Dynamic Islands in the Wadden Sea

WADDEN SEA ECOSYSTEM No. 33 – 2014

Dynamic Islands in the Wadden Sea

Publishers
Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany;
Trilateral Salt Marsh and Dunes Expert Group

Editors

Ulrich Hellwig	IfAUM, Institute for applied environmental biology and monitoring, Wurster Landstr. 11, D-27638 Wremen, ifaum@ewe.net
Martin Stock	Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein, Schloßgarten 1, D-25832 Tönning, martin.stock@lkn.landsh.de

Cover photos
Above: Zuiderduin (Rijkswaterstaat, https://beeldbank.rws.nl/)
Below: Scharhörn (Martin Stock)

Lay-out
Gerold Lüerßen

This publication should be cited as:
Hellwig, U. and Stock, M. (Eds.) 2014. Dynamic Islands in the Wadden Sea.
Ecosystem No. 33: 1-134. Common Wadden Sea Secretariat, Wilhelmshaven, Germany.
www.waddensea-secretariat.org, Wilhelmshaven Germany.

WADDEN SEA ECOSYSTEM No. 33

Dynamic Islands in the Wadden Sea

Ulrich Hellwig
Martin Stock

2014
Common Wadden Sea Secretariat

Contents

Editorial

The ongoing geological processes in the coastal and marine environment of the Wadden Sea have been instrumental in the formation of the world's largest temperate zone tidal flat system.

The ceaseless activity, driven by the forces of water and wind, constantly creates, re-shapes, destroys and renews geomorphic and physiographic features on a variety of spatial and temporal scales. In turn, these changes induce ecological and biological responses that create a complex coastal ecosystem teeming with plant and animal life as well as immense geological interest.

Indeed, these outstanding qualities of geology, hydrology, morphology, ecology and biodiversity have led to the entire Wadden Sea along the coasts of The Netherlands and Denmark being declared a UNESCO World Heritage Site. Criterion VIII stated that the area is an outstanding example representing major stages of Earth's history, including the record of life, significant ongoing geological processes in the development of landforms, and significant geomorphic or physiographic features.

Large scale examples of continuous geological processes and morphological interactions are on public view in the Wadden Sea. Among the most spectacular are the creation, continual shifting and changing, and ultimate disappearance of many of the region's uninhabited natural islands, along with all the biota they support.

In this Wadden Sea Ecosystem issue we have collected a series of papers dealing with the development of small uninhabited islands to demonstrate dynamic processes at work on different scales.

The objectives for this issue are

- to present an overview of dynamic islands throughout the Wadden Sea,
- to illustrate the main geomorphological features and to describe the consequences for biota,
- to obtain an understanding of general developments and regional differences in island dynamics throughout the Wadden Sea,
- to exemplify the value and significance of natural dynamics in the Wadden Sea to a broader public and to decision makers, and
- to highlight the intrinsic value and importance of natural processes to the ecosystem.

These objectives are difficult to achieve. We therefore start with a couple of papers which set the scene. The articles represent the scientific views of each author. We present these articles in a geographic sequence from The Netherlands as the westernmost extremity to Denmark as the northernmost. The articles span a range of topics, from a description of dynamic islands of a complete region to geomorphological studies, botanical evaluations and inter-disciplinary analysis, and even a historical review of a vanished island.

The articles discuss islands in various states, from evolving land masses like Norderoogsand and Kachelotplate through senescent islands like Trischen and probably Mellum, to the study of human creations like Scharhörn and Nigehörn.

Most of the islands are on the move and amply demonstrate this dynamic. Moving rates proved to be very different. The highest mean shifting rates are reported from The Netherlands whereas Scharhörn, in the mouth of the inner Elbe, shows the lowest value and highest rate of stability. We see how shifting rates change over the years and are determined by sediment supply in conjunction with singular, mostly storm-related, events. Extreme weather and tide conditions, combined with changes in hydrodynamics, seem to be the drivers of dynamic changes to the islands, but of course there is the underlying influence of sea level rise.

To gain a better understanding of the value of natural dynamics on the level of whole islands we recommend a continuation of monitoring approaches on the dynamics of unprotected islands in an inter-disciplinary approach. The TMAP standards are a good starting point.

Ulrich Hellwig
Martin Stock

Dynamic Wadden Sea islands in The Netherlands

A. S. Kers

Dynamic Wadden Sea islands in The Netherlands

Introduction

This article shows the process of erosion and growth of a few highly dynamic islands in the Dutch Wadden Sea. It provides an overview of the emergence and disappearance of sandbanks, the emergence of the first vegetation, erosion of whole dune systems at some barrier reef islands and the processes influencing a moving island in the middle of the Wadden Sea.

