune foot over the seaward slope, and a decrease landward (Figure 3.12). However, on a point-by-point basis, such a direct relation cannot be confirmed (Figure 3.12, lower panel).

3.4 Discussion

3.4.1 Sedimentation across foredunes

Earlier measurements of sand deposition on incipient dunes (Hesp, 1983, 1988) and established dunes (Sarre, 1989; Arens, 1996a; Arens *et al.*, 2001a; Petersen *et al.*, 2011; Ollerhead *et al.*, 2013) on timescales of days to months showed how the vegetation limit and density influence sedimentation. In general, sedimentation across foredunes follows a distinct profile, where sedimentation increases rapidly past the vegetation line, reaches a maximum at some distance from this line and decreases again farther landward. The results obtained here confirm that also on time steps of years, sedimentation patterns follow this general profile, although further distinctions can on the basis of the presented results.

Several studies have demonstrated the effect of vegetation density on the width of the sedimentation band for time periods of weeks (Hesp, 1983; Arens, 1996a; Arens *et al.*, 2001a). These studies make a distinction between low density and high density, or bare and vegetated slopes. Adding to that, the results presented here demonstrate that characteristic sedimentation profiles can be defined for three distinct vegetation patterns. Besides vegetation density, these types incorporate the spatial configuration of vegetation over the slope. Profiles with a static, dense zone of vegetation (type 1, Figure 3.10) cause a relatively abrupt increase in sedimentation with a distinct peak. In a situation with a shore-parallel vegetated incipient-dune ridge (type 2), there are two sedimentation peaks, both in the incipient zone and on the established dune, with lower sedimentation in the bare zone separating the two. Where a patchy vegetation zone exists in front of the dune foot (type 3), sedimentation is more evenly spread because sand in saltation can travel farther up the dune in between the vegetation patches. If

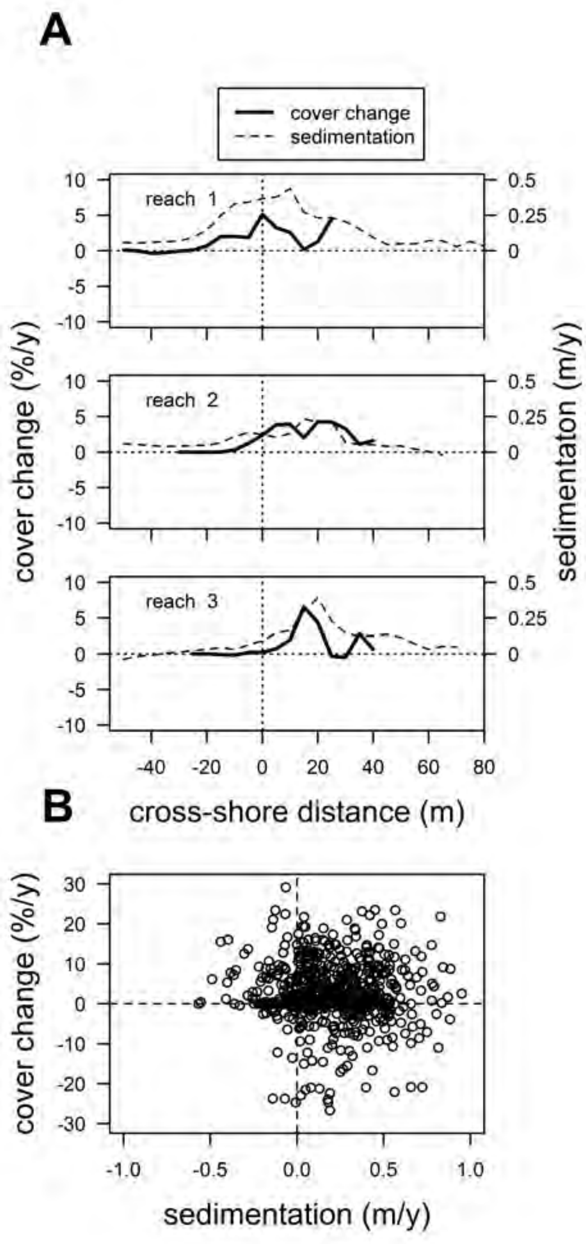

Figure 3.12: Correlations between sedimentation and changes in vegetation cover. (A) Average change in vegetation cover (black lines) as a function of cross-shore distance, calculated per reach. The cross-shore extent of the vegetation data is limited to the seaward slope, with distance relative to the dune foot in 2003. Average sedimentation is also indicated (dashed line). (B) Scatterplot of cover change and sedimentation rate for all profiles, with sedimentation and cover change calculated between 2003 and 2011.

these vegetation and sedimentation patterns persist, they will give rise to different morphological developments, viz. formation of a secondary crest on the seaward slope or near the dune foot (type 1 and 2) or seaward and vertical growth of the entire dune (type 3).

Hesp (1983) found reasonable correlations between plant density and sand accretion on incipient dunes over a period of several weeks. A similar correlation was however not found in the results presented here (Figure 3.9A and B). Even at very low vegetation cover, considerable sedimentation may take place, e.g. 0.4 m/year at 1% cover, while high-density vegetation does not necessarily trap more sand. This might be caused by (1) the longer temporal scale adopted in the analysis presented here and (2) the gradual sand depletion of the foredune slope. First, in contrast to sedimentation over a couple of weeks, 2-yearly values of sedimentation represent a net result of a large number of transport events with different wind velocities and direction. While each individual event may have a clear correlation between sand deposition and vegetation cover, net accretion over a longer period also comprises aeolian transport from oblique or offshore wind directions, causing different patterns of airflow, sand transport and sand deposition. After deposition, sand re-distribution, e.g. upslope translation by speed-up within the canopy (Hesp *et al.*, 2013) might further mask correlations between surface cover and sand-level change.

Second, sand supply is not equally distributed over the foredune slope. From foot to crest, there are inverse trends of decreasing transport and increasing vegetation cover. As sand is transported across the foredune, the sand load gradually depletes with distance from the vegetation line. Hence, less sand is brought to the upslope parts where cover is generally high. This is accounted for by calculating the fraction of sand that is deposited at a certain point to the total load of sand that passes at that point. These results are in better agreement with expectations, although 100% trapping is never achieved. This indicates that sand grains may pass even fully covered areas, likely by means of grains re-bounding on the vegetation canopy, and suspension, both allowing grains to effectively bypass dense vegetation cover (Petersen *et al.*, 2011; Hesp *et al.*, 2013). The reasonable correlation between vegetation cover and trapping efficiency shows that although vegetation cover cannot be used to estimate sand-level changes at a given point or vice versa, it can be used to predict a relative profile of sedimentation across the foredune slope.

3.4.2 Interaction

Vegetation and sedimentation interact. Vegetation patterns affect sand transport, as confirmed by our results. Conversely, the amount of deposition also affects the vitality of marram grass (Disraeli, 1984; De Rooij-Van Der Goes *et al.*, 1995; Van der Putten and Peters, 1997; Maun, 1998; Konlechner *et al.*, 2013). Marram grass requires a certain amount of burial for optimal growth. Yearly burial of 0.10 to 0.60 m leads to vigorous vegetation (Martin, 1959) and the grass tolerates burial of at least 1 m/year (Ranwell, 1958). This fits the observed range of sedimentation on Ameland (cf. Figure 3.9A, -0.2 to 0.7 m/year), and the expansion of vegetation found in most transects indicates that conditions are suitable for marram grass indeed. Values exceeding the assumed tolerance limit for marram do occur, but do not last longer than 1 year. Other grasses present at the study site may have different tolerance limits (Yuan *et al.*, 1993; Greipsson and Davy, 1996).

Based on these literature values and assuming marram grass is the dominant species, vegetation cover and change in cover were expected to show a bell-shaped curve with sedimentation rates, with optimum values around 0.1-0.6 m/year and tailing off when sedimentation rates become either higher or lower (e.g. Baas, 2002; Maun, 2009). However, on the basis of this dataset, we cannot confirm such a direct relation between vegetation growth and sedimentation (Figure 3.9A and B and Figure 3.12B). Vegetation cover may increase even where erosion takes place, as long as there is net accretion over the entire 10-year period. Apparently, dune grasses that are well established can handle a wide range of sedimentation and erosion values, especially since there is no serious competition of other plants due to the harsh conditions on the foredune. When vegetation is established, with a strong root and rhizome system, it may be more resistant against sub-optimal conditions than vegetation that is still establishing. In the field, the colour of the marram grass indicates clearly whether it receives sufficient sedimentation or not. Whether the sedimentation balance has strong effects on cover, however, is not known.

Given the good correlations between vegetation and sedimentation patterns and the lack of correlation between sedimentation and changes in vegetation cover, it is tempting to conclude that while vegetation strongly controls patterns of sedimentation, the sedimentation balance in turn does not strongly control the development of vegetation. However, it should be noted that the vegetation data available here only indicate which fraction of the surface is covered or not and do not convey any information on the vitality, height or cm-scale density of the plants. Furthermore, the calculated sedimentation represents the net change over multiple years and thus neglects any fluctuations on a smaller timescale. Such fluctuations may be of importance for vegetation vigour (e.g. if they occur in the growing season or not), but cannot be detected on the basis of yearly data. Hence, we can only conclude that the multi-year sedimentation balance at a particular point is not a strong control on the expansion of foredune vegetation at the same point. Likely, other factors such as moisture and nutrient availability and salt spray play an equally important role, masking possible correlations between sand accretion and vegetation growth (Maun, 2009).

Our understanding of this relationship could be significantly improved by increasing measurement frequency and spatial resolution, e.g. by using unmanned aerial vehicles several times per year to measure both elevation and vegetation (Mancini *et al.*, 2013), and continue this over several years. Such measurements provide easy extraction of vegetation patterns, facilitating more detailed analysis of bio-geomorphological interactions on the foredune slope. Furthermore, instead of 2D analyses, a 3D approach can be adopted to examine spatial variability and effects of single vegetation patches on sedimentation.

3.5 Conclusions

Data on elevation and vegetation cover of the foredunes of the island of Ameland were combined to study the patterns of sedimentation and vegetation. Although the results are not as definitive as one might hope for, several conclusions can be drawn on the basis of our results.

Multi-year observations of sand deposition on a foredune confirm the general patterns observed on shorter timescales. Sedimentation increases from beach to foredune, with a maximum on the seaward slope. This maximum lies between 5 and 20 m landward of the seaward limit of vegetation. Sedimentation then decreases again landward. This general patterns is further modified by the spatial configuration of the vegetation. When vegetation cover is patchy, sand may travel farther upslope. When a shore-parallel zone of incipient dunes is present, over half of the sediment input may be trapped in these incipient dunes. Due to inverse trends of decreasing sand transport and increasing vegetation cover with distance upslope, dense vegetation cover does not necessarily trap more sediment, but it tends to trap a larger fraction of the sand that passes.

In all three studied stretches, vegetation cover increases in time. Most of this expansion takes place in the direct vicinity of existing vegetation patches at rates up to 0.5 m/year. Establishment of new patches dominantly occurs near the dune foot, leading to seaward shifts in the vegetation limit. Although in general vegetation growth co-occurs with sedimentation, change in vegetation cover cannot be linked to sedimentation on a point-by-point basis.

Acknowledgements

The research was conducted within the Dutch research program Knowledge for Climate (Theme 1: Climate-proof Flood Risk Management). Field data on vegetation cover were provided by Joppe de Groot. We thank Bernard Bauer and an anonymous reviewer for their useful comments on the manuscript.

3.6 Appendix A

Vegetation classification results of the 2011 aerial photos are validated with field measurements of vegetation cover from May 2011. Vegetation height was measured every 0.5 m along six validation transects crossing the foredune from foot to crest, all within reach 1 (Figure 3.1).

The same locations on the aerial photographs were classified using the automated classification. Measurements of vegetation height were converted to bare/vegetation by interpreting a vegetation height of 0 m as bare and a vegetation height above 0 m as vegetated. The accuracy of the photo classification is determined as the percentage of points classified correctly:

$$accuracy = 100\% \cdot (n_{\text{correct bare}} + n_{\text{correct vegetated}})/n_{\text{total}} \tag{3.1}$$

The classification shows a good agreement with field measurements, with classification accuracy between 71% and 100% (Figure 3.13). This indicates that vegetation patterns on the seaward slope are adequately represented by the image classification.

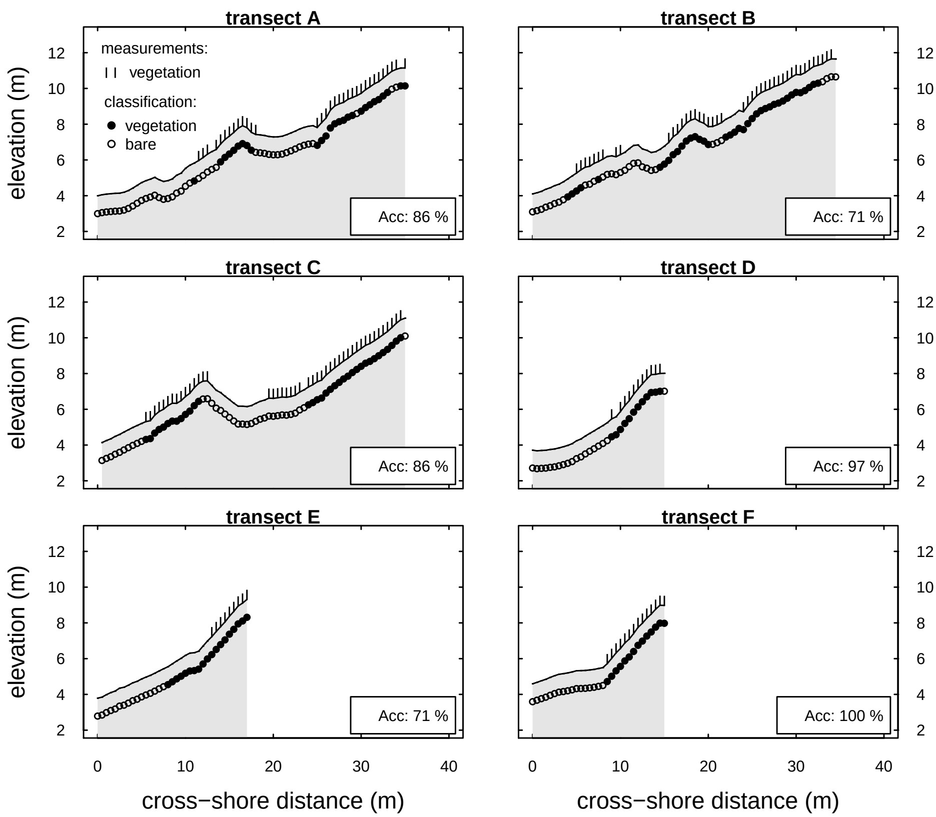

Figure 3.13: Comparison between field measurements and image classification of vegetation cover along the six validation transects on Ameland (A–F). The vertical sticks on the surface indicate the measured presence of vegetation along the transect. Open and filled circles below the surface indicate the classification result at the corresponding position. Agreement between measurements and classification is shown for each transect.

4

Modelling the geomorphic evolution of coastal foredunes: response to sea-level rise and climate change

4.1 Introduction

Along many sandy coastlines, coastal dunes form the first line of defence against the sea. The development and evolution of coastal dunes depends on sediment supply, beach morphology, vegetation effectiveness and climatic variables such as wind climate, sea level and wave conditions (Hesp, 2002; Pye, 1990; Short and Hesp, 1982). A change in one of these factors has consequences for dune development. Recent climate-change scenarios for the Netherlands project a sea-level rise (SLR) of 0.40 to 1.05 m between 1990 and 2100, increased drought in summer, but no change in wind climate and storminess (Van den Hurk *et al.*, 2007; Katsman *et al.*, 2011; De Winter *et al.*, 2013). Such changes have the potential to significantly influence dune evolution. In the light of flood risk in countries where dunes form the main line of defence, this modelling study investigates the effects of such changing conditions on the development of coastal dunes.

In order to adapt to the expected sea-level rise, the Dutch government has implemented a policy of dynamic preservation, in which sand nourishments are carried out to allow the beach-dune system to accrete vertically, keeping pace with rising sea level and maintaining the level of flood protecting (Hillen and Roelse, 1995; De Ruig, 1998). However, it is unclear how the nourished sand is distributed in the foredune system. In addition, management efforts are carried out to restore dune mobility and aeolian dynamics to maintain biodiversity (Provoost *et al.*, 2011; Arens *et al.*, 2013a). However, the effectiveness of this measure in

Based on: Keijsers JGS, De Groot AV, Riksen MJPM. Modelling climate-change effects on coastal foredunes. Submitted to *Journal of Geophysical Research: Earth Surface* terms of long-term landscape dynamics is not clear. A second goal is therefore to study the effects of sand nourishments and remobilization interventions on the coastal dune landscape.

Climate effects on coastal dunes have mostly been studied on timescales of centuries. In general, changes in wind climate, storminess and sea level were found to control onset and termination of aeolian activity and dune formation (e.g. Aagaard *et al.*, 2007; Clemmensen and Murray, 2006; Klijn, 1990). Although such relationships from the field can be used to explain historic trends, they lack the resolution for making quantitative predictions of future dune development on a scale of decades.

Conceptual models of dune morphology as a function of e.g. shoreline dynamics, vegetation cover and wind climate provide a good starting point for evaluating the direction of dune evolution over decades (Pye, 1990; Psuty, 1992; Hesp, 2002). Shoreline retreat associated with sea-level rise is expected to result in landward migration of dunes as a consequence of more frequent foredune scarping. While retreating, the foredune may maintain its shape (Davidson-Arnott, 2005; Ollerhead *et al.*, 2013) or evolve into parabolic dunes or transgressive sheets (Pye, 1990). However, dunes may also prograde when the rate of sediment supply offsets SLR (Carter, 1991; Hesp, 2002). The wide range of possible responses, resulting from the large variety of environments in which foredunes exist, combined with the lack of quantitative information, limits the applicability of these conceptual models to qualitative predictions of meso-scale dune development.

Computer models are able to simulate dune development in response to changes in one or more specific parameters, suitable for investigating climate-change effects on coastal dunes. Available simulation models for dune dynamics in deserts and vegetated environments, range from rule-based (Werner, 1995; Baas, 2002), process-based (e.g. Van Dijk *et al.*, 1999; Durán and Herrmann, 2006) to regression models (Ryu and Sherman, 2014). Studies employing these models highlight the critical importance of biogeomorphic interactions in dune field morphology.

A number of investigations extrapolated on the rule-based principles of the Werner (1995) model. By introducing the interactions between vegetation on aeolian transport, a variety of vegetated dune landscapes was reproduced, determined by the wind regime, sand supply and vegetation characteristics (Nishimori and Tanaka, 2001; Baas, 2002). Further investigations using this type of models show that landscape mobility and stability strongly depend on the vegetation characteristics (Baas and Nield, 2007; Pelletier *et al.*, 2009; Baas and Nield, 2010). Recently, a sequence of studies using process-based models of coastal dune fields found variations in dune-field morphology in response to differences in backshore width, vegetation growth rates and aeolian supply (Luna *et al.*, 2011, 2012; Durán and Moore, 2013).

Several studies have examined the possible effects of climate on dune evolution. Climate change might lead to either dune field stabilisation or mobilisation as a consequence of changes in vegetation growth (Nield and Baas, 2008a; Barchyn and Hugenholtz, 2012). Using historical data as a basis for a regression model, Ryu and Sherman (2014) predicted an increase in vegetation cover in coastal dune fields in response to climate change in the United States. Feagin *et al.* (2005) used a limited set of rules to model impacts of sea-level rise on vegetation patterns, showing inland displacement of entire plant communities. For high-end scenarios, the succession was found to break down, thus reducing the biogeomorphic dune building capacity. Similarly, a modelling study by Durán and Moore (2014) suggests that the rate of re-vegetation rate after storms largely determines whether barrier islands are able to recover or not. If biogeomorphic dune recovery exceeds dune erosion, vegetated dunes and barrier islands achieve high elevations. Alternatively, if the return time of overwash events is less than the time required for vegetation recovery, a barrier island does never recover and remains in a state of low elevation. In this perspective, climate-change related changes in storm frequency or vegetation growth have the potential to shift a system from one state to the other.

So far, a well-validated modelling instrument, including the interplay between vegetation, hydrodynamics and vegetation, to predict foredune development under sea-level rise and climate on the meso-scale has been lacking. To study the combined effects of changes in vegetation cover and sea-level rise on foredune evolution, we use a cellular model of dune, beach and vegetation (DUBEVEG), adapted from (Werner, 1995; Baas, 2002). Although the DUBEVEG model was originally developed for exploratory simulations, this chapter takes the next step to rigorously test the model against field observations.

The questions we address in this chapter are: (1) how does climate change influence foredune evolution on the timescale of decades? and (2) to which extent do dynamic preservation strategies mitigate climate-change effects? First, model calibration and validation is performed with data from the Dutch coast. Second, a set of climate and management scenarios is used to analyse foredune evolution in response to climate change and dune management.

4.2 Model outline

The model employed in this study (DUBEVEG, i.e. DUne, BEach, VEGetation) simulates the aeolian, hydrodynamic and biotic processes relevant for coastal dune morphodynamics on a cellular basis, in which sand slabs are moved from one cell to another based on a number of rules (De Groot *et al.*, 2011). The rules are intended to replace a complex set of interacting physical laws, such as those governing aeolian transport, sediment availability, wind flow over a complex surface and vegetation response to burial.

The model consists of three modules: an aeolian transport module, a marine processes module and a vegetation module. The aeolian transport module represents the core of the model. After a fixed number of its iterations, the vegetation module is called to update the vegetation cover. The number of iterations between each vegetation update defines the number of transport iterations per year (Baas, 2002). The marine processes are run once every 2 weeks, corresponding to a spring-neap tidal cycle (De Groot *et al.*).

The spatial extent of the model comprises the beach and foredune, defined as the zone between the mean water line and the point 50 m landward of the original foredune crest. The alongshore extent is 10 m for sensitivity runs and 25 m for the other runs. The spatial resolution is 1 m horizontally, and 0.1 m vertically.

4.2.1 Aeolian transport

The dune formation module is largely based on the DECAL algorithm (Baas, 2002), which is itself an extension of the dune model of Werner (1995). A detailed description of the aeolian transport algorithm can be found in (Baas, 2002; Nield and Baas, 2008b). The topography consists of stacks of discrete slabs of sand on the grid of the model domain. Wind transport of sand is mimicked by repeatedly picking up slabs one by one and moving them to the next downwind cell, in this study the onshore direction. Erosion and deposition of slabs are governed by probabilities (p_e and p_d, respectively) that depend on vegetation and 'shadow zones'. The fate of each sand slab is determined by drawing from a uniform random distribution and comparing this to the probabilities. The angle of repose is enforced through avalanching if the slope gets too steep. On the lee side of each dune, a sheltered zone is defined from which slabs cannot be eroded ('shadow zone').

Vegetation decreases sand transport and enhances deposition (Wasson and Nanninga, 1986; Buckley, 1987). This effect is modelled by changing the erosion and deposition probabilities proportionally to the vegetation cover in a cell (Figure 4.1). With higher vegetation cover, the deposition probability increases and the erosion probability decreases. Erosion of sand is virtually zero once vegetation cover exceeds 15-50% (Lancaster and Baas, 1998; Kuriyama *et al.*, 2005; Levin *et al.*, 2008; Buckley, 1987; Wasson and Nanninga, 1986), but it is still possible for sand grains to pass densely covered cells, either by passing through bare 'streets', travelling in suspension, re-bounding off vegetation or transport within the canopy (Arens, 1996a; Petersen *et al.*, 2011; Youssef *et al.*, 2012; Hesp *et al.*, 2013; Dupont *et al.*, 2014; Keijsers *et al.*, 2015). This effect is modelled by setting the maximum p_d to a value below 1. In addition, the presence of vegetation increases slope stability, so steeper angles can be maintained.

Wind strength is assumed to be unidirectional and of constant velocity throughout the simulations. The potential aeolian transport per metre alongshore (Q in $m^3/m/y$) is equal to (Nield and Baas, 2008b):

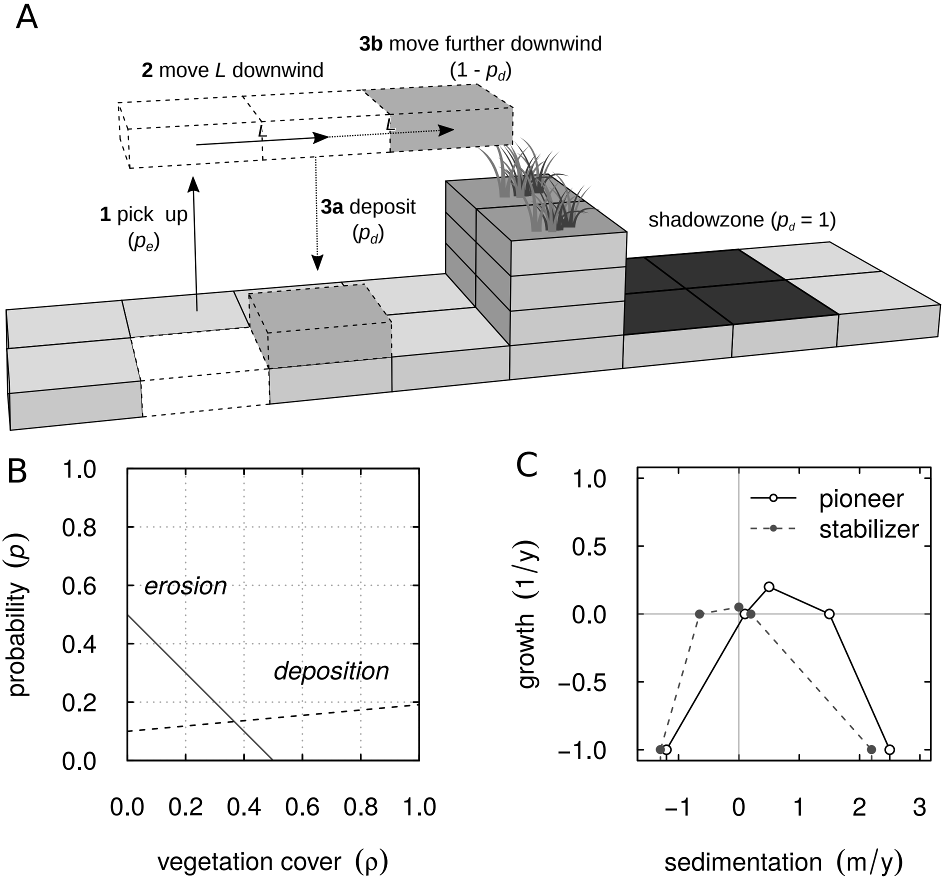

Figure 4.1: Process of slab movement in the aeolian sand transport component. (A) Process of slab movement with pick up (1), down-wind movement (2) and subsequent deposition (3a) or (3b) further downwind movement. Erosion and deposition probabilities are controlled by vegetation cover in each cell and presence of shadow zones in the lee of tall topography. (B) Erosion and deposition probabilities as a function of vegetation cover. Erosion probability decreases linearly and is no longer possible when vegetation cover exceeds 0.5. Deposition probability increases with vegetation cover, but never exceeds 0.2. (C) Growth functions control response of vegetation to a given level of burial or erosion (Baas, 2002).

$$Q = h_s \cdot L \cdot \frac{p_e}{p_d} \cdot n \tag{4.1}$$

where h_s is the slab height (m), L is the hop length of a slab (m), p_e and p_d are the probability of erosion and deposition, and n is the number of aeolian iterations per year (year^{-1}). Different wind climates and thus potential transport are modelled by adapting the erosion probability p_e.

Sand availability is limited by the presence of groundwater. Groundwater level lies between the equilibrium beach profile and mean sea level at an elevation proportional to the equilibrium profile ($z_{groundwater} = a \cdot z_{equilibrium}$). No aeolian erosion is possible below groundwater level or below mean sea level.

4.2.2 Vegetation development

Each cell has a dimensionless vegetation cover C_v, where a value of 0 means fully bare surface and 1 means fully covered surface. Establishment and development of vegetation is modelled as a function of sedimentation, which is determined for each cell once per year. Bare cells can become vegetated via (1) establishment of vegetation in a previously bare cell or (2) lateral expansion of vegetation into bare surrounding cells.

Establishment of vegetation into a previously bare cell represents the germination and development of vegetation from seeds or rhizome fragments distributed by the sea or by wind (Van der Stege, 1965; Wallén, 1980; Putten, 1990; Hilton *et al.*, 2005). Dispersal and distribution of seed and rhizomes is assumed to be uniform over the beach and dune, hence the probability for becoming vegetated ($p_{establishment}$) is equal for all bare cells.

Once established, vegetation may spread through lateral expansion (Gemmell *et al.*, 1953; Huiskes, 1979), with rates in the order of 1 m/year for marram grass (Keijsers *et al.*, 2015). This process is simulated by giving each cell neighbouring a vegetated cell (8-cell neighbourhood), either partly vegetated or bare, an equal probability ($p_{lateral}$) for vegetation growth.

Vegetation development within (newly) vegetated cells is controlled by the growth functions following the DECAL model (Baas, 2002; Baas and Nield, 2007; Nield and Baas, 2008b). These give the response of vegetation by defining tolerance limits to burial and erosion and the sedimentation balance for which growth is optimal (Figure 4.1). Once full surface cover is reached, no further growth is possible. Seasonality is not included.

Two types of vegetation are modelled: a burial-tolerant species representing a foredune pioneer such as marram grass (*Ammophila arenaria*, species 1), and a more conservative species, representing buckthorn-type vegetation (*Hippophae rhamnoides*, species 2) (Nield and Baas, 2008a). Marram grass depends on the input of fresh sediment for growth (Van der Putten *et al.*, 1993). Optimal growth takes place when burial is between 0.10 to 0.55 m/year

(Martin, 1959; Maun, 2009; Van der Putten *et al.*, 1993) and the species tolerates burial up to 1 m/year (Huiskes, 1979) or even 2 m/year (Baas and Nield, 2010). The second, more conservative species has optimal growth under neutral conditions, but can tolerate some erosion and burial. Growth is slower than the pioneer species and establishment of this type is only possible when a cell has experienced no sedimentation or erosion during the previous year. Establishment and lateral expansion probabilities are assumed to be equal for the two vegetation types.

4.2.3 Marine processes

Erosion and deposition by the sea were modelled using a rule-based approach. Once every two weeks - a spring-neap tidal cycle - the module takes the highest offshore tide level recorded for this period, determines the vertical limit of wave run-up, calculates wave dissipation across the actual topography and adjusts the topography accordingly.

The highest water level is obtained from a record of offshore water levels. First, this level is converted to a nearshore level by accounting for set-up and run-up effects using the empirical relation of Stockdon *et al.* (2006). This relation describes the vertical of wave run-up as a function of foreshore slope (β_f) and offshore wave height (H_0) and wave length (L_0) and has been derived for a wide range of slope and wave conditions.

$$R_{2\%} = 1.1 \cdot \left(0.35\beta_f \sqrt{(H_0 L_0)} + \frac{1}{2}\sqrt{H_0 L_0 (0.563\beta_f^2 + 0.004)}\right) \tag{4.2}$$

Wave data can be obtained from nearby wave gauges or from empirical relationships between tide level and wave conditions (e.g. Van Aalst, 1983; Den Heijer *et al.*, 2012).

The resulting maximum tide level is multiplied by a factor (F_{energy}) to yield and measure of 'hydrodynamic energy' that controls the potential for erosion and deposition, which is subsequently dissipated over the beach and dune topography. Calculated from the seaward boundary to the landward boundary, the amount of energy dissipation in cell i is inversely proportional to the water depth in that cell (i.e. $dissipation = 1/waterdepth$), up to a lower limit of water depth to avoid very high dissipation in shallow water. We assume that dissipation solely depends on local water depth and keep incoming wave height, steepness and celerity constant. In analogy with existing dissipation equations (Thornton and Guza, 1983; Dally *et al.*, 1985; Dean, 1991), dissipation then reduces to $1/waterdepth$. Dissipation in each cell reduces the energy available for landward cells, until all energy is dissipated. The energy remaining at the depth limit is dissipated over the landward cells, assuming a dissipation rate equal to that at the depth limit.

Finally, the amount of erosion or deposition in each cell is calculated as the remaining energy times the difference between actual topography and equilibrium topography. This equilibrium beach profile is simplified as a plane that follows the beach slope from the initial topography between 0 m and 2.5 m above mean sea level and continues under the original foredune if it is eroded. This means that when hydrodynamic energy is larger than 1, topography is reset to equilibrium topography and when hydrodynamic energy is 0, there is no effect. Where the momentary profile is below the equilibrium profile, sand is added, representing sediment supply from the sea. This process is therefore responsible for both dune erosion and sand supply to the beach. Erosion by slumping is included by subsequently running the avalanching routine from the aeolian module.

Effects of sea-level rise on the beach profile in long-term model runs is incorporated by forcing the equilibrium profile landward and upward in proportion to the sea-level rise (S) and nearshore slope (b). The landward retreat R of the equilibrium profile is then determined as $R = S\,/\,tan(b)$ and the vertical shift is equal to the amount of sea-level rise (Bruun, 1962; SCOR Working Group 89, 1991; Davidson-Arnott, 2005).

4.3 Methodology

4.3.1 Study site

The model is applied to the beach-dune system of two barrier islands in the north of the Netherlands: Ameland and Terschelling (Figure 4.2A). Coastline orientation of the islands is North-North-West to North, while dominant wind direction is West. Yearly aeolian sand input to the dunes is between 15 and 20 m^3/m/y. Both islands have semi-diurnal, mesotidal tides with a mean tidal range of approximately 2 m (Rijkswaterstaat, 2014d). The sandy beaches have a mean grain size of 0.2 mm (Guillén and Hoekstra, 1997; Van der Wal, 2004). Dune vegetation on the backshore and seaward foredune slope is dominated by pioneer species, such as marram grass (*Ammophila arenaria*), sand couch (*Elytrigia juncea*) and lyme grass (*Leymus arenarius*). Inland of the crest, the proportion of woody species increases, such as sea buckthorn (*Hippophae rhamnoides*).

4.3.2 Datasets for calibration and validation

Model results are compared with elevation profiles of the JARKUS dataset (Rijkswaterstaat, 2014b). This dataset contains yearly elevation profiles, measured across fixed beach-dune transects that cover the foreshore, the beach and the first dune ridge with a cross-shore resolution of 5 m. Profiles are 250 m apart, derived from LIDAR measurements with an estimated vertical accuracy of 0.1 m (De Graaf *et al.*, 2003). An extensive description of the dataset can be found in (De Vries *et al.*, 2012b; Keijsers *et al.*, 2014b).

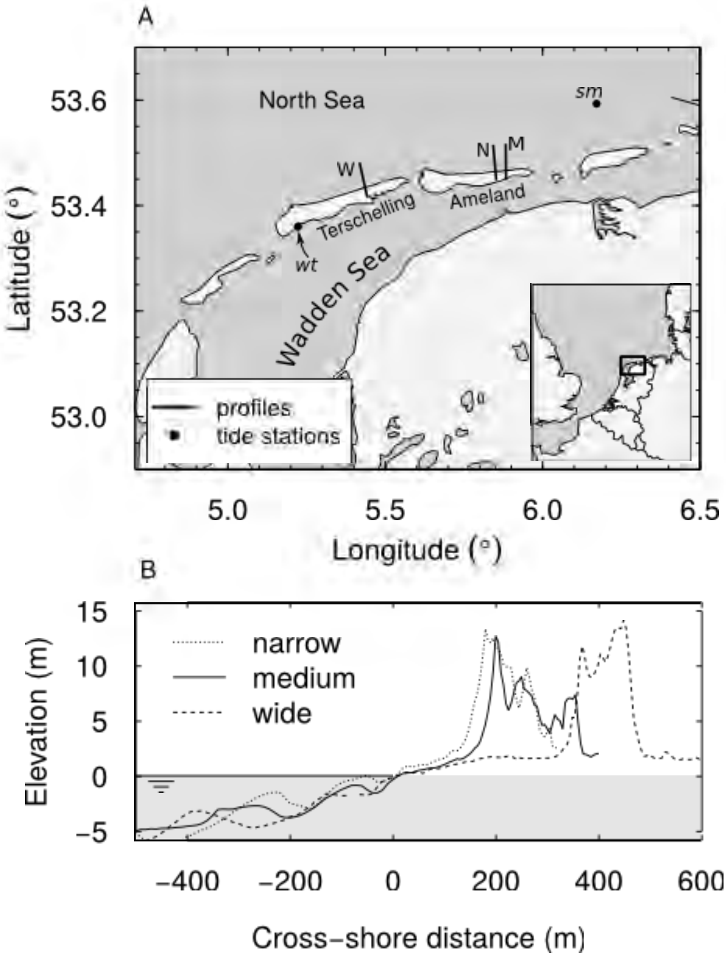

Figure 4.2: Study area with selected profiles. A: Location of the calibration and validation profiles on the islands of Ameland (right) and Terschelling (left): N = narrow profile, M = medium profile, W = wide profile. Location of tide gauges indicated: *wt* = West-Terschelling and *sm* = Schiermonnikoog. B: Cross-shore elevation profiles of the selected profiles.

