J Coast Conserv (2017) 21:409–419
DOI 10.1007/s11852-016-0446-8

Tales of island tails: biogeomorphic development and management of barrier islands

Alma V. de Groot[1] · Albert P. Oost[2] · Roos M. Veeneklaas[3] · Evert Jan Lammerts[4] · Willem E. van Duin[1] · Bregje K. van Wesenbeeck[2]

Received: 2 December 2015 / Revised: 4 May 2016 / Accepted: 9 June 2016 / Published online: 21 June 2016

Abstract The Frisian islands (Southern North Sea) have extensive island tails, i.e. the entire downdrift side of an island consisting of salt marshes, dunes, beaches and beach plains, and green beaches. Currently, large parts of these tails are ageing and losing dynamics, partly due to human influence. This may mean a loss of young stages on the long term, and current management is not enough to counteract this. To aid the development of new interventions aiming at (re)introducing natural dynamics, a conceptual model of island-tail development under natural and disturbed conditions was developed, based on existing data, field visits and literature. The development of an island tail follows the general pattern of biogeomorphic succession. The first phase consists of a bare beach plain. In the second phase, embryonic dunes form. In the third phase, green beaches, dunes and salt marshes form, including drainage by creeks and washovers. In the fourth phase, vegetation succession continues and the morphology stabilises. Human interference (such as sand dikes and embankments) reduces natural dynamics and increases succession speed, leading to a reduction in the diversity in landforms and vegetation types. Both for natural and human-influenced island tails, succession is the dominant process and large-scale rejuvenation only occurs spontaneously when large-scale processes cause erosion or sedimentation. Island tails cannot be kept permanently in a young successional stage by reintroducing natural dynamics through management interventions, as biogeomorphic succession is dominant. However, such interventions may result in local and temporal rejuvenation when tailored to the specific situation.

Keywords Salt marsh · Vegetation succession · Wadden Sea · Dunes · Nature management

Introduction

The barrier islands in the West- and East-Frisian Wadden Sea can be categorized as mixed energy, micro- to upper mesotidal barrier islands (Fig. 1). Despite their individual characteristics, they consist of various recognizable elements, such as the island head, one or several dune arcs, one or several washover complexes, island tail and the beach and shoreface (Oost et al. 2012). Most islands are inhabited and are used for agriculture and tourism. The island tails, however, are often protected as nature reserve (as National Park and/or within Natura 2000) for their specific vegetation and importance for breeding birds.

An island tail is the downdrift part of a barrier island, i.e. the tapering part of the drumstick-shaped island, away from the dominant transport direction (Fitzgerald et al. 1984). It contains several landscape elements: going from the open sea towards the back-barrier first a beach and/or beach plain, then dunes, washovers, salt marshes with creeks, and finally intertidal flats (Doing 1982; Ehlers 1988; Oost et al. 2012). The geomorphology and vegetation types are strongly related (Doing 1982), given that ecosystem engineering plant species are essential for the formation of dunes and salt marshes

---

Vegetation nomenclature follows Van der Meijden, 2005. Heukels' Flora van Nederland, 23rd ed.

✉ Alma V. de Groot
alma.degroot@wur.nl

[1] IMARES Wageningen UR, P.O. Box 57, 1780 AB Den Helder, The Netherlands

[2] Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands

[3] Bosgroep Noord-Oost Nederland, Balkerweg 48a, 7738 PB Witharen, The Netherlands

[4] EGG Consult, P.O. Box 1537, 9701 BM Groningen, The Netherlands

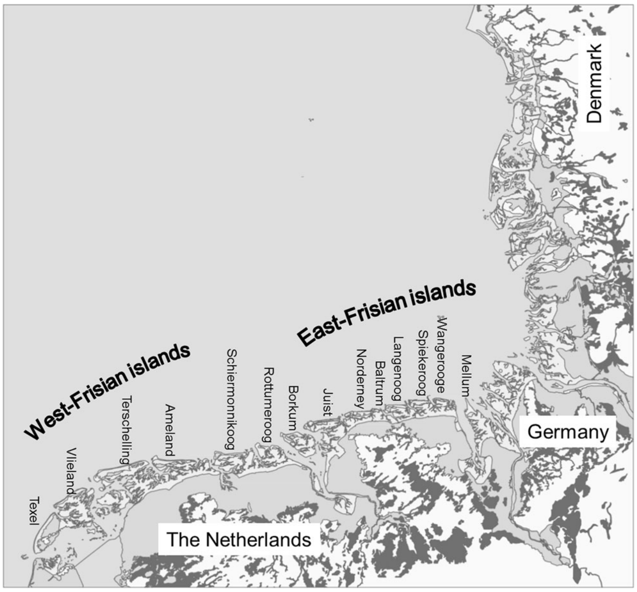


Fig. 1 The barrier islands of the Southern North Sea

(Doing 1982; Ehlers 1988; Corenblit et al. 2015), and that there are strong gradients in hydrodynamic energy, inundation, and salt spray. The geomorphology of island tails may change through time as the result of inlet and ebb-delta channel migration, sea-level rise, lateral salt-marsh growth, dune migration, and washover development (Oost et al. 2012; Wang et al. 2012).

At the moment, large parts of the island tails are ageing and losing dynamics (Esselink et al. 2009). On the salt marshes, which make up a considerable part of an island tail, vegetation succession is a natural process that depends on time since colonisation, nutrient availability, elevation relative to Mean High Water (MHW), drainage, soil development, and herbivory (Adam 1990; De Leeuw et al. 1993; Olff et al. 1997; Bakker 2014). When a salt marsh is reaching maturity (here about 100 y, Olff et al. 1997) the vegetation reaches monocultures of Sea couch (*Elytrigia atherica*) and, more recently, locally stands of Reed (*Phragmites australis*). Dunes and dunes slacks on the island tails undergo similar vegetation succession towards climax stages (Dijkema and Wolff 1983). Without human interference, the dynamic nature of the Wadden Sea leads to the periodic erosion of older island landforms and creation of opportunity for pioneer stages (Ehlers 1988), thus resulting in natural rejuvenation on various timescales. In addition, the dynamics of wind and water may to set back or delay vegetation succession through regular disturbance (Löffler and van den Hooff 2011).

However, also human impact, becoming more pronounced since 1900 (Thorenz 2011), has played a marked role in the loss of dynamics and consequential aging. Interventions such as fixating dunes and building sand-drift dikes (Ehlers 1988; Oost et al. 2012), creating drainage ditches, embankments, anthropogenic nitrogen deposition, and coastal defence affected hydrodynamics, hydrology and sediment transport, which in turn and led to accelerated vegetation succession, loss of area, and limited development of new tidal marshes (Esselink et al. 2009). The resulting loss of young successional stages implies a loss of biodiversity on the long term.