Meandering of the gullies: erosion and sedimentation

In a few decades whole back-barrier channel systems can change. The example given below is from the eastern point of Schiermonnikoog. In 1975 it was about three and a half kilometres shorter than it is now, in 2014. In addition, Simonszand, a large sandbank between Schiermonnikoog and Rottumerplaat, changed shape and the 'Eilanderbalg' channel meandered in a more straightforward fashion (Fig. 1).

From the aerial photo (Fig. 2) we can distinguish two major processes:

- Simonszand has disappeared in the last century because the outside of the Eilanderbalg channel has eroded the sandbank (see b), while the eastern tip of Schiermonnikoog is growing because of increasing sedimentation in the inner bend of the channel.
- The western part of Rottumerplaat is disappearing fast because of erosion by the large 'Lauwers' channel. Since the early 1980s two kilometres of dunes have eroded (Nicolai *et al.*, 2001).

In the future several things could happen:

- The eastern point of Schiermonnikoog disappears again, because the Eilanderbalg channel will reconnect with the North Sea at (a). If that happens the channel at (b) could silt and Simonszand could expand to the west again.
- The western part of the Eilanderbalg channel silts again (and the erosion of Schiermonnikoog will stop), because it will be connected to the Spruit channel (Fig. 2, d).
- The meandering of the Lauwers continues, causing extended erosion of Rottumerplaat.

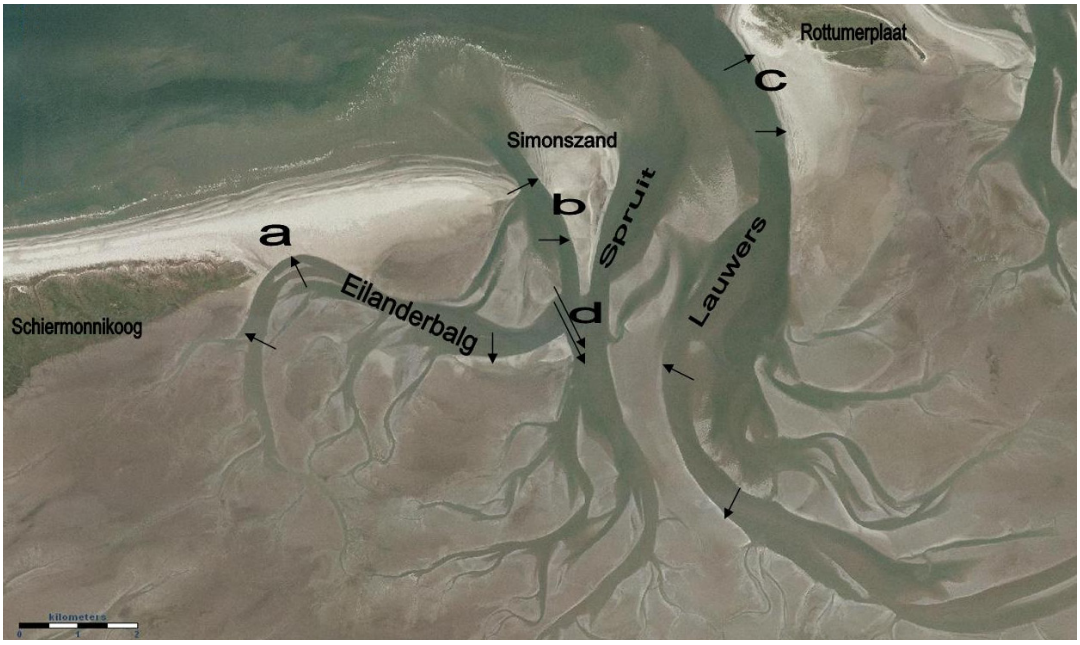
All these processes will continue, the extent depending on the prevailing winds, currents, waves, soils and geomorphology. New areas will appear and disappear on a large scale. This is what gives the Wadden Sea its unique nature. An overview of the morphodynamics of the Wadden Sea is given by Reijngoud (1998).

From sand bank to a new island

When the dynamic activities affecting a sandbank or beach plain are relatively low for several years, primary dunes may arise. In the lee of these dunes green beaches can form with a variety of salt and brackish plants. Examples within the last 10 years in The Netherlands are the Hors at Texel, the Vliehors at Vlieland, the Cupido's polder at Terschelling, the north western beach at Ameland (van Tooren & Krol, 2005) and almost the whole beach area of Schiermonnikoog (Bakker *et al.*, 2005). Two further examples are given below: the Richel and Noordrif.

Fig. 1:
Map from 1975 of the area east from Schiermonnikoog (Rijkswaterstaat, waterstaatkaart).