To test the model in different circumstances, a site was selected with a narrow beach (138 m, Ameland profile 17.8), a medium width (185 m, Ameland profile 20.0) and a wide beach (345 m, Terschelling profile 22.0, Figure 4.2B). All have similar nearshore slopes and had a relatively static shoreline position throughout the calibration/validation period 2002-2011. They are located near the down-drift tails of the barrier islands, where management intensity has generally been low since 1990 (Arens and Wiersma, 1994; De Ruig and Hillen, 1997; De Jong *et al.*, 2014). The narrow profile has received a shoreface nourishment in 2010 and a beach nourishment in 2011. No narrow profiles were available without such management history. The medium profile is used for model calibration, the narrow and wide profiles are used for validation.

Sea-level data for the marine processes module are obtained from the nearby tide gauge West-Terschelling (Figure 4.2A), which has reliable data from 1935 onwards. Tide stations 2 and 3 have a better location relative to the test sites, but they have comparatively short time series starting in 1989 and 1981, respectively. Sea-level statistics for the common period show high agreement between the three stations, which vindicates the use of the West-Terschelling data for the selected site.

The measurements from 1935 (beginning of the measurements) to 2013 were de-trended by subtracting the observed linear trend of approximately 1 mm/year. The de-trended time series was subsequently used to determine the distribution of sea-level maxima for each 2-week period throughout the year (Figure 4.3A). Measured tide levels show clear seasonality, with highest tides occurring between November and March and relatively low maxima between May and August, reflecting the strong dependence of local water level on storms.

Relationships between 2-weekly maximum tide level and wave height and wave length were derived for station Schiermonnikoog (Figure 4.2A). Both wave parameters show a roughly linear dependence on tide level: $H_0 = -2.637 + 2.931h$ ($R^2 = 0.70$) and $L_0 = -30.59 + 46.74h$ ($R^2 = 0.64$) (Figure 4.3B and C). These relationships are used to calculate wave run-up as a function of foreshore slope (β_f) and maximum tide level (h).

Data on the distribution of vegetation cover across the beach and foredune were extracted from greyscale air photos from 2003, 2006, 2009 and 2011. Pixels were assigned to either bare surface or vegetated on the basis of pixel value, where dark pixels represent vegetation and light pixels represent the sandy surface (Keijsers *et al.*, 2015).

4.3.3 Model performance indicators

Three aspects of the simulation output are of interest: (1) the simulated accretion/erosion volume of the dune; (2) the simulated change in elevation; and (3) simulated vegetation cover. Together, these aspects capture how much sediment is transferred to the foredune, where the sediment is deposited and how vegetation is distributed.

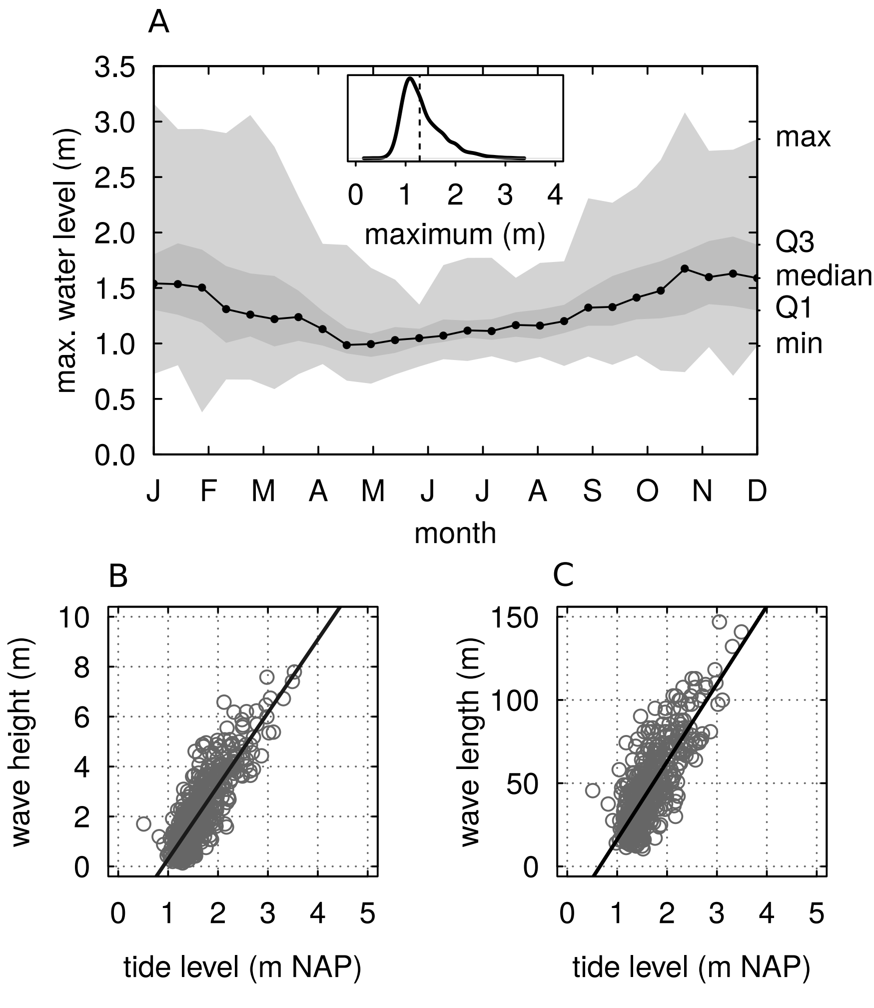

Figure 4.3: Tide-level and wave statistics for the West-Terschelling tide gauge and Schiermonnikoog wave buoy. (A) Statistics of sea-level maxima measured at tide gauge station West-Terschelling. Calculated from 2 week-periods for 1935-2002. Shaded areas indicate range between maximum and minimum (light grey) and first and third quartile (dark grey). Black line represents the median. Inset shows log-normal distribution of all 2-weekly maxima with the geometric mean of 1.3 m indicated. (B) Correlation between wave height and tide level for each 2-weekly maximum tide level between 1991 and 2013. (C) Correlation between wave length and tide level for each 2-weekly maximum tide level between 1991 and 2013. Data from Rijkswaterstaat (2014c)

The quality of model performance with respect to these 3 aspects is quantified by the Model Efficiency (ME, (Nash and Sutcliffe, 1970), Equation 4.3). This index measures goodness-of-fit of the modelled series (SIM) to the measured series (OBS), with values between $-\infty$ and 1. The closer ME is to 1, the better the agreement. If ME is below 0, the mean observed value is a better predictor than the model. To be able to compare model output with measured values, model output is reduced from 2D to 1D by taking alongshore averages of elevation and vegetation cover. Finally, each model run results in a value for ME_V, ME_{dz} and ME_{Cv}, representing the goodness-of-fit of the three aspects.

$$ME = 1 - \frac{\sum(OBS - SIM)^2}{\sum(OBS - \overline{SIM})^2} \tag{4.3}$$

Because the vegetation cover data do not allow distinction between species, cover maps of species 1 and 2 are summed to arrive at a total vegetation cover that is comparable to the observations.

4.3.4 Derivation of parameter settings

For most of the parameters, measured values or realistic ranges can be obtained from measurements or literature (Table 4.1).

Same parameter values have been changed in comparison to previously reported values. The number of aeolian iterations has been set at 52, or weekly iterations, so the marine routine is run after two aeolian iterations. Since sand transport on beaches is known to be spatially variably in response to limiting conditions such as moisture or lag deposits (Jackson and Nordstrom, 1997; Van der Wal, 1998a), the p_e is set at 0.5 instead of 1.0, which means each slab on the beach surface has a 50% chance of being eroded. To arrive at an aeolian transport potential of 20 m^3/m/year, the bare-cell deposition probability p_{db} is set at 0.13 (Equation 4.1). Lastly, the vegetation cover limit above which surface erosion becomes impossible is set at 50%, corresponding with high-end values from literature (Levin *et al.*, 2008).

Peak growth rate of species 1 and 2 for the vegetation component are set at 0.2 and 0.05, respectively, which is in the range of realistic values from Baas and Nield (2007) and indicates pioneer species are able to increase in density over the course of several years. Probabilities of lateral expansion and pioneer establishment are estimated from the analysis of a sequence of aerial photos from the study site (Keijsers *et al.*, 2015). Lateral expansion of vegetated patches was 0.3-0.5 m/year. Translated to a 1 m grid, this means a neighbouring grid cell is filled with vegetation in 2-4 years. The yearly probability of a neighbour cell becoming vegetated is therefore estimated at 25-50%. Since this value represents the upper limit of observed expansion, a slightly more conservative 20% is adopted.

Code	Name	Unit	Value	Reference
n	iterations per year	y^{-1}	26	Equation 4.1
h_s	slab height	m	0.1	Nield and Baas (2008b)
L	slab hop length	cells	1	Nield and Baas (2008b)
G	groundwater depth	-	0.8	Poortinga *et al.* (2015)
p_e	erosion probability of bare cell	-	0.5	Equation 4.1
C_{limit}	vegetation cover that prevents erosion	-	0.5	Levin *et al.* (2008)
p_{db}	deposition probability of a bare cell	-	0.13	Equation 4.1
p_{dv}	deposition probability of a vegetated cell	-	0.3	calibration
β_s	shadow angle	degrees	15	Baas (2002)
θ_b	angle of repose for bare cells	degrees	30	profile measurements
θ_v	angle of repose for vegetated cells	degrees	35	profile measurements
F_{energy}	hydrodynamic energy factor	-	1	calibration
F_{diss}	energy dissipation factor	-	0.012	calibration
h_{min}	depth limit in calculation of energy dissipation	m	0.4	calibration
$a_1 - e_1$	x-coordinate of vertex A-E, species 1	m/year	[-1.5, 0.1, 0.5, 1.5, 2.2]	Martin (1959); Nield and Baas (2008a); Maun (2009); Van der Putten *et al.* (1993); Zarnetske *et al.* (2012a)
$peak_{sp1}$	peak growth, species 1	y^{-1}	0.2	Wallén (1980); Baas and Nield (2007)
$a_2 - e_2$	x-coordinate of vertex A-E, species 2	m/year	[-1.5, 0.1, 0.5, 1.5, 2.2]	(Nield and Baas, 2008a)
$peak_{sp2}$	peak growth, species 2	y^{-1}	0.05	(Baas and Nield, 2007)
$p_{lateral}$	probability of lateral expansion of vegetation	-	0.20	Keijsers *et al.* (2015)
$p_{establishment}$	probability of establishment of new vegetation	-	0.05	Keijsers *et al.* (2015)

Table 4.1: Definition and estimated values of model parameters. References to literature values are provided.

Compared to clonal expansion, establishment from seeds contributes little to the reproduction of marram grass (Huiskes, 1979). Keijsers *et al.* (2015) found that 85% of newly vegetated area lies within 2 m of existing vegetation. Hence, the probability of non-neighbouring, bare cells to become vegetated is estimated at 5%.

4.3.5 Calibration, validation and sensitivity analysis

Calibration is used to determine appropriate values for those parameters for which no reference values or data are available: F_{diss}, h_{min} in the marine component and p_{dv} in the aeolian component.

Appropriate values for these parameters are determined by evaluating the performance for all combinations of these parameters within their lower and upper limits, as determined from preliminary sensitivity analysis. To account for the stochastic properties in the aeolian component, the average Model Efficiency of 5 simulations is reported.

To further test model sensitivity, dune characteristics are investigated for different initial parameter values. To this end, three factors that, based on a preliminary sensitivity analysis, strongly determine the model output are varied within a range of -100% to +100%. First, the effect of a change in erodibility is investigated by adjusting the erosion probability of a bare cell (p_e). Second, the influence of pioneer vegetation vigour is examined by varying the peak growth rate of species 1 ($peak_{sp1}$). Lastly, the influence of dune erosion is established by changing the rate of energy dissipation over the beach (F_{diss}).

4.3.6 Scenario development

For the Dutch situation, climate scenarios predict sea-level rise, increased temperatures, increased yearly precipitation and increased moisture deficit that may be relevant for foredune development (Reed *et al.*, 2009; Keijsers *et al.*, 2014a; KNMI *et al.*, 2014). Sea-level rise affects the width of the dry beach and the height of surge levels, reducing the availability of sand for aeolian transport and increasing wave attack. High-end scenarios of SLR for the Netherlands indicate a rise of 0.40 - 1.05 m from 1990 to 2100 (i.e. 4 to 10 mm/year) (Katsman *et al.*, 2011). Maximum moisture deficit in the growth season is estimated to increase by 1% - 50% by 2100 and temperatures are expected to increase by 1.3 to 3.7 °C (KNMI *et al.*, 2014). Increased summer drought may reduce vegetation growth, whereas higher temperatures may stimulate it, the net effect for dune species at a particular site not being known (Carter, 1991; Reed *et al.*, 2009; Ryu and Sherman, 2014).

To evaluate the effects of such projected changes on foredunes for a wider region than only the Dutch setting, a more general set of climate-change scenarios was developed, consisting of a combination of sea-level rise and vegetation growth. Sea-level rise is implemented by linearly increasing the mean sea level in the model and shifting the equilibrium beach profile landwards and upwards (see 4.2.3). Effects of increasing moisture deficit and increasing temperature on vegetation development are included by gradually changing the vegetation growth rate, i.e. the peak growth rate and probabilities of establishment and lateral expansion.

To create a phase-space of dune evolution, 5 rates of sea-level rise (0 to 20 mm/year with 5 mm/year steps) and 5 trends in vegetation growth (-1%/year to +1%/year with steps of 0.5%/year) were combined, yielding 25 scenarios in total. The climate scenarios were run from 2002 to 2100, so that a known initial vegetation cover and topographic profile could be used.

Two-weekly maximum tide levels were generated, taking into account seasonal variation in maximum sea levels. A time series was constructed by randomly drawing from a log-normal distribution with mean and standard deviation obtained from historic sea-level data of gauge station West-Terschelling (Rijkswaterstaat, 2014c) (Figure 4.3A). A linear rise in mean sea level is added to the generated series for the climate-change scenarios.

A second set of model runs is used to evaluate the effectiveness of the current coastal management policy in The Netherlands, which aims to mitigate negative consequences of SLR by sand nourishments. Sand nourishments are applied to increase the bed level of the beach profile between -15 and + 3 m proportional to the sea-level rise. As a consequence, the shoreline position is maintained. This policy is implemented by shifting the equilibrium profile vertically with a displacement equal to the amount of SLR.

Finally, the possibility for dune remobilisation by removing vegetation is tested. Dune remobilisation is a practice that is currently being carried out at several places in the Netherlands. This scenarios is implemented by removing all vegetation from the beach and dunes halfway into the 100-year simulations. For this scenario, sea-level rise is fixed at 5 mm/year, corresponding to the most likely scenario for the Netherlands, whereas all vegetation growth scenarios are used.

Unless noted otherwise, the alongshore dimension is limited to 25 m and the cross shore distance is limited to the zone between the shoreline and the point 50 m landward of the first dune ridge. To avoid migration of dunes outside of the model domain, the cross-shore extent is increased to 200 m beyond the crest for climate-change simulations. The model's stochasticity is accounted for by performing 5 simulations for each model configuration and using the averaged model output for analysis.

4.4 Results

4.4.1 Model calibration, validation and sensitivity

Model calibration showed optimal performance for $p_{dv} = 0.3$, $F_{diss} = 0.013$ and $h_{min} = 0.4$. ($ME_V = 0.96$, $ME_{dz} = 0.66$ and $ME_{Cv} = 0.89$). The resulting output shows a beach-dune system with a linear beach slope and a sparsely vegetated foredune face (Figure 4.4A). Vegetation cover is zero on the beach and increases rapidly beyond the dune foot. In the alongshore direction, variability in topography and vegetation is limited, giving a relatively homogeneous beach and dune. Model performance was assessed for elevation changes, dune-volume trends and vegetation cover.

Long-shore averaged topographic change is captured well (Figure 4.4B), with maximum sand deposition on the seaward slope of the dune. The landward decrease in sand deposition is captured satisfactorily, although a secondary peak in deposition on the landward side is not reproduced.

Vegetation cover is reproduced adequately (Figure 4.4C). The transition from bare beach to vegetated dune fits the observed pattern well. Observations show a pronounced peak in cover, followed by a bare zone halfway the dune slope. The model shows a similar peak, but only shows a zone of reduced cover. This indicates that the observed vegetation patterns are captured by the model, but actual cover values may be over-predicted. Pioneer vegetation is present mainly between the dune foot and dune crest, coinciding with the zone of deposition. Landward of the crest, pioneer cover decreases rapidly, implying a contrasting rapid increase in stabiliser species cover.

The modelled trend in dune volume shows good agreement with observations (Figure 4.4C). Initially, volume increases linearly, but slows between year 4 and 6. This is related to minor dune erosion during storm surges.

The validation runs were performed with the calibrated optimal values. These runs also show good agreement between modelled and observed dune development: $ME_V = 0.98$, $ME_{dz} = 0.12$ and $ME_{Cv} = 0.62$ for the narrow profile and $ME_V = 0.80$, $ME_{dz} = 0.60$ and $ME_{Cv} = 0.94$ for the wide profile.

The impact of initial parameter choices is investigated by varying the value of three important parameters, controlling either aeolian input, dune erosion intensity or vegetation growth, respectively (Figure 4.5). Ten-year simulations are performed, using the same configuration as for the calibration runs.

Dune size is very sensitive to changes in erodibility (A). The level of aeolian input strongly determines the ratio of pioneer and stabiliser species present in the dune zone: with low input, stabiliser species dominate, while pioneer species thrive in high input conditions (B). Bare area remains relatively constant, irrespective of the level of sand input. High input

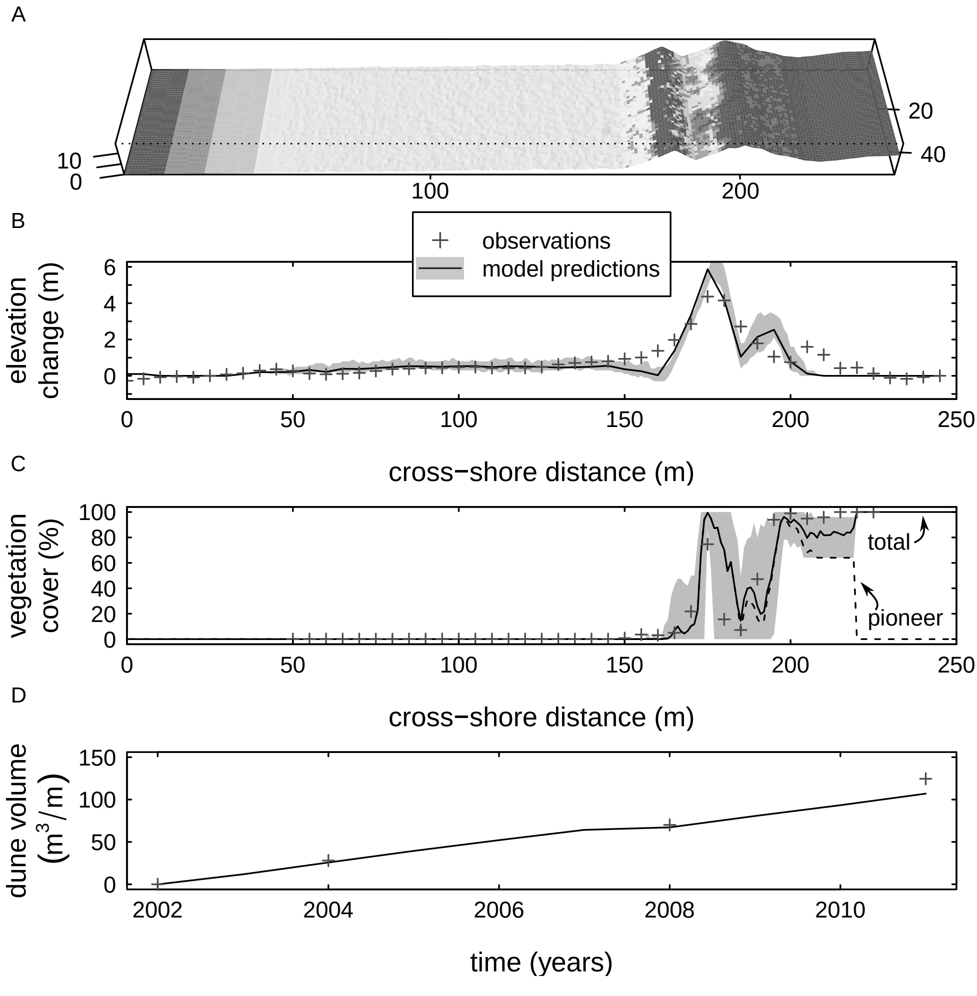

Figure 4.4: Model output of the optimal run for the medium profile between 2002 and 2011: (A) 3D topography and vegetation cover in 2011; (B) cross-shore elevation change; (C) cross-shore vegetation pattern, dashed line represents cover of pioneer species; and (D) development of dune volume relative to 2002. Crosses represent observations, black lines represent model simulations. Grey bands show alongshore range of values.

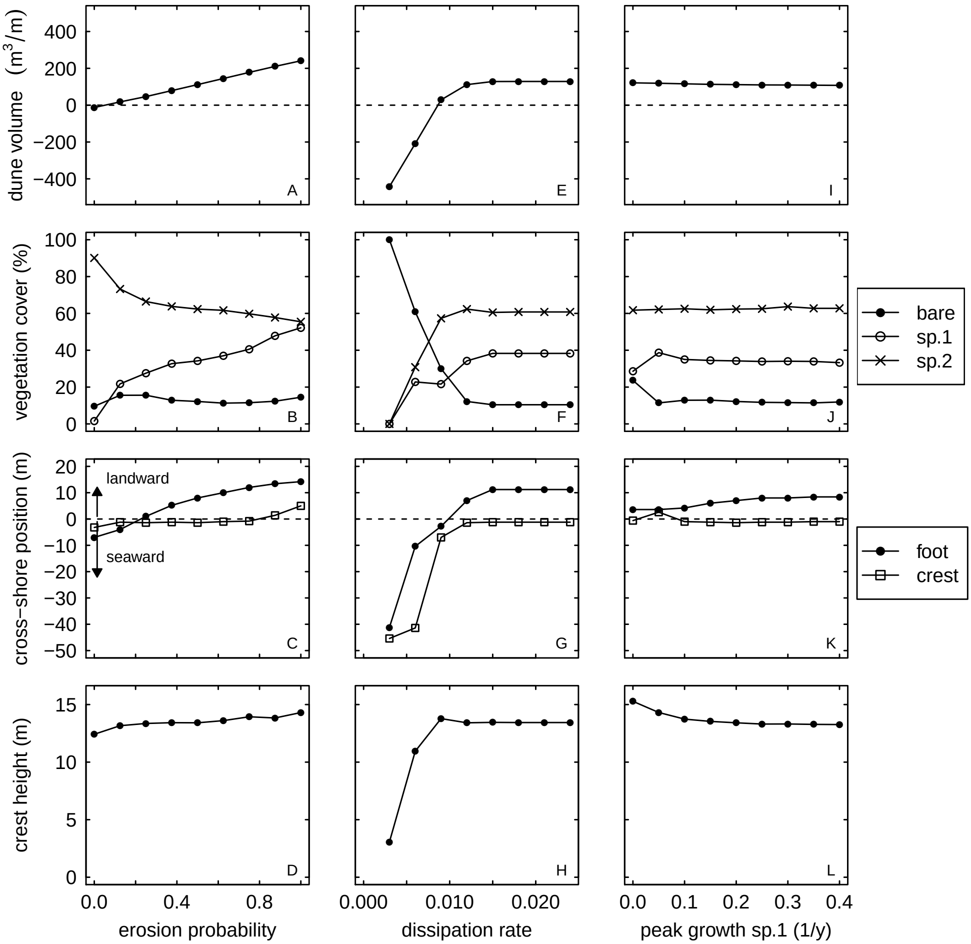

Figure 4.5: Effect of changing three important model parameters from -100% to +100% on simulated dune characteristics. Simulations using same configuration as the calibration runs. A-D: effect of changing erosion probability (p_e); E-H: effect of changing dissipation rate (F_{diss}); I-L: effect of changing peak growth rate of the pioneer species ($peak_{sp1}$). Dune characteristics are quantified as final dune volume, fraction of bare and vegetated area, position of the dune foot and crest relative to their initial positions and height of the crest.

also promotes seawards building of the dune (C). Since the additional sand is used primarily for seawards building, crest height does not vary strongly with input (D).

Dissipation strength strongly determines the fate of the dune (E-H). Values of F_{diss} below 0.012 lead to rapid dune loss, as most of the hydrodynamic energy is able to reach the dune foot. Dune evolution does however not respond strongly to increased dissipation, with final dune-foot positions roughly equal for all runs with $F_{diss} > 0.012$.

Compared to the previous parameters, variations in vegetation growth rate do not induce marked change (I-L). Increased pioneer-species growth promotes seaward movement of the dune foot, because a larger fraction of the incoming sand is trapped near the foot (K). For lower growth rates, sand transport reaches farther up the dune, leading to increasing height (L). It should be noted that landscape adjustment to changes in plant growth characteristics may take place over the course of several decades (Nield and Baas, 2008a).

4.4.2 Climate-change scenarios

Climate change scenarios were run from 2002-2100 and the predicted foredune evolution was compared between the scenarios (Figure 4.6). Foredune characteristics for are compared and analysed with respect to the sea-level rise (SLR) and vegetation growth rate (VGR) scenario (see 4.3.6).

The scenario results indicate that dune evolution is largely controlled by SLR. The effect of decreasing or increasing vegetation growth rate is less pronounced.

Sea-level rise forces the foredune to move landwards. The higher the rate of SLR, the farther landward the dune retreats, up to 150 m for the 20 mm/year scenario. For the no-rise scenario, the foredune is able to expand seawards slightly.

Besides varying distances of landward movement, differences are predicted in the extent of vertical dune growth as a result of SLR. Final dune height relative to the mean sea level decreases from over 25 m in the no-rise scenario to less than 15 m in the 20 mm/year scenario. For SLR up to 15 mm/year, vertical growth occurs and final dune height exceeds initial dune height.

Lastly, the morphology and vegetation cover vary between scenarios. With high vegetation growth and no sea-level rise, an additional dune crest is formed seawards of the existing crest (e.g. SLR = 0 mm/year, VGR = +1%/year). In all other cases, sea-level rise dominates the vegetation pattern, leaving a bare seaward face and vegetated landward side. With increasingly adverse conditions for dune development, i.e. stronger sea-level rise and reduced vegetation growth, vegetation cover is reduced, leading to bare, somewhat rounded transgressive dunes (e.g. SLR = 15 mm/year, VGR = -1%/year).

Final dune characteristics for the different scenarios are summarized in Figure 4.7. The plots show the sand volume, dune-foot position and crest height relative to the initial values

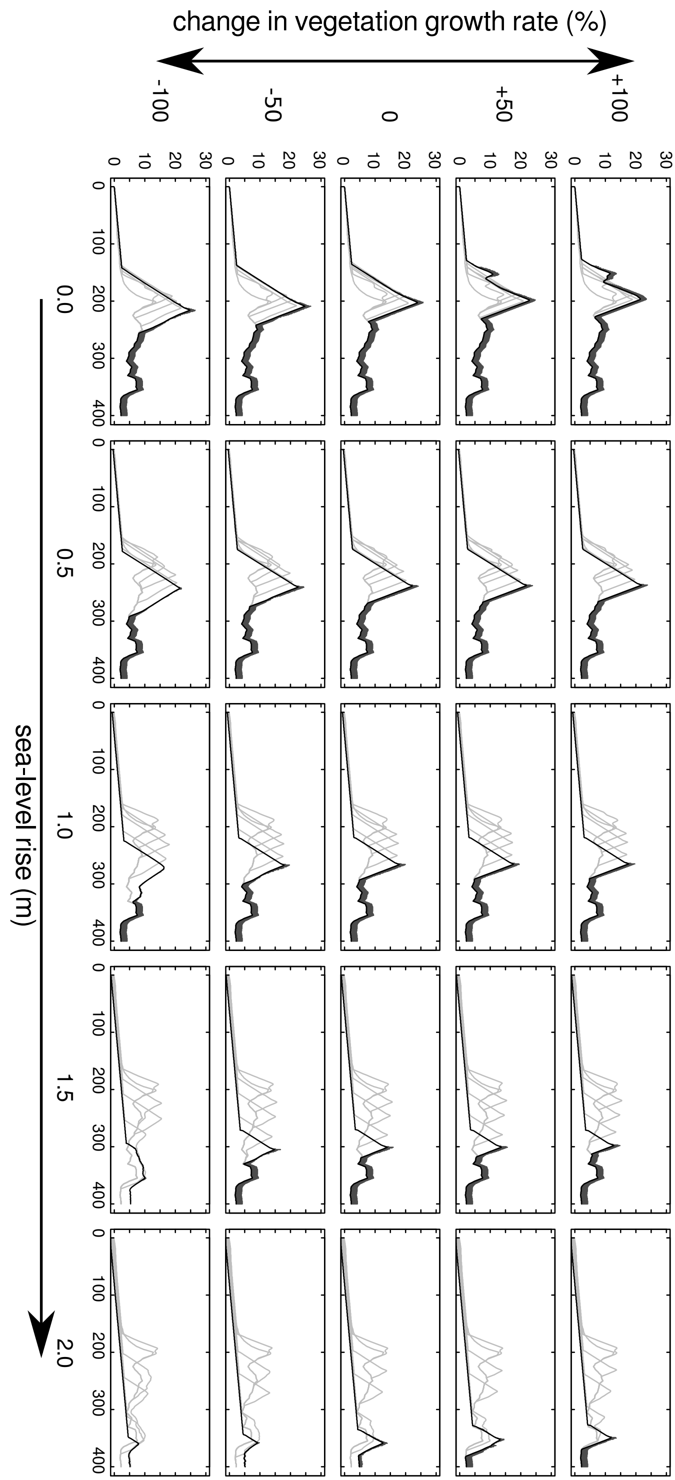

Figure 4.6: Development of beach-dune profiles from $t = 2002$ to $t = 2100$ as a function of sea-level rise and vegetation growth scenarios. The final profile in plotted in black, intermediate profiles at 20 year intervals are in grey. Horizontal and vertical axes of profile plots are in metres. Dark grey shading represents vegetation, with height proportional to the degree of vegetation cover. Sea is to the left, dominant wind direction from left to right.

and the final vegetation cover. From these values, it can be estimated for which conditions the foredune is able to maintain its volume, height or cross-shore position.

Dune volume is maintained or enhanced for scenarios with sea-level rise below 10 mm/year (Figure 4.7A). For a given rate of sea-level rise below 10 mm/year, final dune volume is higher for reduced-growth scenarios, which indicates that a reduction in vegetation growth can be beneficial for volume preservation. This effect can be explained by considering the fraction of slabs transported across the crest. As vegetation cover decreases, more slabs are transported across the crest, where they are stored outside the range of common dune erosion events. In high-growth scenarios, more slabs are stored on the seaward dune face, where they are readily removed by wave erosion.

Dune-foot position is maintained only for the no-rise scenarios (Figure 4.7B). Interpreting the decreasing distance between contour lines, landward retreat seems to accelerate with increasing rates of SLR.

Foredune height with respect to the mean sea level can be preserved for SLR up to 15 mm/year (Figure 4.7C). For a given rate of SLR, maximum crest height is attained when vegetation growth is reduced. This reflects an better conditions for aeolian transport towards the crest, promoting vertical growth.

The influence of beach width on foredune response was investigated by comparing the impacts of a given scenario on the narrow, medium and wide profile (Figure 4.8).

Dune development on the narrow profile is clearly different for the 0 mm/year and 5 mm/year SLR scenarios (Figure 4.8A). Under the no-change regime, the foredune gradually expands seawards for the first two decades, after which the position remains rather constant. In contrast, seawards expansion under the SLR scenario is limited and after 2020, the dune starts to retreat at a rate of 0.3 m/year. This is roughly equal to the rate at which the sea transgresses, calculated as the product of SLR and beach slope.

On the medium profile, both scenarios show similar developments initially, but after 2020, the paths diverge (Figure 4.8B). Without SLR, the dune-foot oscillates around an equilibrium position roughly 20 m seawards of the initial point. With SLR, the foredune does not expand as far seawards and instead of staying at this seawards limit, it gradually retreats at a rate similar to that of the narrow profile.

In contrast, the foredune on the wide profile continues to move seawards over a distance of 100 m in both scenarios (Figure 4.8C). Under SLR, the expansion approaches its maximum near the end of the simulation, with an increasing frequency of erosion events and consequently a wider range of possible trajectories.

Even though the dune-foot positions tend to align with an equilibrium position on the longer term, the timing and magnitude of storm events strongly influence development on a smaller timescale. Depending on the sequence of events, dune development may notably

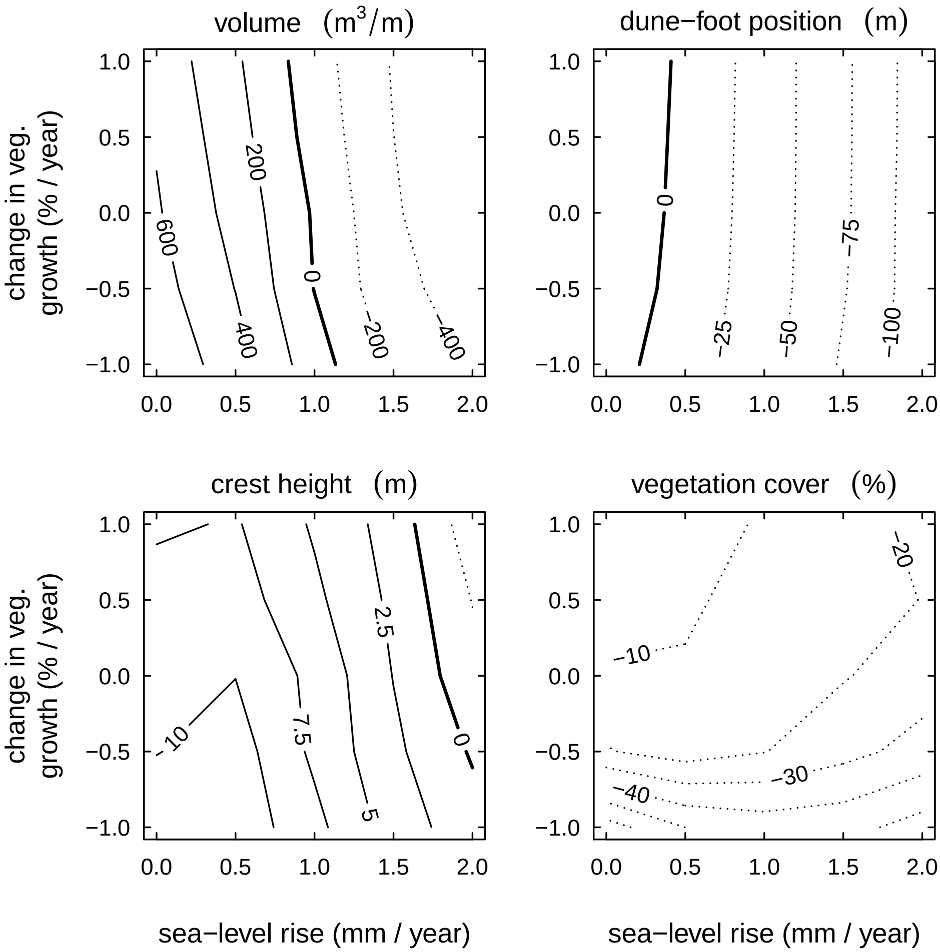

Figure 4.7: Final foredune characteristics for the 25 climate-change scenarios, with values interpolated from known positions. Solid lines represent iso-lines of positive values, dashed lines represent iso-lines of negative values. All values are relative to the initial ($t = 2002$) conditions. The rise in mean sea level is subtracted from dune height to account for the vertical displacement of the dune-foot level.