The (potential) loss of young stages and biodiversity as a result of human impact inspired trilateral conservation targets defined for the Wadden Sea by The Netherlands, Germany and Denmark. The targets are a specification of the UNESCO criteria for the Wadden Sea World Heritage property and are related to the European Birds and Habitats Directives, Water Framework Directive, and Marine Strategy Framework Directive (Common Wadden Sea Secretariat 2010). They aim (amongst others) to increase the natural dynamics of beaches, primary dunes, beach plains and primary dune slacks in connection with the offshore zone, as well as to maintain the full range of variety and natural dynamics of salt marshes, and to obtain an increased presence of a complete natural vegetation succession. The aim to maintain the complete successional series implies that there should be regular new formation of pioneer stages through natural dynamics, as older successional stages develop spontaneously from those. Not mentioned in the trilateral targets but important for island tails is that sea-level rise may pose a threat to stabilised barrier islands, whereas island with natural dynamics are more resilient under extreme storms (Feagin et al. 2010; Oost et al. 2012).

Current management of island tails mainly consists of 'letting nature be nature'. This is inspired by the fact that, despite human impact, these island tails are some of the most natural parts of Germany and The Netherlands. Additionally, livestock grazing is practiced on several of the older marshes and dunes, both for vegetation management and agricultural purposes. Livestock grazing increases vegetation diversity but is insufficient for real rejuvenation, as accretion and landscape development continue and are not set back to a pioneer situation. Other types of nature management (sod-cutting, changes in hydrology, de-embankment, etc.) are practiced but are relatively rare on the island tails. Given the continuous stabilisation of the island tails, the current management is not sufficient for reaching the trilateral targets.

Alternative management measures to counteract these human influences and reach the above targets, could involve reintroducing the natural dynamics of wind and water into the system, e.g. by creating opportunities for overwash and aeolian activity that could set back vegetation succession. Ideally, once the opportunity is created, the natural dynamics should maintain themselves. Such management interventions are currently considered in The Netherlands. There are, however, large uncertainties around how to carry out such interventions, and whether it is at all possible to increase biodiversity sustainably through reintroducing dynamics. To be able to assess this, a better understanding of the development of island tails is needed with respect to the geomorphology, hydrodynamics and hydrology, vegetation and fauna, and their interactions (cf. Hobbs and Norton 1996). For this, we developed a conceptual model of island-tail development under natural and disturbed conditions that can serve as frame of reference for nature managers and scientists. Based on existing literature and new data analysis, it is evaluated which are the strongest factors determining vegetation succession, and consequently on which factors management for rejuvenation should be aimed.

Study area

The study focusses on the Wadden Sea in The Netherlands and Lower Saxony (Germany), as this is a relative homogenous part of the international Wadden Sea (Fig. 1). The region is a barrier system developed in the Holocene, with barrier islands consisting of sands and muds and a large intertidal area between the mainland (generally consisting of embanked former salt marshes) and the islands (Ehlers 1988). The Holocene sea-level rise and ample sediment availability have been the key factors in the development of the system. Additionally, large-scale embankments dating from the Early Middle ages to the 20th century and large storm surges during the Middle Ages strongly determine the shape of the current Wadden Sea (Reise 2005). On a small number of places, moraines from the Pleistocene form the core of the barrier islands. Tidal range increases from 1.4 m in the west to approximately 3 m to the east in the German Bight (Postma 1982), leading to a general decrease in barrier length from west to east.

Building on the available information, vegetation development was studied in more detail for the island tails of Terschelling (NL), Schiermonnikoog (NL) and Spiekeroog (D). The three islands all have at least one dune arc system (Oost et al. 2012) and polder, and the island tails are well developed. The tails are located at the eastern part of the islands, as the dominant sediment transport direction along the Wadden Sea coast is from west to east. The salt marsh of Terschelling mostly dates from the 1930's, whereas that of Schiermonnikoog exhibits a chronosequence from 200-y old marshes to recently-formed ones (Jager 2006), and Spiekeroog has developed gradually since the 1940's – 1960's (Veeneklaas et al. 2013).

Methods

The Wadden Sea is a well-studied system and we could make use of a large set of existing data. This was supplemented with field visits to several islands (Terschelling, Ameland, Schiermonnikoog, Norderney, and Spiekeroog) in which concepts and literature findings were checked. Used data include: aerial photographs (e.g. Ten Haaf and Buijs 2008) dating from the beginning of the 20th century; qualitative historical descriptions from the 19th and 20th century; JARKUS data (elevation profiles from the foreshore to the dunes for the Dutch islands); LiDAR data; topographic maps; age map (Schiermonnikoog); vegetation maps; measurements of the thickness of salt-marsh deposits; vegetation composition (permanent quadrats); elevation measurements; sedimentation rates; literature with overviews of the Frisian islands (Dijkema and Wolff 1983; Ehlers 1988; Oost 1995; Petersen and Pott 2005). The data were used to expand on the model island (Oost et al. 2012). As there exist no island tails with a fully undisturbed development, natural island-tail development had to be reconstructed from historical maps and (aerial) photographs.

Conceptual model

Variations in island tails

When comparing the island tails of the Frisian islands that are big enough to have one (i.e. there needs to be at least one well-developed dune arc system), the first thing that stands out is the variety in size (Fig. 2). The island tail of Vlieland is virtually non-existent, whereas the island tails of Terschelling and Schiermonnikoog are – with sizes of about 8 km – almost the size of the entire island of Spiekeroog. Also the relative size of a tail with respect to rest of the island is very variable. These variations are related to the differences in age and developmental stage of the tails, tidal range (larger tidal ranges tend to lead to smaller islands), sediment balance (e.g. trough embankments elsewhere in the tidal basin (Fitzgerald et al. 1984; Oost 1995)), dynamics of the ebb-tidal delta and inlet, and human impact (Wolff 1986; Oost et al. 2012). As a result of the different sizes and ages, not all tails contain the same elements, or the same number and size of elements. However, the elements are generally placed in more or less comparable spatial layouts (Doing 1982), and the development follows a recognisable pattern. Consequently, a conceptual model for the development of island tails was constructed.