Fig. 2: Aerial photo of the eastern part of the Dutch Wadden Sea from 2012, with erosion and sedimentation processes of the channel systems (photo: DKLN 2012, het Waterschapshuis).



The Richel

Fig. 3 (right): Harbor seal (*Phoca vitulina*) on a sand bank in the Wadden Sea.

The Richel is a sandbank south of Vlieland. It is well known among tourists travelling to Vlieland and Terschelling, because of the large numbers of seals that can be seen from the boat. Both species Harbor seal (*Phoca vitulina)* and Grey seal (*Halichoerus grypus*) can be seen.

For a long time the Richel was known as just a sandbank. However, between 2011 and 2012 a new "island" arose with primary dunes and vegetation of Sand Couch (*Elytrigia juncea* subsp. *boreoatlantica*) (Fig 4).

Fig. 4: Emergence of a 750 m long vegetated dune area over a period of one year at the sandbank Richel, south of Vlieland (Photo 1990: Rijkswaterstaat, Photos 2011, 2012: DKLN 2012, het Waterschapshuis).

1990

2011

2012

2012 (detail)

Noordrif

The Noordrif is the most northern piece of land in The Netherlands. It is a large beach plain north of the island of Rottumerplaat. Each year from about 1990 onwards, embryo dunes have appeared in summer (Fig. 5a,b) and been washed away in winter (Kers & Koppejan, 2005).

Since 2005 more and more sand has been transported from the eroded western dunes of Rottumerplaat to the Noordrif north of the bay. As a result, the dunes have become higher and salt marsh vegetation has established itself in the shallow valleys in between (Fig. 6, 7 and 8.

Figure 6 shows that the low dunes of the Noordrif were almost connected to Rottumerplaat. However over several years material has been washed away. Nowadays this area is the biggest wash over in The Netherlands with a size of about 500 x 1,000 meters (Fig. 7 and 8.) It is a place where you can find the rare plant community of *Salicornietum decumbentis* (Janssen *et al.*, 2012).

In recent years the vegetation of the Noordrif has grown rapidly to the east with Sand Couch establishing on embryo dunes and to the south along the bay with Glasswort fields (*Salicornia stricta* & *S. europaea*).

Fig. 5a,b: Photos of the Noordrif in 2003 with embryo dunes.

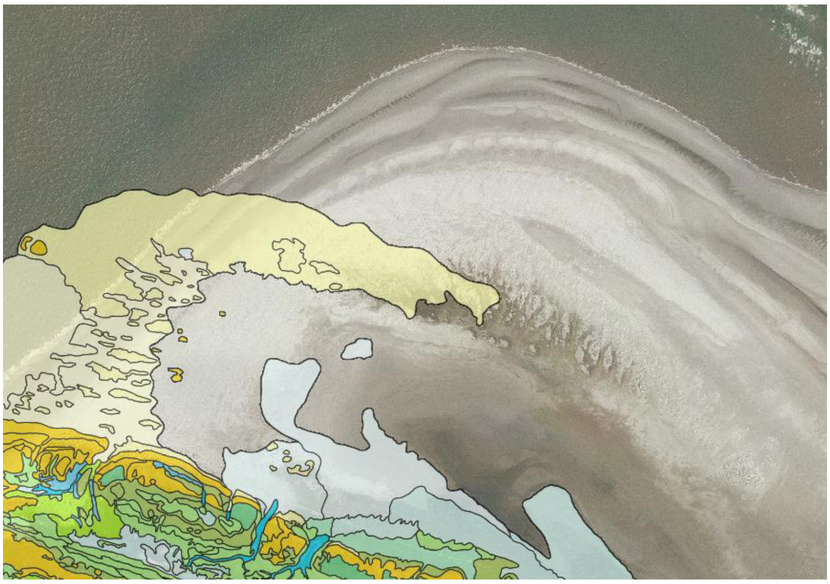


Fig. 6: Difference between vegetation map 2004 (Rijkswaterstaat) and photo 2012 (DKLN 2012, het Waterschapshuis).

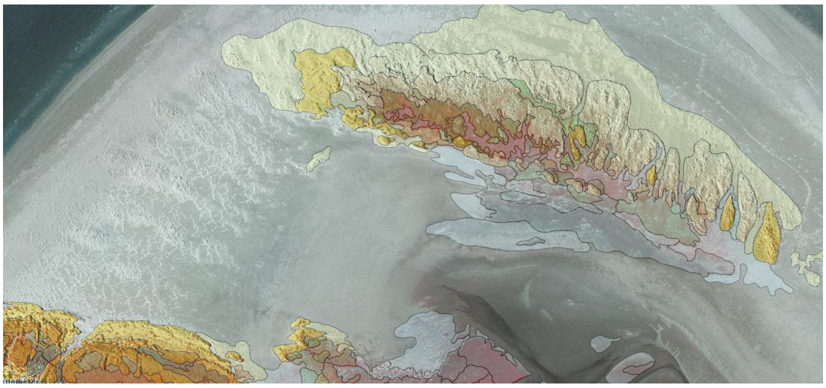


Fig. 7: Same situation 6 years later: Vegetation map 2010 and false colour photo from 2010 (Rijkswaterstaat).