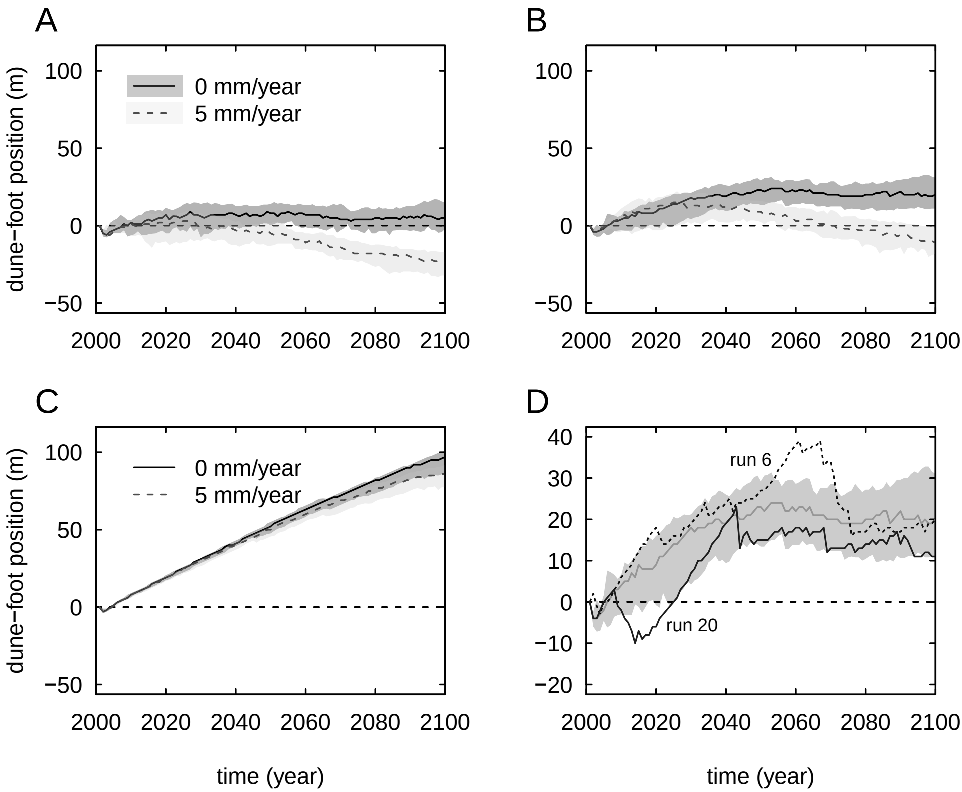

Figure 4.8: Foredune evolution in response to sea-level rise. Dune-foot movement in the 0 mm/year and 5 mm/year SLR scenarios, for the narrow (A), medium (B) and wide profile (C) relative to the initial position. Shaded bands indicate the 10% to 90% intervals of 25 runs, solid lines indicate the median. (D) Dune-foot development in the 0 mm/year scenario for the medium profile, showing the average (dotted line) and two extreme individual model runs (solid lines). Positive values are seawards, negative values are landwards.

divert from the average trend (Figure 4.8D).

Example run 6 shows that in a period with relatively low storminess (no water levels above 3 m), the foredune continues to build seawards, exceeding the average value by 20 m in 2060. Upon the start of a more stormy period in 2070, the foredune is rapidly forced back towards the average of the ensemble.

Example run 20 experiences a stormy periods in the first two decades, resulting in a dune-foot position that is 20 m landwards of the average position at that time. After the storm events, the dune foot recovers uninterrupted for two decades at rates of 1-2 m/year, until it approaches the equilibrium position and storm impacts become more frequent.

Besides controlling the dune-foot trajectory, storm events strongly control the landward sand flux (Figure 4.9). Significant storm events, identified as negative changes in dune volume, may trigger a reduction in vegetation cover of the dune (Figure 4.9B). This is due to the direct removal of vegetation by the waves and indirectly by burial of vegetation downwind of the erosion escarpment.

If vegetation cover is sufficiently reduced, sand transport reaches farther up the slope and eventually passes the crest (Figure 4.9C). The time lag between some erosion events and the onset of landward transport occurs because large volumes of sand released from the erosion scarp are initially trapped in the densely vegetated zone in front of the crest. These volumes exceed the vegetation's burial tolerance limit, leading to a decrease in vegetation cover the year afterwards and permitting fluxes across the crest. Following an erosion event, landward fluxes increase rapidly, then decline gradually as vegetation re-stabilizes the seaward slope. From 2060 onwards, vegetation does not fully recover and landward transport is more continuous.

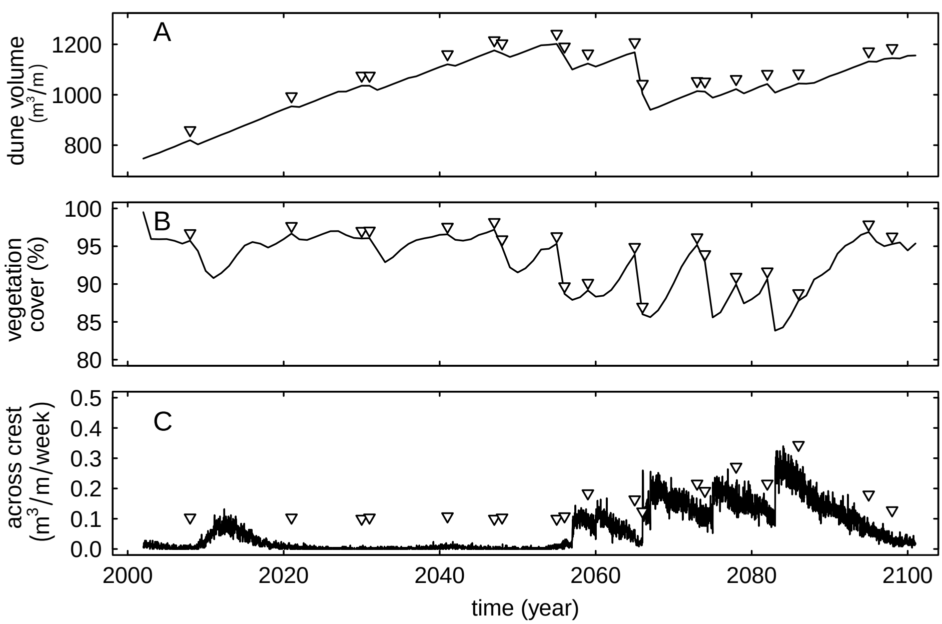

Figure 4.9: Sand flux passing the crest. (A) Development of dune volume, erosion events identified by triangles ($\Delta V < 0$); (B) Development of vegetation cover in the dune zone. Triangles indicate erosion events identified in panel A; and (C) weekly amount of sand that is transported across the foredune crest. Triangles indicate erosion events identified in panel A.

4.4.3 Sand nourishments

Sand nourishments can be used to maintain shoreline position and elevate the beach in proportion to sea-level rise. If the same climate-change scenarios are run, but with a fixed shoreline position and and vertically adjusting beach profile, foredune evolution follows different trajectories (Figure 4.10).

Compared to the results without nourishments, dune development does not vary as strongly between scenarios. In all cases, the dune foot is able to move seawards initially, after which the position remains constant at approximately 150 m from the shoreline. Increasing vegetation growth rates promote sand trapping on the seaward slope, facilitating the formation of new crests seawards of the original crest. In contrast, a reduction in vegetation growth rate enhances landward transport, leading to sand trapping in the shadow zone of the dune and contributing to a gain in height and volume. Largest dune volumes are obtained without SLR and -1%/year vegetation growth reduction.

Furthermore, the foredunes develop vertically, gaining over 10 metres in height by 2100. The extent of sand deposition landwards of the initial crest is controlled by the vegetation scenario. With decreasing growth rates, larger volumes of sand are able to pass the crest, contributing to the final dune volume.

4.4.4 Dynamic dune management

Finally, the dynamic dune management scenarios were run, removing vegetation from the entire model domain at $t = 2050$. The system response is expressed in terms of re-vegetation of the foredune and landward transport (Figure 4.11A,B).

In the first three decades, the vegetation cover in the different scenarios develops similarly, showing oscillations representing wave erosion and subsequent recovery. After 2035, differences between high and low vegetation growth scenarios become more apparent. Right before the intervention, vegetation cover for the low -1%/year scenario is 30 % lower than the cover in the +1%/year scenario.

Following the disturbance, the seaward slope remains relatively bare for at least five years in all scenarios, with consequently high landward transport rates, approaching the potential rate of 20 m^3/m (Equation 4.1). For scenarios of enhanced vegetation growth, vegetation cover is nearly at pre-disturbance levels after two decades and landward transport ceases after three decades. In the -0.5%/year and -1.0%/year scenarios, vegetation never adequately recovers, leading to uninterrupted landward transport for the remainder of the simulation, even though at $t = 2050$, growth is reduced by only 25% and 50%, respectively. In the -1%/year case, the density of newly established pioneer vegetation is insufficient to adequately modify erosion/deposition rates to levels within its tolerance. As a consequence, the positive

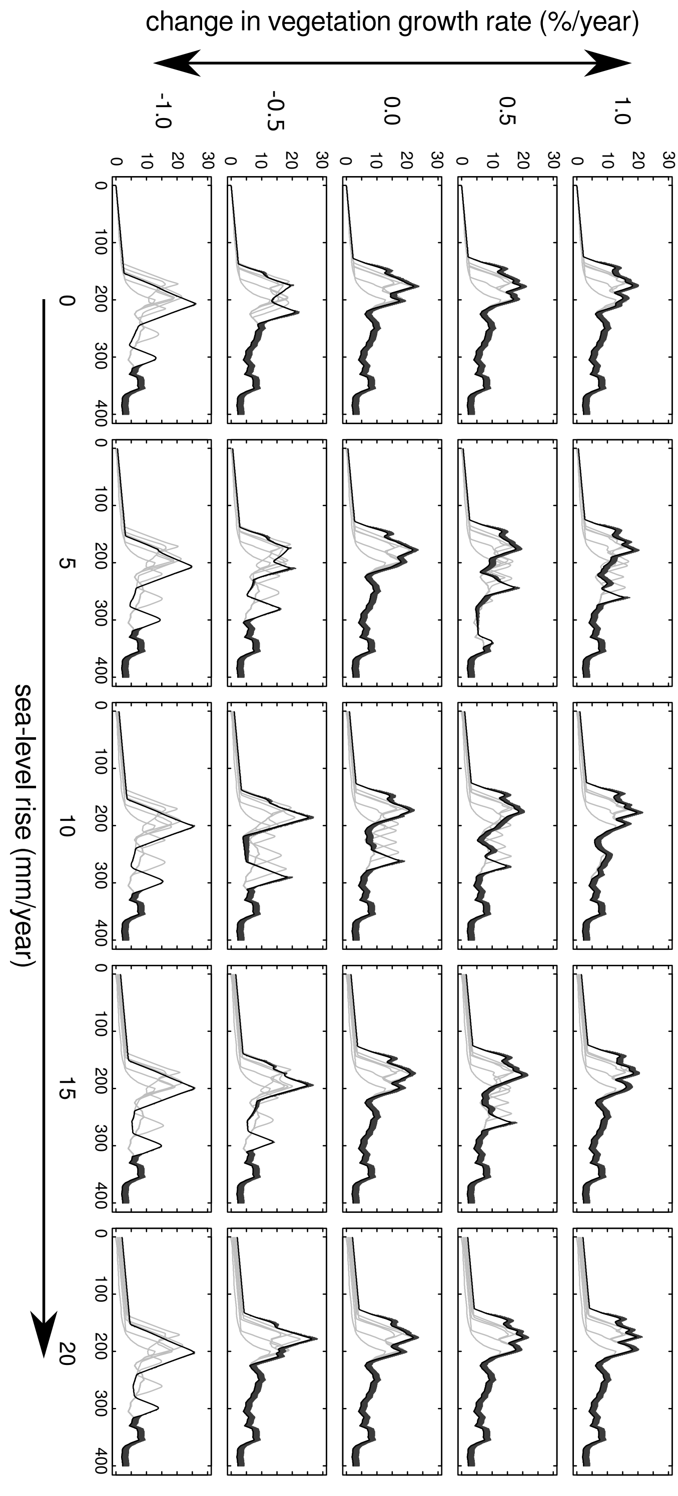

Figure 4.10: Development of beach-dune profiles from $t = 2002$ to $t = 2100$ as a function of sea-level rise and vegetation growth scenario. The final profile in plotted in black, intermediate profiles at 20 year intervals are in grey. Horizontal and vertical axes of profile plots are in metres. Dark grey shading represents vegetation, with height proportional to the degree of vegetation cover. The beach profile is artificially raised proportionally to sea-level rise, so the shoreline is maintained at its initial position.

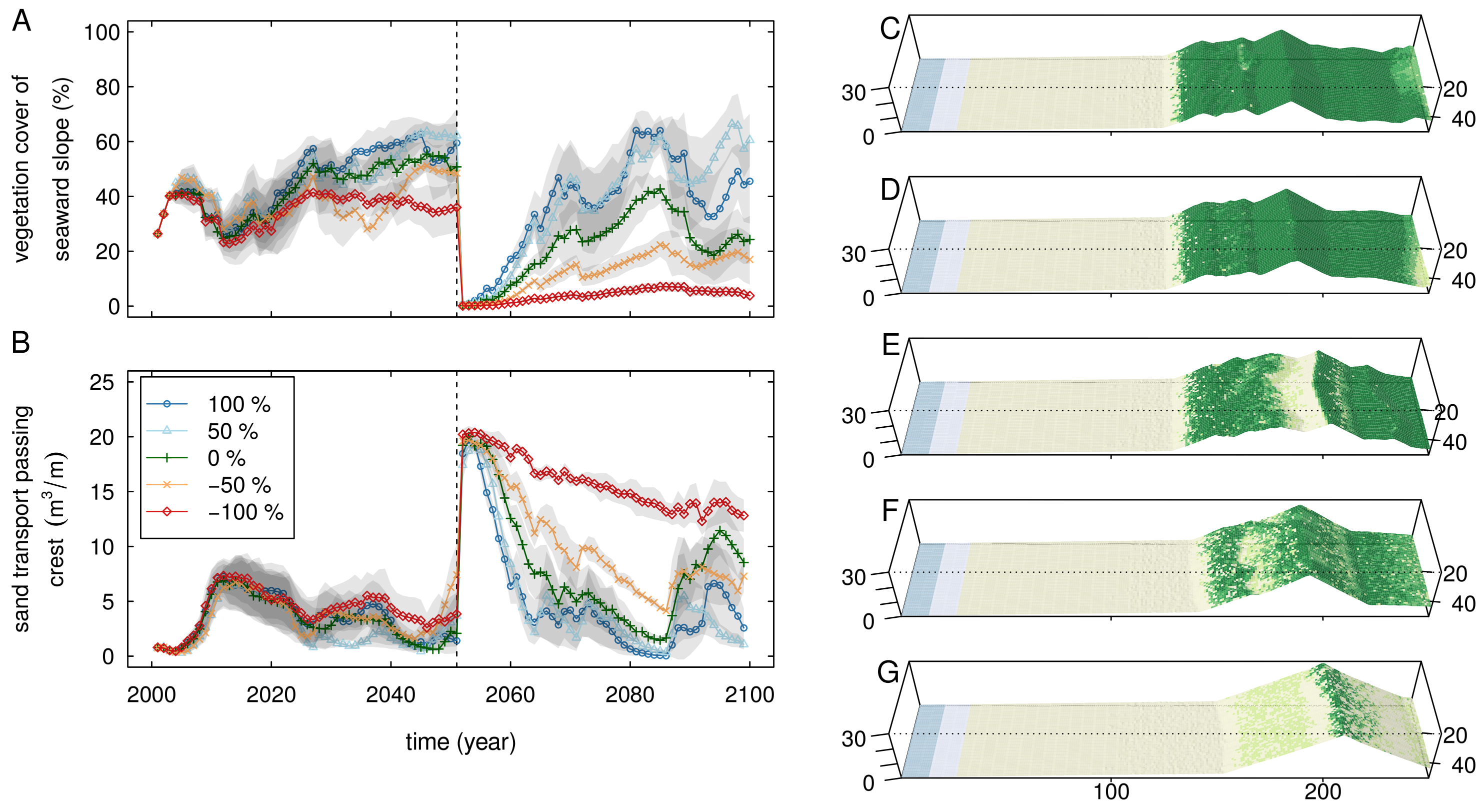

Figure 4.11: Foredune evolution following removal of all vegetation at $t = 2050$. Sea-level rise is 5 mm/year for each run. A: Development of vegetation cover for the different vegetation growth scenarios. B: Development of dune height for the different vegetation growth scenarios. C-G: Final topography and vegetation cover for the different vegetation scenarios, from +1%/year (C) to -1%/year (G). Surface and vegetation cover cell sizes are coarsened by a factor 4 for displaying. Distance and elevation in metres.

biogeomorphic feedback is not engaged, plant cover remains low, surface erosion continues and conditions remain unfavourable for pioneers to establish and expand. Sand transport across the crest continues and the dune gradually migrates landwards.

Although vegetation cover on the seaward slope recovers in the 0%/year scenario, there is still enhanced mobility in the final landscape, with a bare ridge that gradually moves landwards (Figure 4.11E). This indicates that once re-mobilised, dune mobility can maintain itself to some extent.

Figure 4.11 indicates that the rate and extent of recovery is dependent on the vegetation growth scenario. At some growth rate, re-stabilisation no longer takes place. To identify this threshold, additional runs were performed in which the vegetation-growth rate was abruptly decreased simultaneously with a clearance intervention. After the intervention, the growth rate was kept constant at the reduced level. The initial growth rate was reduced from 0% to 100% with steps of 10% and the responses of vegetation cover and landward aeolian transport were recorded.

Results show that both the rate and extent of recovery within 50 years is strongly related to the vegetation-growth rate (Figure 4.12A,B). Pre-disturbance levels are only achieved with the 0% reduction scenario. A reduction of 40% shows that vegetation recovers sufficiently to eliminate landward transport. Further reductions lead to inadequate recovery and uninterrupted landwards transport.

The separation point between recovering and non-recovering scenarios can be identified by comparing the maximum vegetation cover and minimum landwards transport occurring past the recovery for the different scenarios (Figure 4.12C,D). The results indicate that re-stabilisation is possible up to growth reductions of 40%. Vegetation growth rate can be reduced by 10-40% without major consequences for landscape response. Although the rate of recovery may be lower, vegetation cover is fully restored and landward transport is stopped within a number of decades. However, a reduction of 50% precludes re-stabilisation of the foredune system. The seaward slope remains mostly bare (< 20% cover) and landward transport continues (> 10 m^3/m). Reducing the growth rate even further does not significantly alter the foredune's response. Thus, there is a limit to which vegetation growth can be reduced without compromising the system's ability to recover.

4.5 Discussion

4.5.1 Dune evolution

Although the number of rules included in the model is fairly limited, the DUBEVEG model shows good performance in simulating the foredune development on three sites with different beaches. Observed trends in dune volume and changes in topography and vegetation cover

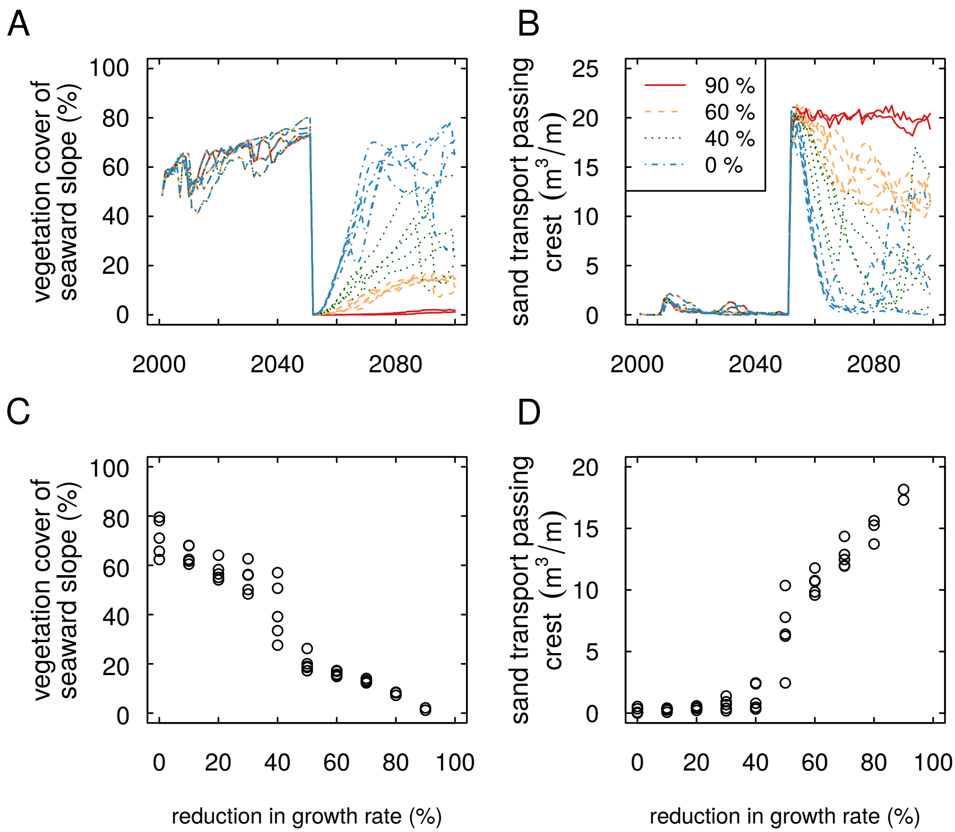

Figure 4.12: Foredune recovery after removing all vegetation at $t = 2050$ for different reductions in vegetation growth rate. From 2001 to 2050, the growth rate was kept equal for all simulations. After 2050, the rate was reduced by 10% to 100%. Five runs were performed for each rate. Development of vegetation cover on the seaward slope (A) and sand transport across the crest (B), for reductions of 90, 60, 40 and 0%. Extent of recovery for different values vegetation growth rate: highest vegetation cover of the seaward slope between 2051 and 2100 (C) and lowest rate of transport across the crest between 2051 and 2100 (D).

are reproduced with good accuracy. In contrast to most models of vegetated dune fields (e.g. Van Dijk *et al.*, 1999; Arens *et al.*, 2001a; Baas, 2002; Luna *et al.*, 2011; Durán and Moore, 2013), DUBEVEG explicitly determines both dune erosion by waves and dune building by aeolian transport and vegetation. Therefore, this model is a step forward in modelling coastal foredunes. It additionally has the advantage of low computation times, which allows extensive calibration and long-term simulations as shown here.

In the simulations of foredune evolution between 2002 and 2100 without SLR, the dune-foot position moves seawards towards a certain limit (cf. Figure 4.8A-C). This implies that for a given profile, sea level and wave climate, there is an equilibrium position at which erosion and accretion of the dune foot are roughly balanced. Where the dune foot is landwards of the equilibrium, dune-foot erosion is reduced and seawards expansion takes place. The closer to the equilibrium position, the more frequent the dune foot is eroded until the erosion finally balances accretion. When a change in one of controlling factors occurs, the equilibrium position changes and the dune-foot position adapts accordingly. For instance, a 5 mm/year SLR gradually forces the position landwards (cf. Figure 4.8A-C).

Although horizontal growth is halted when the dune-foot position is at equilibrium, dunes may continue to grow vertically (Figure 4.6). This is caused by sand deposition near the crest and landward of it, contributing to vertical growth. As frequent dune scarping takes place, vegetation is removed from the seaward slope, exposing bare surface and stimulating aeolian transport upslope (Figure 4.9). The exposed sand is transported further upslope and is deposited near the vegetated crest, leading to higher dunes. This mechanism is also instrumental in the preservation of volume in retreating dunes in response to SLR (Davidson-Arnott, 2005; Ollerhead *et al.*, 2013). As this sequence of steps is simulated but not explicitly modelled, it can be considered an emergent property of the model (Fonstad, 2006).

For the narrow and medium profile and moderate rates of SLR (e.g. 5 mm/year), the model predicts a landward movement of the foredune, where the foredune is able to preserve its volume and height while migrating landward. Whether dune volume is maintained,depends on the landward flux relative to the rate of sand loss on the seaward slope by wave attack. For higher rates of sea-level rise, crest migration via landward transfer of sand cannot keep pace with the landward migration of the dune foot. As a consequence, the dune volume and crest height are not maintained and a decline of dune size takes place (Figure 4.6, SLR=20 mm/year).

The model predictions show trends previously described in conceptual models of foredune evolution (Carter, 1990; Hesp, 2002; Psuty, 1992; Pye, 1990; Sherman and Bauer, 1993). Under a fixed sea level, predictions for the narrow and medium beach are similar to the expected trends for a stable shoreline, with limited horizontal expansion and mostly vertical dune growth (Figure 4.6, SLR = 0 mm/year). If sea-level rise is applied, results confirm the expected evolution for recessional shorelines, with a retreating dune foot, increase in landward transport and vertical growth (Figure 4.8, 4.9). In contrast, the dune-foot of the wide profile continues its seawards expansion despite SLR, similar to dunes on prograding shorelines in the conceptual models. This discrepancy between expected and modelled behaviour indicates that the wide profile is not in equilibrium initially. Indeed, in the years preceding the start of the simulations, the wide profile's shoreline position has moved seaward at approximately 9 m/year between 1980 and 1990, resulting in a total progradation of approximately 100 m. Given that rates of dune-foot movement are in the order of 1-2 m/y (Figure 4.8 and Ruessink and Jeuken (2002)), the dune-foot position is bound to lag behind considerably, which explains why the 2002 profile is not in equilibrium and dune-foot migration therefore continues after 2002.

The model does not predict a clear limit on dune height for the 100-year simulations of a no-change scenario. Models that include wind speed-up over steep topography or deceleration upwind of the dune find a limit on dune height Momiji *et al.* (2000); Pelletier (2009); Durán and Moore (2013). The DUBEVEG model treats airflow as constant across the domain except for the shadow zones. Theoretically, vertical growth is expected to slow down for taller dunes, as the path length for slabs to reach the crests becomes longer as the dune gets taller. Such limitation is however not observed in standard 100-year simulations.

For the 15 and 20 mm/year SLR scenarios however, dune heights seem to reach a certain limit. This is related to the length of the period available for vertical growth. During landward retreat, there are phases in which the dune foot and crest position are relatively stable. In these phases, vertical growth takes place until a major storm surge erodes the seaward slope, eventually reaching the original crest. Enhanced landward transport following such erosion event leads to the formation of a new crest, landwards of the original crest. The return time of the eroding storms controls the time available for vertical growth, effectively limiting the height of the foredune.

A large disruption of the vegetation cover leads to a rapid increase in landward transport. Depending on the vegetation growth scenario, the system either returns to the previous vegetated state or remains bare (Figure 4.11B). For a no-change scenario, vegetation recovery takes at least three decades. This is in agreement with field observations of dune mobility following remobilisation efforts in the Netherlands (Arens *et al.*, 2013a). Mobility and landward transport becomes more persistent for the two scenarios with a gradual reduction in the vegetation growth rate (-0.5 and -1.0%/year). In both cases, dunes do not recover to pre-disturbance levels throughout the simulated period.

Additional tests show that there is a threshold growth rate (50% of the initial growth rate) below which recovery is no longer possible and dunes remain in a bare state (Figure 4.12). This threshold separates the vegetated dune state from the bare state and likely reflects a critical vegetation density required for the positive sediment-trapping feedbacks to occur (Balke *et al.*, 2014). If growth rates are below the threshold, pioneer vegetation cover never attains sufficient density to adequately reduce aeolian activity and thereby enable further expansion and establishment of new seedlings. This threshold signifies a potential fragility of the system, indicating a lower limit on vegetation growth required to maintain dune resilience to large disturbances.

Plausible high-end scenarios dictate a rise of 0.4 - 1.05 m between 1990 and 2100 for the Netherlands (Katsman *et al.*, 2011; KNMI, 2014). Given the model results (Figures 4.6 and 4.7) and assuming sufficient sand supply, dunes near beaches similar to those at our modelling sites are expected to migrate landward around 0-50 m, while preserving their volume and increasing in height. Dunes backing very wide beaches may even continue to build seawards. The preservation of dune volume implies that flood protection level is maintained during retreat.

However, accommodating the associated retreat is often not feasible, requiring maintenance of the current dune-foot position. By fixing the shoreline position, as dictated by the dynamic preservation policy in The Netherlands (MinV&W, 2000), the landward retreat of the dunes and reduction in dune size are mitigated (Figure 4.10). Dunes are able to maintain their cross-shore position and accrete vertically. In terms of both volume and height, values under the fixed shoreline conditions exceed those achieved under the retreating shoreline conditions, which is beneficial for flood protection.

4.5.2 Modelling aspects

The model is based on a number of simple rules and has the capacity to accurately reproduce foredune dynamics over a period of years to a decade. Also, multi-decadal simulations show good agreement between modelled evolutionary trends and the evolution predicted from conceptual models. However, some model assumptions should be kept in mind when interpreting the results.

The marine module of the model was intentionally kept as simple as possible, including only first-order, local processes. These processes were translated into rules in a same conceptual way as the original DECAL, to gain the best possible connection between the two modules.

We assume a simple upward and landward shift of the beach profile in response to sea-level rise, proportional to the nearshore slope (Bruun, 1962; SCOR Working Group 89, 1991; Davidson-Arnott, 2005; Zhang *et al.*, 2004). However, there are other possible large-scale effects of sea-level rise on sediment budgets and large-scale morphology that may affect beach evolution and through that dune formation (Stive, 2004). For example, at the study site the response of back-barrier area, ebb-tidal deltas and interactions with the barrier island system may predominate the expected upward and landward shift (Stive, 2004; Walters *et al.*, 2014). Additionally, changes in alongshore transport gradients may mask the expected shoreline response to sea-level rise (Aagaard and Sørensen, 2012).

The model assumes abundant sand supply to the beach. Each iteration of the marine component replenishes the equilibrium beach profile, replacing the volume of sand that has been moved into the dune zone. The equilibrium beach profile therefore represents a neutral beach sediment budget. Any changes to this sediment budget may significantly influence dune evolution, e.g. by accelerating landward migration for a negative beach budget or slowing down erosion and promoting landward building instead for a positive beach budget (Psuty, 1992; Sherman and Bauer, 1993).

Wind regime in the model is unidirectional and perpendicular onshore. In reality, wind direction is highly variable and often oblique onshore. Variable wind directions were previously implemented by changing the trajectory of slab movement across the grid (Baas, 2002), or by rotating and resampling the grid (Bishop *et al.*, 2002; Baas, 2002). This influences dune morphology relative to a unidirectional regime. However, both implementation methods carry significant disadvantages so that the validity of the outcome is uncertain. Moving a slab first a number of steps onshore and then a number of steps alongshore (as in Baas, 2002), means that that slab has to interact with each cell in its path and that one move consists of several vegetation-slab interactions with possibly different vegetation cover. Rotating and resampling imposes problems with morphology that is lost along the domain's edges and with sediment conservation (Bishop *et al.*, 2002; Baas, 2002). It is however possible to define a yearly wind regime with alternating onshore and alongshore transport directions. Although such a regime would enhance lateral re-distribution of sand, its effects on established dune morphology are not expected to be large given the alongshore homogeneity of morphology and plant cover.

4.6 Conclusion

Although relatively simple in its formulations, the results of our calibrated and validated model of beach, dune and vegetation development are in good agreement with measured foredune evolution on a scale of years to decades. This indicates that integrating the full set of aeolian, marine and biotic processes is essential for predicting foredune evolution.

Model predictions for various climate-change scenarios show that sea-level rise largely controls foredune evolution. More specifically, the rate of sea-level rise determines if and to which extent landward retreat takes place and whether landward sand fluxes are sufficient for the foredune to migrate landward while maintaining volume and/or height. Dune volume can be maintained for SLR up to 10 mm/y, while dune height is able to keep pace with sea-level rise up to 15 mm/y.

A gradual reduction in vegetation growth rate, such as related to climate change, hardly alters dune evolution. However, dune evolution after a one-time clearing of all vegetation depends strongly on vegetation growth rate. Whereas a foredune is able to become re-vegetated and recover its previous volume under vigorous vegetation growth, such recovery is not achieved if the growth rate is below a certain threshold. This might lead to rapid changes from stable to mobile dunes and highlights the possible fragility of beach-dune systems.

Acknowledgements

Data used to create the figures and results will be available at doi:10.4121/uuid:43f07a3f-cd60-4fc2-beeb-2c305ed0f71c. This study was supported by the Dutch research program Knowledge for Climate (Theme 1: Climate Proof Flood Risk Management, for JK and AdG) and the IPOP grant of Wageningen UR 'Ecological optimization of dynamic coastal defence' (AdG). Andreas Baas, Frank Berendse, Pieter Slim, Han van Dobben, Leo Stroosnijder and Aart Kroon are thanked for their discussion during model development.

5

Adaptation strategies to maintain dunes as flexible coastal flood defence in the Netherlands

5.1 Introduction

Along sandy shorelines of the world, coastal dunes often represent the main protection against flooding from the sea. At the same time, dunes are used for recreation, they provide a drinking water supply and they form an ecological niche in which plants are adapted to extreme conditions (Arens *et al.*, 2001b). Bird (1985) has reported that 70% of the world's sandy shorelines were eroding or had a negative sediment budget resulting in erosion and inland displacement of the shoreline. Psuty and Silveira (2010) indicated many of the world's shorelines are erosional, with beaches and dunes continuing to exist in the face of inland displacement and a negative sediment budget. Apparently, the beach-dune system in itself is able to 'survive' as long as there is no obstruction against inland migration. However, in most cases, the tolerance for inland migration of the system is limited by housing and infrastructure.

Climate change and sea-level rise may influence many of the processes and variables involved in beach/dune dynamics. From a management perspective, it is important to understand the direction and magnitude of the different effects. This knowledge should govern the most appropriate management options to be deployed, with a view to either managing shoreline retreat, maintaining the shoreline position or even extending it seaward. Retreat is an option for undeveloped coasts. Currently, the Netherlands have adopted a strategy to maintain the position of the shoreline by applying regular sand nourishments. This strategy

Based on: JGS Keijsers, A Giardino, A Poortinga, JPM Mulder, MJPM Riksen and G Santinelli (in press). Adaptation strategies to maintain dunes as flexible coastal flood defense in the Netherlands. *Mitigation and Adaptation Strategies for Global Change*

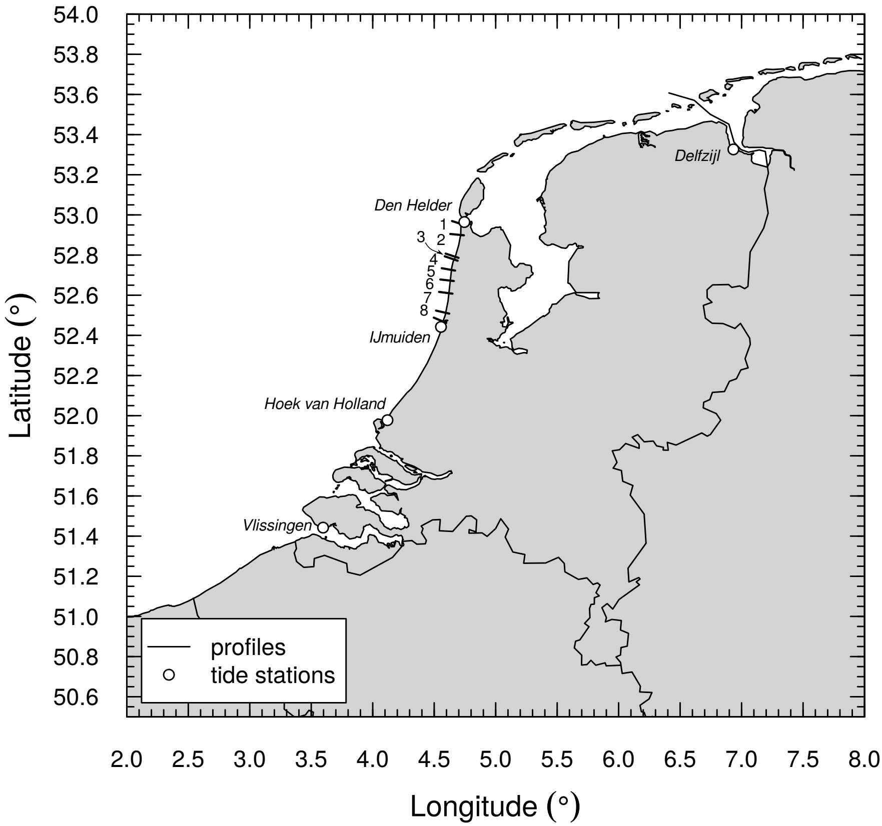

Figure 5.1: Location of the study area (North Holland) and position of the measurement stations for sea level and meteorology used for analysis. Stations Vlissingen and Den Helder are used for both sea level and wind data, the other stations are used only for sea-level trend analysis. The study area is divided into eight sub-sections, defined by similar natural morphological behaviour and nourishment strategy.

allows the coastal zone to grow with sea level, i.e. to increase its surface level to match sea-level rise. If changes in beach/dune dynamics are significant, another strategy might be better suited.

Focussing on the Netherlands (Figure 5.1), this chapter investigates the impacts of anthropogenic climate change on foredune building and then discusses the implications for managing the Dutch coast.