Biogeomorphic succession

Systems in which biota exert a strong influence on the geomorphology and vice versa are called biogeomorphological (or biogeomorphic) ecosystems (Viles 1988). Such systems are identified along rivers and for dunes, salt marshes and mangroves, and develop through a number of characteristic phases from a situation dominated by physical processes to one dominated by biotic processes, together called biogeomorphic succession (Corenblit et al. 2007, 2015; Balke 2013). Initially, the substrate is bare and the geomorphic processes dominate. In the second phase, or pioneer phase,

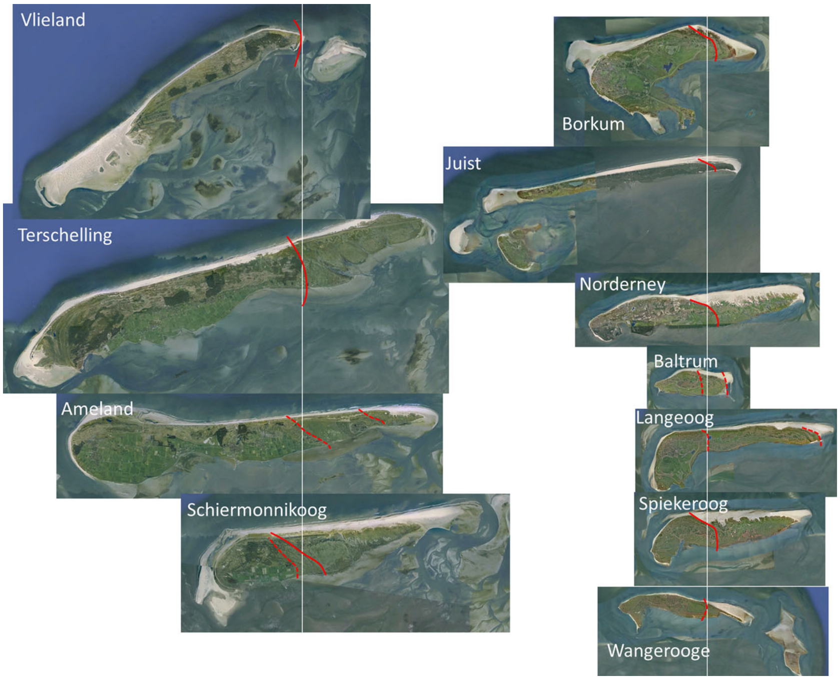


Fig. 2 Overview of the island tails of The Netherlands (*left*) and Lower Saxony (*right*). The scale of the figures is identical. Tidal range increases from upper left to lower right. *Lines* indicate the western border of the island tail (*solid* = certain, *broken* = uncertain), and the islands are shifted such that the beginning of the island tail lies around the *white line*). Imagery: Google Earth

pioneer organisms establish, but are largely controlled by the hydrodynamic and aeolian forces. For the organisms, facilitation dominates (Bertness and Callaway 1994) and many of the organisms are ecosystem engineers (Jones et al. 1994). When the influence of the biota gains strength and a larger percentage of the surface is covered with vegetation, the third, biogeomorphic phase commences, where the landscape processes are dominated by biogeomorphic interactions. In the final, ecological phase, the biological processes dominate the landscape. Here, the concept of biogeomorphic succession is applied not only to the individual elements of salt marsh and dunes, but to the entire set of landscapes and their developments that together form an island tail (Fig. 3).

First phase

On island tails, the first biogeomorphic phase consists of a bare beach plain of several kilometres long that stretches from the updrift dune-arc complex to the downdrift inlet (Fig. 3). This beach plain forms either when a large sand bar welds to the island (Terschelling, Ehlers 1988, and Spiekeroog, Röper et al. 2013), develops gradually (Schiermonnikoog, Olff et al. 1997), or consists of an eroded dune-arc system (in the case of Ameland combined with episodic growth and erosion, Ehlers 1988). Still, the development of landscape elements in the following phases takes place regardless of how the beach plain forms. The beach plain is highest approximately halfway the open sea and the back-barrier and may contain very shallow channels carved out during overwash. During strong winds, moving barchanoid dunes may develop and cover a large part the beach plain. Overwash events redistribute these again.

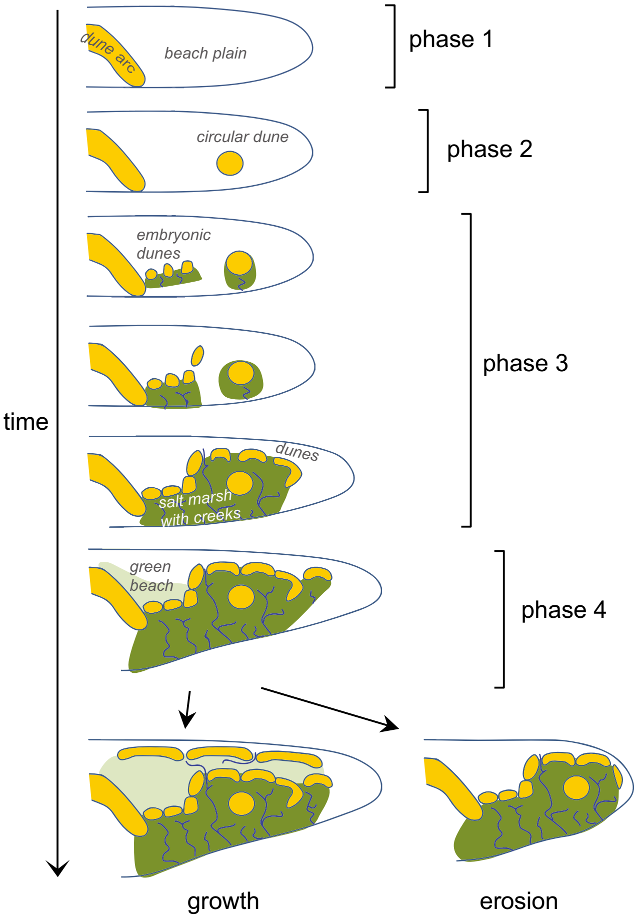


Fig. 3 Conceptual model of island-tail development (after Ten Haaf and Buijs 2008)

Second phase

In the pioneer phase, pioneer plants such as *Elytrigia juncea* establish (Van Dieren 1934; Bakker 1976). This development takes place at the highest place, halfway the open sea and the back-barrier, and adjacent to the existing dune-arc complex (Fig. 3). Here, storm surges deposit driftline material and hydrodynamic forces are intermittent enough to allow for windows of opportunity for vegetation establishment (Balke et al. 2011; Balke 2013). The pioneer plants catch and bind the aeolian sand, and after a number of years without strong storm surges, an embryonic dune field develops (Van Heteren et al. 2006).