Fig. 8a-c: Noordrif 2011/2012. In the right upper corner of the aerial photo (Rijkswaterstaat 2011) lies the island of Rottumerplaat, bottum left the Noordrif with the new dune area and in between the biggest wash over of the Netherlands. The photos in the field are from 2012 of the Noordrif. In 10 years time the area has changed from embryo dunes into a complete dune and salt marsh system with lots of plant species and a population of rabbits *Oryctolagus cuniculus* (right).

Erosion of a natural (non-protected) barrier reef island

Some areas in the Dutch Wadden Sea show erosion of a barrier reef island, like the northern part of Texel or the western part of Ameland or Rottumeroog. As a matter of safety, the area will in general be protected by sand replenishment or by the construction of artificial structures. However, in some areas, like Rottumerplaat and Rottumeroog, coastal protection has been stopped since 2005 to allow natural processes to take place. Below, the erosion of Rottumerplaat is discussed.

Figure 2 shows that the big Lauwers channel creates a lot of erosion at the western part of Rottumerplaat. Nicolai *et al.* (2001) describe that in the early 1980s, 1.5 kilometres of the Westerduinen had disappeared. Ten years later an additional 500 metres of dune had gone and from 2011 onwards the former sand dike has started to be eroded (Fig. 9).

In figure 10 a vegetation map from 2004 is superimposed on a photo from 2012. In eight years 450 metres of dunes have disappeared, which is an erosive rate of 56 metres per year. Nicolai *et al.* (2001) estimates that almost 1.5 kilometres disappeared between1980-2000, which gives an erosion of 75 metres per year. The rate of erosion was probably higher in the beginning than it is today.

Nevertheless, when we look at figure 2 we see that the meandering of the Lauwers still goes on. When it becomes a similar shape to the Eilanderbalg it may erode the whole existing area of Rottumerplaat. The sand dike of the island is 3.18 kilometres long. With a minimum rate of erosion of 55 meters per year this area may disappear in less than 60 years.

A protected and a non-protected Wadden Sea island

In contrast to the well known barrier reef islands of Terschelling or Schiermonnikoog, there are only two real Wadden Sea islands in The Netherlands, which lie in the middle of the Wadden Sea. These little islands are Griend, south of Terschelling, and Zuiderduin, south of Rottumeroog. Griend is an island that has been protected in recent decades by a sand dike, while Zuiderduin is purely natural.

Griend

In the first half of the 20th century Griend was a high dynamic island. In 1988 it was protected by a few sand dikes (Fig. 11) to benefit thousands of breeding birds, especially the Sandwich Tern *Thalasseus sandvicensis,* and many migratory birds like the Red Knot *Calidris canutus* (Fig. 12).

In the last 10 years the most westerly sand dike has been eroded (Fig. 13). On the mudflats

Fig. 9a-d: Erosion at the western part of Rottumerplaat. At the north side of the sand dike there is a big breach that leads into the former primary dune slack Noordslufter. At the south side the whole green beach that was present in 2006 has gone in 2011. In 2011, the channel Lauwers reaches the sand dike, which starts to erode.

Fig. 9a-b (left): North side of the sand dike in 2006 and 2011

Fig. 9c-d (right): South side of the sand dike in 2006 and 2011

Fig. 10: Vegetation map of Rottumerplaat from 2004, drawn on an aerial photo from 2012. The dotted line at the left is the distance (ca. 450 metres) that has been eroded in the period of eight years.