Aeolian transport	Dune erosion	Vegetation development
Wind climate	Sea level	Temperature
Sediment availability	Wave climate	Water availability
Sediment characteristics	Sediment characteristics	Nutrient availability
Beach profile	Beach profile	Sedimentation
		Competition

Table 5.1: Dominant processes in foredune development and their controlling variables in meso-scale dune development

5.2 Dominant processes in foredune development

Foredunes are defined as: 'a ridge of irregular sand dunes, typically found adjacent to beaches on low-lying coasts, and partially covered with vegetation' (Mayhew, 2006). Foredunes form where there are plentiful quantities of sand, sufficient prevailing winds to transport sand, and vegetation to help trap sand (e.g. Houser and Ellis, 2013). Under these criteria, small incipient foredunes are formed. These dunes have an ephemeral character as they may be removed completely by wave attack during a storm surge. However, if favourable dune-building conditions prevail, then the incipient foredunes increase in extent and volume, developing into more permanent and established foredunes.

The morphodynamics of established foredunes depend on the balance between accretive processes (sediment input through aeolian transport) and erosive processes (dune erosion by wave attack). Both processes are dependent on climatically driven forces: wind delivers the energy for aeolian transport (e.g. Bagnold, 1954; Svasek and Terwindt, 1974; Davidson-Arnott and Law, 1990; Bauer and Davidson-Arnott, 2002), while sea level and wave conditions are the driving forces for dune erosion (e.g. Vellinga, 1982; Van de Graaff, 1986). Generally, accretion is a slow process which can occur over periods of months to years, whereas dune erosion takes place in hours to days. Patterns of sedimentation and stability of foredunes are further controlled by vegetation (Bressolier and Thomas, 1977; Hesp, 1983; Sarre, 1989; Arens, 1996a). The relationship between climatic controls and dune development is well described by Reed *et al.* (2009) and Hesp (2002). Table 5.1 shows the important variables in foredune development.

Both accretion and erosion are influenced by variables and processes acting on time scales from seconds to centuries, which makes coastal dune development complex and difficult to predict. Over longer periods, the net sediment balance determines the response of the beach-dune system: negative scenario: inland displacement; equilibrium scenario: results in stability or balance; and a positive scenario: seaward displacement of the beach-dune system

(Pye, 1990; Psuty, 1992; Hesp, 2002).

5.3 The impact of climate change on foredune development

The influence of sea level rise on dune or coastal erosion has been the focus of considerable research (Davidson-Arnott, 2005; Feagin *et al.*, 2005; Ranasinghe *et al.*, 2012; Rosati *et al.*, 2013). In contrast, changes in the other climatic variables involved in dune morphodynamics or vegetation growth, such as, wind climate and precipitation, have received less attention. Changes in wind climate have been linked with changes in orientation of dune ridges (Van Straaten, 1961), periods of higher activity of dune fields in the Netherlands (Jelgersma and Van Regteren Altena, 1969) and blow-out development (Jungerius *et al.*, 1991; Hesp, 2002). This study examines whether significant changes in these physical processes will contribute to changes in dune morphodynamics based on the current climatic change scenarios for the Netherlands (Van den Hurk *et al.*, 2006, 2007).

5.3.1 Recent climatic trends

Wind climate variability and trends of station Den Helder (De Kooy) and Vlissingen (Figure 5.1) were investigated for the period 1906 – 2010 (KNMI). Distributions of daily averaged wind velocity and direction over time intervals from years to multiple decades were compared. For all intervals, strong variability was found in both wind speed and wind direction, but no systematic trend. These findings are in agreement with The Wasa Group (1998) and Smits *et al.* (2005), who studied the wind climate for the European and Dutch coast, respectively. They found a large natural variability at all timescales, but no systematic changes in the frequency of moderate or strong wind events during the 20th century. For the same time period, Van Oldenborgh and Van Ulden (2003) found no discernible trend in wind direction. Neither for the wave climate, which is closely related to the wind climate (Van Straaten, 1961), any systematic trends could be discerned over the 20th century (The Wasa Group, 1998).

Sea level trends were analysed for five different locations, with data covering the period 1880-2010 (Rijkswaterstaat, 2014c). In order to account for the increasing temporal density through time, all data were resampled to the coarsest temporal resolution of 3 h. For all gauging stations, the yearly median and maximum were calculated. Simple linear regression of the medians and maxima was applied to identify trends in time (Figure 5.2).

For all the stations, the rise in median sea level varied between 1.3 mm/y (Vlissingen) and 2.1 mm/y (Delfzijl). Due to a large year-to-year variability, the R^2 of linear regressions over time varied between R^2 = 0.50 and 0.76. However, for all locations, there is a clear upward trend. For the maximum measured sea level, the linear regression also shows an upward

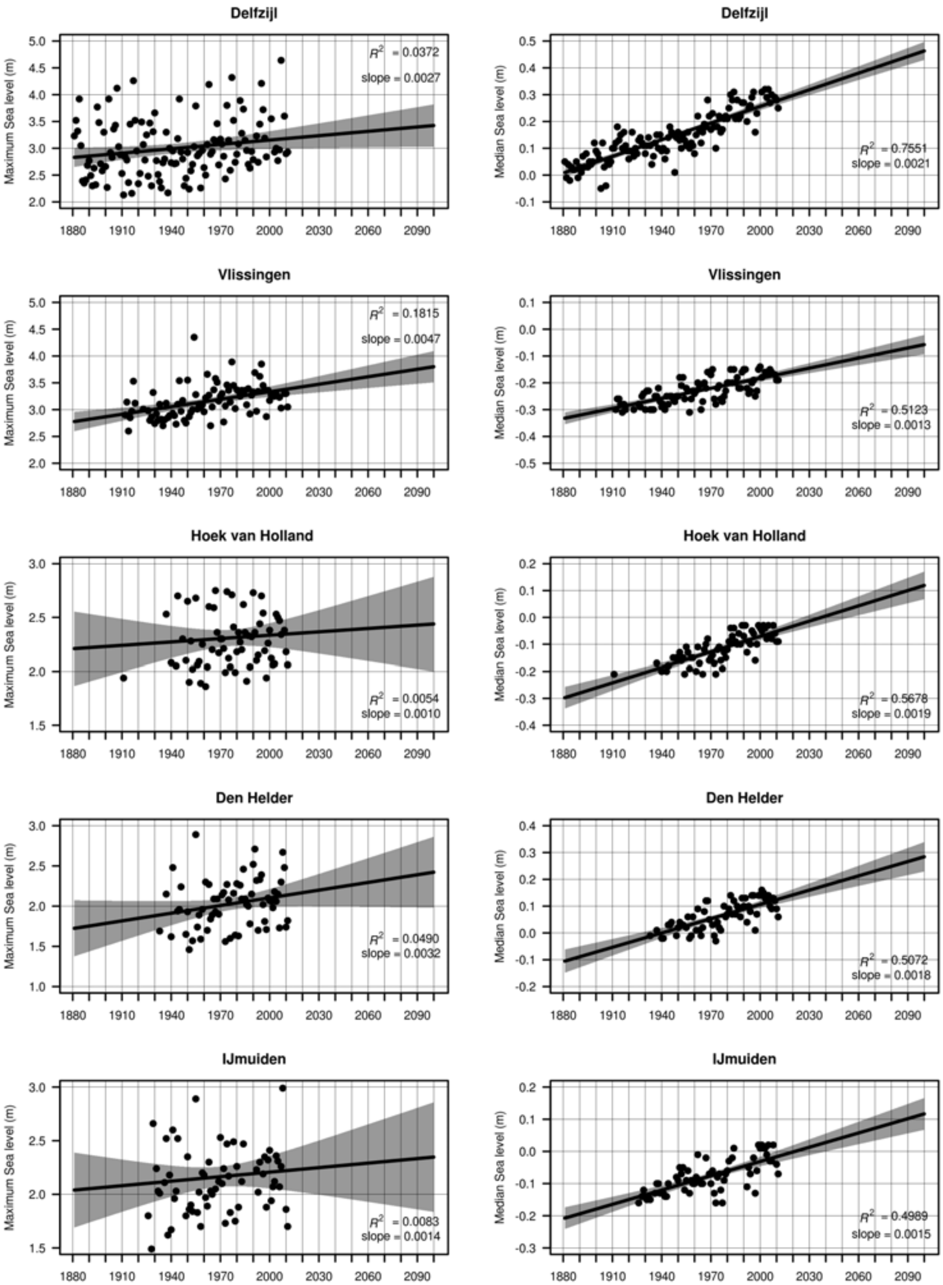

Figure 5.2: Recent trends in yearly maximum sea levels (left) and yearly median sea levels (right) for the five tide stations in the Netherlands. Shaded areas indicate 95% confidence intervals of the regression line

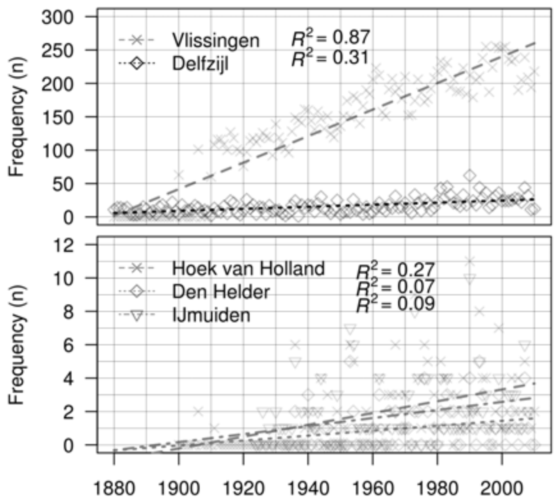

Figure 5.3: Frequency of water levels >2 m for five tide stations in the Netherlands. The increasing frequency of high water levels for Vlissingen is likely resulting from local morphological changes

trend for all locations. However, the correlations are weak and a systematic trend of higher maximum sea levels can thus not be concluded. The relatively weak trends in maximum sea levels may be related to the inherently large year-to-year variability, caused by differences in timing and occurrence of spring tides and storm surges. This variability overshadows any underlying trend.

The frequency of extreme values in the water level dataset is of primary interest, as a shift towards more extreme values would increase the likelihood of dune erosion. Based on the 3-hourly dataset of sea levels, the frequency of water levels > 2 m was calculated for every year (Figure 5.3). There is a remarkably strong linear increase in high water levels in Vlissingen. However, Vlissingen is an exception in this context, with generally higher water levels as well as higher maximum water levels. This exception can be explained by morphological changes in the area of the tide station (Langendoen, 1987), causing a larger tidal range and hence a trend in frequency of extreme values. For the other four stations, there is high year-to-year variability in number of days with high water, displaying a weak positive linear relationship (Figure 5.3). The data do not suggest any evidence for an increase in high water events, despite generally higher sea levels. This is in agreement with results from Bijl *et al.* (1999), who found no significant increase in storminess over north-western Europe.

Time series of yearly averaged temperatures in the Netherlands show an increase of 1.6 K from 1901 to 2005, most pronounced in February and March (Van den Hurk *et al.*, 2006). Besides global warming, a part of this increase can be attributed to changes in dominant wind directions (Van Oldenborgh and Van Ulden, 2003).

Precipitation in the Netherlands shows large inter-annual variability. However, trends from 1951-2009 show annual precipitation has increased by between 0 to 250 mm or 0 to 35%, with highest values along the coast (Daniels *et al.*, 2014).

5.3.2 Future climatic trends

Climate projections are generally derived from regional climate models (RCMs) that use output of global circulation models (GCMs) as boundary conditions. To account for uncertainty in model input and model formulations, initial conditions and formulations are varied between runs, providing a range of possible outcomes for the variable under consideration. The climate variable projections of Van den Hurk *et al.* (2006, 2007), as they apply to dune formation, are used. These were the most recent projections at the time of writing.

In the 20th century, there was no evidence for wind direction or velocity change due to climate change. A number of studies used GCMs to explore possible future changes in wind patterns focussing on storminess (Van den Hurk *et al.*, 2007; Pryor *et al.*, 2012; De Winter *et al.*, 2013). These studies found that climate projections have a high variability, depending on the scenario used. Moreover, while annual maximum wind speeds originate largely from the west in the Netherlands, there is still large yearly and decadal variability in wind speed and wind directions. Due to this natural variability and the variations evident in the different GCM outputs, it is difficult to rely on these for future projections. It should also be noted that while wind velocity and wind direction are important drivers for aeolian sediment transport at the small (local) scale, correlations between wind climate and dune growth on a seasonal to yearly scale, are generally weak (Davidson-Arnott and Law, 1996; De Vries *et al.*, 2012b; Ollerhead *et al.*, 2013).

Sea level rise is expected to continue, reaching between +15 and +35 cm in 2050 relative to 1990 (Van den Hurk *et al.*, 2006, 2007). Storm-surge levels are not expected to change. Some studies derived a small but statistically significant increase in extreme surge events (Lowe and Gregory, 2005; Boldingh Debernard and Petter Røed, 2008; Grabemann and Weisse, 2008), but other studies found that an increase in sea level does not affect storm surge height and frequency in the North Sea (Langenberg *et al.*, 1999; Sterl *et al.*, 2009; De Winter *et al.*, 2013). It should be noted that storm surges are relatively rare and natural variability is too large to clearly identify definite trends (Langenberg *et al.*, 1999).

Mean yearly temperatures are expected to rise somewhat faster than in the 20th century, between 0.9 K and 2.8 K by 2050 in summer and between 0.9 K and 2.3 K in winter (Van den Hurk *et al.*, 2006). Differences between low and high estimates are mainly due to uncertainties in response of sea surface temperature and regional atmospheric circulation to global warming (KNMI, 2006; Van den Hurk *et al.*, 2007).

Climatic variable	Historic trend (1900-2005)	Future trend (1990-2050)
Temperature	+ 1.6 K	+ 0.9 K to+2.8 K
Annual precipitation sum	+ 20%	summer: -19 to +3% winter: +3 to +14%
Sea level	+ 10 to +20 cm	+15 to +35 cm
Storm frequency	≈	≈
Wind climate	≈	≈

Table 5.2: Recent and expected future change in climatic variables that control dune-building. ≈ indicates little or no change. References in text.

The climate scenarios show a large range for the expected change in precipitation. Summer precipitation is likely to change by +3 to -19%, while winter precipitation is expected to increase by the same order of magnitude (Van den Hurk *et al.*, 2006). Compared to observed changes from 1959 – 2009 and inter-annual variability in yearly precipitation, the expected change in precipitation is relatively small.

The historical and future trends for the different climatic variables are summarized in Table 5.2. We can conclude that, compared to both the wide range in predictions and the wide range in inter-annual variability, these expected changes are relatively small.

5.3.3 Effects of climate change on foredune development

Aeolian transport

Given that wind climate is not expected to change dramatically by 2050 (Table 5.2), the potential for aeolian transport likely remains unchanged. Similarly, the change in precipitation is relatively small relative to the inter-annual rainfall variability and, therefore, the effect on aeolian transport is expected to be limited, especially as transport can still be significant during rainfall (Van Straaten, 1961; Jackson and Nordstrom, 1998).

Dune erosion

Sea-level rise results in an increase in dune erosion, related to higher water levels in front of the dune foot (De Winter, 2014). In some cases, landward retreat can take place while coastal dunes maintain their volume (Davidson-Arnott, 2005; Ollerhead *et al.*, 2013). Along the Dutch coast however, before implementation of an 'hold-the-line' policy in 1990, many regressive foredunes showed a decrease in dune width (Arens and Wiersma, 1994).

Using a probabilistic model calibrated for the coast of Noordwijk, just south of our focus area in North Holland (Figure 5.1), Li *et al.* (2014) predicted with a sea-level rise of 0.4 m, there would be an 8% increase in dune erosion volumes for each return period. As sea-level rise between 1990 and 2050 is below 0.4 m (0.16 to 0.34 m), the expected increase in erosion volumes is somewhat smaller.

Vegetation growth

In a case study of the impact of climate change on Dutch ecology, Witte *et al.* (2012) argue that due to decreasing precipitation in the growing season and increasing potential evaporation, the moisture deficit for coastal dune vegetation increases under climate change. This deficit, which is defined as the difference between actual and potential transpiration, is a measure of water shortage for plants Bartholomeus *et al.* (2012). When compared to the deficit in the current climate, the expected values are 30% to >100% larger, which reduces the vitality and vigour of the vegetation. The reduction of vegetation growth may result in larger bare surfaces, which means larger areas exposed to wind erosion and hence aeolian activity and dune building (Arens, 1996a; Witte *et al.*, 2012). It is difficult to estimate the actual response of vegetation growth to climate change, in particular for *Ammophila arenaria* (Marram grass), as coastal dunes represent a highly stressed environment, where salt spray and abrasion by aeolian transport also play a limiting role.

To summarise, the expected climate change has both positive and negative effects on dune growth. Dune erosion volumes are expected to increase by 5-10%, whereas vegetation growth is likely to be reduced due to an increasing moisture deficit in the growing season.

5.4 Former and current management approaches and their effects on foredune development

The predicted changes in dune building processes due to climate change comprise an increase in erosional activity and an indifferent change in dune accretion. Therefore, a net deficit is expected in the beach-dune sediment balance, with conditions expected to favour the inland replacement of foredunes. Paleogeographic reconstructions (Zagwijn, 1986) and sediment budget calculations (Beets *et al.*, 1994; Van der Spek, 1995; Beets and Van der Spek, 2000) reveal that since the last Ice Age, net sediment influx into the coastal zone of the Netherlands gradually reduced and eventually ceased between 2500 to 2000 BP. The present net natural sediment input into the Dutch coastal zone is negligible (Van der Meulen *et al.*, 2007; Mulder *et al.*, 2008). At the same time, sea-level rise causes a larger accommodation space for sediments, representing a growing sediment demand. Regardless, the balance in the coastal zone between demand and supply of sediments is in deficit. The effect of this negative sediment balance on beaches and dunes (Pye, 1990; Psuty, 1992), and on the coastal zone as a whole, leads to a retreating coast (Nichols, 1989; Beets and Van der Spek, 2000).

To counteract erosion and to maintain the dunes as coastal defence, the Dutch traditionally have intensively managed their coastal zones. A 'soft engineering' approach involves the placement of sand fences between the sea and the foredune, along with the planting of *Ammophila arenaria* (Marram grass) (Arens *et al.*, 2001b; De Jong *et al.*, 2014), and has been used to stimulate local sedimentation in the dune system. However, this intensive management approach did not prevent an inland movement of the coastline.

In 1990 the Dutch government implemented the Dynamic Preservation policy (Ministerie van Verkeer en Waterstaat, 1990). This policy was based on a cost/benefit analysis of alternatives 'managed retreat', 'hold-the-line' and 'seaward extension', showing that hold-the-line would present the best balance between cost of maintenance and benefits in terms of preserved dune area (MinV&W, 1989). The Dynamic Preservation policy implies a soft engineering approach that tackles the net sediment deficit, not only by interfering with the sediment transfer process, but also through sand nourishments into the coastal zone. Implementation of the policy was guided by an operational goal at the medium scale: preservation of the 'reference coastline', the so called 'basiskustlijn' (BKL) representing the 1990 coast line position (De Ruig and Hillen, 1997). Every year, the position of the momentary coastline (MKL) is compared with the BKL and nourishments are considered where MKL falls below BKL.

In 2000, the policy was extended with an operational goal at a larger scale: preservation of the sand volume in the coastal zone, defined as the area between the -20 m depth contour and the inner dune boundary (Van Koningsveld and Mulder, 2004; Mulder *et al.*, 2011). The total average yearly sand nourishment volume since 1991 amounting 6 million m^3, was doubled to 12 million m^3 from 2001 (MinV&W, 2000). Since 2001, Dutch coastal policy has evolved from an 'hold-the-line' into a larger scale and longer term 'maintain-the-system' approach, in which the functionality of the entire coastal zone is preserved rather than the position of the coastline alone.

Several types of nourishments can be applied: (1) dune reinforcement; (2) beach nourishment; or (3) shoreface nourishment. The type of the nourishment determines whether it has an immediate or gradual effect (Table 5.3).

Dune reinforcements are placed directly on the dune face, thereby providing an immediate enhancement of dune sand volume. Safety levels increase as the total amount of dune volumes increases. Beach nourishments are generally applied in areas with narrow, low dunes or when the beach width is not sufficiently wide for recreational purposes (Van Rijn, 2011). Standard beach nourishments are designed to follow a nearly constant slope in the cross-shore profile, while banquette-shaped nourishments are designed with a larger amount

Nourishment type	Enlarge dune volume		Limit dune erosion	
	Immediate	Gradual	Immediate	Gradual
Dune reinforcement	✓			
Beach nourishment	✓		✓	
Shoreface nourishment		✓		✓

Table 5.3: Functions (✓) of the different types of nourishments in relation to dune development at different time scales. 'Immediate' indicates an effect which is directly visible or in a limited period of time (i.e. from days to months). 'Gradual' indicates an effect which becomes noticeable on a time scale of years.

of sand in the upper part of the profile which becomes nearly flat, so that restaurants and other tourist attractions on the beach can directly benefit from this flat part of the profile.

Beach nourishments provide benefit to the foredunes by widening the beach, providing protection against erosion, and by increasing the elevation of the beach, providing a larger volume of available sediment. However, the nourished sand has to be carefully selected to avoid a reduction in aeolian transport due to poorly sorted sand or shell fragments (Van der Wal, 1998b). Furthermore, beach nourishments also limit dune erosion by increasing the dissipation of smaller waves (Van der Wal, 2004; Giardino *et al.*, 2013).

Shoreface nourishments are generally used in areas with wide, high dunes with the aim of increasing the beach and dune volume in the medium-term (5-10 years) using natural processes. Sand is placed at a depth of 5-10 m, corresponding to an existing sand bar. Besides increasing the net sand volume available in the nearshore, by increasing on-shore transport through wave asymmetry and a decrease in alongshore currents, shoreface nourishments act as a wave filter, reducing the impact of larger waves, similar to a submerged breakwater. Shoreface nourishments are more economical than beach nourishments as sand can be easily dumped in shallow waters.

Since 1990, sand nourishments have become common practice in the Netherlands. Total sand nourishment volumes have been growing over time, with an increasing preference for shoreface nourishments over beach nourishments. The nourishment volumes applied along the North Holland coast between 1965 and 2010, divided between different nourishment types, are shown in Figure 5.4.

Van Rijn (2011) showed that before implementation of the coastal preservation policy in 1990, the majority of the North Holland coast was subject to structural erosion. After implementation of the nourishment policy, positive volume trends were observed overall. Figure 5.5 shows the effects of different type of nourishments on momentary coastline (MKL) and dune foot position for a specific cross-shore transect. Prior to 1990, both coastline and

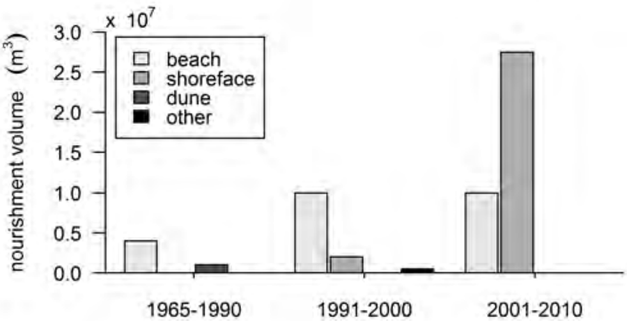

Figure 5.4: Different types and volumes of nourishments applied over time along the North-Holland coast. Data derived from the nourishment database (Rijkswaterstaat, 2013).

dune-foot position migrated landwards. Following the regular nourishments, both positions show a seaward trend instead. The effects of nourishments on dune volumes for different sections in the study area are shown in Figure 5.6. The figure was computed from linear trends in dune volume, for three time windows, based on the yearly cross-shore transects in the JARKUS dataset. This dataset contains yearly elevation profiles across the beach and dune, every 250 m along the Dutch coast, starting from 1965 (Rijkswaterstaat, 2014a). The trends were averaged for the 8 different areas shown in the figure, and characterized by similar natural morphological behaviour and nourishment strategy. The figure shows a clear increase in the dune volume trend following the implementation of the nourishment strategy in 1990. The seaward shift in dune foot position and the increase in dune volumes resulted in a decrease in the probability of breaching by more than one order of magnitude (Giardino *et al.*, 2014).

With the success of the sand nourishment approach in stimulating the supply side of the sediment balance, the traditional soft engineering methods have been abandoned. Under this new dynamic dune management, dunes no longer need to be reconstructed artificially after storm damage. Instead, dune recovery is purely left to natural processes governed by sediment supply, aeolian sediment transport regime and vegetation development. The outcome of these processes is expressed in changes in dune volume and shape. De Jong *et al.* (2014) found that under conditions where sediment supply is not limited, the dynamic dune management approach leads to similar dune growth rates, as achieved by the 'traditional' soft engineering approaches.

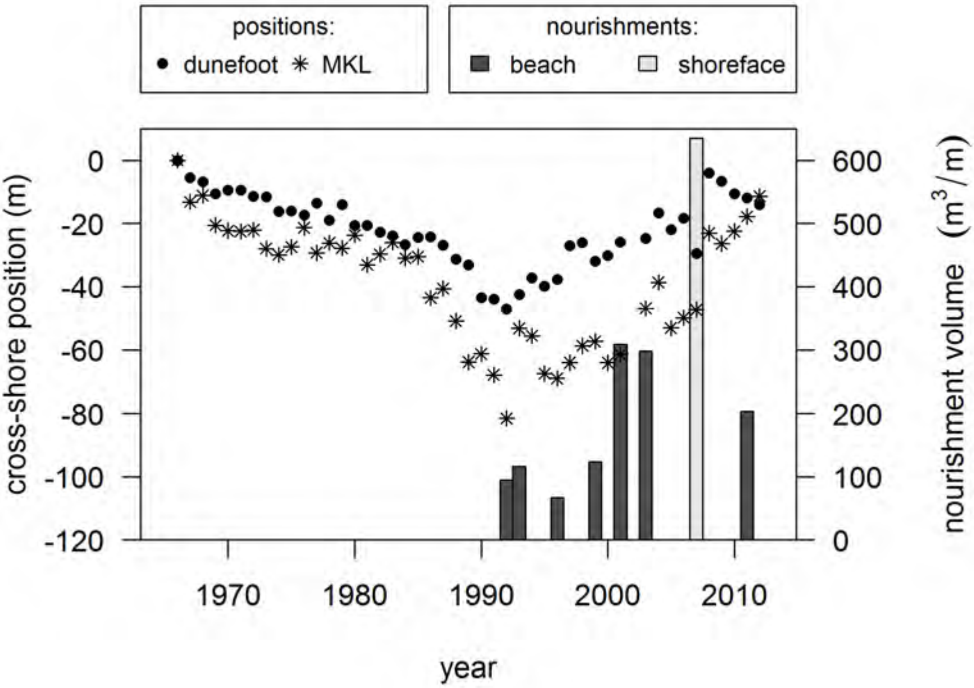

Figure 5.5: Effect of different nourishment types (the vertical bars) on momentary coastline position (MKL) and dune foot position. The left axis shows the position of the MKL and dune foot relative to their positions in 1966, where more negative values indicate more landward positions. The right axis shows the volume of the nourishments. Data from JARKUS transect 5480

5.5 Discussion

Management results along the North Holland coast since the 1990s indicate that a combined approach of sand nourishments and dynamic dune management have succeeded in reducing the negative impacts of sea level rise during this period. The dune development data presented in Figure 5.5 and 5.6 suggest that in areas of sediment abundance, a positive beach sediment budget, and adequate rainfall, it is unlikely that relatively small changes in storm frequency and intensity or vegetation development will result in major changes in coastal dune dynamics. Thus, it can be justified that much of the focus of management activities should be on the effects of sea level rise and ongoing morphological evolution of the coast.

By keeping the sediment balance of the system in equilibrium with sea level rise, the 1990 policy in the Netherlands has resulted in stabilization of the coast line and a slight expansion of the foredunes. Dunes have grown, thus protection against flooding has improved, and functions of public water supply, recreation and natural values, have been safeguarded. The

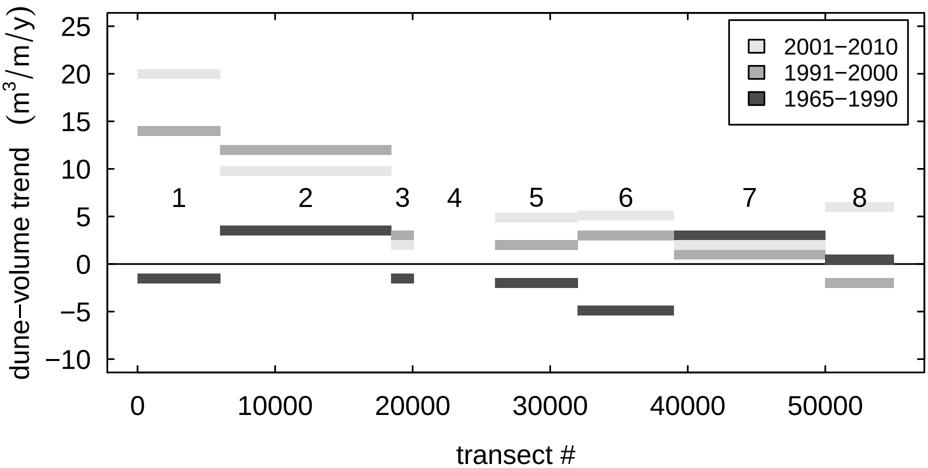

Figure 5.6: Trends in dune volume along the North Holland coast, calculated for three different periods: 1965–1990, 1991–2000, and 2001–2010. The numbered sections refer to the eight sub-sections within the study area (Figure 5.1). Sub-section 4 consists of a seawall and has no fore-dunes

question remains whether this management approach will still be viable and effective when climate change causes a decline in dune building.

Climate change will generally favour the inland displacement of the foredune, due to an enhanced decline in the sediment balance of the beach-dune system. The management approach of utilising sand nourishments offers the best opportunity to counteract any negative consequence of such an inland displacement by tackling the fundamental cause of the problem and maintaining and restoring the sediment balance of the system. The main requirement is that the quantity of sand supplied is increased proportionally to the increase in sediment deficit within the coastal zone.

The present approach in the Netherlands links the distribution of sand nourishments to the definition of a reference coast line, and the total volume to the definition of a coastal foundation (Mulder *et al.*, 2011). The success of this approach since the 1990s shows its potential to also adapt to future climate change. Will it be feasible to raise the total nourishment volume? From a resources perspective, the answer is positive. The North Sea represents an immense resource of sand and the conditions for exploitation appear to be technically and economically feasible (Rijkswaterstaat, 2011). The raising of sand nourishment volumes will ultimately be, in the face of global warming impacts, a political decision.

The authoritative Delta Committee (Deltacommissie, 2008), advised the Dutch government to raise nourishment volumes, and in the latest National Water Plan (MinI&M, 2009), the government has announced to investigate ways of raising the total yearly volume from

12 to 20 million m^3 per year. The present national Delta Programme, designed to protect the Netherlands against flooding and to ensure readily available supplies of freshwater (MinI&M, 2011), embraces this approach, and expect a raise in annual nourishment volumes up to 24 million m^3 after 2020 (MinI&M, 2013). Apparently, there still seems to be political consensus on an approach to 'maintain-the-system'.

Simultaneously, new ways are investigated to optimize the distribution method of coastal sand nourishments, seeking a better integration of coastal protection and coastal development (MinI&M and EZ, 2013). In general, as in 1989 (MinV&W, 1989), it may still be true that 'holding-the-line' provides the best balance between cost of maintenance and benefits in terms of preserving valuable dune area. However, a further differentiation in spatial and temporal distribution of nourishments might have positive effects on the cost/benefit balance. On the one hand this has triggered a mega nourishment experiment implemented in 2011 (Stive *et al.*, 2013), to investigate the cost-effectiveness and effects on morphological, ecological and economical functions of the coast. On the other hand, options have been investigated to abandon the 'hold-the-line' principle for and move towards a 'managed retreat' approach at locations where protection against flooding is not at stake, e.g. in wide dune areas where erosion and a landward migration might have positive effects on biodiversity of the dunes (e.g. AKK, 2011; Arens *et al.*, 2013a).

Parallel to all plans to continue allowing the coastal system to keep pace with the rising sea level, new concepts are being developed to reduce the flood damage potential in the polder areas landward of the dunes (e.g. MinI&M, 2009; De Moel *et al.*, 2014).

5.6 Conclusions

Analysis of the effects of climate change on dune-building factors indicate an increase in erosional activity and no change in dune accretion. For the Netherlands, all conditions seem in place to adapt to these effects in a way that preserves the integrity and characteristics of the foredunes, contributing to the preservation and even the enhancement of coastal protection and other ecosystem functions in the coastal zone. Core of the approach is a policy that has evolved from 'hold-the-line' into 'maintain-the-system'. By keeping the sediment budget of the overall system in balance with relative sea level rise, boundary conditions for long term coastal development are kept at a constant level. Differentiation in time and in space of nourishment volumes offers a flexible method to respond to changes in the beach-dune system that affect ecosystem functions.

Whether a similar approach might apply to other low lying, sandy shoreline areas, not only depends on their specific physical and ecological characteristics, but also on the technical, economic and political conditions and constraints. Nevertheless, even though a detailed copy of the Dutch approach may not apply, the general principle to take long term systems behaviour as a starting point, might.

6

Soft Engineering *vs.* a Dynamic Approach in Coastal Dune Management: A Case Study on the North Sea Barrier Island of Ameland, The Netherlands

6.1 Introduction

Coastal zones are of strategic importance in Europe. Almost half of the population of the European Union (EU) lives 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 89000 km of shoreline (Ciavola and Stive, 2012). In coastal zones, dunes act as 'soft' flood defences, protecting low-lying interior lands against flooding. To ensure coastal safety in the future, insight is needed on how these 'soft' flood defences are likely to develop under various types of management (Bochev-Van der Burgh *et al.*, 2009, 2011).

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

The Dutch have traditionally intensively managed their coastal zones. 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 the planting of *Ammophila arenaria* (marram grass) (Arens *et al.*, 2001b). From 1990, however, '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

Based on: B De Jong, JGS Keijsers, MJPM Riksen, J Krol and PA Slim (2014). 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* **30**(4): 670–684

Defences defined dynamic coastal management as ‘managing the coast in such a way that natural processes, whether stimulated or not, can take place undisturbed in as far as possible, as long as the safety of the inland area is ensured’ (TAW, 2002). Dynamic coastal management is 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 towards 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, habitat type 2120), and the priority habitat type ‘fixed coastal dunes with herbaceous vegetation’ (grey dunes, type 2130) (De Ruig and Hillen, 1997; 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 analysed to discern changes in dune shape, height, and volume for the period between 1980 and 2010. This timeframe 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).

6.1.1 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; direction, occurrence, and magnitude of storm erosion; and human impact and use. Coastal dune management aims to control these factors in such way as to fulfil desired ecosystem services, like coastal safety and recreation.

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 'building with nature', which makes use of natural processes, stimulating these in such a way as to increase coastal safety or improve ecological quality.

For both strategies, several types of measures can be discerned: 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 of measure is characteristic of the 'building with nature' strategy, whereas the last two are more closely associated with the soft engineering approach.

6.1.2 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 'grey' 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 practised. 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.

6.1.3 Building With Nature

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 (1^e Kustnota) (Ministerie van Verkeer en Waterstaat, 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 stop 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 shoreface, or in front of a foredune ridge (Bochev-Van der Burgh *et al.*, 2009). Initially, most nourishments were done on beaches, though later insights (from 1997) led to more sand placement on the shoreface (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). Beach and foreshore nourishment changes dune morphology as well, both directly and indirectly via its influence on sediment transport processes (De Vries *et al.*, 2012a). Bochev-Van der Burgh *et al.* (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 the 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 *et al.*, 2007; De Groot *et al.*, 2012). Overall, nature in the coastal dunes benefited from sand nourishments, as reduction 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 as a result (Luna *et al.*, 2011).

Sediment supply and, in particular, beach width and fetch length, are critical factors in dune initiation and growth (Hesp *et al.*, 2013). In case that the beach profile remains the same after a storm, the main effects of the two management types studied here will be evident in vegetation recovery time and the consequences of this for the sediment trapping efficiency and thus volume growth rate of the dune.

6.2 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, the Netherlands. Dynamic coastal dune management was introduced in these two sections in 1995 and 1999, respectively. In this chapter we describe the characteristics of the research area, the data collection and analysis methods used to determine the impact of dynamic coastal dune management. 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 are described and discussed here (e.g. beach width and shape, vegetation, water levels, wave heights, and nourishments).