Third phase

In the third phase, the freshwater lens that develops under the embryonic dune field allows the establishment of *Ammophila arenaria*, leading to the formation of white dunes that are outside the reach of the seawater. These dunes may either develop into one or more large circular dunes, an intermittent foredune (Röper et al. 2013) or, when sand supply is cut off by the seaward establishment of vegetation, low hummocky dunes. The dunes shelter the back-barrier side of the island tail from the dynamics from the open sea, so that salt-marsh vegetation can establish and clays and silts can be deposited (Olff et al. 1997, Fig. 3). The combination of pre-existing topography, flow-channelling effect of the vegetation, and spatial variations in accretion leads to the formation of a channel network in the salt marsh (Allen 2000; Schwarz et al. 2014). Headward erosion gradually increases the size and density of the creek network over the following decades. The creek network either ends in a depression flanked by dunes, or is connected to a washover channel. In the first and second phase, overwash could move virtually freely over the island tail during storm surges. In the third phase, overwash becomes channelled between the developing dunes. At the side of the already existing dune-arc complex, a washover complex develops (Ehlers 1988): a wide (several hundreds of metres), low-lying area with microbial mats and/or green-beach vegetation, flanked by dunes on either side and the salt-marsh on the back-barrier side (Fig. 3). In between the developing dunes, smaller washovers develop that have a clear throat and lack the extensive area of microbial mats, probably because the amount of fresh groundwater outflow at these locations is limited. The washovers and washover complexes function as sand transport pathway from the beach towards the back-barrier area, either during overwash or by subsequent aeolian transport (Ehlers 1988; Nielsen and Nielsen 2006). Some of the creeks are connected to a washover channel, and some washovers are connected to salt-marsh creeks, but there are also many cases in which no connection is made.

Green beaches (the local name for a mosaic of salt-marsh, dune-slack and dune vegetation, often in combination with microbial mats) develop seaward from the dunes (Fig. 3), where freshwater outflow from the dunes facilitates vegetation establishment. Their shape can vary from rather flat and dominated by microbial mats, to being dominated by embryonic dunes, depending on the amount of freshwater seepage and sand availability. The presence of a green beach strongly reduces aeolian sediment supply to the dunes.

Windows of opportunity for vegetation establishment are pivotal for when certain landscape elements can develop (Balke et al. 2011), and thus the speed of the development from the second into the third phase and which elements are present at a certain time. These windows of opportunity depend on meteorological variations that determine e.g. water levels and precipitation, and thus seed dispersal, germination and (wave) erosion. Consequently, there is a distinct element of chance in the spatial and temporal development of an island tail.

Fourth phase

In the fourth phase, the individual parts of the island tail undergo vegetation succession and the morphology stabilises. The dunes merge into a new dune arc and may become vegetated with shrubs and trees. The washovers gradually fill up. The salt marsh continues to expand onto the intertidal flats and the creek system partly deepens and partly fills in. When the salt marsh has risen considerably above the tidal flats, an eroding cliff may form that theoretically on the long term would create space for new marsh formation (Yapp et al. 1917). Some of the green beaches develop quickly into a primary dune slack (e.g. on Schiermonnikoog), whereas others can stay in the same state for decades (e.g. on Spiekeroog). The effect of soil formation becomes more pronounced, and sand and salt spray reach less far into the lee side of an island tail, leading to the transition from white to grey dunes. The time it takes for a tail to develop from a bare beach plain into a full-grown fourth phase is approximately 50–100 years.

The long-term fate of the island tail depends not on the development of the island tail itself, but on the processes of the barrier island and inlets that act on larger spatial and temporal scales. Those determine the net sediment budget and thus the growth or erosion of the island tail. In the case of growth, new but often smaller landscape elements form: a green beach and dunes seawards of the dune arc or at the distal end of the tail, and salt-marsh growth onto the intertidal flats and distal end. In this way, parts of the island tail may be in a different phase of the biogeomorphic succession than others.

Human impact

The here described development is the spontaneous development without human interference. However, all Frisian island tails have experienced human impact to a smaller or larger degree (Table 1), often technical interventions intended to efficiently use the area. These include reinforcing the dunes (for coastal protection), embanking the salt marsh (for agriculture and human settlements), draining and protecting the salt marsh (for agriculture in the form of livestock grazing), and driving on the beach (for recreation or patrolling). For nature conservation, measures such as sod-cutting (in the dunes), changing artificial drainage (salt marsh) and livestock grazing were applied. But also human activities further away, such as natural gas extraction, sand nourishments, and embankments in the back-barrier basin affect island tails. All of these have had more or less impact on the development of the island tails, but the largest impact by far is from the construction of sand-drift dikes. Sand-drift dikes were constructed on all Dutch inhabited islands and a limited number of German ones, as a way to stabilise the coast and prepare for the embankment of the Wadden Sea (Oost et al. 2012). Sand-drift dikes were constructed till approximately the 1960's and measured several kilometres in length, spanning virtually the entire island tail. The sand-drift dikes effectively meant an accelerated development towards a closed dune arc, in which also washover complexes were closed (Fig. 4). By reducing the dynamics of wind and water from the open sea, any existing dune and washover morphology on the sheltered back-barrier side became frozen in time, and the bare area quickly developed into a large salt-marsh area. The development of the island tail depends on in which phase of the development the sand-drift dike was constructed (Fig. 4). When early in the development, such as on Terschelling (Roozen and Westhoff 1985), a large but rather monotonous salt-marsh area develops in which rapid vegetation succession takes place. When the island tail was already in phase 3, such as on Ameland and Schiermonnikoog (Ehlers 1988), embryonic dunes were 'fossilized' and could not grow out as sand transport was cut off, and salt-marsh development accelerated. Spatial variation was high in the first decades, but strongly declined afterwards. The island tail of Spiekeroog shows the development without a sand-drift dike, with the washover complex playing an important role in the spatial variation in landscape types.

Table 1 Types of human interference on island tails, with references where these types are described for the Wadden islands

Type	Reference
Technical	
Sand fences	Bochev-van der Burgh 2012
Marram planting	Bochev-van der Burgh 2012
Sand-drift dikes	Bochev-van der Burgh 2012; Oost et al. 2012
Embanking local salt marsh	Ehlers 1988
Stone revetments	Van Loon-Steensma and Slim 2012
Drainage (e.g. ditching salt marsh)	Veeneklaas et al. 2013
Brushwood groynes	
Driving over the beach	
Nature management	
Livestock grazing	Bakker et al. 2000
Adapting drainage	Linders et al. 2013
Sod cutting	Linders et al. 2013
Indirect	
Embanking in back-barrier area	Fitzgerald et al. 1984; Oost 1995
Mining (gas and salt extraction)	Dijkema et al. 2010; Van Dobben and Slim 2012
Sand nourishments	De Jong et al. 2014

A sand-drift dike does not necessarily exclude all dynamics on the island tail: the sand-drift dike of Schiermonnikoog was repeatedly breached and left in that state (Ehlers 1988; Oost et al. 2012), on Schiermonnikoog and Ameland salt-marsh and dune formation commenced downdrift from the end of the sand-drift dikes, and on Terschelling a smaller dune and salt-marsh area (Cupidopolder) developed seawards of the sand-drift dike. This has however not compensated for the loss of dynamics on the rest of the tail.