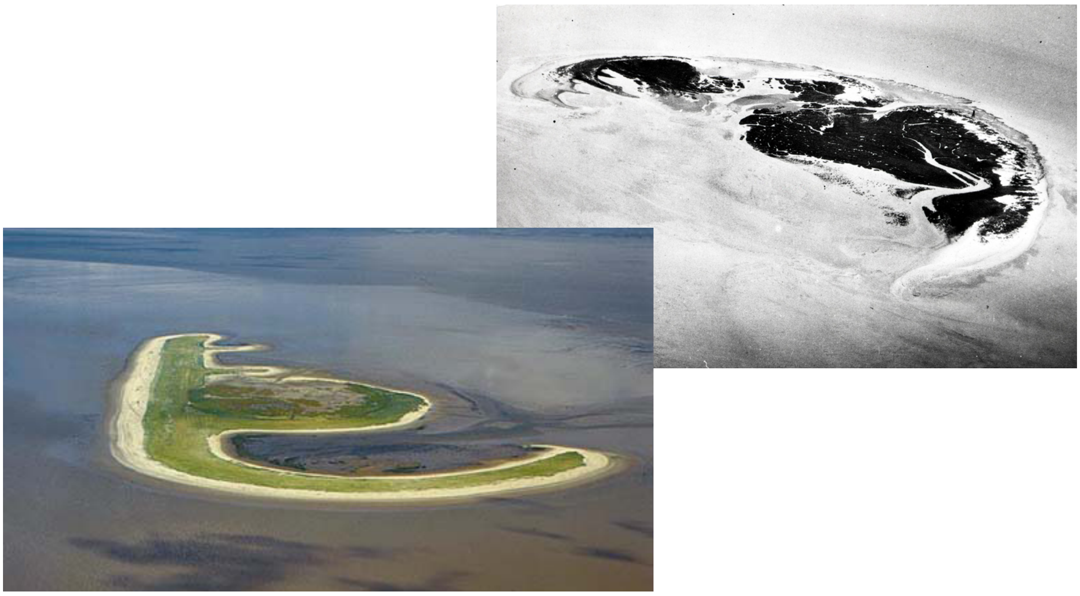


Fig. 11 a-b: Photo from Griend in the first half of the 20th century (photo: Rijkswaterstaat). Below a photo from 1988. In this period the island was protected by some artificial sanddikes (photo: GCN, Terschelling).

Fig. 12: Griend is famous for the large numbers of resting birds, here thousends of Red Knot (*Calidris canutus,*) Bar-tailed Godwit (*Limosa lapponica)* and Eurasian Oystercatcher (*Haematopus ostralegus*).

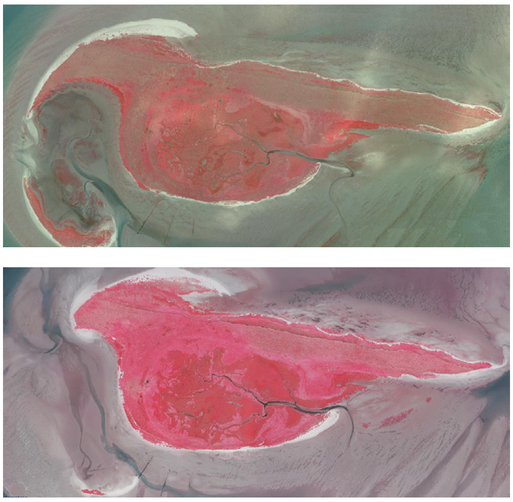


Fig. 13a-b: The island of Griend in 2006 and 2012. In this period the western sand dike has eroded away. False colour photos (Rijkswaterstaat).

Fig. 14 (right): Sea couch (*Elytrigia atherica)* at Griend is increasing, because of the aging of the salt marsh.

pioneer vegetation is missing and on the island the vegetation has stabilized and the climax vegetation with Sea Couch (*Elytrigia atherica)* has increased (Fig. 14).

Because of its unique value for breeding and resting birds there are plans to renew the erosion protection in the near future.

Zuiderduin

Zuiderduin, south of Rottumeroog, is a natural island of approx 40 hectares. The whole island is unprotected and moves eastward. Figure 15 shows a map of 2004, drawn over an aerial photograph of 2012. At the western point (see dotted line) the bank is eroded by 135 metres, so the island moves eastwards at average speed of 17metres per year. The total island is about 885m long, so with a speed of 17 metres per year, the whole island renews in c. 50 years.

Figure 16 shows what a natural island like Zuiderduin consists of: a high dynamic shell bank, lots of different pioneer vegetation, a relatively young salt marsh and some special breeding birds.

It is interesting when we compare the two islands. Figure 17 reveals contrasting salt marsh vegetation ratios between Griend (protected island) and Zuiderduin (non-protected island). Griend has much more climax vegetation and fewer pioneer zones compared with Zuiderduin. All the vegetation zones of Zuiderduin are also more equally divided.

Perspectives

If we look at the examples of dynamic places where erosion takes place, we can conclude that something new is always being created. These new dynamic areas are undisturbed places where natural processes are free to work and areas are colonised naturally with unique flora and fauna. The processes and the consequences are both fascinating and beautiful to humans. All these aspects are also defining criteria in the nomination of the Dutch-German Wadden Sea as a World Heritage Site (CWSS, 2008).

One final, important detail: when nature creates itself, there are no fees!