6.2.1 Case study area

The case study was done on the coast of the Dutch North Sea barrier island of Ameland (53°28’N, 5°54’E) (Figure 6.1). The northern coastline of Ameland 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 the coastal dunes between transects 19.6 and 21.6. Here, dynamic coastal management was introduced in two foredune sections in different years (Figure 6.2). 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 alongshore current direction is also west to east. The dominant wind direction is south-west, with highest wind speeds in autumn. The tidal range at Ameland is approximately 2 m (semi-diurnal), and a single foredune ridge about 10 m above NAP backs the beach (NAP = 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 non-calcareous district of the Netherlands, but the lime content is about 1.3% in the beach sand and 0.5%

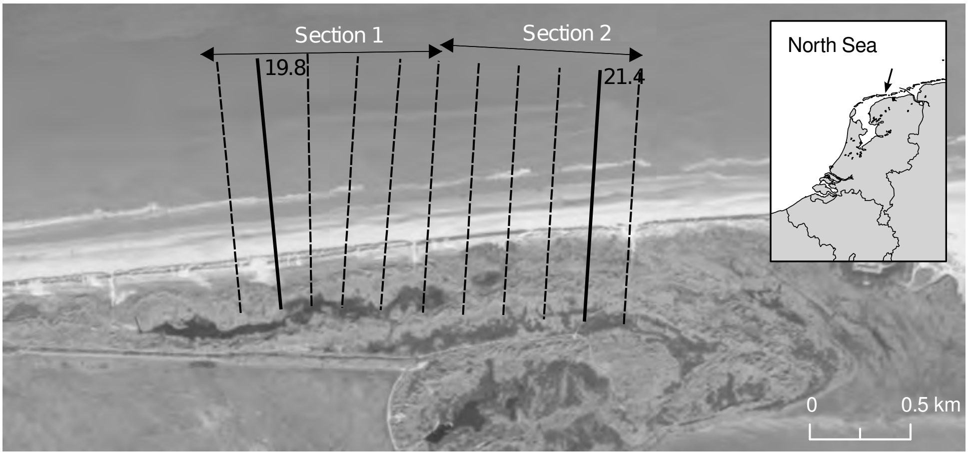

Figure 6.1: Location of the Dutch barrier island Ameland in relation to The Netherlands and the two research areas on the island's eastern end, labelled Section 1 and Section 2. JARKUS Transects within both sections are indicated by lines, with characteristic transects 19.8 and 21.4 marked by solid lines. The number represents distance in km from a point at the western end of Ameland. Aerial photo of 2014. Source: Esri and Aerodata/Cyclomedia.

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 *et al.* (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.

At the study site, extraction of natural gas 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 *et al.*, 2011). The 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 Panel on Climate Change (IPCC) (Church *et al.*, 2001), a sea-level rise of 0.44 m can be expected by 2100.

6.2.2 Other Factors Beside Dune Management Influencing Dune Formation

To be able 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 are examined as well.

Figure 6.2: 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 'grey 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.

High-Water Events

High-water events indicate storm surges that could potentially cause erosion of the foredune (Ruessink and Jeuken, 2002; Zhang *et al.*, 2002; Van Rijn, 2009). Yet they are just that, an indication, because other factors, like wind force and wind direction, are important as well (e.g. Morton, 1994). The Dutch Department of Public Works measures water level and wave height and makes these data available via Waterbase (`www.waterbase.nl`). For water level, this study uses data taken from the Wierumergronden measurement station located off-shore in the North Sea north-east 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°0'E).

Because no data earlier than 1981 was available, water levels were analysed for the period after 1981. For each month in the study period, the highest water level and wave height were

Year, Month	Water level (cm)	Wave height (cm)	High-water event
1981, November	275	710	X
1983, February	273	663	X
1989, February		686	
1990, February	297		X
1990, December	253	814	X
1991, December	255		
1993, February		758	
1994, January	269	725	X
1999, February	251	756	X
1999, December		669	
2000, January	266	723	X
2006, November	272	880	X
2007, January	253		
2007, March	271		
2007, November	281	841	X
2008, March		680	
2009, October		693	

Table 6.1: 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 events' (final column) are 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 `http://live.waterbase.nl/waterbase_wns.cfm?taal=nl`.

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 6.1).

High-water and high-wave events coincided in eight of the months studied (see column 'high-water event' in Table 6.1). 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

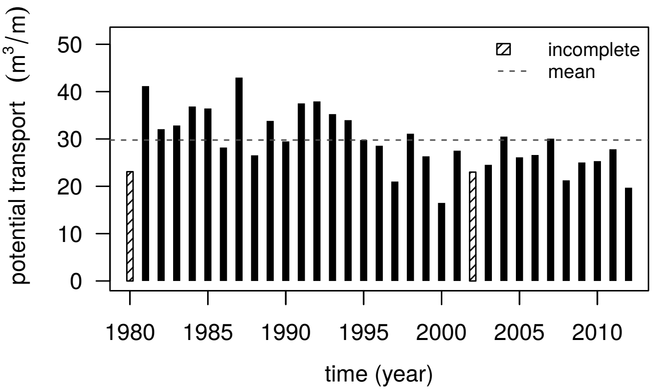

Figure 6.3: Yearly potential sediment transport based on climate data from the meteorological station of De Kooy, Den Helder, The Netherlands (52°56'N 4°47'E)

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 from 1994. To study the wind climate from 1980 to 2010, another station has 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 6.3). 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 explain for changes in dune growth rate, the position of the shoreline (where elevation is 0 m +NAP) and dune-foot (where elevation is 3 m +NAP) was calculated. Furthermore, time sequences of profiles were examined to explore changes in the height of the beach (Figure 6.4).

Transects 19.6 to 20.4 show that the height of the beach increases from 1980 to 2010. This coincides with seaward movement of the dune foot while the shoreline position remains constant, causing a reduction in the width of the dry beach from 200 m in 1980 to 150 m in

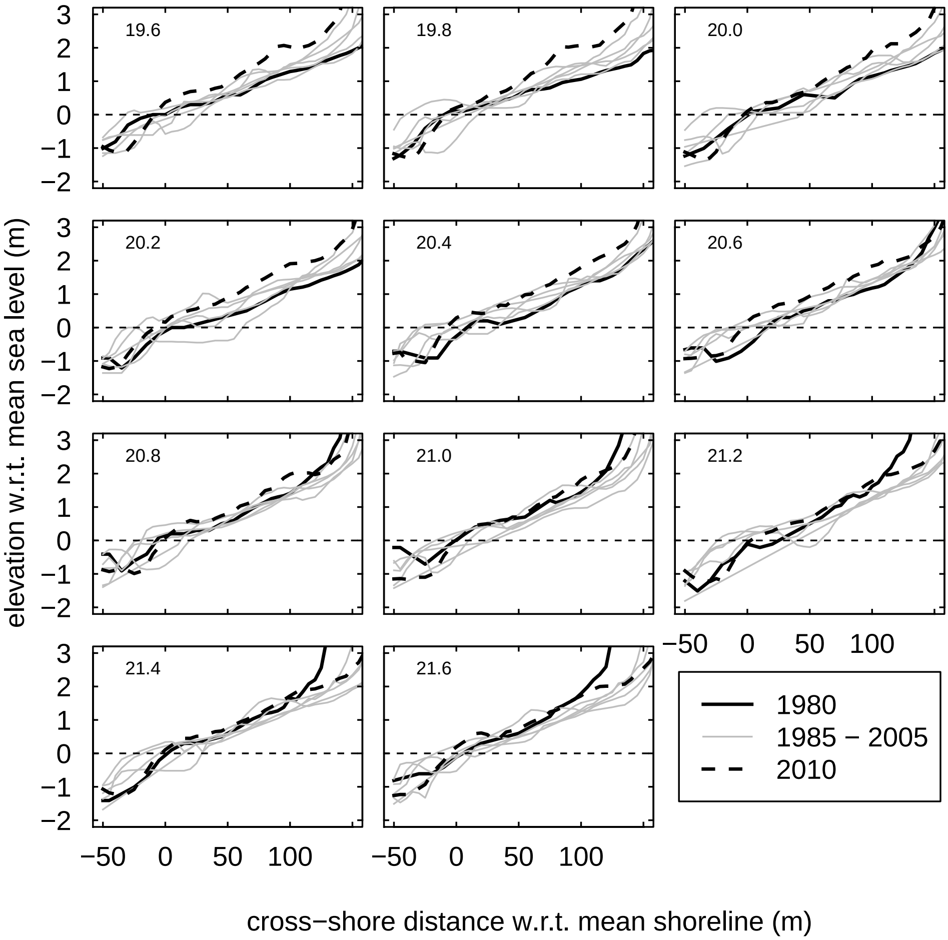

Figure 6.4: Cross-shore profiles of the zone between the average shoreline position ($z = 0$ m) and dune-foot ($z = 3$ m) for all transects in the area. For clarity, only one measurement per 5 years is given. Sea is to the left, dune to the right.

Year	Position	Amount (m^3/m)	Location (km)
1980	Foredune	367	10.0 - 16.0
1990	Foredune	202	12.4 - 17.0
1992	Beach	178	11.4 - 19.6
1996	Beach	388	7.2 - 1.2
1998	Foreshore	312	13.0 - 21.0
2003	Foreshore	332	9.4 - 13.6
2006	Beach	220	11.0 -16.0
2006	Foreshore	300	12.0 - 17.0
2010	Foreshore	539	11.0 - 14.6
2010	Foreshore	562	14.8 - 16.8

Table 6.2: Foredune, beach and foreshore nourishments on the northern coast of Ameland, applied near or within the study area between 1980 and 2010. Data derived from Deltares (2012)

2010. In transects 20.6 to 21, there is little change in beach morphology and both the dune foot and shoreline position are 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 are minimal in the research period.

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 needed). Table 6.2 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 *et al.*, 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 can therefore be taken to maintenance of the coastline (Provinciaal Overlegorgaan Kust Fryslân, 2000). For the study area this implies that only in 1998 a foreshore nourishment was applied.

6.2.3 Data and Data Analysis

Dune Morphology and Volume

To estimate the effect of the change in management on dune development we made use of JARKUS data. Since 1964, the Dutch Public Works Department has maintained a database of cross-shore profiles of the Dutch coast (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. Levelling was used from 1964, followed by (aerial) stereo-photogrammetry from 1977, and finally laser altimetry from 1996 (Minneboo, 1995; Bochev-Van der Burgh *et al.*, 2011). The accuracies of these methods are estimated as 0.01 m for levelling (Oosterwijk and Ettema, 1987), 0.1 m for stereo-photogrammetry (Veugen, 1984), and 0.1 m for laser altimetry (De Graaf *et al.*, 2003). The Dutch Public Works Department 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 (decimetres 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 *et al.* (2011); and De Vries *et al.* (2012a). 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:

$$V = \sum_{i=1}^{n} \left(Av\left(H_i, H_{i+1}\right) - 3 \right) \cdot D_{i,i+1} \tag{6.1}$$

where V is the volume of the foredune, $Av\left(H_i, H_{i+1}\right)$ 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 meters 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 results in 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 on significance by an independent-samples *t*-test using IBM© SPSS® Statistics.

Dune Ecology and Appearance

To analyse 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: (0) languishing (light green leaves, > 70% dead biomass), (1) dense (green leaves, 30 – 70% dead biomass), and (2) thriving (dark green leaves, < 30% dead biomass). Plant species were identified according to Stace (2010).

6.3 Results

To analyse 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 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.

6.3.1 Dune Morphology and Volume

Dune Foot Position

The position of the dune foot varied over time in both sections (Figure 6.5). 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 behaviour of the dune foot position showed similar patterns.

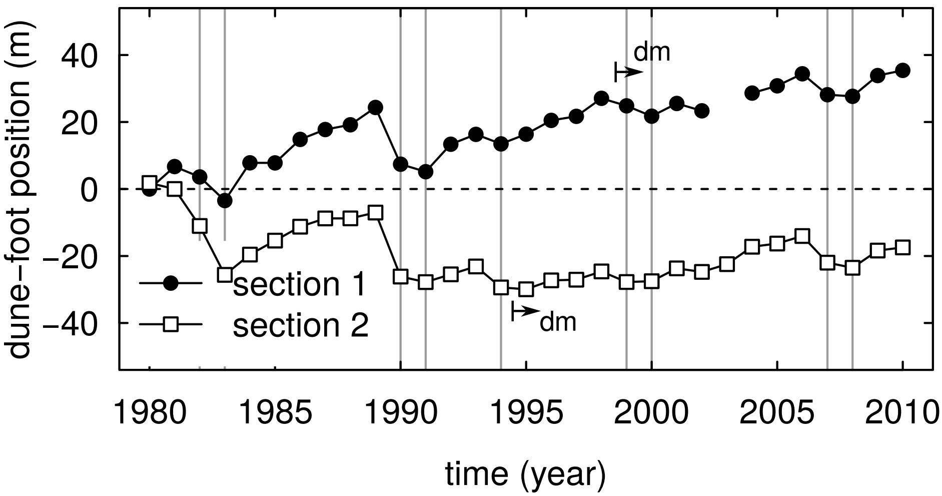

Figure 6.5: Relative position of the dune foot (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section, with positive values indicating a seaward shift of the dune foot position. Vertical lines indicate high-water events (storms). Introduction of dynamic management is indicated by arrows (dm).

Crest Position

The relative crest position at first moved seaward in Section 1 and landward in Section 2 (Figure 6.6), 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. However, in Section 1 stabilization started in 1994, before dynamic management was introduced.

Crest Height

Crest height increased steadily in Section 1, but stabilized at about 6 m after 2004 (Figure 6.7). 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 6.8). 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

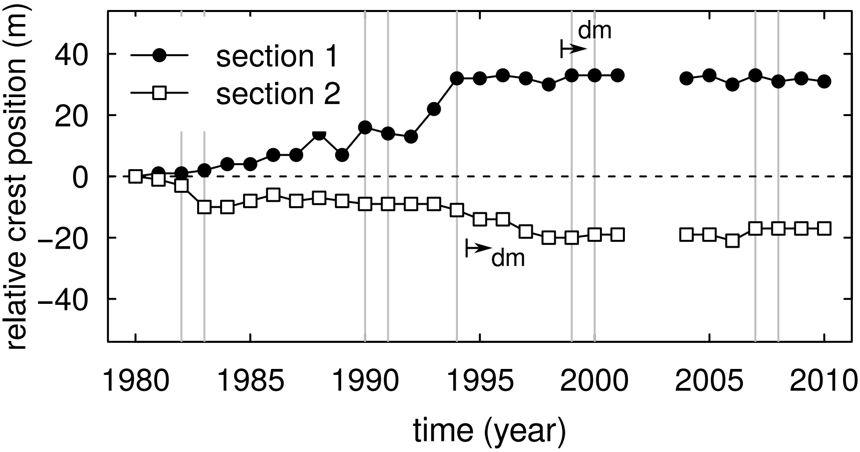

Figure 6.6: Relative position of the dune crest (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section, with positive values indicating a seaward shift in crest position. Vertical lines indicate high-water events (storms). Introduction of dynamic management is indicated by arrows (dm).

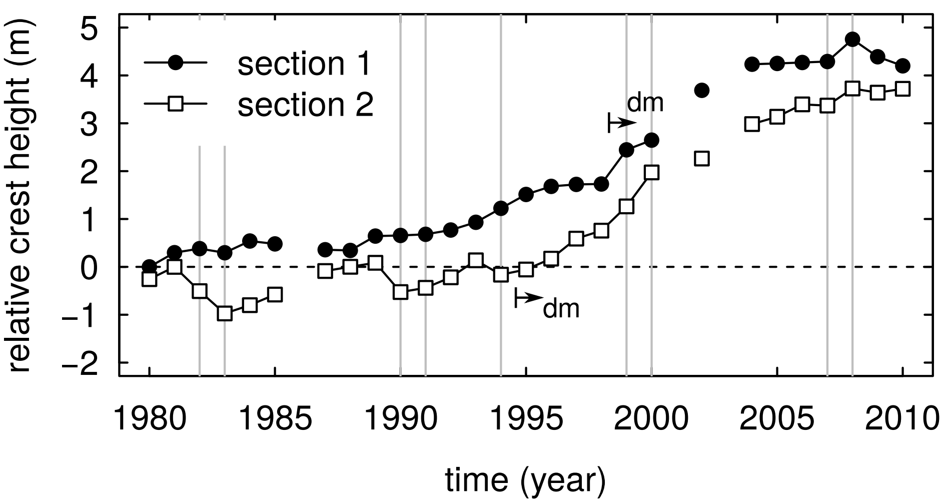

Figure 6.7: Relative height of the crest (1980 = 0) in sections 1 and 2 between 1980 and 2010. The y-axis shows average annual values for all transects in a section. Vertical lines indicate high-water events (storms). Introduction of dynamic management is indicated by arrows (dm).

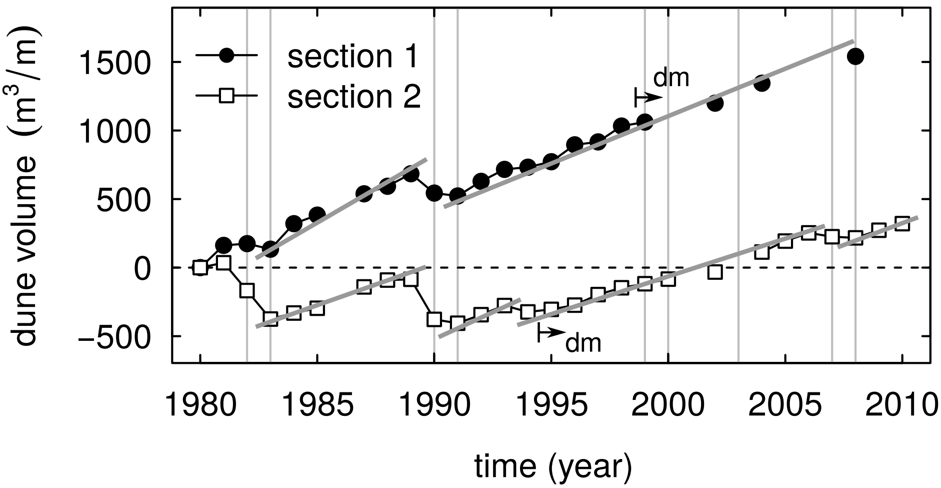

Figure 6.8: Foredune volume in sections 1 and 2 between 1980 and 2010. Two and four linear trend lines are shown for section 1 and section 2, respectively. Vertical lines indicate high-water events (storms). Introduction of dynamic management is indicated by arrows (dm).

in the study area (transects 19.6 to 21.6) of 24.8 m^3 per year between 1983 and 1989, and 19.2 m^3 per year between 1991 and 2008. Even including the years of decrease, the total volume of the foredune rose from 264.1 m^3 in 1980 to 597.5 m^3 in 2008, an average growth of 11.9 m^3 per year. Between 1997 and 2006 the trend lines for the two sections were almost parallel (slope of 11.1 m^3/year for Section 1 versus 10.3 m^3/year for Section 2).

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 6.3).

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.

The 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.

Management type	Section 1 Eng.	Section 1 Dyn.	Section 1 p	Section 2 Eng.	Section 2 Dyn.	Section 2 p
Dune foot position change (m/year)	4.4	2.5	0.01	2.4	1.9	0.43
Crest position change (m/year)	0.9	-0.3	0.24	0.2	-1.0	0.05
Crest height change (m/year)	0.2	0.2	0.30	0.2	0.2	0.75
Volume change per transect (m^3/year)	3,302	2,453	0.09	1,695	2,052	0.32

Table 6.3: Average changes per section in dune foot position, crest position, crest height, and volume with results of independent-samples t-test (p). Period of traditional management using a soft engineering approach (Eng.) is 1980-1998 for Section 1, and 1980-1994 for Section 2. Period of dynamic coastal management (Dyn.) is 1999-2010 for Section 1, and 1995-2010 for Section 2. For calculating p in Section 1, six years in the period 1990-1998 (engineering) versus six years in the period 1999-2010 (dynamic) were compared 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.

6.3.2 Characteristic Profiles

Two characteristic transects, transect 19.8 and transect 21.4 are described in more detail here.

Transect 19.8

The profile in Figure 6.9 is characteristic of transect 19.6 to 20.6. After 1980, the foredune developed rapidly in height and in the 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 6.10).

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

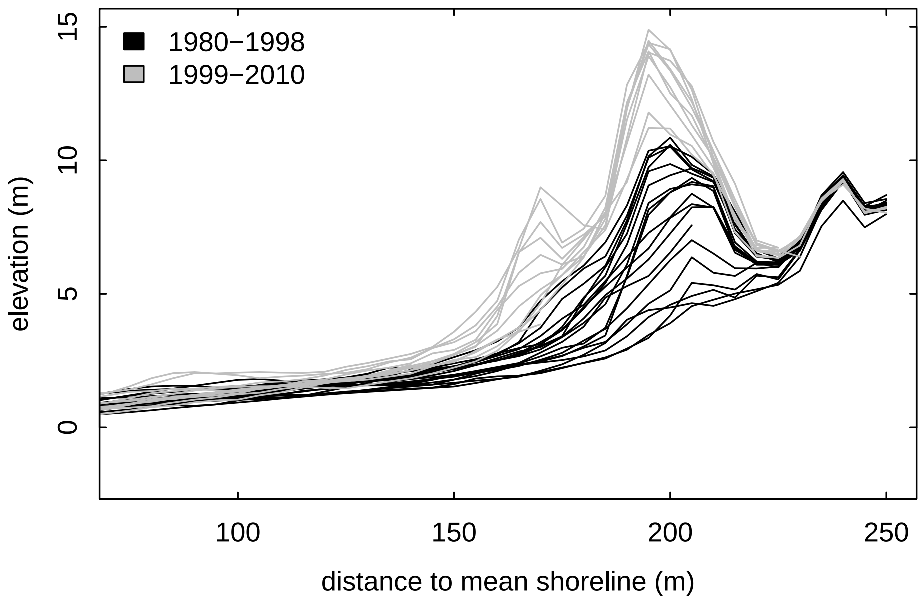

Figure 6.9: Cross-shore profile of the foredune at transect 19.8 for the period of traditional soft engineering management (black) and dynamic management (grey). Sea is to the left.

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.

6.3.3 Ecological Effects of Dynamic Coastal Management

Table 6.4 shows the plant species present in the two sections. Section 2 has fewer species than Section 1, but species richness increased over the years in both sections (after a dip in 1999).

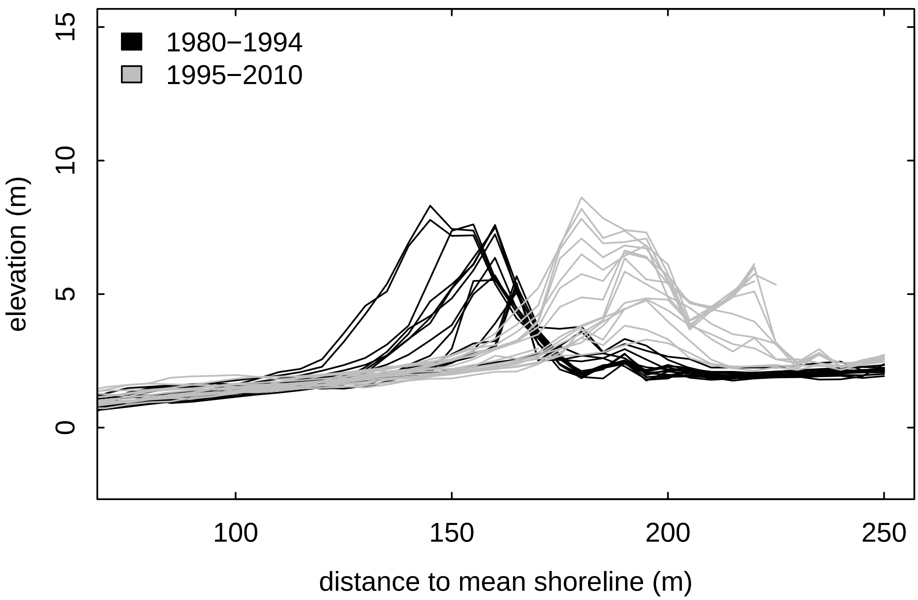

Figure 6.10: Cross-shore profile of the foredune at transect 21.4 for the period of traditional soft engineering management (black) and dynamic management (grey). Sea is to the left.

The characteristic (vascular) plant species are clearly increasing (Table 6.4). Three typical 'white dune' 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. *A. arenaria*, which is characteristic of the foredune in-between these zones, showed no change. It was present on every plot during the whole period (Table 4).

Section 1 (transects 19.6 to 20.6), 1995-2002

The seaward part of this section 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

	Section 1 ($n = 10$)			Section 2 ($n = 10$)		
Characteristic species	1995	1999	2002	1995	1999	2002
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

Table 6.4: Presence of characteristic plant species in Section 1 and Section 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 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.

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 this section 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.

6.4 Discussion

The traditional, soft engineering approach to management aimed at catching 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 6.5). 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 6.6). In Section 2 we see a small landward shift. Looking at the individual profiles (Figure 6.10) 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 6.7). Arens (2007), too, 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 6.9). The differences in dune development between Section 1 and Section 2 cannot be explained by management type.

The changes in foredune volume (Figure 6.8, Table 6.3) 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 above does 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 *et al.* (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 6.5). 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 6.6).

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 *et al.* (2007) of other locations along the Dutch coast where a dynamic management regime was introduced.

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 6.11. 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). Gas extraction began in 1985, with the first soil subsidence recorded in 1986.

Volume increase (Figure 6.11) is continual but interrupted. The largest interruptions (in 1981, 1990, and to a lesser extent, in 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 for example in 2006 that a foredune with a cliff, created by storm surge, was soon restored by aeolian sediment supply. Arens (2007) found that incipient dunes 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 *et al.* (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

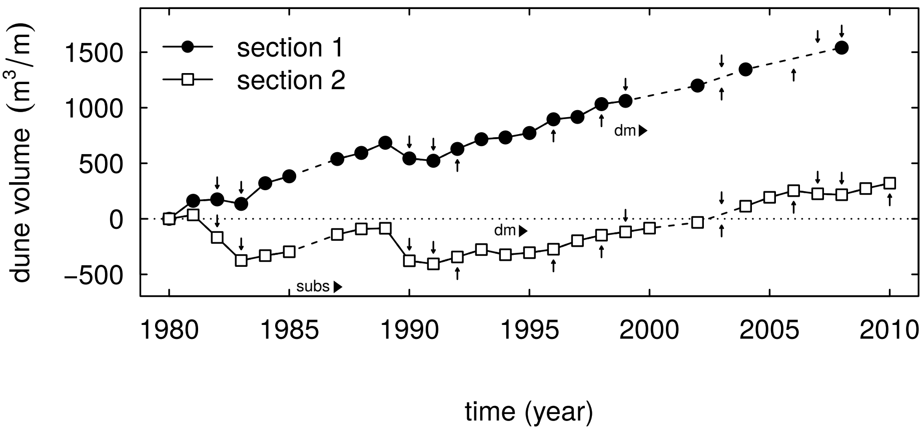

Figure 6.11: Foredune volumes of sections 1 and 2 between 1980 and 2010, with markers for high-water events (downward arrows) and beach nourishments within the study area (upward arrows) on the coast of Ameland. The introduction of dynamic coastal management (dm) and the onset of soil subsidence (subs) are indicated.

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 *et al.*, 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 shoreface, 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 *et al.*, 2011).

6.4.1 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 a-typical 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.

Determining the crest position showed inaccuracies, 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 in case both the 'old' and 'new' crest 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 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 unsure 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.

6.5 Conclusions

The goal of dynamic coastal management can be formulated as '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.

- Introduction of dynamic coastal management did not negatively affect volume growth of the foredune in the investigated sections of the Dutch coast of Ameland.
- Dynamic coastal management resulted in 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.

- 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.
- The relatively small impact of the 2006 and 2007 storms on dune volume suggests a better protection of the dune front by natural vegetation. However, without knowing the exact force of the different storms on the dunes, 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.

Finally, we would like to stress the importance of the Dutch 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.

7

Synthesis

The chapters in this thesis describe the dynamics of foredunes along the Dutch coast, analyse the possible effects of climate change on dune evolution and identify the implications of climate change for coastal management in The Netherlands. This chapter reports the findings of the research questions defined in Chapter 1 and discusses the implications and limitations of these answers and their contribution to science.

7.1 Which factors control year-to-year variations in dune growth on the Dutch coast?

Conclusions The prediction of dune evolution requires accurate estimates of yearly sand input by aeolian transport and sand loss by marine erosion. Both processes are influenced by many small-scale processes that are impossible to measure or simulate with sufficient detail over mesoscale time spans. Larger-scale relationships between dune growth and climatic and topographic parameters were thus used to explain the spatiotemporal variations in dune growth.

Sand input to dunes in the absence of storms was 10-20 m^3/m. Yearly dune growth was more variable along the shore when storms were present (Figure 7.1, upper panel). Part of these alongshore variations were due to differences in beach width. Both alongshore and temporal variations were best explained by variations in storm impacts, so the the year-to-year evolution of dunes, despite being accretionary landforms, may be due more to temporal variations in erosion than to variations in accretion. Long-term dune growth increased with beach width but evened out towards wider beaches, with a maximum rate of 10-20 m^3/m (Figure 7.1, lower panel).

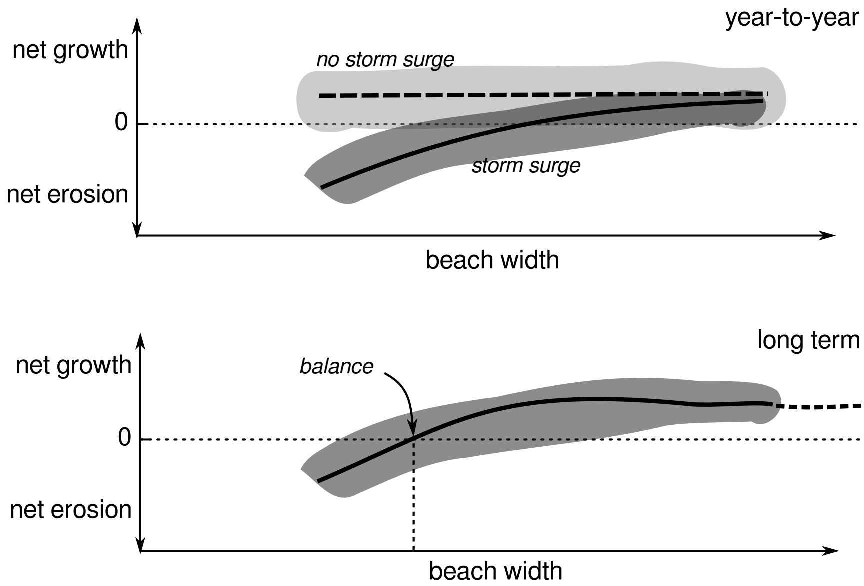

Figure 7.1: Diagram of main findings for this research question. Upper: relationship between beach width and dune growth/erosion in years with and without storm surges. The difference between both conditions decreased towars the wider beaches. Lower: long-term dune growth as a function of beach width. A critical beach width, where growth and erosion were in balance, separated eroding and accreting dunes. Growth did not increase beyond a given maximum, even on very wide beaches.

Discussion Wider beaches offer a larger supply of sand and longer fetch lengths for maximising sand fluxes (Davidson-Arnott and Law, 1990; Bauer and Davidson-Arnott, 2002), so beach beach width would be expected to have a positive effect on sand. The results, however, indicated that dune growth without major storms was relatively constant across the range of beach widths, which implied that sand input was not strongly correlated with beach width.

One possible explanation for this discrepancy was that the available fetch length is sufficient for maximum aeolian transport on all beaches. This minimum distance required to reach maximum transport is generally 10 - 50 m (Svasek and Terwindt, 1974; Davidson-Arnott and Law, 1990). Arens (1996b) and Van der Wal (1998a), however, measured increasing sand fluxes over distances up to several hundred meters on very wide beaches. Such distances are likely due to strong supply limitation by moisture (Davidson-Arnott, 2005; Davidson-Arnott *et al.*, 2008) or to lag deposits (Van der Wal, 1998a). Typical beach widths in the Netherlands are above 80 m, and the dominant wind direction is not perpendicular to the coast, so available fetch lengths generally exceed the reported critical lengths and sand input is independent of beach width.

The rates of dune growth over several years were highest on beaches near or exceeding 200 m in width (Figure 2.11). Critical beach width can be defined as the width corresponding to an average dune growth of 0 m^3/m/y, indicating a balance between erosion and accretion. This value is site specific and ranges from 80 m for Holland, 100 m for Texel and Vlieland to 150 m for Ameland, reflecting differences in coastline orientation relative to the dominant dune-building and storm winds (Klijn, 1981). Van der Burgt (1934) and Klijn (1981) defined a 'critical distance' between the high water line and the dune foot. They find a distance of 50-80 m for the Holland Coast, coinciding with our findings. If these minima are violated, dune erosion can restore the critical distances, forming a negative feedback between beach width and dune erosion. This form of self-regulation allows the natural beaches to maintain the critical width, forcing dune retreat if necessary.

Modelling implications Modelling requires capturing the balance between erosion and accretion. The maximum surge level can be used to determine the likelihood of marine erosion and combined with beach width, to derive a first-order approximation of the amount of erosion. Such an approximation greatly simplifies prediction of dune erosion for long-term model simulations, although it lacks the detail of more sophisticated erosion models (Van Rijn, 2009; Van Thiel de Vries, 2009; Vellinga, 1982).

The field data discussed above indicated that aeolian input could be approximated by assuming a fixed rate of aeolian sand input for a given coastline orientation and wind characteristics, representing the cumulative effect of many smaller scale transport events. Any dune erosion during the period could be subtracted from the sand input to yield the net change in volume (cf. Figure 2.12). The assumption of a fixed rate is supported by observations of strongly linear dune growth along sections of the Holland coast in periods without major storms (De Vries *et al.*, 2012a). Spatio-temporal variations in transport rate due to wind unsteadiness, fluctuating transport capacity, and variable surface conditions (Bauer and Davidson-Arnott, 2002; Baas and Sherman, 2005, 2006; Davidson-Arnott and Bauer, 2009) tend to average out over longer time spans.

Fixed rates can only be used when seasonal variations in sand delivery are unimportant. Such seasonal variations may be important in the establishment of vegetation and incipient dune formation. The establishment of dune vegetation depends on the presence of 'windows of opportunity', in which seed dispersal is followed by a disturbance-free period to allow germination and establishment (Balke *et al.*, 2014). The timing of transport events relative to time-dependent vegetation density also strongly influences the patterns of deposition (Hesp, 2002). If the growing season coincides with high rates of aeolian transport, incipient dunes form rapidly. In contrast, incipient dune building is less efficient if high rates coincide with low cover conditions, and sand will be transported farther landwards. Neglecting seasonal variations might therefore inadequately represent windows of opportunity.

7.2 How do biogeomorphic interactions control foredune shape?

Conclusions The interactions between vegetation and sedimentation on coastal foredunes were investigated by combining mesoscale topographical data and information on vegetation cover. Sand deposition on foredunes had a characteristic pattern, beginning with a sharp increase beyond the seaward limit of vegetation, with a maximum approximately 15 m farther landwards and then gradually decreasing (Figure 7.2, upper panel).

The amount of sand trapped at a given point relative to the total amount passing the point, i.e. the trapping efficiency, was positively correlated with plant cover. Suspended particles can move over dense vegetation and high-speed winds can move sand within the canopy, so even a complete vegetation cover cannot reach a trapping efficiency of 100%. The correlation between plant cover and trapping efficiency can be used to determine sedimentation patterns and thus foredune morphological development.

Vegetation growth had two dominant modes: (1) establishment of new vegetation near the dune foot; and (2) lateral expansion of existing patches over the entire foredune slope (Figure 7.2, lower panel). Bare patches could persist for several years. A direct link between sedimentation rate and the rate of plant growth could not be demonstrated. The dune vegetation can apparently thrive under rates of burial experienced on the Dutch sites of 0.0-1.0 m/y.

Discussion The results described the reinforcing feedbacks between plant growth and sand trapping. These processes are understood, but little quantitative information is available on how these physical-biological feedbacks control dune morphology.

The measured sedimentation patterns generally agreed with those of previous studies on shorter timescales (e.g. Sarre, 1988; Hesp, 1989; Arens, 1996a). Our data analysis confirmed the strong effect that vegetation pattern can have on sedimentation pattern and indicated an empirical relationship between vegetation cover and trapping efficiency on a foredune. This relationship was derived from observations with time steps of several years, representing the net effects of multiple transport events under different conditions.