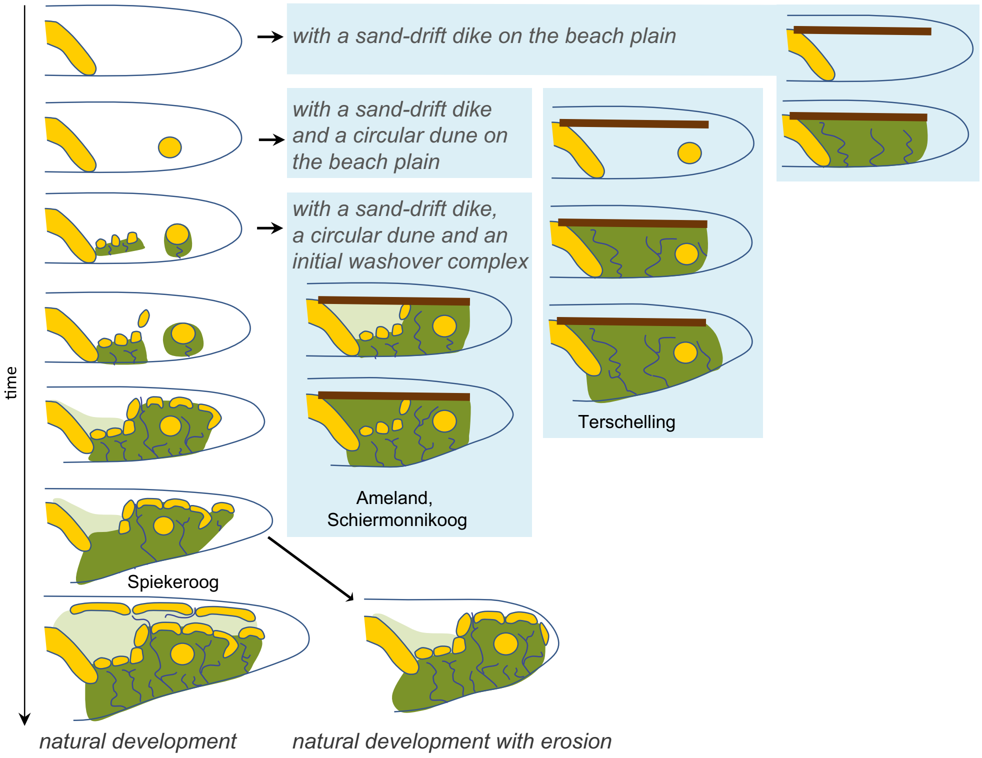
Disturbances & regression & natural dynamics

During biogeomorphic succession, natural disturbances or internal processes may set back part of the system to an earlier stage. Large-scale rejuvenation of island tails has not been observed the past century, but there are various processes that can cause rejuvenation on a smaller scale.

The most notable disturbance affecting island tails in this region are storm surges and storm winds. With overwash and flooding water depths that are characteristically of the order of a few meters, they are not as extreme as hurricanes on the US East coast (Masselink and van Heteren 2014), but are still strong enough for morphological adjustments, such as overwash and washover deposition, dune erosion, dune deflation, and salt-marsh edge erosion. These may lead to destruction or burial of the vegetation and hence vegetation regression (i.e. rejuvenation). The area covered by washover deposits depends on the developmental stage of the tail and becomes limited once the salt marsh has established (Ten Haaf and Buijs 2008; De Groot et al. 2011). The role of washover in vegetation composition of island tails needs further study. Frequent storm disturbance is probably one of the mechanisms in which low-lying washover complexes can survive for several centuries and how fresh dune slacks are set back through inundation with seawater. For the salt marsh, storm surges are often a constructive rather than a destructive force, as they deposit fine-grained sediment and are vital to its survival (Schuerch et al. 2012).

Local processes that can lead to rejuvenation include grubbing and trampling of geese, inhibited drainage at the salt

Fig. 4 Island-tail development under undisturbed (*left*) and disturbed (*right*) conditions, with examples of island tails



marsh further from the intertidal flats caused by differential accretion (Veeneklaas et al. 2013), salt-marsh cycling (Yapp et al. 1917), overgrazing by rabbits, extensive driftline deposition, and spontaneous blocking of creeks.

The circumference of an island tail varies on the long term due to several processes: shifts in position of the inlets, pseudo-cyclic shifts of ebb-tidal delta and back-barrier channels, coastal erosion, sediment delivery from the ebb-tidal delta, and overwash (Dean 1988; Sha 1989; Davis 1994; Van Veen et al. 2005; Cheung et al. 2007; Ten Haaf and Buijs 2008; Elias et al. 2012). Such changes may lead to the formation of new beach plains, and it is expected that the current erosion of the tails of Ameland and Terschelling will, somewhere within the next century, give way to new beach plains to be colonised. Barrier roll-over caused by large-scale coastal erosion offers another opportunity for rejuvenation.

Discussion

General

The development of island tails on the scale of a century is one of progressing biogeomorphic and vegetation succession, with locally regression through internal and external processes. The biogeomorphic succession will lead to reduced dynamics over time as a natural phenomenon, including a reduction in biodiversity. Large-scale setbacks, other than complete erosion, have not been observed the past century and seem to happen only on longer timescales. An example of this is the destruction by storms and storm surges of the dune-arc complex of East Ameland between 1665 and 1825. More than half a century later, the first colonisation took place that resulted in the island tail as we know it today. Normally such developments will take many decades to several centuries and may well alternate with long periods of relative stasis, such as on Borkum. Given that a possible construction – destruction cycle of an island tail may take several centuries, and the characteristic development time to a phase four island tail takes 50–100 y, full development of a given island tail towards the fourth phase is very likely (cf. Feagin et al. 2010).

This may lead to conflicts between natural landscape development and the management aims of preserving for instance significant areas of pioneer landscapes. Even in a phase-four island tail, dynamics at the edges of the tails will probably allow for the continuation of smaller-scale pioneer communities. To obtain equal areas of the complete natural vegetation succession series, as the trilateral targets are often interpreted, all island tails within the Wadden Sea should, at a given time, be in different stages of their development. Management should then be aimed at safeguarding the various successional stages, and hence biodiversity, on a larger scale than one island tail, taking into account dispersal strategies, average times of population persistence and windows of opportunity (e.g. Oostermeijer and Hartman 2014). As island heads may contain similar elements and communities as island tails (dunes, green beaches and salt marshes), they should be included in such nature-management strategies. The current challenge is that human impact has led to more uniformity between the island tails. The consequences for the survival of certain communities and species would be subject for further study.