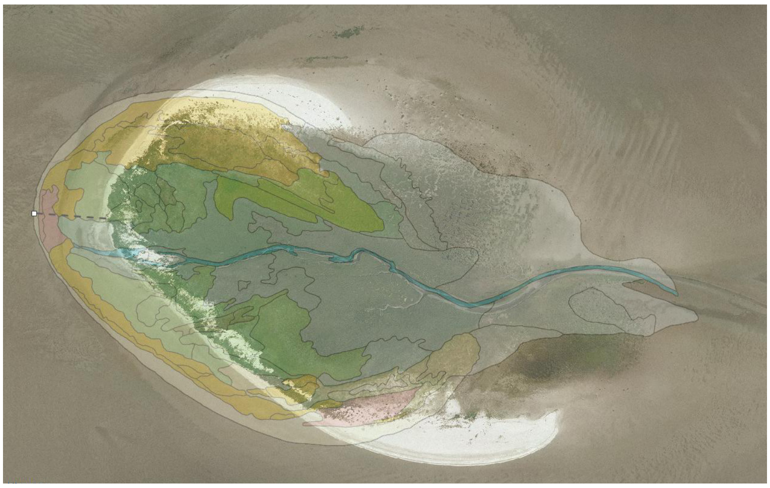


Fig. 15:
Zuiderduin, vegetation map 2004 (Rijkswaterstaat), drawn on an aerial photo of 2012 (DKLN 2012, het Waterschapshuis).

Fig. 16:
Zuiderduin is surrounded by a shell bank (a & h), with breeding colonies of gulls, Eurasian spoonbill (*Platalea leucorodia*) (d) and Great cormorant (*Phalacrocorax carbo*) (f). Other special breeding birds are Little egret (*Egretta garzetta*)and Peregrine (*Falcon Falco peregrinus*). Special plants are Oakes' evening primrose (*Oenothera oakesiana*) (a), Flixweed (*Descurainia sophia*) and Wild cabbage (*Brassica oleracea* ssp. *oleracea*) (e). Enclosed by the shell bank there is a salt marsh (b). At the most western point you can find an old clay bank where the former salt marsh consisted (g), the eastern point is covered with *Salicornia* fields (c). (Aerial photo: Rijkswaterstaat).