Event-scale measurements have shown that transport pathways depend on wind conditions (Walker *et al.*, 2009; Hesp *et al.*, 2013). Sand transport with moderate winds (e.g. 8 - 12 m/s) is dominated by saltation, and plant canopies are relatively static. Sand transport via suspension during storm winds (> 12 m/s), however, becomes more important and canopies streamlined. Trapping efficiencies consequently vary with wind velocity (Zarnetske *et al.*, 2012a). To better simulate sedimentation patterns, separate curves could be derived to describe the trapping efficiency under normal and storm conditions, which would also provide

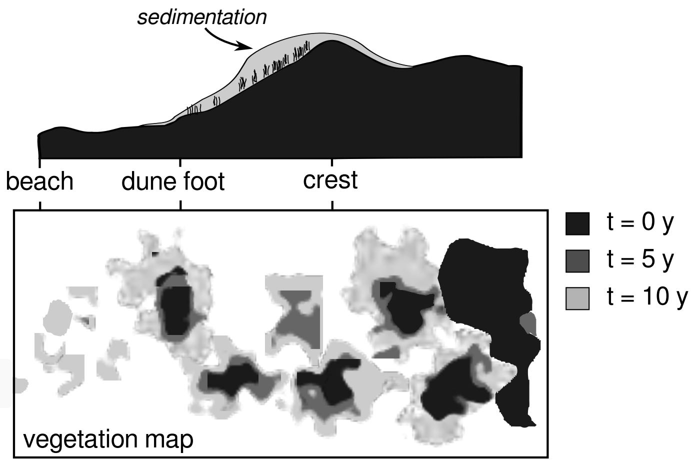

Figure 7.2: Diagram of main findings relating to this research question. Upper: general profile of sand deposition on an accreting foredune slope. After a rapid increase coincident with the dune foot, sedimentation decreases gradually towards the crest. Lower: development of vegetation cover through time, showing (a) the lateral expansion of existing patches ; and (b) establishment of small new patches near the foot.

options for investigating the effect of different wind characteristics on dune development in a further iteration of the model.

Reported fractions of vegetation cover that prevent aeolian transport (C_{crit}) range from 14 to 50 % (Lancaster and Baas, 1998; Wasson and Nanninga, 1986; Buckley, 1987; Wiggs *et al.*, 1995; Levin *et al.*, 2008, e.g.). The results in this chapter, however, indicated that sand was transported considerable distances on densely vegetated slopes and that sand could move even across fully covered positions (Fig. 3.9). A correct representation of this process is essential for predicting foredune morphology. Transport with dense canopies and the absence of a threshold for aeolian transport can be explained by two different phenomena:

- Very high wind speeds (> 11 m/s) and topographic acceleration can lead to transport *within* vegetation canopies (Hesp *et al.*, 2013). Common values for C_{crit} are based on moderate wind speeds and relatively flat surfaces and may not be valid for such extreme conditions, but may be typical for coastal foredunes.

- Sand is readily eroded from bare beaches, partly transported in suspension above the canopy, and is distributed over a large distance (~50 m) (Petersen *et al.*, 2011). No new sediment is picked up on the foredune slope, but beach-derived grains can still be transported.

The observation that transport continued considerable distances over dense canopies contrasted with the original model formulation of the DUBEVEG model used to simulate foredune dynamics (Baas, 2002; De Groot *et al.*, 2012). The original model defined a critical vegetation cover that both eliminatesderosion ($p_{erosion}$ = 0) and trapped all sediment ($p_{deposition}$ = 1). The observed sedimentation patterns indicated that defining such a critical vegetation cover was not realistic for foredunes. To simulate more appropriate aeolian transport patterns on a foredune, the probabilities of erosion and deposition were lowered, which considerably improved model performance.

Vegetation currently grows vigorously in response to typical burial rates of 0-1 m/y. We found no evidence for reduced growth at either extreme of the burial rate. If plant growth has indeed followed an optimum curve (Maun, 2009), the burial tolerance has not been exceeded in the study area, and dune growth is consequently not at a maximum. Changes in the rate of sand supply, the rate of vegetation growth rate, or species composition in response to climate change, however, could alter the vegetation vigour, resulting in a change in the rate of dune building and hence flood protection (Seabloom *et al.*, 2013; Zarnetske *et al.*, 2012a).

The plant-accretion feedback on sand dunes represents a positive feedback system, so even a gradual change, might induce a sudden catastrophic change (Holling, 1973; Scheffer *et al.*, 2001; Rietkerk *et al.*, 2004). Such shifts have been reported for various ecosystems, such as estuarine marshes that rapidly decrease or increase in size in response to changes in sea level (Day Jr. *et al.*, 2000; Kearney *et al.*, 2002).

Catastrophic changes are related to two alternative stable states. A fully developed estuarine marsh dominated by the dense and stiff grass *Spartina spp.* can have in one of two alternative stable states: either low-elevation bare flats or high-elevation vegetated marshes (Fagherazzi *et al.*, 2007; Wang and Temmerman, 2013). A bare flat may become vegetated by the natural redistribution of sediments when it reaches a threshold elevation (Balke *et al.*, 2014), after which rapid accretion follows. This accretion induces a rapid shift from bare flat to established marsh. Accretion continues to an upper limit, where the marsh is no longer flooded and therefore does not receive any new sediment.

The beach-dune environment has similar mechanisms. The distribution of elevations is similarly bi-modal, corresponding to either bare (< 3 m) or vegetated (> 3 m) areas (cf. Fig. 3.6). The threshold elevation must be exceeded for vegetation to successfully establish. A lower limit of 2.5-3.0 m above sea level has been reported for marram grass (Svasek and Terwindt, 1974; Klijn, 1981). The height of incipient dunes can change by 0.3 - 0.5 m/year (Goldsmith, 1978; Hesp, 1989) after establishment, much more rapidly than the accretion of the surrounding bare beach. Elevation has a clear upper limit in a tidal marsh, but not for a foredune, so area are vegetated across a wide range of elevations.

Biogeomorphic dune building has similarities to the biogeomorphic processes in marshes, so the possibility for catastrophic shifts in coastal dunes is worth investigating. An equivalent shift in the beach-foredune systems would be the transition from a vegetated foredune to a bare sandsheet or a parabolic dune or vice versa. These transitions can be described in a diagram of stable states (Figure 7.3). Let the starting point be t_1. An increase in stress due to climatic change gradually reduces the vegetation cover by t_2, but dunes are still vegetated. If the stress levels increase a bit further, the vegetation cover crosses a threshold (*DP2*). At this point, there is a critical transition to a fully mobile dune without vegetation (t_3). Reducing the stress again does not lead to higher vegetation cover, although the stress has returned to its initial value (t_4). A given stress level thus produces two alternative stable states. Successful remobilisation requires the system moving from t_1 to t_4, which requires a large reduction in vegetation cover, e.g. by clear-cutting (Arens *et al.*, 2004).

Transitions from mobile (bare) to stable (vegetated) have occurred. Large parts of the Dutch coastal dune fields consist of parabolic dunes that developed between 800 and 1850 AD (Jelgersma and Van Regteren Altena, 1969; Klijn, 1990; Arens *et al.*, 2004). The dunes in The Netherlands have since largely undergone a transition to a stabilised state as a consequence of management activities and/or a more favourable climate for plant growth (Arens *et al.*, 2013b).

The reverse transition to enhance ecological values and safety has recently attracted interest. A transition from stable to mobile can be caused by either (1) environmental change, e.g. a gradual change in the drift potential, passing the *DP2* threshold to t_3 (Fig. 7.3); or (2) large disturbances (from t_1 to t_4), such as fires, weather extremes, pests (Scheffer *et al.*, 2001), or the intentional removal of vegetation. The surface dynamics of a bare dune following the transition may be too hostile for the vegetation to re-establish and re-stabilise the surface, allowing dunes to remain mobile.

An environmental change may cause a transition if minimum elevation required for vegetation establishment is no longer reached, e.g. in response to a rise in sea level (Kirwan *et al.*, 2010), or a rise i nsea level in constrained environments (Feagin *et al.*, 2005; Durán and Moore, 2014). Without vegetation, accretion cannot keep pace with a rise in sea level and dune building is no longer possible, disrupting the successional process (Feagin *et al.*, 2005) and trapping the system 'in a perpetual state of low elevation and maximum vulnerability to storms' (Durán and Moore, 2014). Frequent erosion may also favour pioneer plant species adapted to recently over-washed zones. These species subsequently render sand unavailable and thus prevent recovery via sand trapping and vertical growth by dune-building species. The system consequently remains topographically low and vulnerable to overwash (Wolner

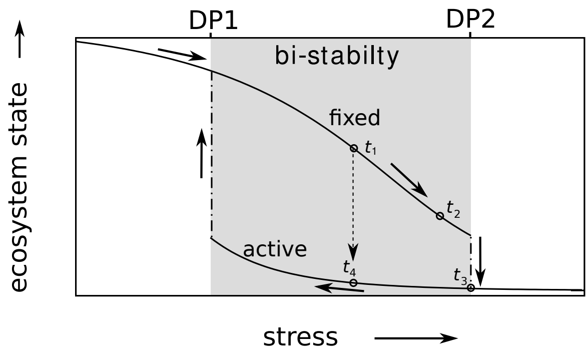

Figure 7.3: Bi-stability and hysteresis in vegetated dunes. The lines represent the equilibrium vegetation cover for a given drift potential. Adapted from Yizhaq *et al.* (2009)

et al., 2013).

Dune fields have been remobilised by intentional large disturbances. The experimental removal of vegetation has successfully initiated sand sheets or parabolic dunes next to a vegetated foredune, which have persisted for more than a decade (Arens *et al.*, 2013a). Climatic projections for 1990-2100 do not indicate a marked change in wind characteristics or annual precipitation for inducing critical transitions. The growth rate of vegetation, however, may slightly decrease as a consequence of drought (Chapter 5). A reduction in the growth rate would reduce the rate at which dunes re-stabilise after disturbances. If the vegetation growth rate is too low to pass the density threshold and reduce surface activity to levels within its tolerance, dunes remain bare and landward transport continues, promoting longer-term mobilisation after a major disturbance.

7.3 What are the impacts of climate change on the meso-scale evolution of coastal dunes?

Conclusions The Wageningen dune-beach-vegetation model DUBEVEG was calibrated and validated with measurements of dune development on the Dutch coast. The good agreement between observations and predictions indicated that the model successfully incorporated the suite of bio-geomorphic and marine processes involved in dune building. Scenarios of climate change were run to establish the impacts of various rates of sea-level rise and changes in the growth rate of the vegetation.

Dune evolution was strongly influenced by a sea-level rise. The higher level increased the frequency and magnitude of dune erosion. The foredune migrated landwards in response (Figure 7.4, upper panel). The rate of rise determined whether the dunes were able to preserve their height or sand volume while retreating. Dune volume was maintained for rates up to 5 mm/y, and crest height was able to keep pace with the sea-level rise up to 10 mm/y.

Changes in growth rates of vegetation are most manifest when dune evolution is analysed as a response to large disturbances. If vegetation is removed midway through a simulation, the growth rate determines whether the dune is able to re-vegetate. If the growth rate is below a threshold, dunes are no longer able to recover and remain mobile, with high rates of landward transport causing landward migration and sand loss to the landward side of the model domain. This result indicated an important sensitivity of the foredune system to climate change.

Assuming upper projections of sea-level rise projections for The Netherlands of 0.4-1.05 m between 1990 and 2100 (Katsman *et al.*, 2011), the model can provide an estimate of dune development for 2002-2100 for the Ameland site. Assuming an abundant sand supply and no changes to the beach sediment budget, the model predicted a landward migration of 0-50 m, roughly preservating dune volume and increasing crest height (Figure 7.4, lower panel). If the retreat is feasible with urban development, this prediction thus does not involve a rapid decline in the degree of flood protection.

Discussion Although depending on a combination of highly variable processes, the modelling indicated that the long-term evolution of a dune had an element of predictability. The sequence of storms and consequently the trajectory of dune evolution cannot be predicted, but expected trends in dune size and morphology can be quantified. Two important aspects were identified: (1) development towards an equilibrium; and (2) landward migration as a function of landward fluxes and seaward losses.

The model predicted that the dune foot would tend to align with the position where accretion and erosion were roughly balanced. A position seawards of this equilibrium increased the likelihood of erosion, whereas a landward position promoted dune building. A system, in this case a thriving foredune (cf. morpho-ecological stage 1 of Hesp (1982, 2002)) is able to return to its characteristic landform (Brunsden and Thornes, 1979) as long as he interval between perturbations exceeds the required recovery time. Storms reset the foredune to a more erosional stage, with a bare, steeper seaward slope and no incipient dunes. If perturbation intervals are smaller than the recovery time over a longer period, the dune becomes increasingly erosional and may finally be removed completely (Hesp, 2002). The model, however, indicated that extreme rates of sea-level rise and reduction of vegetation growth were required to inhibit dune formation under the given conditions of sand supply and vegetation.

An interesting question is whether dune evolution is governed by trends or (extreme)

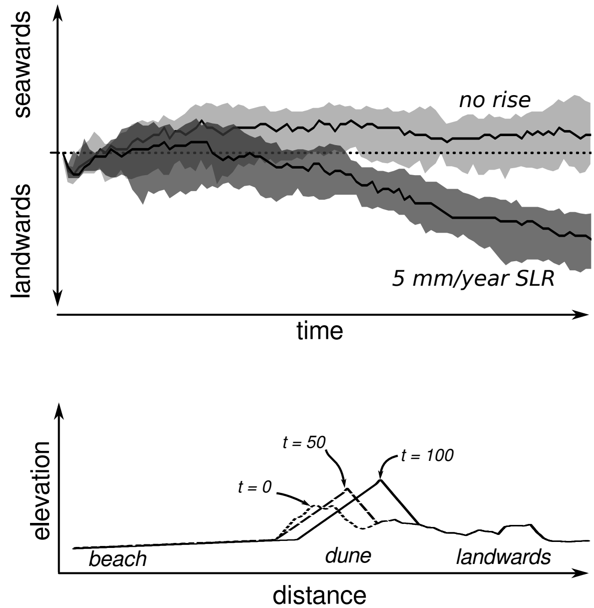

Figure 7.4: Diagram of main findings for this research question. Upper: modelled effect of 5 mm/y of sea-level rise on the dune-foot position, compared to a static sea level. Without SLR, the dune-foot oscillates around an equilibrium position approximately 100 m from the shoreline. Including SLR leads to a gradual landward retreat at a rate roughly equal to the shoreline regression. Lower: development of foredune profile through time, showing (a) landward retreat; and (b) vertical development from enhanced landward transport and crestal deposition.

events. The development of the dune-foot position for a given scenario of sea-level rise suggested that the foot gradually moves landwards in response to the rising sea level, aligning itself with an accretion/erosion equilibrium (Figure 4.8B, mean of all runs). The long-term trend in dune development would thus be controlled by changes in sea level. On a shorter term, the sequence of individual storm events and periods of recovery would determine the state of the foredune. These storm-recovery fluctuations are superimposed on the long-term trend within a relatively limited range. Extreme events, however, have a long-term impact on the trajectory, removing the foot far from its apparent equilibrium and dominating the gradual landward trend over many decades (Figure 4.8B, extreme runs). The sea-level trend, though, controls the long-term balance between erosion and accretion and the foot consequently adjusts towards equilibrium.

The model reproduced the enhanced landward aeolian fluxes in response to wave attack, similar to the the conceptual model of the impact of sea-level rise on sandy shores (Davidson-Arnott, 2005). For simplicity, that conceptual model assumed that all sand eroded from the seaward slope was transferred to the lee slope by onshore winds. The results presented here indicated that the volumes of sand eroded from the seaward slope and the volume that was transferred landwards were not necessarily equal and that the balance between them strongly determined the manner of dune retreat.

A dune will either be able to maintain its size or will gradually decrease, depending on the rate of landward transport relative to the rate of sand loss on the seaward side. Foredunes in lower scenarios of sea-levle rise migrated landwards while maintaining volume and gaining height (Figure 4.6), for example when sand fluxes towards the crest and landward side exceeded the loss of sand on the seaward side. Landward fluxes cannot match the losses on the seaward side as rates of sea-level rise increased, and foredunes gradually decreased in height and size.

The model was used to predict dune development under a range of climatic scenarios. Each scenarios was repeated five times to determine the uncertainty associated with the timing and magnitude of storms. This uncertainty, however, represents only one source. Geomorphological prediction has several other sources of uncertainty, including (Haff, 1996): (1) model imperfection, (2) omission of important processes, (3) lack of knowledge of initial conditions, (4) sensitivity to initial conditions, (5) unresolved heterogeneity, and (6) occurrence of unaccounted external forcing.

Uncertainties associated with model imperfection and initial conditions were minimised by calibrating the results to field data and by starting the model from known initial conditions. Model formulations are easily refined, but the introduction of more detailed formulations or additional parameters is not always desirable (Brasington and Richards, 2007; Murray, 2007). Simple parameterisations based on large-scale field observations are more reliable than small-scale, physically based process descriptions for modelling large-scale behaviour (Murray, 2007). Detailed descriptions of moisture, lag-deposits, and airflow dynamics were replaced in the DUBEVEG model by a simple probabilistic approach that was calibrated against observations. For example, each sand slab had a 50% probability of being picked up by the wind. This replacement adequately reproduced the desired behaviour.

The sensitivity of the model to small perturbations in initial conditions may be large on a short timescale (weeks), but the evolution on a longer term (decades) can be expected to conform more or less to the average trajectory (Figure 4.8). The purpose of these simulations was not to generate an accurate representation of future morphology, but to illustrate possible evolutionary trajectories, so this source of uncertainty was less relevant.

Unaccounted external forcing is an important source of uncertainty. Scenarios of climate-change were simplified to a combination of sea-level rise and gradual change in vegetation growth based on an assessment of the most important factors. The uncertainty associated with storms was statistically anticipated by running multiple possible storm sequences. However, the uncertainty of the effects of climate change on vegetation cover is more difficult to assess (Haff, 1996). Interactions between species may change in response to climate change, strongly alleviating or aggravating the impact compared to the isolated effect on a single plant type (Zarnetske *et al.*, 2012b; Seabloom *et al.*, 2013). Increasing storm frequency may change species composition (Gornish and Miller, 2010; Wolner *et al.*, 2013). Vegetation cover perhaps changes abruptly in response to prolonged drought or other major stresses, instead of the modelled gradual change. Abrupt changes in cover may greatly exceed the consequences of a gradual change in vegetation cover, as indicated by the perturbation runs (Figure 4.11, 4.12).

Despite the sources of uncertainty, the model effectively integrated the fundamental dune-building processes, including biogeomorphic dune-building and marine erosion. Previous studies of the effect of climate change on coastal dunes have mainly focused on the impacts of sea-level rise on dune erosion (De Winter, 2014; Li *et al.*, 2014) or the rate of landward migration of the shoreline (Ranasinghe *et al.*, 2012). These factors constitute the main impacts on coastal erosion, but the modelling results obtained here demonstrated that including landward transport as a consequence of biogeomorphic interactions was critical for determining the long-term response of foredunes to climate change and consequently of flood risk.

7.4 What are the effects of dynamic coastal management on the evolution of coastal dunes?

Conclusions The model results indicated that climate change would increase dune erosion and the landward migration of dunes. Depending on the scenario, flood risk did not necessarily increase, because dunes were able to maintain their height and volume up to a limit of sea-level rise. Landward retreat, however, is not feasible in many cases and adaptation strategies are necessary. Using sand nourishments to 'grow with the sea level' was an effective adaptive strategy to mitigate the negative impacts of climate change on dunes, allowing dune development despite sea-level rise (Figure 7.5). A natural and ecologically valuable dune zone was feasible if this strategy was combined with dynamic coastal management, with minimal or no dune maintenance. A reduction in vegetation cover promoted landward transport, which positively contributed to the vertical accretion of a larger dune zone.

This strategy of preservation requires the entire coastal zone to accrete vertically to keep pace with sea level on the longer term, demanding increasingly larger volumes of sand and its redistribution over the beach, dune and secondary dunes. This strategy is feasible from a perspective of sand availability, but excluding nourishments and allowing retreat along certain stretches might eventually be more economical.

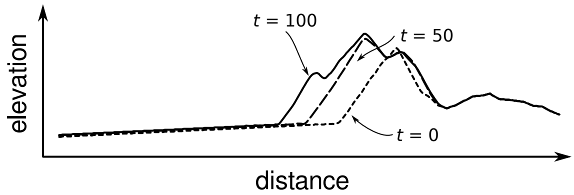

Figure 7.5: Diagram of the main findings for this research question. Development of the nourished foredune profile through time, showing (a) seaward expansion, and (b) formation of new secondary dune ridges seawards of the original crest.

Discussion The analysis of recent coastal data indicated that negative trends in dune development have been halted since the implementation of the dynamic preservation policy. Long-term simulations under the same nourishment policy have indicated that the policy effectively the mitigates negative effects of sea-level rise on dune development (Chapter 4).

A low-maintenance alternative to soft-engineering positively influenced a foredune's natural and ecological quality, without compromising flood protection. Dynamic management is a suitable supplement to nourishments, as long as sufficient sand and beach width is in place to ensure long-term dune growth.

The model simulations indicated that a reduction in vegetation cover by either wave erosion or a climatic reduction in vegetation growth promoted landward aeolian transport (Figures 4.10, 4.9). This increased transport would enhance biodiversity and promote the vertical accretion of a wider dune zone, including the grey dune zone behind the foredune. Allowing natural processes such as wave erosion to reduce cover therefore contributes to the 'grow-with-sea-level' objective for a larger area (Arens *et al.*, 2013a).

The current Dutch policy of nourishment policy requires increasingly large volumes of sand in the long term and consequently frequent disturbances of, for example, the ecosystem and beach recreation. Evaluating the benefits of alternative strategies is therefore worthwhile.

Added sand in the simulated nourishments scenario was distributed evenly across the entire beach profile. Alternative types of nourishment, however, can be designed. De Winter (2014) found that concentrating anourishment on the foredune considerably reductd dune erosion relative to an equal but homogeneous nourishment and consequently concluded that the same safety could be attained with less sediment. Bringing sand to the beach is more costly than bringing it to the shoreface but may be more effective in reducing erosion. Bringing sand to the beach also negatively affects biogeomorphic processes and does not improve the natural appearance.

Another option is to accommodate natural retreat. The model results indicated that natural dunes would retreat at moderate rates of sea-level risebut with the conservation of volume and height. Dunes can thus retreat landwards without reducing flood safety, and locally accommodating this process might be more efficient than continuing the nourishment policy, for example near erosion hotspots (Van Duin *et al.*, 2004). Projects involving landward retreat, however, often suffer from a lack of public acceptance (Klein *et al.*, 1998). The Dutch government has already assigned retreat zones inland of weak spots in the coastline to allow landward solutions in the future (MinV&W, 2000).

Experiments have recently begun with so-called mega-nourishments, such as the Sand Engine near Ter Heijde, The Netherlands (Stive *et al.*, 2013). Instead of applying several traditional nourishments, a single large nourishment is applied locally. This nourishment will gradually feed adjacent beaches, promoting dune development. Mega-nourishments have several benefits to nature and society compared to regular nourishments. They (1) have a longer lifetime, requiring less frequent disturbance, (2) promote a natural progression alongshore, reducing the area of perturbation, (3) increase the space for recreation and nature (Mulder and Tonnon, 2010; Stive *et al.*, 2013; Temmerman *et al.*, 2013).

The large beach volume created with mega nourishments initially prohibits any wave erosion of the foredune. Without such perturbations, the original foredune may stabilise, thereby reducing aeolian transport towards the landward side of the foredune. Wave erosion is occasionally possible with smaller nourishments, enhancing the natural dynamics on the foredune slope and landward side. The natural dynamics of the original foredune might thus benefit more from the regular regime than from the mega-nourishments. Mega-ourishments, though, are potentially able to create new ecological zones, such as incipient dunes, dune slacks (Grootjans *et al.*, 2002), and lagoons (Stive *et al.*, 2013).

Weighing the costs and benefits of different strategies of coastal management is not straightforward. For example, initial construction costs of mega nourishments may exceed those of regular nourishments, but this extra cost is offset by the economic value of the benefits to nature and society. After evaluating the impacts using ecological, societal and economic criteria, including flexibility and robustness, Horstman *et al.* (2009) concluded that large-scale solutions based on soft-engineering and aiming for seaward expansion were ideally suited for long-term coastal management. Such solutions offer adequate of space for foredune development and the possibility to benefit from the self-regenerating capacity of foredunes. The long-term effects on, for example, marine ecology, groundwater and terrestrial ecology, however need to be properly understood before large-scale implementation. Detailed monitoring and research is carried out within the NatureCoast project to improve our understanding of these effects.

7.5 Outlook and recommendations

On the basis of the above limitations and challenges, several recommendations can be made for future research:

- We need to establish which combination of meteorological and geomorphic conditions lead to sand deposition in the dunes. This effort will require simultaneous measurements of meteorological parameters, sand fluxes on the beach and in the dunes, and changes in elevation. Such information is required to improve the predictive modelling of sand supply to the dunes.

- Empirical relationships between vegetation cover and sand erosion/deposition need to be determined for different wind conditions. As shown by Petersen *et al.* (2011) and Hesp *et al.* (2013), strong winds may deform the canopy and generate transport over long distances. An inability to account for this effect may lead to the underestimation of landwards transport.

- Vegetation patterns strongly determine patterns of sand deposition and erosion and consequently incipient dune formation and foredune morphology. Our understanding of the conditions that determine the dispersal and establishment of vegetation, however, is limited. We therefore need to monitor the short-term effects of a number of plant-growth factors, such as surface activity, moisture content, and salinity, on the dispersion and development of vegetation on the beaches and foredunes.

- Transitions could occur between vegetated and bare dune states, but considerable stress combined with a large disturbance was required. Further research on the stability of these stated and the conditions or events that might induce a shift is thus needed for a better understanding of these shifts.

- The effects of mega-nourishments on dune formation need to be established. Aside from the evident changes to beach morphology, many other factors that influence dune formation may be altered by the intervention, e.g. groundwater dynamics, geochemistry and terrestrial ecology. These factors will need to be incorporated for a complete view.

- Variable boundary conditions need to be included in the model to allow simulations of dune development as a function of varying sand budgets and management regimes. The boundary conditions can be derived from the output of larger-scale morphodynamic models, such as GEOMBEST (Stolper *et al.*, 2005; Zhang *et al.*, 2015).

Bibliography

Aagaard T, Davidson-Arnott R, Greenwood B and Nielsen J, 2004a. Sediment supply from shoreface to dunes: Linking sediment transport measurements and long-term morphological evolution. *Geomorphology* 60: 205–224.

Aagaard T, Nielsen J, Jensen S and Friderichsen J, 2004b. Longshore sediment transport and coastal erosion at Skallingen, Denmark. *Geografisk Tidsskrift* 104: 5–14.

Aagaard T, Orford J and Murray AS, 2007. Environmental controls on coastal dune formation; Skallingen Spit, Denmark. *Geomorphology* 83: 29–47.

Aagaard T and Sørensen P, 2012. Coastal profile response to sea level rise: A process-based approach. *Earth Surface Processes and Landforms* 37: 354–362.

Adriani MJ and Terwindt JHJ, 1974. Sand stabilization and dune building. Technical Report 68, Rijkswaterstaat, The Hague.

AKK, 2011. De toekomst van de 'stille' kustlandschappen: toekomstperspectieven voor de kustversterking, ecologie, landschap, drinkwaterwinning en betreedbaarheid van de Hollandse kustboog voor de periode 2050-2010. Technical report, Coastal Quality Studio (Atelier Kustkwaliteit).

Anthony E, 2013. Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. *Geomorphology* 199: 8–21.

Anthony EJ, Vanhee S and Ruz MH, 2006. Short-term beach-dune sand budgets on the north sea coast of France: Sand supply from shoreface to dunes, and the role of wind and fetch. *Geomorphology* 81: 316–329. doi:http://dx.doi.org/10.1016/j.geomorph.2006.04.022.

Arens S, Baas A, Van Boxel J and Kalkman C, 2001a. Influence of reed stem density on foredune development. *Earth Surface Processes and Landforms* 26: 1161–1176.

Arens S, Jungerius P and Van der Meulen F, 2001b. Coastal Dunes. In: Warren A and French J (eds.) *Habitat Conservation: Managing the Physical Environment*, pp. 29–27. John Wiley & Sons Ltd, Chichester, UK.

Arens S, Slings Q and de Vries C, 2004. Mobility of a remobilised parabolic dune in Kennemerland, The Netherlands. *Geomorphology* 59: 175–188.

Arens S, Van Boxel J and Abuodha J, 2002. Changes in grain size of sand in transport over a foredune. *Earth Surface Processes and Landforms* 27: 1163–1175.

Arens SM, 1996a. Patterns of sand transport on vegetated foredunes. *Geomorphology* 17: 339–350.

Arens SM, 1996b. Rates of aeolian transport on a beach in a temperate humid climate. *Geomorphology* 17: 3–18.

Arens SM, 2007. Duurzame verstuiving in de Holland duinen: kans, droom of nachtmerrie. Eindrapport Fase 1 (In Dutch). Technical Report RAP2007.02, Arens-BSDO.

Arens SM, 2009. Preadvies Duin- en Kustlandschap. Technical Report Rapport DK nr. 2009/dk113-O, Directie Kennis, Ministerie van Landbouw, Natuur en Voedselkwaliteit, Ede, The Netherlands.

Arens SM, Löffler MAM and Nuijen EM, 2007. Evaluatie dynamisch kustbeheer Friese Waddeneilanden. Technical report, Rijkswaterstaat Noord-Nederland.

Arens SM, Mulder JPM, Slings QL, Geelen LHWT and Damsma P, 2013a. Dynamic dune management, integrating objectives of nature development and coastal safety: Examples from the Netherlands. *Geomorphology* 199: 205–213.

Arens SM, Slings QL, Geelen LHWT and Van der Hagen HGJM, 2013b. Restoration of Dune Mobility in The Netherlands. In: Martínez ML, Gallego-Fernández JB and Hesp PA (eds.) *Restoration of Coastal Dunes*, Springer Series on Environmental Management, pp. 107–124. Springer, Berlin Heidelberg. ISBN 978-3-642-33444-3. doi: 10.1007/978-3-642-33445-0_7.

Arens SM, Van Kaam-Peters HME and Van Boxel JH, 1995. Air flow over foredunes and implications for sand transport. *Earth Surface Processes and Landforms* 20: 315–332.

Arens SM, Van Puijvelde SP and Brière C, 2010. Effecten van Suppleties op Duinontwikkeling. Rapportage Geomorfologie. Technical report, Rijkswaterstaat-Waterdienst, Den Haag, The Netherlands. 216 p.

Arens SM and Wiersma J, 1994. The Dutch Foredunes: Inventory and Classification. *Journal of Coastal Research* 10: pp.189–202.

Baas A, 2002. Chaos, fractals and self-organization in coastal geomorphology: Simulating dune landscapes in vegetated environments. *Geomorphology* 48: 309–328.

Baas A and Nield J, 2010. Ecogeomorphic state variables and phase-space construction for quantifying the evolution of vegetated aeolian landscapes. *Earth Surface Processes and Landforms* 35: 717–731.

Baas A and Sherman D, 2006. Spatiotemporal variability of aeolian sand transport in a coastal dune environment. *Journal of Coastal Research* 22: 1198–1205.

Baas ACW and Nield JM, 2007. Modelling vegetated dune landscapes. *Geophysical Research Letters* 34. doi:10.1029/2006GL029152.

Baas ACW and Sherman DJ, 2005. Formation and behavior of aeolian streamers. *Journal of Geophysical Research: Earth Surface* 110: 1–15. doi:10.1029/2004JF000270.

Bagnold R, 1941. *The physics of blown sand and desert dunes*. Methuen, London.

Bagnold RA, 1954. *The physics of blown sand and desert dunes*. Methuen and Co., Ltd., London.

Bakker M, Van Heteren S, Vonhögen L, Van Der Spek A and Van Der Valk B, 2012. Recent coastal dune development: Effects of sand nourishments. *Journal of Coastal Research* 28: 587–601.

Bakker WT, 1968. A mathematical theory about sand waves and its application on the Dutch Wadden Isle of Vlieland. *Shore and Beach* 36: 4–14.

Balke T, Herman PMJ and Bouma TJ, 2014. Critical transitions in disturbance-driven ecosystems: indentifying Windows of Opportunity for recovery. *Journal of Ecology* 102: 700–708.

Barbier EB, Hacker SD, Kennedy C, Koch EW, Stier AC and Silliman BR, 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81: 169–193.

Barchyn T and Hugenholtz C, 2012. Aeolian dune field geomorphology modulates the stabilization rate imposed by climate. *Journal of Geophysical Research F: Earth Surface* 117: F02035.

Bartholomeus RP, Witte JPM and Runhaar J, 2012. Drought stress and vegetation characteristics on sites with different slopes and orientations. *Ecohydrology* 5: 808–818.

Bauer BO and Davidson-Arnott RGD, 2002. A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects. *Geomorphology* 49: 89–108.

Bauer BO, Walker IJ, Baas AC, Jackson DW, Neuman CM, Wiggs GF and Hesp PA, 2013. *Critical Reflections on the Coherent Flow Structures Paradigm in Aeolian Geomorphology*, pp. 111–134. John Wiley & Sons, Ltd. ISBN 9781118527221.

Beets D, Van der Spek A and Van der Valk L, 1994. Holocene evolution of the Dutch coast. Technical report, Geological Survey of The Netherlands.

Beets DJ and Van der Spek AJF, 2000. The Holocene evolution of the barrier and the back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply. *Geologie en Mijnbouw / Netherlands Journal of Geosciences* 79: 3–16.

Bijl W, Flather R, De Ronde JG and Schmith T, 1999. Changing storminess? An analysis of long-term sea level data sets. *Climate Research* 11: 161–172.

Bird ECF, 1985. *Coastline Changes*. Wiley and Sons, New York.

Bishop SR, Momiji H, Carretero-GonzÃąlez R and Warren A, 2002. Modelling desert dune fields based on discrete dynamics. *Discrete Dynamics in Nature and Society* 7: 7–17.

Bochev-Van der Burgh LM, Wijnberg KM and Hulscher SJMH, 2009. Dune morphology along a nourished coastline. *Journal of Coastal Research* Special Issue No 56 (Proceedings of the 10th International Coastal Symposium): 292–296.

Bochev-Van der Burgh LM, Wijnberg KM and Hulscher SJMH, 2011. Decadal-scale morphologic variability of managed coastal dunes. *Coastal Engineering* 58: 927–936.

Boldingh Debernard J and Petter Røed L, 2008. Future wind, wave and storm surge climate in the Northern Seas: a revisit. *Tellus A* 60: 427–438.

Bollweg A and Vaessen E, 1997. Extractie van strandprofielen uit laseraltimetrie: resultaten van de laseraltimetrieprojecten van 1996. Technical report, Meetkundige Dienst van Rijkswaterstaat.

Braat L, Ten Brink P, Bakkes J, Bolt K, Braeuer I, B TB, Chiabai A, Ding H, Gerdes H, Jeuken M, Kettunen M, Kirchholtes U, Klok C, Markandya A, Nunes P, Van Oorschot M, Peralta-Bezerra N, Rayment M, Travisi C and Walpole M, 2008. The Cost of Policy Inaction: The Case of Not Meeting the 2010 Biodiversity Target. Technical report, Alterra, Wageningen, The Netherlands. 312 p.

Brasington J and Richards K, 2007. Reduced-complexity, physically-based geomorphological modelling for catchment and river management. *Geomorphology* 90: 171 – 177. doi: 10.1016/j.geomorph.2006.10.028. Reduced-Complexity Geomorphological Modelling for River and Catchment Management.

Bressolier C and Thomas YF, 1977. Studies on wind and plant interactions on French Atlantic coastal dunes. *Journal of Sedimentary Petrology* 47: 331–338.

Brunsden D and Thornes J, 1979. Landscape sensitivity and change. *Transactions, Institute of British Geographers* 4: 463–484.

Bruun P, 1962. Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division* 88: 117–130.

Buckley R, 1987. The effect of sparse vegetation on the transport of dune sand by wind. *Nature* 325: 426–428.

Burroughs S and Tebbens S, 2008. Dune retreat and shoreline change on the Outer Banks of North Carolina. *Journal of Coastal Research* 24: 104–112.

Carter R, 1990. Geomorphology of coastal dunes in Ireland. In: *Dunes of the European coasts, Catena Supplement 18*, pp. 31–40.

Carter RWG, 1991. Near-future sea level impacts on coastal dune landscapes. *Landscape Ecology* 6: 29–39.

Chapman D, 1990. Aeolian sand transport - an optimized model. *Earth Surface Processes & Landforms* 15: 751–760.

Cheung KF, Gerritsen F and Cleveringa J, 2007. Morphodynamics and Sand Bypassing at Ameland Inlet, The Netherlands. *Journal of Coastal Research* 23: pp.106–118.

Christiansen MB and Davidson-Arnott R, 2004. Rates of landward sand transport over the foredune at Skallingen, Denmark and the role of dune ramps. *Geografisk Tidsskrift* 104:

31–43.

Church JA, Gregory JM, Huybrechts P, Kuhn M, Lambeck K, Nhuan MT, Qin D and Woodworth PL, 2001. Changes in sea level. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, Van der Linden P, Dai X, Maskell K and Johnson CA (eds.) *Climate Change 2001: The Scientific Basis*, pp. 639–693. Cambridge University Press, Cambridge, UK.

Ciavola P and Stive M, 2012. Thresholds for storm impacts along European coastlines: Introduction. *Geomorphology* 143-144: 1–2.