Sand-drift dikes have been very effective in causing the desired effect at the time, i.e. an increase in stability of the island tails and increase of the vegetated surface area. Ecologists were enthusiastic in the beginning as the area quickly developed into the species-rich part of phase 3: large salt-marsh areas developed and green beaches turned into dune slacks with high conservation value (Van der Veen et al. 1997). As a consequence of the sand-drift dikes, the area of back-barrier salt marshes is now larger than it was in the previous centuries (Dijkema 1987) and many islanders believe that without sand-drift dikes, island tails would not exist. Only later came the notion that the speeded-up development was a cause for monotony in later stages and that the lack of overwash processes might lead to a sediment deficit of the barrier (Oost et al. 2012), even if vegetation succession was also facilitated by the increased atmospheric nitrogen deposition.

Interventions

The effect of a sand-drift dike is essentially an artificial foredune that accelerates the development towards phase four. Without a sand-drift dike, the same island tails would by now most probably also be in a late phase three or in phase four, but then with more spatial variation and more opportunities for local rejuvenation. The notion of reintroducing abiotic dynamics on island tails with sand-drift dikes is inspired by the intermediate disturbance hypothesis (Grime 1973), where disturbances provide the opportunity for organisms from early successional stages to recolonise, leading to the presence of all successional stages and thus high biodiversity. Given our current knowledge of the parts of the island tails without sand-drift dikes, the biogeomorphic succession seems stronger than the disturbances, so that the current level of natural disturbances may increase biodiversity on decadal timescales, but does not maintain it over a timespan of a century at the scale of a single island tail. Biogeomorphic succession is the cause that the reintroduction of dynamics of wind and water by washover recreation on an island tail of phase four will not result in the creation of a fully phase two or early phase three island tail, unless large-scale intentional clearing is done to set the succession back strongly. Soil formation, clay deposition, and established vegetation will in many cases resist the erosional forces of wind and water that would introduce dynamics in an early phase two situation. Reintroducing dynamics can therefore never guarantee that all successional stages will be restored and hence that biodiversity will be significantly and long-lastingly restored.

Recommendations

Despite local human interferences, island tails have a large degree of naturalness compared to many landscapes of Northwest Europe. Passive management by natural processes is therefore most suited. However, the many human interferences have decreased the dynamics of wind and water to such a degree, that the threshold for natural set-back of succession has become too high. In that case, additional measures could be considered that reintroduce dynamics on a decadal timescale and create room for pioneer communities. With that come the following recommendations:

Regarding naturalness and sustainability, one-off interventions are preferred over ones that need to be repeated. Ideally, the natural processes need to be able to take over after the intervention. Processes observed on the many small, unmanaged islands of the Wadden Sea may give direction to the way to do this (Hellwig and Stock 2014). However, as biogeomorphic succession continues, the effects of interventions will at best last several decades if not less.

Work with the large-scale processes and developments rather than against them. That means that nature managers and coastal managers should discuss the possibility of local erosion to increase dynamics as long as there are no concerns for coastal safety (Hillen and Roelse 1995).

Take into account the spatial dependence and dynamics of the elements and adjust management to the preservation of this dependence and dynamics. For example: for a dynamic foredune and considerable landward aeolian sand transport to exist, a non-vegetated beach is needed to provide sufficient sand availability. When a green beach is present, activation of the dunes will only have small, local effects.

As each island tail and even part of an island tail has a unique history, large-scale development, and opportunities, interventions need to be tailored to a specific location. In some places, breaching the sand-drift dike is the only option for rejuvenation, whereas on other locations large-scale erosion will lead to spontaneous erosion events. Breaching a sand-drift dike has best chances where there is a lower part in the landscape.

Value the older successional stages. The presence of the full set of successional stages will lead to the largest biodiversity as different flora and fauna have their optimum in different phases. In salt-marshes and dune slacks the youthful stages are often considered most valuable regarding the species richness and number of red-list species of the vegetation (e.g. Bakker 1989; Grootjans et al. 2008). However, climax stages do not necessarily have the lowest conservational value overall: for example, on the salt marsh, invertebrates have highest biodiversity in the climax stage (Van Klink 2014).

Possible drawbacks of rejuvenation should be taken into account and mitigated if needed, such as potential effects on coastal safety (although generally negligible, De Groot et al.

2015), reduced accessibility during storm events (recreation), and reduced predictability of flora and fauna composition.

The conceptual model presented here is also applicable to newly forming islands on a bare sand flat, without an adjacent dune arc complex (Doing 1982). In this case, the same biogeomorphic succession applies, but without the formation of a washover complex and possibly a smaller area of green beach, as less outflowing groundwater is available. Examples of such islands are Richel, Rottumeroog, Kachelotplate, Mellum and Trischen (Hellwig and Stock 2014).

Conclusions

The concept of biogeomorphic succession can not only be applied to individual landforms along the interface of land and water, such as dunes and salt marshes, but also to the assembly of landforms present on (the tail of) a barrier island.

Human interference has reduced the natural dynamics of island tails and accelerated succession, leading to a reduction in the diversity in landforms and vegetation types.

Both for natural and human-influenced island tails, succession is the dominant process and large-scale setbacks in succession most likely only occur when large-scale processes cause the erosion of part of the island tail.

Passive management by natural processes is most suited on island tails. In case bottlenecks for pioneer species are perceived, reintroducing hydro- and aeolian dynamics may locally create rejuvenation. However, island tails as a whole cannot be kept permanently in a young successional stage by reintroducing natural dynamics, as biogeomorphic succession is dominant. Therefore, it is recommended to take large-scale developments into account in island-tail management: for the large-scale formation of young successional stages, ample time and space for natural processes are essential, i.e. patience and land surface.

Acknowledgments We would like to thank Elske Koppenaal and Jan Bakker for providing access to long-term salt-marsh data from the University of Groningen as background information for the conceptual model, and Oscar Bos for help with the figures. This study was funded by the OB+N network, Deltaprogramma Waddengebied, and Programma naar een Rijke Waddenzee (all parts of the Dutch Ministry of Economic Affairs). The OB+N expert team Dunes and Coast is thanked for critical comments and suggestions.

References

Adam P (1990) Saltmarsh ecology. Cambridge University Press, Cambridge, 461pp

Allen JRL (2000) Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quat Sci Rev 19(12):1155–1231

Bakker JP (1976) Phytogeographical aspects of the vegetation of the outer dunes in the Atlantic province of Europe. J Biogeogr 3(2): 85–104

Bakker JP (1989) Nature management by grazing and cutting: on the ecological significance of grazing and cutting regimes applied to restore former species-rich grassland communities in the Netherlands. Kluwer Academic Publishers, Dordrecht

Bakker JP (2014) Ecology of salt marshes; 40 years of research in the Wadden Sea. Wadden Academy, Leeuwarden

Bakker JP, Bos D, De Vries Y (2000) To graze or not to graze: that is the question. In: W.J. Wolff, K. Essink, A. Kellerman & M.A. Van Leeuwe (Editors). Proceedings of the 10th international scientific wadden sea symposium. Ministery of agriculture, nature management and fisheries, Department of Marine Biology, University of Groningen, Groningen, pp. 67–88

Balke T (2013) Establishment of biogeomorphic ecoystems; A study on mangrove and salt marsh pioneer vegetation. PhD Thesis, Radboud Universiteit Nijmegen.