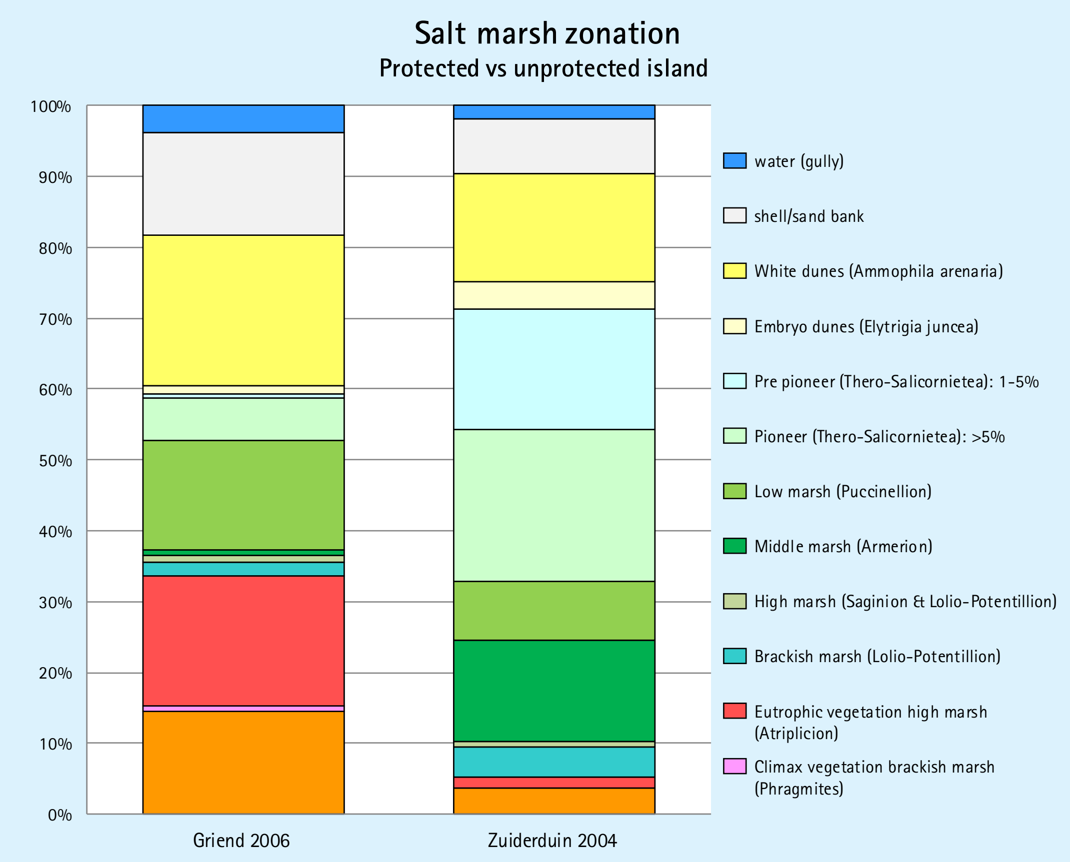


Fig. 17: Surface ratio comparison of salt marsh vegetation between a protected and a non-protected island. Data after Houkes, 2008 (Griend) and Bergwerff *et al.*, 2006 (Zuiderduin).

Acknowledgements

I would like to thank Joost Buiks who helped me with the translation of the article.

Literature

Bakker, J.P., R.M. Veeneklaas, A. Jansen & A. Samwel, 2005. Een nieuw Groen Strand op Schiermonnikoog. De Levende Natuur, juli 2005.

Bergwerff, J.W., A.S. Kers & K.W. van Dort, 2006. Toelichting bij de vegetatiekartering

Rottum 2004. Op basis van false colour-luchtfoto's 1: 5000. Rijkswaterstaat, Adviesdienst Geo-Informatie & ICT, Delft. Rapportnr. AGI-2006-GSMH-019.

Common Wadden Sea Secretariat (CWSS), 2008. Nomination of the Dutch-German Wadden Sea as World Heritage Site - Volume one. Wilhelmshaven, Germany.

Houkes, G.H.M, 2008. Toelichting bij de vegetatiekartering Griend 2006. Op basis van false colour-luchtfoto's 1: 5000. Rijkswaterstaat, Data-ICT-Dienst, Delft.

Janssen, J.A.M., R. Haveman, A.S. Kers & I. de Ronde, 2012. De Zandzeekraal-associatie (Salicornietum decumbentis) in Nederland. Stratiotes 2012.

Kers, A.S. & H. Koppejan, 2005. De Groene Stranden van Rottumerplaat. De Levende Natuur, juli 2005.

Nicolai, A., E. Nuijen, T.A. van der Heide, W. Weijman, B. Witvoet, G.G. van Brakel & R. Deen, 2001. Rottumeroog en -plaat veranderen... Een evaluatie van monitoringsgegevens en beheer over de periode 1996-2001. Notanummer NN-ANW 01-01. Rijkswaterstaat DNN, Staatsbosbeheer regio Groningen-Drenthe en LNV Directie Noord.

Reijngoud, T.T., 1998. De morfodynamica van de Waddenzee op verschillende ruimte- en tijdschalen. 89p. Waddenvereniging, Harlingen.

Tooren, B.F. van & J. Krol, 2005. Een Groen Strand op Ameland. De Levende Natuur, juli 2005.

Author

A. S. Kers
Prunusstraat 14
2636 BG Schipluiden
Netherlands

Initial barrier island evolution (Kachelotplate, central Wadden Sea): sediment–vegetation interaction

Achim Wehrmann
Michael Schwartz
Norbert Hecker
Gerd Liebezeit

Initial barrier island evolution (Kachelotplate, central Wadden Sea): sediment-vegetation interaction

Introduction

The Wadden Sea is separated from the open North Sea by a long chain of barrier islands, extending from Texel (The Netherlands) in the west to Fanø (Denmark) in the north. In the innermost part of the German Bight between the Jade-Weser and Elbe estuaries only ephemeral sandbank islands occur. Based on their geological evolution two basic types of barrier islands occur: dune islands (West Frisian and East Frisian Islands) and geest/marsh islands (North Frisian Islands, Texel) (Fig. 1). Postglacial development of the East Frisian dune islands started when Holocene sea level rise reached the area of the present coast around 8,000 to 7,500 years before present (yBP) as documented by 14C-dated brackish plant material from nearshore settings (24m below chart datum) off Wangerooge Island (Hanisch 1980). Therefore, these islands represent very young geological units formed during the late phase of sea level rise. Simultaneous to the retrogradational (landward) coast line migration the barrier island chain also shifted in a southeastward direction as indicated by typical back-barrier sediments (semi-consolidated mud beds and salt marsh horizons) today exposed on the seaward side of the islands (Freund & Streif 2000; Freund 2003; this study). For the last 2,000 years the rate of southward displacement was more than 100m per century (Barckhausen 1969, Streif 1990).