Clemmensen LB and Murray A, 2006. The termination of the last major phase of aeolian sand movement, coastal dunefields, Denmark. *Earth Surface Processes and Landforms* 31: 795–808.

Commission E, 2007. Interpretation Manual of European Union Habitats. Technical Report EUR 27, European Commission Environment Directorate-General, Brussels, Belgium. 142 p.

Cooper JAG, Jackson DWT, Navas F, McKenna J and Malvarez G, 2004. Identifying storm impacts on an embayed, high-energy coastline: examples from western Ireland. *Marine Geology* 210: 261–280. doi:10.1016/j.margeo.2004.05.012.

Dally WR, Dean RG and Dalrymple RA, 1985. Wave height variation across beaches of arbitrary profile. *Journal of Geophysical Research* 90: 11917–11927.

Daniels E, Lenderink G, Hutjes R and Holtslag A, 2014. Spatial precipitation patterns and trends in The Netherlands during 1951-2009. *International Journal of Climatology* 34: 1773–1784.

Davidson-Arnott R and Bauer B, 2009. Aeolian sediment transport on a beach: Thresholds, intermittency, and high frequency variability. *Geomorphology* 105: 117 – 126. doi:http://dx.doi.org/10.1016/j.geomorph.2008.02.018.

Davidson-Arnott R and Stewart C, 1987. The effect of longshore sand waves on dune erosion and accretion, Long Point, Ontario. In: *Proceedings of the Canadian Coastal Conference*, pp. 131–144.

Davidson-Arnott RGD, 2005. Conceptual model of the effects of sea level rise on sandy coasts. *Journal of Coastal Research* 21: 1166–1172.

Davidson-Arnott RGD and Law MN, 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom K, Psuty N and Carter R (eds.) *Coastal dunes: form and process*, pp. 177–200. John Wiley & Sons, Ltd, Chichester, Chichester.

Davidson-Arnott RGD and Law MN, 1996. Measurement and Prediction of Long-Term Sediment Supply to Coastal Foredunes. *Journal of Coastal Research* 12: 654–663.

Davidson-Arnott RGD, Yang Y, Ollerhead J, Hesp PA and Walker IJ, 2008. The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. *Earth*

Surface Processes and Landforms 33: 55–74. doi:10.1002/esp.1527.

Day Jr JW, Britsch LD, Hawes SR, Shaffer GP, Reed DJ and Cahoon D, 2000. Pattern and process of land loss in the Mississippi Delta: A spatial and temporal analysis of wetland habitat change. *Estuaries* 23: 425–438.

De Graaf H, Oude Elberink S, Bollweg A, Brügelmann R and Richardson L, 2003. Inwinning droge JARKUS profielen langs Nederlandse kust. Technical report, Rijkswaterstaat.

De Groot AV, Berendse F, M RMJP, Baas ACW, Slim PA, van Dobben HF and Stroosnijder L, 2011. Modelling coastal dune formation and associated vegetation development. *Geophysical Research Abstracts* URL `http://meetingorganizer.copernicus.org/EGU2011/EGU2011-4959.pdf`.

De Groot AV, Berendse F, Riksen MJPM, Baas ACW, Keijsers JGS, Slim PA, van Dobben HF and Stroosnijder L. Coastal dune and swale development in relation to beach nourishments. *in prep* .

De Groot AV, De Vries S, Keijsers JGS, Riksen MJPM, Ye Q, Poortinga A, Arens SM, Bochev-Van der Burgh LM, Wijnberg KM, Schretlen JL and Van Thiel de Vries JSM, 2012. Measuring and modeling coastal dune development in the Netherlands. In: *NCK-Days*, pp. 105–110.

De Jong B, Keijsers JGS, Riksen MJPM, Krol J and Slim P, 2014. Soft engineering versus dynamic approach in coastal dune management: A case study on the North Sea barrier island of Ameland, The Netherlands. *Journal of Coastal Research* 30: 670–684.

De Moel H, van Vliet M and Aerts JCJH, 2014. Evaluating the effect of flood damage-reducing measures: A case study of the unembanked area of Rotterdam, the Netherlands. *Regional Environmental Change* 14: 895–908.

De Rooij-Van Der Goes PC, Van Der Putten WH and Peters BA, 1995. Effects of sand deposition on the interaction between *Ammophila arenaria*, plant-parasitic nematodes, and pathogenic fungi. *Canadian Journal of Botany* 73: 1141–1150.

De Ruig J, 1998. Coastline management in The Netherlands: Human use versus natural dynamics. *Journal of Coastal Conservation* 4: 127–134.

De Ruig JHM and Hillen R, 1997. Developments in Dutch coastline management: Conclusions from the second governmental coastal report. *Journal of Coastal Conservation* 3: 203–210.

De Vriend HJ and Van Koningsveld M, 2012. Building with Nature: Thinking, Acting and Interacting Differently. Technical report, Ecoshape, Dordrecht, the Netherlands. 39 p.

De Vries S, Southgate HN, Kanning W and Ranasinghe R, 2012a. Dune behavior and aeolian transport on decadal timescales. *Coastal Engineering* 67: 41–53.

De Vries S, Southgate W H amd Kanning and Ranasinghe R, 2012b. Dune development and aeolian transport along the Holland coast. In: Kranenburg WM, Horstman EM and

Wijnberg KM (eds.) *NCK-Days 2012: Crossing Borders in Coastal Research*, pp. 125–129. Enschede,The Netherlands.

De Winter RC, 2014. Dune erosion under climate change. Phd thesis, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands.

De Winter RC, Sterl A, De Vries JW, Weber SL and Ruessink G, 2012. The effect of climate change on extreme waves in front of the Dutch coast. *Ocean Dynamics* 62: 1139–1152.

De Winter RC, Sterl A and Ruessink BG, 2013. Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs. *Journal of Geophysical Research D: Atmospheres* 118: 1601–1612.

Dean RG, 1991. Equilibrium Beach Profiles: Characteristics and Applications. *Journal of Coastal Research* 7: 53–84.

Delgado-Fernandez I, 2010. A review of the application of the fetch effect to modelling sand supply to coastal foredunes. *Aeolian Research* 2: 61–70. doi:10.1016/j.aeolia.2010.04.001.

Delgado-Fernandez I, 2011. Meso-scale modelling of aeolian sediment input to coastal dunes. *Geomorphology* 130: 230–243.

Delgado-Fernandez I and Davidson-Arnott R, 2011. Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events. *Geomorphology* 126: 217–232.

Deltacommissie, 2008. Samen Werken Met Water. Een land dat leeft, bouwt aan zijn toekomst. Bevindingen van de Deltacommissie 2008 (in Dutch; summaries in English on website `www.deltacommissie.nl`). Technical report.

Deltares, 2012. De Nederlandse Kust in Beeld. website. URL `https://publicwiki.deltares.nl/display/GEC/Home`.

Den Heijer C, Baart F and Van Koningsveld M, 2012. Assessment of dune failure along the Dutch coast using a fully probabilistic approach. *Geomorphology* 143-144: 95–103.

Disraeli DJ, 1984. The effect of sand deposits on the growth and morphology of *Ammophila breviligulata*. *Journal of Ecology* 72: 145–154.

Dong Z, Luo W, Qian G and Lu P, 2008. Wind tunnel simulation of the three-dimensional airflow patterns around shrubs. *Journal of Geophysical Research F: Earth Surface* 113: F02016.

Dupont S, Bergametti G and Simoëns S, 2014. Modeling aeolian erosion in presence of vegetation. *Journal of Geophysical Research: Earth Surface* 119: 168–187.

Durán O and Herrmann H, 2006. Vegetation against dune mobility. *Physical Review Letters* 97: 1088001. doi:10.1103/PhysRevLett.97.188001.

Durán O and Moore LJ, 2013. Vegetation controls on the maximum size of coastal dunes. *Proceedings of the National Academy of Sciences* 110: 17217–17222.

Durán O and Moore LJ, 2014. Barrier island bistability induced by biophysical interactions.

Nature Climate Change Advance online publication: 1–5. doi:10.1038/NCLIMATE2474.

Edelman T, 1967. Vormveranderingen aan zandige kukust. Deel II: Het dwarstransport en het materiaaltransport haaks op de kust. Technical report, Studierapport Rijkswaterstaat 67-3.

ESRI, 2011. ArcGIS Desktop Version 10.

Eysink WD, Dijkema KS, Van Dobben HF, Slim PA, Smit CJ, Sanders ME, Schouwenberg EPAG, Wiertz J and De Vlas J, 2000. Samenvatting Monitoring Effecten van Bodemdaling op Ameland-Oost: Evaluatie na 13 Jaar Gaswinning. Technical report, Begeleidingscommissie Monitoring Bodemdaling Ameland, Assen, the Netherlands.

Fagherazzi S, Palermo C, Rulli MC, Carniello L and Defina A, 2007. Wind waves in shallow microtidal basins and the dynamic equilibrium of tidal flats. *Journal of Geophysical Research: Earth Surface* 112.

Feagin RA, Sherman DJ and Grant WE, 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment* 3: 359–364.

FitzGerald D, Fenster M, Argow B and Buynevich I, 2008. Coastal impacts due to sea-level rise. *Annual Review of Earth and Planetary Sciences* 36: 601–647.

Fitzgerald DM, Penland S and Nummedal D, 1984. Control of barrier island shape by inlet sediment bypassing: East Frisian Islands, West Germany. *Marine Geology* 60: 355–376.

Fonstad MA, 2006. Cellular automata as analysis and synthesis engines at the geomorphology-ecology interface. *Geomorphology* 77: 217–234.

Fryberger SG and Dean G, 1979. Dune forms and wind regime. In: McKee ED (ed.) *A study of global sand seas*. United States Government printing Office, Washington.

Gares P, Davidson-Arnott R, Bauer B, Sherman D, Carter R, Jackson D and Nordstrom K, 1996. Alongshore variations in aeolian sediment transport: Carrick Finn Strand, Ireland. *Journal of Coastal Research* 12: 673–682.

Géhu J, 1983. *European dune and shoreline vegetation*. Council of Europe, Strasbourg.

Gemmell AR, Greig-Smith P and Gimingham CH, 1953. A Note on the Behaviour of *Ammophila Arenaria* (L.) Link, in Relation to Sand-Dune Formation. *Transactions of the Botanical Society of Edinburgh* 36: 132–136. doi:10.1080/13594865309441601.

Giardino A, De Boer W, Den Heijer K, Huisman B, Mulder J and Walstra DJ, 2013. Innovative approaches and tools for erosion control and coastline management.

Giardino A, Santinelli G and Vuik V, 2014. Coastal state indicators to assess the morphological development of the Holland coast due to natural and anthropogenic pressure factors. *Ocean and Coastal Management* 87: 93–101.

Gillette DA, Herbert G, Stockton PH and Owen PR, 1996. Causes of the fetch effect in wind erosion. *Earth Surface Processes and Landforms* 21: 641–659.

Goldsmith V, 1978. Coastal dunes. In: Davis RAJ (ed.) *Coastal Sedimentary Environments*.

Springer Verlag.

Gornish E and Miller T, 2010. Effects of storm frequency on dune vegetation. *Global Change Biology* 16: 2668–2675. doi:10.1111/j.1365-2486.2009.02144.x.

Grabemann I and Weisse R, 2008. Climate change impact on extreme wave conditions in the North Sea: An ensemble study. *Ocean Dynamics* 58: 199–212.

Greipsson S and Davy AJ, 1996. Sand accretion and salinity as constraints on the establishment of Leymus arenarius for land reclamation in Iceland. *Annals of Botany* 78: 611–618.

Grootjans AP, Geelen HWT, Jansen AJM and Lammerts EJ, 2002. Restoration of coastal dune slacks in the Netherlands. *Hydrobiologia* 478: 181–203. doi:10.1023/A:1021086832201.

Guillén J and Hoekstra P, 1997. Sediment Distribution in the Nearshore Zone: Grain Size Evolution in Response to Shoreface Nourishment (Island of Terschelling, The Netherlands). *Estuarine, Coastal and Shelf Science* 45: 639 – 652. doi:10.1006/ecss.1996.0218.

Guillén J, Stive MJF and Capobianco M, 1999. Shoreline evolution of the Holland coast on a decadal scale. *Earth Surface Processes and Landforms* 24: 517–536. doi:10.1002/(SICI)1096-9837(199906)24:6<517::AID-ESP974>3.0.CO;2-A.

Haff PK, 1996. Limitations on Predictive Modeling in Geomorphology. In: Rhoads BL and Thorn CE (eds.) *The Scientific Nature of Geomorphology*. John Wiley & Sons.

Hardisty J, 1994. Beach and nearshore sediment transport. In: Pye K (ed.) *Sediment transport and depositional processes*, pp. 216–255. Blackwell, London, UK.

Helmer W, Vellinga P, Litjens G, Goosen H, Ruijgrok E and Overmars W, 1996. Growing with the sea. Technical report, World Wide Fund for Nature.

Herrmann H, 2002. Evolution and shapes of dunes. *Comptes Rendus Physique* 3: 197–206.

Hesp PA, 1981. The formation of shadow dunes. *Journal of Sedimentary Petrology* 51: 101–112.

Hesp PA, 1982. Dynamics and morphology of foredunes in S.E. Australia. Ph.D. thesis, University of Sydney.

Hesp PA, 1983. Morphodynamics of incipient foredunes in New South Wales, Australia. In: Brookfield ME and Ahlbrandt TS (eds.) *Eolian Sediments and Processes*, pp. 325–342. Elsevier Science Publishers B.V., Amsterdam.

Hesp PA, 1988. Surfzone, beach and foredune interactions on the Australian south east coast. *Journal of Coastal Research* Special Issue No. 3: 15–25.

Hesp PA, 1989. A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. *Proceedings of the Royal Society of Edinburgh Section B: Biological Sciences* 96: 181–201.

Hesp PA, 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology* 48: 245–268.

Hesp PA, 2012. Surfzone-beach-dune interactions. In: Kranenburg W, Horstman E and Wijnberg K (eds.) *NCK-days 2012*, pp. 35–40. University of Twente, Department of Water Engineering & Management, Enschede, the Netherlands.

Hesp PA, Davidson-Arnott R, Walker IJ and Ollerhead J, 2005. Flow dynamics over a foredune at Prince Edward Island, Canada. *Geomorphology* 65: 71–84.

Hesp PA, Walker IJ, Chapman C, Davidson-Arnott R and Bauer BO, 2013. Aeolian dynamics over a coastal foredune, Prince Edward Island, Canada. *Earth Surface Processes and Landforms* 39: 1566–1575.

Hesp PA, Walker IJ, Namikas SL, Davidson-Arnott R, Bauer BO and Ollerhead J, 2009. Storm wind flow over a foredune, Prince Edward Island, Canada. *Journal of Coastal Research* Special Issue 56 (Proceedings of the 10th International Coastal Symposium): 312–316.

Hillen R and Roelse P, 1995. Dynamic preservation of the coastline in the Netherlands. *Journal of Coastal Conservation* 1: 17–28. doi:10.1007/BF02835558.

Hilton M, Duncan M and Jul A, 2005. Processes of *Ammophila arenaria* (Marram Grass) invasion and indigenous species displacement, Stewart Island, New Zealand. *Journal of Coastal Research* 21: 175–185.

Holling CS, 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics* 4: 1–23.

Horstman EM, Wijnberg KM, Smale AJ and Hulscher SJMH, 2009. On the consequences of a long-term perspective for coastal management. *Ocean and Coastal Management* 52: 593–611. doi:10.1016/j.ocecoaman.2009.08.009.

Houellebecq M, 2015. *Onderworpen*. Arbeiderpers.

Houser C and Ellis J, 2013. Beach and Dune Interaction. In: Shroder JF (ed.) *Treatise on Geomorphology*, volume 10, chapter 10, pp. 267–288. Academic Press, San Diego.

Houser C, Hapke C and Hamilton S, 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology* 100: 223–240.

Huiskes AHL, 1979. *Ammophila Arenaria* (L.) Link (*Psamma Arenaria* (L.) Roem. et Schult.; *Calamgrostis Arenaria* (L.) Roth). *Journal of Ecology* 67: 363–382. doi: 10.2307/2259356.

Jackson NL and Nordstrom KF, 1997. Effects of time-dependent moisture content of surface sediments on aeolian transport rates across a beach, Wildwood, New Jersey, U.S.A. *Earth Surface Processes and Landforms* 22: 611–621.

Jackson NL and Nordstrom KF, 1998. Aeolian transport of sediment on a beach during and after rainfall, Wildwood, NJ, USA. *Geomorphology* 22: 151–157.

Jelgersma S and Van Regteren Altena JF, 1969. An outline of the geological history of the coastal dunes in the western Netherlands. *Geologie en Mijnbouw* 48: 335–342.

Jungerius PD, Verheggen AJT and Wiggers AJ, 1981. The development of blowouts in 'The Blink', a coastal dune near Noordwijkerhout, The Netherlands. *Earth Surface Processes and Landforms* 6: 375–396.

Jungerius PD, Witter JV and van Boxel JH, 1991. The effects of changing wind regimes on the development of blowouts in the coastal dunes of The Netherlands. *Landscape Ecology* 6: 41–48.

Kabat P, Fresco LO, Stive MJF, Veerman CP, Van Alphen JSLJ, Parmet BWAH, Hazeleger W and Katsman CA, 2009. Dutch coasts in transition. *Nature Geoscience* 2: 450–452.

Katsman C, Sterl A, Beersma J, van den Brink H, Church J, Hazeleger W, Kopp R, Kroon D, Kwadijk J, Lammersen R, Lowe J, Oppenheimer M, Plag HP, Ridley J, von Storch H, Vaughan D, Vellinga P, Vermeersen L, van de Wal R and Weisse R, 2011. Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta-the Netherlands as an example. *Climatic Change* 109: 617–645.

Kawamura R, 1951. Study of sand movement by wind. Technical report, University of Tokyo Report of the Institute of Science and Technology.

Kearney MS, Rogers AS, Townshend JRG, Rizzo E, Stutzer D, Stevenson JC and Sundborg K, 2002. Landsat imagery shows decline of coastal marshes in chesapeake and delaware bays. *Eos* 83: 173–178.

Keijsers J, Giardino A, Poortinga A, Mulder J, Riksen M and Santinelli G, 2014a. Adaptation strategies to maintain dunes as flexible coastal flood defense in The Netherlands. *Mitigation and Adaptation Strategies for Global Change* in press.

Keijsers JGS, De Groot AV and Riksen MJPM, 2015. Vegetation and sedimentation on coastal foredunes. *Geomorphology* 228: 723–734.

Keijsers JGS, Poortinga A, Riksen MJPM and Maroulis J, 2014b. Spatio-Temporal Variability in Accretion and Erosion of Coastal Foredunes in the Netherlands: Regional Climate and Local Topography. *PLoS ONE* 9(3): e91115.

Ketelaar G, Van der Veen W and Doornhof D, 2011. Bodemdaling, Monitoring Effecten van Bodemdaling op Ameland-Oost (In Dutch). Technical report, Begeleidingscommissie Monitoring Bodemdaling Ameland.

Ketner-Oostra R and Sýkora KV, 2012. Effect van overstuiving op korstmosrijke duinen op Terschelling (In Dutch). *De Levende Natuur* 113: 167–173.

Kirwan M, Guntenspergen G, D'Alpaos A, Morris J, Mudd S and Temmerman S, 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37: L23401.

Klein R, Smit M, Goosen H and Hulsbergen C, 1998. Resilience and vulnerability: Coastal dynamics or Dutch dikes? *Geographical Journal* 164: 259–268.

Klijn JA, 1981. Nederlandse kustdukust: Geomorfologie en bodems (Dutch coastal dunes;

geomorphology and ssoil). Phd thesis, Landbouwhogeschool, Wageningen, The Netherlands.

Klijn JA, 1990. The Younger Dunes in The Netherlands; chronology and causation. In: Bakker TW, Jungerius PD and Klijn JA (eds.) *Dunes of the European Coast, Geomorphology – Hydrology – Soils*, volume 18 of *Catena Supplement*, pp. 89–100.

KNMI, 2006. Climate in the 21st century: four scenarios for the Netherlands. Technical report, KNMI.

KNMI, 2014. Daily weather data of the Netherlands.

KNMI, Attema J, Bakker A, Beersma J, Bessembinder J, Boers R, Brandsma T, Van den Brink H, Drijfhout S, Eskes H, Haarsma R, Hazeleger W, Jilderda R, Katsman C, Lenderink G, Loriaux J, Van Meijgaard E, Van Noije T, Van Oldenborgh GJ, Selten F, Siebesma P, Sterl A, De Vries H, Van Weele M, De Winter R and Van Zadelhoff GJ, 2014. KNMI'14: Climate Change scenarios for the 21st Century – A Netherlands perspective. Report, KNMI. URL `www.climatescenarios.nl`.

Komar PD and Cary RC, 1976. Erosion of Siletz Spit, Oregon. *Shore Beach* 44: 9–15.

Konlechner TM, Hilton MJ and Orlovich DA, 2013. Accommodation space limits plant invasion: *Ammophila arenaria* survival on New Zealand beaches. *Journal of Coastal Conservation* 17: 463–472.

Kriebel D and Dean R, 1985. Numerical simulation of time-dependent beach and dune erosion. *Coastal Engineering* 9: 221–245.

Krol J, 2006. Monitoring Dynamisch Kustbeheer Ameland-Oost. Technical report, Natuurcentrum Ameland, the Netherlands, Nes Ameland, The Netherlands. 25 p.

Krol J, 2011. Monitoring van Inundatie in Duinvalleien op Oost-Ameland 2001–2011. Technical report, Natuurcentrum Ameland, the Netherlands.

Kroon A and Hoekstra P, 1990. Eolian Sediment Transport on a Natural Beach. *Journal of Coastal Research* 6: pp.367–379.

Kroy K, Sauermann G and Herrmann H, 2002. Minimal model for aeolian sand dunes. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* 66: 031302/1–031302/18.

Kuriyama Y, Mochizuki N and Nakashima T, 2005. Influence of vegetation on aeolian sand transport rate from a backshore to a foredune at Hasaki, Japan. *Sedimentology* 52: 1123–1132. doi:10.1111/j.1365-3091.2005.00734.x.

Lancaster N and Baas A, 1998. Influence of vegetation cover on sand transport by wind: field studies at Owens Lake, California. *Earth Surface Processes and Landforms* 23: 69–82.

Langenberg H, Pfizenmayer A, Von Storch H and Sündermann J, 1999. Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. *Continental Shelf Research* 19: 821–842.

Langendoen E, 1987. Onderzoek naar de vergroting van het getijverschil te Vlissingen (in

Dutch). Master thesis, Technical University Delft, Delft, the Netherlands.

Larson M, Erikson L and Hanson H, 2004. An analytical model to predict dune erosion due to wave impact. *Coastal Engineering* 51: 675–696.

Leatherman S, Zhang K and Douglas B, 2000. Sea level rise shown to drive coastal erosion. *Eos* 81: 55–57.

Leenders JK, Sterk G and Van Boxel JH, 2011. Modelling wind-blown sediment transport around single vegetation elements. *Earth Surface Processes and Landforms* 36: 1218–1229.

Lettau K and Lettau HH, 1978. *Exploring the world's driest climate*, chapter Experimental and micro-meteorological field studies of dune migration, pp. 110–147. University of Wisconsin Press, Madison.

Levin N, Kidron GJ and Ben-Dor E, 2008. A field quantification of coastal dune perennial plants as indicators of surface stability, erosion or deposition. *Sedimentology* 55: 751–772.

Li F, Van Gelder PHAJM, Vrijling JK, Callaghan DP, Jongejan RB and Ranasinghe R, 2014. Probabilistic estimation of coastal dune erosion and recession by statistical simulation of storm events. *Applied Ocean Research* 47: 53–62. doi:http://dx.doi.org/10.1016/j.apor.2014.01.002.

Lima A, Sauermann G, Herrmann H and Kroy K, 2002. Modelling a dune field. *Physica A: Statistical Mechanics and its Applications* 310: 487–500.

Löffler MAM, 2008. Eilanden Natuurlijk: Natuurlijke Ontwikkeling en Veerkracht op de Waddeneilanden. Technical report, Het Tij Geleerd, Groningen, The Netherlands. 95 p.

Louisse CJ and Meulen Fvd, 1991. Future Coastal Defence in the Netherlands: Strategies for Protection and Sustainable Development. *Journal of Coastal Research* 7: pp.1027–1041.

Lowe JA and Gregory JM, 2005. The effects of climate change on storm surges around the United Kingdom. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 363: 1313–1328.

Luna M, Parteli E and Herrmann H, 2012. Model for a dune field with an exposed water table. *Geomorphology* 159-160: 169–177.

Luna MCMM, Parteli EJR, Durán O and Herrmann HJ, 2011. Model for the genesis of coastal dune fields with vegetation. *Geomorphology* 129: 215–224.

Luo W, Dong Z, Qian G and Lu J, 2014. Near-wake flow patterns in the lee of adjacent obstacles and their implications for the formation of sand drifts: A wind tunnel simulation of the effects of gap spacing. *Geomorphology* 213: 190–200.

Lynch K, Jackson DWT and Cooper JAG, 2008. Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development. *Earth Surface Processes and Landforms* 33: 991–1005.

Mancini F, Dubbini M, Gattelli M, Stecchi F, Fabbri S and Gabbianelli G, 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: The structure from motion approach on coastal environments. *Remote Sensing* 5: 6880–6898.

Martin WE, 1959. The Vegetation of Island Beach State Park, New Jersey. *Ecological Monographs* 29: 2–46.

Martinez ML, Maun MA and Psuty NP, 2004. The fragility and conservation of the world's coastal dunes: geomorphological, ecological and socioeconomic perspectives. In: Martinez ML and Psuty NP (eds.) *Coastal dunes: Ecology and Conservation*, pp. 355–370. Springer-Verlag, Berlin.

Masselink G and Van Heteren S, 2014. Response of wave-dominated and mixed-energy barriers to storms. *Marine Geology* 352: 321–347.

Maun MA, 1998. Adaptations of plants to burial in coastal sand dunes. *Canadian Journal of Botany* 76: 713–738.

Maun MA, 2009. *The biology of coastal sand dunes*. Oxford University Press, Oxford, UK.

Maun MA and Lapierre J, 1984. The Effects of Burial by Sand on *Ammophila Breviligulata*. *Journal of Ecology* 72: 827–839.

Maun MA and Perumal J, 1999. Zonation of vegetation on lacustrine coastal dunes: Effects of burial by sand. *Ecology Letters* 2: 14–18.

Mayhew S, 2006. A Dictionary of Geography.

MinI&M, 2009. Nationaal Water Plan (In Dutch). Technical report, Ministerie van Infrastructuur en Milieu.

MinI&M, 2011. Deltaprogramma in the Netherlands. Technical report, Ministerie van Infrastructuur en Milieu.

MinI&M, 2013. Nationale visie kust. Kompas voor de kust (in Dutch). Technical report, Ministerie van Infrastructuur en Milieu.

MinI&M and EZ, 2013. Deltaprogramma 2014, Kust; Bijlage D: Bestuurlijke keuzes nationale Visie Kust (in Dutch). Technical report, Ministerie van Infrastructuur en Milieu, Ministerie van Economische Zaken.

Ministerie van Verkeer en Waterstaat, 1990. Kustverdediging na 1990: beleidskeuze voor de kustlijnzorg. Technical report, Ministry of Transport, Public Works and Water Management.

Minneboo F, 1995. Jaarlijke kustmetingen: Richtlijnen voor de inwinning, bewerking en opslag van gegevens van jaarlijkste kustmetingen. Technical Report rapport RIKZ-95.022, Rijksinstituut voor kust en zee.

MinV&W, 1989. Kustverdediging na 1990: Discussienota (in Dutch). Technical report, Ministerie van Verkeer en Waterstaat.

MinV&W, 2000. 3e Kustnota. Traditie, Trends en Toekomst (3rd Coastal Policy Document, in Dutch). Technical report, Ministerie van Verkeer en Waterstaat.

MinV&W, 2009. Nationaal Waterplan (in Dutch). Technical report, Ministerie van Verkeer en Waterstaat, Den Haag, The Netherlands.

Miot da Silva G, Siadat Mousavi S and Jose F, 2012. Wave-driven sediment transport and beach-dune dynamics in a headland bay beach. *Marine Geology* 323-325: 29–46.

Momiji H, Carretero-González R, Bishop SR and Warren A, 2000. Simulation of the effect of wind speedup in the formation of transverse dune fields. *Earth Surface Processes and Landforms* 25: 905–918.

Morton RA, 1994. Factors controlling storm impacts on coastal barriers and beaches: a preliminary basis for near real-time forecasting. *Journal of Coastal Research* 18: 486–501.

Mulder J, Hommes S and Horstman E, 2011. Implementation of coastal erosion management in the Netherlands. *Ocean and Coastal Management* 54: 888–897.

Mulder JPM and Tonnon PK, 2010. "Sand Engine": Background and design of a mega nourishment pilot in the Netherlands. In: *Proceedings of International Coastal Engineering Conference, 32, Shanghai, China*, pp. 1–10.

Mulder JPM, Van Der Spek AJF and Van der Meulen MJ, 2008. Coastal zones and climate change: a sediment perspective on adaptation.

Murray AB, 2007. Reducing model complexity for explanation and prediction. *Geomorphology* 90: 178 – 191. doi:10.1016/j.geomorph.2006.10.020. Reduced-Complexity Geomorphological Modelling for River and Catchment Management.

Namikas SL and Sherman DJ, 1995. A review of the effects of surface moisture content on aeolian sand transport. In: Tchakerian VP (ed.) *Desert Aeolian Processes*, pp. 269–293. Chapman & Hall, London.

Nash JE and Sutcliffe JV, 1970. River flow forecasting through conceptual models part I – A discussion of principles. *Journal of Hydrology* 10: 282–290. doi:http://dx.doi.org/10.1016/0022-1694(70)90255-6.

Nichols MM, 1989. Sediment accumulation rates and relative sea-level rise in lagoons. *Marine Geology* 88: 201–219.

Nickling WG, 1984. The stabilizing role of bonding agents on the entrainment of sediment by wind. *Sedimentology* 31: 111–117. doi:10.1111/j.1365-3091.1984.tb00726.x.

Nield J and Baas A, 2008a. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. *Global and Planetary Change* 64: 76–92.

Nield J and Baas A, 2008b. Investigating parabolic and nebkha dune formatrion using a cellular automaton modelling approach. *Earth Surface Processes and Landforms* 33: 724–740.

Nikkels M, 2010. Changes in Coastal Defense Visions and Policies at the Dutch Wadden

Islands over the Last 60 Years. Bachelor's thesis, Wageningen University, Wageningen, the Netherlands. 21 p.

Nishimori H and Tanaka H, 2001. A simple model for the formation of vegetated dunes. *Earth Surface Processes and Landforms* 26: 1143–1150. doi:10.1002/esp.258.

Nordstrom KF and Jackson NL, 1992. Effect of source width and tidal elevation changes on aeolian transport on an estuarine beach. *Sedimentology* 39: 769–778.

Okin GS, 2008. A new model of wind erosion in the presence of vegetation. *Journal of Geophysical Research: Earth Surface* 113: F02S10.

Ollerhead J, Davidson-Arnott R, Walker IJ and Mathew S, 2013. Annual to decadal morphodynamics of the foredune system at Greenwich Dunes, Prince Edward Island, Canada. *Earth Surface Processes and Landforms* 38: 284–298.

Olson JS, 1958. Lake Michigan dune development 2. Plants as agents and tools in geomorphology. *The Journal of Geology* 66: 345–351.

Oost AP, Hoekstra P, Wiersma A, Flemming B, Lammerts EJ, Pejrup M, Hofstede J, van der Valk B, Kiden P, Bartholdy J, van der Berg MW, Vos PC, de Vries S and Wang ZB, 2012. Barrier island management: Lessons from the past and directions for the future. *Ocean & Coastal Management* 68: 18–38.

Oosterwijk H and Ettema M, 1987. Aansluiting hoogte- en dieptemetingen JARKUS m.b.t. de waterpassing. Technical Report Nota GWIO 87.022, Rijkswaterstaat.

Pelletier JD, 2009. Controls on the height and spacing of eolian ripples and transverse dunes: A numerical modeling investigation. *Geomorphology* 105: 322–333.

Pelletier JD, Mitasova H, Harmon RS and Overton M, 2009. The effects of interdune vegetation changes on eolian dune field evolution: a numerical-modeling case study at Jockey's Ridge, North Carolina, USA. *Earth Surface Processes & Landforms* .

Petersen PS, Hilton MJ and Wakes SJ, 2011. Evidence of aeolian sediment transport across an *Ammophila arenaria*-dominated foredune, Mason Bay, Stewart Island. *New Zealand Geographer* 67: 174–189. doi:10.1111/j.1745-7939.2011.01210.x.

Pons LJ and van Oosten MFD, 1976. De bodem van Noord-Holland. Technical report, Stichting voor Bodemkartering, Wageningen.

Poortinga A, Keijsers J, Visser S, Riksen M and Baas A, 2015. Temporal and spatial variability in event scale aeolian transport on Ameland, The Netherlands. *GeoResJ* 5: 23 – 35. doi:j.grj.2014.11.003.

Provinciaal Overlegorgaan Kust Fryslân, 2000. Dynamisch kustbeheer: kustzône Midden en Oost Ameland: een Advies over het Beheer van de Zandige Kustzone op Ameland van km 7 tot km 23. Technical report, Provinciaal Overlegorgaan Kust Fryslân, Projectgroep midden en oost Ameland, Leeuwarden, the Netherlands. 23 p.

Provoost S, Jones M and Edmondson S, 2011. Changes in landscape and vegetation of coastal dunes in northwest Europe: A review. *Journal of Coastal Conservation* 15: 207–226. doi: 10.1007/s11852-009-0068-5.

Pryor SC, Barthelmie RJ, Clausen NE, Drews M, MacKellar N and Kjellström E, 2012. Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Climate Dynamics* 38: 189–208.

Psuty NP, 1988. Sediment budget and dune/beach interaction. *Journal of Coastal Research* Special Issue No. 3: pp.1–4.

Psuty NP, 1992. *Coastal Dunes: Geomorphology, Ecology and Management for Conservation*, chapter Spatial variation in coastal foredune development, pp. 3–13. Balkema, Rotterdam.

Psuty NP and Silveira TM, 2010. Global climate change: An opportunity for coastal dunes?? *Journal of Coastal Conservation* 14: 153–160.

Putten WHVD, 1990. Establishment of *Ammophila arenaria* (Marram Grass) from Culms, Seeds and Rhizomes. *Journal of Applied Ecology* 27: pp. 188–199.

Pye K, 1990. Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, northwest England. In: Nordstrom KF, Psuty NP and Carter RWG (eds.) *Coastal Dunes: Form and Process*, chapter 15, pp. 339–359. Wiley, Chichester, Chichester.

Pye K and Blott SJ, 2008. Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology* 102: 652–666.

Quartel S, Kroon A and Ruessink B, 2008. Seasonal accretion and erosion patterns of a microtidal sandy beach. *Marine Geology* 250: 19–33.

Ranasinghe R, Callaghan D and Stive MJF, 2012. Estimating coastal recession due to sea level rise: Beyond the Bruun rule. *Climatic Change* 110: 561–574.

Ranwell D, 1958. Movement of vegetated sand dunes at Newborough Warren, Anglesey. *Journal of Ecology* 46: 83–100.

Ranwell DS, 1972. *Ecology of salt marshes and sand dunes*. Chapman and Hall, London.

Reed DJ, Davidson-Arnott RGD and Peillo GME, 2009. Estuaries, coastal marshes, tidal flats and coastal dunes. In: Slaymaker O, Spencer T and Embleton-Hamann C (eds.) *Geomorphology and Global Environmental Change*, pp. 130–157. Cambridge University Press, Cambridge, UK.

Rietkerk M, Dekker SC, De Ruiter PC and Van de Koppel J, 2004. Self-Organized patchiness and catastrophic shifts in ecosystems. *Science* 305: 1926–1929.

Rijkswaterstaat, 1973. Stormvloedverslag 2-3 april 1973 (In Dutch). Technical report, Rijkswaterstaat, The Hague.

Rijkswaterstaat, 1990. Verslag van de Crocus-Stormvloedperiode 26 februari t/m 2 maart

1990 (In Dutch). Technical report, Rijkswaterstaat, The Hague.

Rijkswaterstaat, 2010. Kwaliteitsdocument Laseraltimetrie Deel 2: Resultaten Controles Kust 2010. Technical report, Rijkswaterstaat, Data en ICT Dienst, Delft, the Netherlands. 33 p.

Rijkswaterstaat, 2011. Zandwinstrategie voor de Noordzee (in Dutch). Technical report, Rijkswaterstaat Dienst Noordzee, Waterdienst.

Rijkswaterstaat, 2013. Nourishment database. URL `http://opendap.deltares.nl/thredds/catalog/opendap/rijkswaterstaat/suppleties/catalog.html`.