Balke T, Bouma TJ, Horstman EM, Webb EL, Erftemeijer PLA, Herman PMJ (2011) Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. Mar Ecol Prog Ser 440:1–9. doi:10.3354/meps09364

Bertness MD, Callaway R (1994) Positive interactions in communities. Trends Ecol Evol 9(5):187–191

Bochev-van der Burgh LM (2012) Decadal-scale morphologic variability of foredunes subject to human interventions. PhD Thesis, University of Twente, Enschede, 137pp

Cheung KF, Gerritsen F, Cleveringa J (2007) Morphodynamics and sand bypassing at Ameland Inlet, the Netherlands. J Coast Res 23(1): 106–118. doi:10.2112/04-0403.1

Common Wadden Sea Secretariat (2010) Wadden Sea plan 2010. Eleventh trilateral governmental conference on the protection of the Wadden Sea., Common Wadden Sea Secretariat, Wilhelmshaven, Germany

Corenblit D, Tabacchi E, Steiger J, Gurnell AM (2007) Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth Sci Rev 84(1–2):56–86. doi:10.1016/j.earscirev.2007.05.004

Corenblit D, Baas A, Balke T, Bouma T, Fromard F, Garófano-Gómez V, González E, Gurnell AM, Hortobágyi B, Julien F, Kim D, Lambs L, Stallins JA, Steiger J, Tabacchi E, Walcker R (2015) Engineer pioneer plants respond to and affect geomorphic constraints similarly along water–terrestrial interfaces world-wide. Glob Ecolo Biogeogr. doi:10.1111/geb.12373

Davis RA Jr (1994) Barrier island systems—a geologic overview, geology of Holocene barrier island systems. Springer, Berlin Heidelberg, pp. 1–46

De Groot AV, Veeneklaas RM, Bakker JP (2011) Sand in the salt marsh: contribution of high-energy conditions to salt-marsh accretion. Mar Geol 282(3–4):240–254

De Groot AV, Oost AP, Veeneklaas RM, Lammerts EJ, Van Duin WE, Van Weesenbeeck BK, Dijkman EM, Koppenaal EC (2015) Ontwikkeling van eilandstaarten; Geomorfologie, waterhuishouding en vegetatie. Rapport nr. 2015/OBN198-DK, IMARES rapport C183/14, Deltares rapport 1208549.01, O+BN, VBNE, Vereniging van Bos- en Natuurterreineigenaren, Driebergen, 111 pp. http://library.wur.nl/WebQuery/wurpubs/fulltext/336307

De Jong B, Keijsers JG, Riksen MJ, Krol J, Slim PA (2014) Soft engineering vs. a dynamic approach in coastal dune management: a case study on the North Sea Barrier Island of Ameland, the Netherlands. J Coast Res 30(4):670–684

De Leeuw J, De Munck W, Olff H, Bakker JP (1993) Does zonation reflect the succession of salt-marsh vegetation - a comparison of an estuarine and a coastal Bar Island marsh in the Netherlands. Acta Botanica Neerlandica 42(4):435–445

Dean RG (1988) Sediment interaction at modified coastal inlets: processes and policies. Springer, New York

Dijkema KS (1987) Changes in salt-marsh area in the Netherlands Wadden Sea after 1600. In: Huiskes A, Blom CWPM, Rozema J (eds) Vegetation between land and sea. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, p 42–49

Dijkema KS, Wolff WJ (1983) Flora and vegetation of the Wadden Sea islands and coastal areas: final report of the section 'Flora and vegetation of the islands' of the Wadden Sea working group, Report / Wadden Sea Working Group; no. 9. Stichting Veth tot Steun aan Waddenonderzoek, Leiden

Dijkema KS, Kers AS, Van Duin WE (2010) Salt marshes: applied long-term monitoring. In: H. Marencic, K. Eskildsen, H. Farke & S. Hedtkamp (Editors), Science for Nature Conservation and Management: The Wadden Sea Ecosystem and EU Directives. Proceedings of the 12th International Scientific Wadden Sea Symposium. Common Wadden Sea Secretariat, Wilhelmshaven, Germany, Wilhelmshaven, Germany

Doing H (1982) Geomorphology and soil of dunes. In: Dijkema KS, Wolff WJ (eds) Flora and vegetation of the Wadden Sea islands and coastal areas. Stichting Veth tot Steun aan Waddenonderzoek, Leiden

Ehlers J (1988) The Morphodynamics of the Wadden Sea. Balkema, Rotterdam, 397pp

Elias E, Van der Spek A, Wang Z, De Ronde J (2012) Morphodynamic development and sediment budget of the Dutch Wadden Sea over the last century. Neth J Geosci 91(03):293–310

Esselink P, Petersen J, Arens S, Bakker JP, Bunje J, Dijkema KS, Hecker N, Hellwig U, Jensen A-V, Kers AS, Körber P, Lammerts EJ, Stock M, Veeneklaas RM, Vreeken M, Wolters M (2009) Salt Marshes. In: H. Marencic & J. De Vlas (Editors), Quality Status Report 2009. Wadden Sea Ecosystem. Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany; Trilateral Monitoring and Assessment Group (TMAG), Wilhelmshaven, pp. 54

Feagin RA, Smith WK, Psuty NP, Young DR, Martínez ML, Carter GA, Lucas KL, Gibeaut JC, Gemma JN, Koske RE (2010) Barrier islands: coupling anthropogenic stability with ecological sustainability. J Coast Res 26(6):987–992

Fitzgerald DM, Penland S, Nummedal D (1984) Control of barrier island shape by inlet sediment bypassing: East Frisian Islands, West Germany. Dev Sedimentol 39:355–376

Grime JP (1973) Competitive exclusion in herbaceous vegetation. Nature 242(5396):344–347

Grootjans A, Adema E, Bekker R, Lammerts E (2008) Why coastal dune slacks sustain a high biodiversity. In: Martínez ML, Psuty NP (eds) Coastal dunes. Ecology and Conservation. Ecological Studies. Springer, Berlin-Heidelberg, pp. 85–101

Hellwig U, Stock M (2014) Dynamic islands in the Wadden Sea. Ecosystem No. 33 Common Wadden Sea Secretariat, www.waddensea-secretariat.org, Wilhelmshaven, Germany, 1–134pp

Hillen R, Roelse P (1995) Dynamic preservation of the coastline in the Netherlands. J Coast Conserv 1(1):17–28

Hobbs RJ, Norton DA (1996) Towards a conceptual framework for restoration ecology. Restor Ecol 4(2):93–110

Jager TD (2006) Vegetatiekartering 2004 op basis van false colour-luchtfoto's 1:10.000. Rapportnummer AGI-2006-GSMH-015, Rijkswaterstaat, AGI, Delft

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69(3):373–386

Linders HW, Meyer-Spehtmann U, Andretzke H (2013) Monitoring 2012 Kompensationsmaßnahme Ostheller Norderney. Ecoplan Bürogemeinschaft Landschaftsplanung, Leer, 88 pp

Löffler AM, van den Hooff G (2011) Back to basics: natural dynamics and resilience on the Dutch Wadden Sea Barrier Islands. Foundation ERA (Ecological Restoration Advice)

Masselink G, van Heteren S (2014) Response of wave-dominated and mixed-energy barriers to storms. Mar Geol 352:321–347

Nielsen N, Nielsen J (2006) Development of a washover fan on a transgressive barrier, Skallingen, Denmark. J Coast Res 1:107–111

Olff H, De Leeuw J, Bakker JP, Platerink RJ, Van Wijnen HJ, De Munck W (1997) Vegetation succession and herbivory in a salt marsh: changes induced by sea level rise and silt deposition along an elevational gradient. J Ecol 85(6):799–814

Oost AP (1995) Dynamics and sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian inlet. PhD Thesis, Universiteit Utrecht

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, Wang ZB (2012) Barrier island management: lessons from the past and directions for the future. Ocean Coast Manag 68:18–38. doi:10.1016/j.ocecoaman.2012.07.010

Oostermeijer JGB, Hartman Y (2014) Inferring population and metapopulation dynamics of *Liparis loeselii* from single-census and inventory data. Acta Oecol 60:30–39. doi:10.1016/j.actao.2014.08.002

Petersen J, Pott R (2005) Ostfriesische Inseln: Landschaft und vegetation im Wandel, 1. Schlütersche Verlaggesellschaft, Hannover

Postma H (1982) Hydrography of the Wadden Sea: final report 'hydrography' of the Wadden Sea working group, Report / Wadden Sea Working Group; no. 2. Stichting Veth tot Steun aan Waddenonderzoek, Leiden

Reise K (2005) Coast of change: habitat loss and transformations in the Wadden Sea. Helgol Mar Res 59(1):9–21. doi:10.1007/s10152-004-0202-6

Roozen AJM, Westhoff V (1985) A study on long-term salt-marsh succession using permanent plots. Vegetatio 61(1–3):23–32

Röper T, Greskowiak J, Freund H, Massmann G (2013) Freshwater lens formation below juvenile dunes on a barrier island (Spiekeroog, Northwest Germany). Estuar Coast Shelf Sci 121–122:40–50. doi:10.1016/j.ecss.2013.02.004

Schuerch M, Rapaglia J, Liebetrau V, Vafeidis A, Reise K (2012) Salt marsh accretion and storm tide variation: an example from a Barrier Island in the North Sea. Estuar Coasts 35(2):486–500. doi:10.1007/s12237-011-9461-z

Schwarz C, Ye QH, van der Wal D, Zhang LQ, Bouma T, Ysebaert T, Herman PMJ (2014) Impacts of salt marsh plants on tidal channel initiation and inheritance. J Geophys Res Earth Surf . doi:10.1002/2013jf0029002013JF002900

Sha LP (1989) Variation in ebb-delta morphologies along the west and east Frisian Islands, the Netherlands and Germany. Mar Geol 89(1):11–28. doi:10.1016/0025-3227(89)90025-X

Ten Haaf ME, Buijs P (2008) Verdiepende studies Morfologie: Morfologie, hydraulica en ecologie van washoversystemen, Universiteit Utrecht

Thorenz F (2011) Der Beginn des seebautechnischen Inselschutzes auf den Ostfriesischen Inseln. In: J. Kramer (Editor), Tausend Jahre Leben mit dem Wasser in Niedersachsen. Band II. Von der Königlich-Hannoverschen general-direction des Wasserbaues 1823 zur Niedersächsischen Wasser- und Abfall-wirtschaftsverwaltung. Gerhard Rautenberg

Van der Veen A, Grootjans AP, De Jong J, Rozema J (1997) Reconstruction of an interrupted primary beach plain succession using a geographical information system. J Coast Conserv 3(1):71–78

Van Dieren JW (1934) Organogene Dünenbildung; Eine Geomorphologische Analyse der Dünenlandschaft der West-Friesischen Insel Terschelling mit pflanzensoziologischen Methoden. PhD Thesis, Universiteit van Amsterdam, 's-Gravenhage, 304pp

Van Dobben HF, Slim PA (2012) Past and future plant diversity of a coastal wetland driven by soil subsidence and climate change. Clim Chang 110(3–4):597–618. doi:10.1007/s10584-011-0118-5

Van Heteren S, Oost AP, van der Spek AJF, Elias EPL (2006) Island-terminus evolution related to changing ebb-tidal-delta configuration: Texel, the Netherlands. Mar Geol 235(1–4):19–33. doi:10.1016/j.margeo.2006.10.002

Van Klink R (2014) Of dwarves and giants: how large herbivores shape arthropod communities on salt marshes. PhD thesis Thesis, University of Groningen, Groningen

Van Loon-Steensma JM, Slim PA (2012) The impact of erosion protection by stone dams on salt-marsh vegetation on two Wadden Sea Barrier Islands. J Coast Res:783–796. doi:10.2112/jcoastres-d-12-00123.1

Van Veen J, Van der Spek AJ, Stive MJ, Zitman T (2005) Ebb and Flood Channel Systems in the Netherlands Tidal Waters 1. J Coast Res: 1107–1120

Veeneklaas RM, Dijkema KS, Hecker N, Bakker JP (2013) Spatio-temporal dynamics of the invasive plant species *Elytrigia atherica* on natural salt marshes. Appl Veg Sci 16(2):205–216. doi:10.1111/j.1654-109X.2012.01228.x

Viles H (1988) Biogeomorphology. Basil Blackwell, Oxford

Wang ZB, Hoekstra P, Burchard H, Ridderinkhof H, De Swart HE, Stive MJF (2012) Morphodynamics of the Wadden Sea and its barrier island system. Ocean Coast Manag 68:39–57. doi:10.1016/j.ocecoaman.2011.12.022

Wolff WJ (1986) De Waddenzee: eigenschappen van een dynamisch kustgebied. 252, RIJP, 11–22pp

Yapp, R.H., Johns, D., Jones, O.T. (1917). The salt marshes of the dovey Estuary. Part II. The salt marshes. J Ecol, 5: 65–103.