Rijkswaterstaat, 2014a. Dataset documentation JarKus. URL `https://publicwiki.deltares.nl/display/OET/Dataset+documentation+JarKus`.

Rijkswaterstaat, 2014b. Dataset documentation JarKus, url-https://publicwiki.deltares.nl/display/OET/Dataset+documentation+JarKus.

Rijkswaterstaat, 2014c. Historic data on water quantity and quality. URL `http://live.waterbase.nl`.

Rijkswaterstaat, 2014d. Kenmerkende waarden Nes, available at `http://www.rws.nl/images/NES_tcm174-335805.pdf`.

RIKZ, 2003. Traditie, Trends en Toekomst: Het Vervolg : Tweede Voortgangsrapportage over de Uitvoering en Ontwikkeling van Het Kustbeleid. Technical Report RIKZ-2003.0001, Rijksinstituut voor Kust en Zee, Ministerie van Verkeer en Waterstaat, The Hague, the Netherlands. 29 p.

Roelvink D, Reniers A, van Dongeren A, van Thiel de Vries J, McCall R and Lescinski J, 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering* 56: 1133–1152.

Rosati JD, Dean RG and Walton TL, 2013. The modified Bruun Rule extended for landward transport. *Marine Geology* 340: 71–81.

Ruessink B and Jeuken M, 2002. Dunefoot dynamics along the Dutch coast. *Earth Surface Processes and Landforms* 27: 1043–1056.

Ruz M and Meur-Ferec C, 2004. Influence of high water levels on aeolian sand transport: Upper beach/dune evolution on a macrotidal coast, Wissant Bay, northern France. *Geomorphology* 60: 73–87. doi:10.1016/j.geomorph.2003.07.011.

Ryu W and Sherman DJ, 2014. Foredune Texture: Landscape Metrics and Climate. *Annals of the Association of American Geographers* 104: 903–921.

Sallenger AH Jr, Krabill WB, Swift RN, Brock J, List J, Hansen M, Holman RA, Manizade S, Sontag J, Meredith A, Morgan K, Yunkel JK, Frederick EB and Stockdon H, 2003. Evaluation of Airborne Topographic Lidar for Quantifying Beach Changes. *Journal of Coastal Research* 19: 125–133.

Sallenger J Asbury H, 2000. Storm Impact Scale for Barrier Islands. *Journal of Coastal*

Research 16: 890–895.

Sarre R, 1989. The morphological significance of vegetation and relief on coastal foredune processes. *Zeitschrift fur Geomorphologie, Supplementband* 73: 17–31.

Sarre RD, 1988. Evaluation of aeolian sand transport equations using intertidal zone measurements, Saunton Sands, England. *Sedimentology* 35: 671–679.

Saye S, Van der Wal D, Pye K and Blott S, 2005. Beach-dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data. *Geomorphology* 72: 128–155.

Scheffer M, S C, A FJ, Folke C and Walker B, 2001. Catastrophic shifts in ecosystems. *Nature* 413: 591–596.

Schumm SA and Lichty RW, 1965. Time, space and causality in geomorphology. *American Journal of Science* 263: 110–119.

SCOR Working Group 89, 1991. The response of beaches to sea-level changes: a review of predictive models. *Journal of Coastal Research* 7: 895–921.

Seabloom E, Ruggiero P, Hacker S, Mull J and Zarnetske P, 2013. Invasive grasses, climate change, and exposure to storm-wave overtopping in coastal dune ecosystems. *Global Change Biology* 19: 824–832. doi:10.1111/gcb.12078.

Sherman DJ, 1995. Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geology* 124: 339–349. doi:DOI:10.1016/0025-3227(95)00048-4.

Sherman DJ and Bauer BO, 1993. Dynamics of beach-dune systems. *Progress in Physical Geography* 17: 413–447.

Short AD and Hesp PA, 1982. Wave, beach and dune interactions in southeastern Australia. *Marine Geology* 48: 259–284.

Slim PA and Löffler MAM, 2007. Kustveiligheid en Natuur: Een Overzicht van Kennis en Kansen. Technical report, Alterra, Wageningen, The Netherlands. 92 p.

Smits A, Klein Tank AMG and Können GP, 2005. Trends in storminess over the Netherlands, 1962-2002. *International Journal of Climatology* 25: 1331–1344.

Stace C, 2010. *New Flora of the British Isles*. Cambridge University Press, Cambridge, UK, 3rd edition edition. 1232 p.

Sterl A, Van Den Brink H, De Vries H, Haarsma R and Van Meijgaard E, 2009. An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. *Ocean Science* 5: 369–378.

Stive M, 2004. How important is global warming for coastal erosion? An editorial comment. *Climatic Change* 64: 27–39.

Stive M, De Schipper M, Luijendijk A, Aarninkhof S, Van Gelder-Maas C, Van Thiel De Vries J, De Vries S, Henriquez M, Marx S and Ranasinghe R, 2013. A new alternative to saving our beaches from sea-level rise: The sand engine. *Journal of Coastal*

Research 29: 1001–1008.

Stockdon HF, Holman RA, Howd PA and Jr AHS, 2006. Empirical parameterization of setup, swash, and runup. *Coastal Engineering* 53: 573–588. doi:10.1016/j.coastaleng.2005.12.005.

Stolper D, List JH and Thieler RE, 2005. Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behaviour model (GEOMBEST). *Marine Geology* 218: 17–36.

Svasek JN and Terwindt JHJ, 1974. Measurements of sand transport by wind on a natural beach. *Sedimentology* 21: 311–322.

Tansley AG, 1965. *The British Islands and Their Vegetation.* Cambridge University Press, Cambridge, UK. 484 p.

TAW, 2002. Leidraad Zandige Kust. Technical report, Technische Adviescommissie voor de Waterkeringen, Delft, The Netherlands. 224 p.

Temmerman S, Meire P, Bouma T, Herman P, Ysebaert T and De Vriend H, 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504: 79–83.

The Wasa Group, 1998. Changing Waves and Storms in the Northeast Atlantic? *Bulletin of the American Meteorological Society* 79: 741–760.

Thornton EB and Guza RT, 1983. Transformation of wave height distribution. *Journal of Geophysical Research* 88: 5925–5938.

Tsoar H, 2005. Sand dunes mobility and stability in relation to climate. *Physica A: Statistical Mechanics and its Applications* 357: 50–56. doi:http://dx.doi.org/10.1016/j.physa.2005.05.067.

Van Aalst W, 1983. Golfhoogte-waterstandsrelaties t.p.v. de NAP-20 m lijn langs de Nederlandse kust [Wave height - tide level relationships at the -20 isobath along the Dutch coast]. Technical report, Deltadienst, The Hague, The Netherlands.

Van Bohemen HD, 2004. Ecological Engineering and Civil Engineering Works. Phd dissertation, Technical University Delft, Delft, the Netherlands.

Van Boxel JH, Arens SM and Van Dijk PM, 1999. Aeolian processes across transverse dunes. I: modelling the air flow. *Earth Surface Processes & Landforms* .

Van Dalfsen JA and Aarninkhof SG, 2009. Building with Nature: Mega Nourishments and Ecological Landscaping of Extraction Areas. Technical report, European Marine Sand and Gravel Group, Rome, Italy. 6 p.

Van de Graaff J, 1977. Dune erosion during a storm surge. *Coastal Engineering* 1: 99–134.

Van de Graaff J, 1986. Probabilistic design of dunes; an example from The Netherlands. *Coastal Engineering* 9: 479–500. doi:DOI:10.1016/0378-3839(86)90009-8.

Van den Hurk B, Klein Tank A, Lenderink G, van Ulden A, van Oldenborgh GJ, Katsman C, van den Brink H, Keller F, Bessembinder J, Burgers G, Komen G, Hazeleger W and

Drijfhout S, 2006. KNMI Climate Change Scenarios 2006 for the Netherlands. Technical report, KNMI.

Van den Hurk B, Tank AK, Lenderink G, van Ulden A, van Oldenborgh GJ, Katsman C, van den Brink H, Keller F, Bessembinder J, Burgers G, Komen G, Hazeleger W and Drijfhout S, 2007. New climate change scenarios for the Netherlands. *Water Science & Technology* 56: 27–33.

Van der Burgt JH, 1934. Het Noordzeestrand der Waddeneilanden Texel, Vlieland en Terschelling. Technical report, Rijkswaterstaat.

Van der Meulen M, Van der Spek A, De Lange G, Gruijters SHLL, Van Gessel SF, Nguyen BL, Maljers D, Schokker J, Mulder JPM and A RA Van der Krogt, 2007. Regional Sediment Deficits in the Dutch Lowlands: Implications for Long-Term Land-Use Options. *Journal of Soils and Sediments* 7: 9–16.

Van der Putten WH and Peters BAM, 1997. How Soil-Borne Pathogens May Affect Plant Competition. *Ecology* 78: 1785–1795.

Van der Putten WH, Van Dijk C and Peters BAM, 1993. Plant-specific soil-borne diseases contribute to succession in foredune vegetation. *Nature* 362: 53–56.

Van der Spek A, 1995. Holocene sediment influxes in the coastal zone of The Netherlands and the North Sea as a function of sea-level rise and wave- and tide-induced sand transport. Technical report, Geological Survey of The Netherlands.

Van der Stege K, 1965. Verslag betreffende embryonale duinvorming en aanleg van stuifdijken [Report on incipient dune formation and the development of sand drift dikes]. Technical Report Nota K-233, Rijkswaterstaat - Deltadienst.

Van der Stoel CD, Van der Putten WH and Duyts H, 2002. Development of a negative plant-soil feedback in the expansion zone of the clonal grass *Ammophila arenaria* following root formation and nematode colonization. *Journal of Ecology* 90: 978–988.

Van der Wal D, 1998a. Effects of fetch and surface texture on aeolian sand transport on two nourished beaches. *Journal of Arid Environments* 39: 533–547. doi:10.1006/jare.1997.0364.

Van der Wal D, 1998b. The impact of the grain-size distribution of nourishment sand on aeolian sand transport. *Journal of Coastal Research* 14: 620–631.

Van der Wal D, 2000. Grain-Size-Selective Aeolian Sand Transport on a Nourished Beach. *Journal of Coastal Research* 16: pp.896–908.

Van der Wal D, 2004. Beach-dune interactions in nourishment areas along the Dutch coast. *Journal of Coastal Research* 20: 317–325.

Van Dijk PM, Arens SM and Van Boxel JH, 1999. Aeolian processes across transverse dunes. II: Modelling the sediment transport and profile development. *Earth Surface Processes and Landforms* 24: 319–333.

Van Dobben HF and Slim PA, 2012. Past and future plant diversity of a coastal wetland driven by soil subsidence and climate change. *Climatic Change* 110: 597–618.

Van Duin MJP, Wiersma NR, Walstra DJR, Van Rijn LC and Stive MJF, 2004. Nourishing the shoreface: observations and hindcasting of the Egmond case, The Netherlands. *Coastal Engineering* 51: 813 – 837. doi:10.1016/j.coastaleng.2004.07.011. Coastal Morphodynamic Modeling.

Van Koningsveld M and Mulder J, 2004. Sustainable coastal policy developments in the Netherlands. A systematic approach revealed. *Journal of Coastal Research* 20: 375–385.

Van Oldenborgh GJ and Van Ulden AAD, 2003. On the relationship between global warming, local warming in the Netherlands and changes in circulation in the 20th century. *International Journal of Climatology* 23: 1711–1724.

Van Rijn L, 2009. Prediction of dune erosion due to storms. *Coastal Engineering* 56: 441–457.

Van Rijn LC, 2011. Coastal erosion and control. *Ocean and Coastal Management* 54: 867–887.

Van Straaten LMJU, 1961. Directional effects of winds, waves and currents along the Dutch North Sea coast. *Geologie en Mijnbouw* 40: 333–346and363–391.

Van Thiel de Vries JSM, 2009. Dune erosion during storm surges. Ph.D. thesis, TU Delft, Delft, The Netherlands.

van Wesenbeeck BK, Mulder JP, Marchand M, Reed DJ, de Vries MB, de Vriend HJ and Herman PM, 2014. Damming deltas: A practice of the past? Towards nature-based flood defenses. *Estuarine, Coastal and Shelf Science* 140: 1–6. doi:http://dx.doi.org/10.1016/j.ecss.2013.12.031.

Vellinga P, 1982. Beach and dune erosion during storm surges. *Coastal Engineering* 6: 361–387.

Vellinga P, 1986. Beach and dune erosion during storm surges. Ph.D. thesis, University of Technology, Delft.

Verhagen HJ, 1989. Sand waves along the Dutch coast. *Coastal Engineering* 13: 129–147.

Veugen LLM, 1984. De Nauwkeurigheid van Strandprofielen, Fotogrammetrische Acquisitie. Technical report, Rijkswaterstaat, Meetkundige Dienst, Delft, the Netherlands. 20 p.

Vousdoukas MI, Almeida LPM and Ferreira O, 2012. Beach erosion and recovery during consecutive storms at a steep-sloping, meso-tidal beach. *Earth Surface Processes and Landforms* 37: 583–593. doi:10.1002/esp.2264.

Walker I, Davidson-Arnott R, Hesp P, Bauer B and Ollerhead J, 2009. Mean flow and turbulence responses in airflow over foredunes: New insights from recent research. *Journal of Coastal Research* Spec. Issue 59: 366370.

Wallén B, 1980. Changes in Structure and Function of *Ammophila* during Primary Succession. *Oikos* 34: 227–238.

Walters D, Moore LJ, Durán Vinent O, Fagherazzi S and Matiotti G, 2014. Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: Insights from a coupled model. *Journal of Geophysical Research: Earth Surface* 119. doi:doi:10.1002/2014JF003091.

Wang C and Temmerman S, 2013. Does biogeomorphic feedback lead to abrupt shifts between alternative landscape states?: An empirical study on intertidal flats and marshes. *Journal of Geophysical Research: Earth Surface* 118: 229–240. doi:10.1029/2012JF002474.

Wasson R and Nanninga P, 1986. Estimating wind transport of sand on vegetated surfaces. *Earth Surface Processes and Landforms* 11: 505–514.

Werner B, 1995. Eolian dunes: computer simulations and attractor interpretation. *Geology* 23: 1107–1110.

Werner BT and Fink TM, 1993. Beach cusps as self-organized patterns. *Science* 260: pp.968–971.

Wiggs GFS, Baird AJ and Atherton RJ, 2004. The dynamic effect of moisture on the entrainment and transport of sand by wind. *Geomorphology* 59: 13–30.

Wiggs GFS, Thomas DSG and E BJ, 1995. Dune mobility and vegetation cover in the southwest Kalahari Desert. *Earth Surface Processes & Landforms* 20: 515–529.

Witte JPM, Runhaar J, van Ek R, van der Hoek DCJ, Bartholomeus RP, Batelaan O, van Bodegom PM, Wassen J and van der Zee SEATM, 2012. An ecohydrological sketch of climate change impacts on water and natural ecosystems for the Netherlands: bridging the gap between science and society. *Hydrology and Earth System Sciences* 16: 3945–3957.

Wolfe S and Nickling W, 1993. The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography* 17: 50–68.

Wolner CW, Moore LJ, Young DR, Brantley ST, Bissett SN and McBride RA, 2013. Ecomorphodynamic feedbacks and barrier island response to disturbance: Insights from the Virginia Barrier Islands, Mid-Atlantic Bight, {USA}. *Geomorphology* 199: 115–128. doi:http://dx.doi.org/10.1016/j.geomorph.2013.03.035.

Yizhaq H, Ashkenazy Y and Tsoar H, 2009. Sand dune dynamics and climate change: A modeling approach. *Journal of Geophysical Research F: Earth Surface* 114: F01023.

Youssef F, Visser SM, Karssenberg D, Erpul G, Cornelis WM, Gabriels D and Poortinga A, 2012. The effect of vegetation patterns on wind-blown mass transport at the regional scale: A wind tunnel experiment. *Geomorphology* 159-160: 178–188. doi:10.1016/j.geomorph.2012.03.023.

Yuan T, Maun MA and Hopkins WG, 1993. Effects of sand accretion on photosynthesis, leafwater potential and morphology of two dune grasses. *Functional Ecology* 7: 676–682.

Zagwijn W, 1986. *Nederland in het Holoceen*. Staatsdrukkerij, Haarlem/'s-Gravenhage, the Netherlands.

Zarnetske P, Hacker S, Seabloom E, Ruggiero P, Killian J, Maddux T and Cox D, 2012a. Biophysical feedback mediates effects of invasive grasses on coastal dune shape. *Ecology* 93: 1439–1450.

Zarnetske P, Skelly D and Urban M, 2012b. Biotic multipliers of climate change. *Science* 336: 1516–1518. doi:10.1126/science.1222732.

Zhang K, Douglas B and Leatherman S, 2002. Do Storms Cause Long-Term Beach Erosion along the U.S. East Barrier Coast. *Journal of Geology* 110: 493–502.

Zhang K, Douglas B and Leatherman S, 2004. Global warming and coastal erosion. *Climatic Change* 64: 41–58. doi:10.1023/B:CLIM.0000024690.32682.48.

Zhang W, Schneider R, Kolb J, Teichmann T, Dudzinska-Nowak J, Harff J and Hanebuth TJ, 2015. Land-sea interaction and morphogenesis of coastal foredunes: A modeling case study from the southern Baltic Sea coast. *Coastal Engineering* 99: 148 – 166. doi: http://dx.doi.org/10.1016/j.coastaleng.2015.03.005.

Summary

Introduction

Coastal dunes are prominent features along many of the world's sandy shorelines. They are valued for their contributions to flood protection, biodiversity, fresh water supply and recreation. The most seaward dune ridge or foredune is the most dynamic part, showing fluctuations in size and morphology in response to erosion by the sea and subsequent recovery by interactions between wind blown sand and vegetation. Given their dependency on multiple natural processes, coastal dunes may be particularly sensitive to the effects of climate change, including sea-level rise (SLR) and changes in temperature and precipitation.

To mitigate anticipated coastal erosion in the next decades, the Dutch sand nourishment regime will be intensified to raise the beach profile proportionally to the SLR. However, it is not clear how the added sand is distributed within the foredune system and whether this enables foredunes to keep up with sea-level rise. In addition, possibilities for dune re-mobilisation are investigated to enhance landward transport and biodiversity. However, effects of this intervention on foredune dynamics and the dune landscape are not entirely clear.

This thesis has examined yearly to decadal scale foredune dynamics and the impacts of climate change and management options on these dynamics.

Which factors control year-to-year variations in dune growth on the Dutch coast?

Dunes depend on aeolian transport for sand supply. While measurements of aeolian transport show complex spatio-temporal variations, we find that the yearly sand supply to dunes along the Dutch coast is relatively constant, between 10-20 m^3/m irrespective of the beach width (Chapter 2). This means that a wider beach does not necessarily provide more sand to dunes and beach width is not a limiting factor in sand supply to the dunes.

In contrast to the sand input, the amount of sand lost during a storm surge does depend on the beach width. Wider beaches are able to dissipate more of the incoming wave energy and thus protect the dune better than narrow beaches. On a term of decades, this gives rise to steady dune growth on wider beaches and irregular, frequently interrupted growth on narrow ones.

How do biogeomorphic interactions control foredune shape?

The distribution of sand over the foredune, and therefore the morphological evolution, is strongly tied to vegetation patterns (Chapter 3). It was found that deposition patterns across foredunes show a characteristic distribution, starting with a sharp increase upon crossing the seaward vegetation limit, reaching a maximum between 5-20 m further landward and then gradually decreasing inland of the crest. The deposition pattern is further modified by the general vegetation pattern. On a timescale of years, there is no correlation between density of vegetation cover and the amount of accretion. However, by accounting for the gradual depletion of the sand load over the foredune, an empirical relationship can be defined between vegetation cover and its sand trapping efficiency. For fully covered surfaces, sand trapping efficiency is around 50%, indicating that sediment can pass densely covered foredunes.

Although literature suggests a relation between the level of plant burial and plant growth, we found no evidence for enhanced vegetation growth in high-deposition zones. A gain in vegetation cover was found to occur for burial between 0 m/year and 1 m/year, which indicates that lower and upper tolerance limits of burial have not been exceeded. Other growth-limiting factors are likely to be of similar importance, masking any possible dependency of vegetation growth on sand accretion.

What are the effects of climate change on meso-scale evolution of coastal dunes?

The results on yearly erosion/accretion and sedimentation patterns were implemented in a computer for dune evolution called DUBEVEG, developed in Wageningen (Chapter 4). Algorithms for aeolian transport and vegetation growth were taken from existing models and combined with a new module for wave action and dune erosion. The model was calibrated and validated against field measurements. The good agreement between observations and predictions indicates that the model successfully incorporates the suite of biogeomorphic and marine processes involved in dune building.

Model simulations show that the evolution of a dune strongly depends on the sequence of storms and quiet periods. During quiet periods, dunes are able to build seaward at several metres per year as vegetation colonises the area near the dune foot, leading to dune accretion. Following the dune-foot position through time, we find an irregular pattern of seaward advance and regression. However, the average of a large number of runs with varying storm sequences reveals a clear trend. For a given wave climate and beach profile, we find that the model predicts a certain seaward limit to which the foredunes may build, or equilibrium position at which erosion and accretion are balanced. If the momentary position of the dune foot is seaward of this limit, seaward movement can be rapid. If, in contrast, the momentary position is at or seaward of the limit, periods of minor seaward growth are followed by periods of landward retreat, resulting in a oscillation around the equilibrium.

Climate scenarios, consisting of SLR and a gradual change in vegetation growth, were developed to examine climate-change effects on dune dynamics. Sea-level rise largely determines the direction of dune evolution by forcing the dune-foot landwards. The rate of rising controls whether dunes are able to preserve their height or sand volume while migrating landwards. The effect of changing vegetation growth rates, resulting from climate change, is most manifest in dune response to large disturbances. If vegetation is removed halfway into the simulation, vegetation growth rate determines whether a foredune will re-vegetate and re-stabilise: a value below the threshold will preclude complete recovery and the dune remains bare.

What management options are available to mitigate climate-change effects on coastal dune evolution?

Sand nourishments are effective to mitigate the effect of SLR on coastal dunes. Model results show that by raising the beach proportionally to SLR, dunes are able to preserve their dune-foot position, height and volume. Even without nourishments, dunes are able to migrate landwards with conservation of volume and height for SLR up to 10 mm/year. However, the associated landward retreat is often not feasible.

A reduction in vegetation cover, related to either (1) artificial remobilisation, (2) dune-foot erosion or (3) climate change promotes landwards transport and therefore contributes to the long-term preservation of a wider dune zone. If vegetation growth is reduced as a

consequence of increasing summer drought, re-mobilisation becomes more effective, with high rates of landwards transport persisting for several decades.

On the long term, it is recommended to use a combination of sand nourishments and re-mobilisation efforts to preserve the coastline, promote landwards transport and make benefit of a dune's natural self-regenerating capacity. Under the precondition that safety requirements are met, these natural processes enable long-term preservation of flood protection, biodiversity and dynamic landscapes.

Samenvatting

Introductie

Duinen zijn een belangrijk onderdeel van kustlijnen over de hele wereld. Ze bieden bescherming tegen hoog water, vormen een bron van zoet water en bieden een uniek leefgebied voor planten- en diersoorten. De meest zeewaartse duinrug, het *voorduin* of de *zeereep*, bepaalt in belangrijke mate de bescherming tegen stormvloeden.

Duinen ontstaan uit de natuurlijke interacties tussen zandaanvoer door de wind, vastlegging door vegetatie en afslag door de zee. De balans tussen aanvoer en afslag bepaalt het lot van het duin. Gezien hun afhankelijkheid van natuurlijke processen en het grote belang van hun instandhouding, is het noodzakelijk om goed inzicht te hebben in de effecten van klimaatsverandering op duinontwikkeling.

Rekening houdend met een voortzettende zeespiegelstijging is het Nederlandse kustbeleid gericht op het vastleggen van de huidige kustlijn, d.w.z. de huidge positie vasthouden. Dit gebeurt door regelmatige zandsuppleties. Op termijn moet dit ervoor zorgen dat het hele kustfundament inclusief strand en duinen meegroeit met de zeespiegel. Het is echter niet geheel duidelijk hoe het gesuppleerde zand zich verdeeld over de het strand-duinsysteem en of dit de zeereep in staat stelt mee te groeien met de zee zonder dat kustveiligheid in het geding komt.

Om deze vragen te onderzoeken, is in deze dissertatie de dynamiek van de zeereep over tijdsspanne van jaren tot decennia onderzocht. Op basis van historische data zijn verbanden gelegd, die vervolgens werden doorgevoerd in een recent computermodel. Dit model, DUBEVEG, is ontwikkeld in Wageningen en biedt mogelijkheden om effecten van klimaatsverandering en beheersmaatregelen op langjarige duinontwikkeling te onderzoeken.

Bepalende factoren voor jaarlijkse duingroei

Metingen van zandaanvoer door de wind tonen aan dat de variatie in ruimte en tijd erg groot is. Opmerkelijk is dat, wanneer over een langere periode bekeken, de hoeveelheid zand die ten goede komt aan de duinen redelijk constant blijkt, ongeacht de strandbreedte (Hoofdstuk

2). De aanvoer bedraagt zo'n 10-20 m^3 per strekkende meter. Dit betekent dat de zandaanvoer op een breder strand niet noodzakelijkerwijs groter is en dan strandbreedte in Nederland geen beperkende factor voor de aanvoer is.

De hoeveelheid zand die verloren gaat bij een stormvloed varieert wèl sterk: hoe breder het strand, hoe meer het duin beschermd wordt. Dit leidt tot het beeld dat bij brede stranden, zoals op de eilandhoofden en -staarten, duinen een gestage aangroei tonen, terwijl die groei op smallere stranden vaker onderbroken wordt door afslag.

Invloed van bio-geomorfologische interacties op duinontwikkeling

Hoe het aangewonnen zand verdeeld wordt over het duin – en dus de morfologische verandering – hangt samen met het vegetatiepatroon (Hoofdstuk 3). Sedimentatie vertoont een duidelijk patroon: een scherpe toename op de overgang van onbegroeid strand naar begroeid duin en een maximum op 5-20 m van die grens. Verder landwaarts neemt de hoeveelheid snel af. Er is geen directe correlatie tussen de invang en vegetatiebedekking. Wel is er een correlatie tussen de bedekking en de fractie van het passerende zand die wordt ingevangen. Een volledig bedekt oppervlak kan to 50% invangen, de resterende 50% gaat verder landwaarts.

Daarnaast stelt de literatuur dat de groei van duinvegetatie afhangt van de hoeveelheid sedimentatie. Pioniers als helmgras gedijen namelijk het best bij een zekere mate van begraving. Als het helmgras dan beter groeit, is het ook weer beter in staat zand in te vangen. Er bestaat dus een positieve terugkoppeling tussen zandinvang en plantengroei die bepalend is voor de duinmorfologie.

De vegetatiepatronen zelf veranderen weinig door de jaren. Vegetatieclusters blijven lang in stand, al wordt de ruimte ertussen steeds meer opgevuld. De uitbreiding van vegetatie is zichtbaar in twee verschillende vormen: laterale uitbreiding van bestaande pollen op de duinflank en vestiging van nieuwe pollen nabij de duinvoet. In tegenstelling tot de verwachtingen kon de groeisnelheid van vegetatie niet gerelateerd worden aan de hoeveelheid sedimentatie. Groei kon plaatsvinden bij invang van 0 tot 1 m/jaar. Kennelijk zijn er andere factoren die in vergelijkbare mate bepalend zijn voor de groei.

Het effect van klimaatsverandering op duinontwikkeling

Met de opgedane kennis over de balans tussen aangroei en afslag en over de verdeling van zand over het duin is in Wageningen een duinmodel ontwikkeld (Hoofdstuk 4). De beschrijving van eolisch transport en vegetatiegroei zijn gebaseerd op een bestaand model dat transport en duinontwikkeling op kale tot licht-begroeide zandvlaktes simuleert. Door een module voor duinafslag toe te voegen is het nieuwe model in staat de dynamiek van kustduinen te simuleren.

Modelresultaten laten zien hoe sterk duinontwikkeling afhangt van de opeenvolging van stormen en rustigere perioden. Een stormvloed kan de duinvoet een aantal meters terugdringen. In een rustigere periode kan het duin zich herstellen mits vegetatie zich vestigt op de duinvoet. Vijftig verschillende opeenvolgingen van stormen en rustige perioden geven voor 2100 een range van 20 m waarbinnen de duinvoet zich kan bevinden.

Belangrijk is dat het gemiddelde van die vijftig runs een duidelijk patroon vertoont, namelijk een duinvoet die zich op een dusdanige positie instelt dat afslag en herstel in balans zijn. Is de duinvoet zeewaarts van die evenwichtspositie, dan zal de afslag groter zijn dan het herstel en wordt het duin teruggedrongen. Is de duinvoet landwaarts, dan het herstel groter dan de afslag en kan het duin zeewaarts uitbreiden.

De invloed van klimaatsverandering werd onderzocht door verschillende klimaatscenario's te vertalen naar input voor het model. De scenarios bestonden uit een bepaalde zeespiegelstijging en een bepaalde af- of toename in groeisnelheid van vegetatie als gevolg van hogere temperatuur en verandering in neerslag.

Duinontwikkeling is vooral gevoelig voor zeespiegelstijging. Een hogere stand leidt tot meer afslag en dringt het duin langzaam terug. Als gevolg van de afslag is de zeewaartse flank vaak onbegroeid, wat zandtransport richting de duintop en verder landwaarts stimuleert. Als dit zand vervolgens wordt ingevangen aan de landwaartse zijde van het duin, is terugtrekking met behoud van hoogte of zandvolume mogelijk. Of dit behoud ook daadwerkelijk gerealiseerd wordt, is afhankelijk van de snelheid van zeespiegelstijging: zolang zandverlies aan de zeezijde kleiner is dan het landwaartse transport, wordt het volume in stand gehouden. In de simulaties was dit mogelijk tot een stijging van 10 mm/jaar.

Het effect van een afname in vegetatiegroei als gevolg van toenemende droogte is vooral duidelijk in de respons het de zeereep op een grote verstoring. Wordt bijvoorbeeld alle vegetatie verwijderd (bijv. brand, ziekte, beheersmaatregel), dan is de mate van herstel afhankelijk van de groeisnelheid. Is die snelheid lager dan een bepaalde grenswaarde, dan is volledig herstel niet meer mogelijk. In dat geval blijft de zeereep vrijwel onbegroeid, zal zandtransport richting het achterland zich voortzetten en verplaatst het duin zich langzaam landwaarts.

Mogelijkheden voor beheer

Zandsuppleties zijn effectief om het terugdringen van de duinvoet door zeespiegelstijging teniet te doen. Door het strand te laten meegroeien met de zee, zijn ook de duinen in staat hun hoogte aan te passen en hun volume en duinvoet te behouden.

Een (tijdelijke) afname in vegetatiebedekking, hetzij door aflag, hetzij door een ingreep of klimaatsverandering, draagt bij aan landwaarts transport en daarmee aan het meegroeien van een bredere duinzone. Ook is dit positief voor de biodiversiteit.

Op basis van de resultaten wordt aanbevolen een combinatie van suppleties en dynamisch kustbeheer te gebruiken om zo het natuurlijk herstellend en aanpassend vermogen van de zeereep optimaal te benutten, zonder dat de veiligheid in het geding komt.

Dankwoord

> "Toen, op een namiddag in juni 2007, na lang te hebben gewacht en al even lang te hebben getreuzeld, wat langer zelfs dan toelaatbaar was, verdedigde ik voor de jury van de universiteit Paris IV-Sorbonne mijn proefschrift: *Joris-Karl Huysmans, of het einde van de tunnel*. Meteen de volgende ochtend [...] begreep ik dat een deel van mijn leven ten einde was, en waarschijnlijk het beste deel" (Houellebecq, 2015, p. 8).

Veel dank aan allen die hebben bijgedragen aan de voltooiing van mijn proefschrift.

Coen, dank voor de grote onderzoeksvrijheid, de grote lijnen en de rode strepen en de persoonlijke aanpak. Michel, bedankt voor de gemoedelijke, informele begeleiding en het tijdige bijsturen. Fijn dat je altijd bereikbaar was, zodat we alle hindernissen vlot konden nemen. Alma, dank voor je snelle en snedige commentaren en het delen van je enthousiasme op het vlak van de biogeormofologie.

Veel dank aan de collega's in het onderzoeksprogramma Kennis voor Klimaat, met name Jan Mulder en Frans Klijn. Jan, ik heb veel gehad aan de discussies over de richting en opzet van het werk in de beginfase van het onderzoek. Ook de samenwerking voor het artikeltje verliep erg plezierig, waarvoor dank. Frans, veel dank voor je enthousiaste leiding van het consortium 'Climate-Proof Flood Risk Management' en voor het samenbrengen en uitdragen van alle bevindingen.

Voorts dank ik al mijn collega's van de vakgroep SLM voor de vriendschappelijke sfeer en hulpvaardigheid. Ate, het was een genoegen om met je samen te kunnen werken en op dezelfde dag te kunnen promoveren. Ik heb genoten van de nietsontziende discussies, dramatische scriptjes en prachtige plotjes. Corjan, Sya en Celia, *muito obrigado* voor het goede gezelschap en de even ontspannende als prikkelende omzwervingen. Piet, dank voor de mooie dagen in Zuid-Limburg en Kwintelooyen. Het was altijd een welkome onderbreking van het dagelijkse onderzoekswerk.

Jasper, dank voor je gezelschap tijdens onze afstudeerscriptie. Het was een prachtige ervaring die me gestimuleerd heeft verder te gaan in het onderzoek. Ik kijk ernaar uit om weer met je samen te werken in de nabije toekomst. Joeri, ik ben je zeer erkentelijk voor de mooie tijden die we hadden als collega-promovendi in de Dijkstraat. Al was het niet altijd meetbaar productief, de kiem van onze proefschriften is daar gelegd. Luc, ik hef het glas op alle geslaagde avonden, sublieme uren op de veranda, de algehele teloorgang en het zuur in onze poten. Proost!

Pap, Mam, Floor, Daan, Peter en Linda: dank voor jullie steun en uitstekende verzorging in tijden van rust. Ik keerde telkens blakend van gezondheid en vol goede moed terug uit Kessel.

Lieve Geerte, het heeft even geduurd, maar het is nu toch maar mooi af. Dank voor je grote geduld, je vertrouwen en advies. Graag ben ik eenzelfde steun voor jou bij het schrijven van jouw proefschrift.

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

For specialised PhD training

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Joep Gerardus Servatius Keijsers

born on 14 August 1986 in Venlo, The Netherlands

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Wageningen, 30 November 2015

the Chairman of the SENSE board	the SENSE Director of Education
Prof. dr. Huub Rijnaarts	Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Mr Joep Keijsers** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 38 EC, including the following activities:

SENSE PhD Courses

- Environmental Research in Context (2011)
- Workshop Valorisation of PhD Research in Climate Sciences (2014)
- Hyper-temporal earth observation for food security and biodiversity assessment (2012)
- Modelling critical transitions in nature and society (2014)
- Research in Context Activity: Writing a popularising and explanatory article on the scientific and societal relevance of PhD research on the morphological evolution of dunes (Geo.brief, 2014)

Other PhD and Advanced MSc Courses

- PhD competence assessment, Wageningen University (2011)
- Scientific writing, Wageningen University (2013)
- Reviewing a scientific paper, Wageningen University (2013)
- Data management planning, Wageningen University (2013)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'Analyse van de effecten van de kustversterking bij Nieuwvliet en Groede op kustontwikkeling, vegetatieontwikkeling en perceptie omwonenden' (2012)
- Lecturing in BSc course 'Soil and Water II' (2012)
- Assisting fieldwork practical of BSc course 'Erosie en bodem- en waterconservering'(2012-2013)
- Assisting fieldwork practical of BSc course 'Introduction to Land Degradation and Remediation'(2013-2014)
- Assisting computer practical of BSc course 'Hydrogeology' (2014)

Oral Presentations

- *Connecting aeolian sediment transport with foredune development.* Netherlands Centre for Coastal Research (NCK) Days 2012, 15-16 March 2012, Enchede, The Netherlands
- *Coastal dune behaviour at different beach widths*. EGU 2013 General Assembly, 7-12 April 2013, Vienna, Austria
- *Modelling coastal dune development under climate change*. Conference Deltas in times of climate change II, 24-26 September 2014, Rotterdam, The Netherlands
- *Modelling the bio-geomorphological evolution of coastal dunes*. Netherlands Centre for Coastal Research (NCK) Days 2015, 18-20 March 2015, Schoorl, The Netherlands

SENSE Coordinator PhD Education

Dr. ing. Monique Gulickx

The research described in this thesis was carried out within the national research program Knowledge for Climate, Theme 1: Climate Proof Flood Risk Management, which was funded by the Ministry of Infrastructure and the Environment.