Barrier island formation as a function of waves and tides

The Wadden Sea is known as the largest coherent system of sandy to muddy tidal flats in the world (Wehrmann 2014). Nevertheless, barrier islands as well as tidal lagoons are typical landscape elements of shore lines worldwide (Hayes 1979). Limiting hydrodynamic factors of these depositional systems are tidal range and wave energy. Barrier islands are absent in macrotidal environments defined by tidal ranges above 3.5 to 4m (Fig. 1). Micro-tidal environments on the other hand are characterized by tidal lagoons, sand

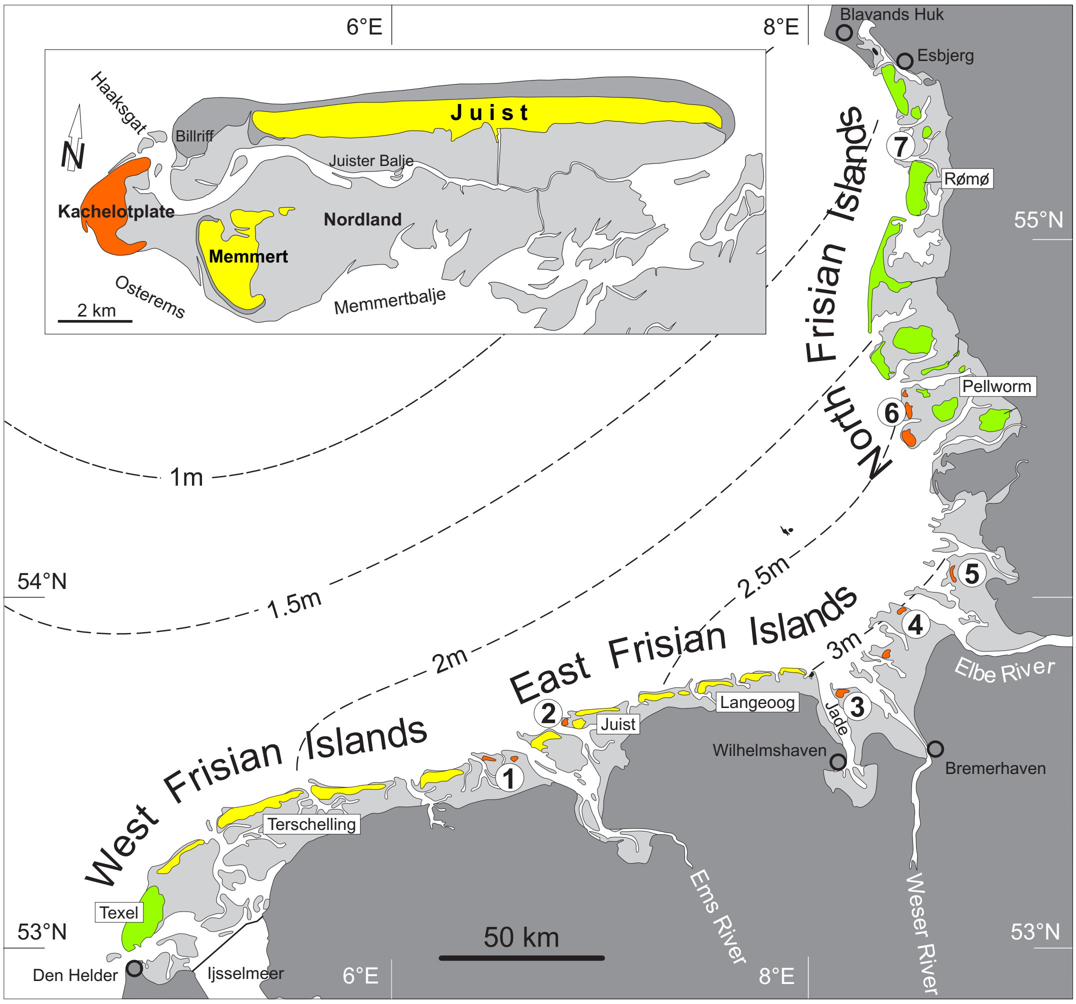


Fig. 1: The large coherent system of Wadden Sea tidal flats (bright grey) is protected towards the open North Sea by a long chain of barrier islands of different geological origin (dune islands = yellow; geest/marsh islands = green). In the innermost part of the German Bight, characterized by macrotidal conditions (tidal range >3.5 m), open tidal flats and ephemeral sand bank islands occur. Dashed lines indicate mean tidal ranges. Highly dynamic islands (orange): Rottumeroog (1), Kachelotplate (2), Mellum (3), Scharhörn/Nigehörn (4), Trischen (5), Norderoogsand (6), Kjeldsand (7).

spits and sand bars. According to Hayes (1979) the East Frisian Islands represent the high-energy end member of barrier islands whereas the West Frisian Islands and the Danish Wadden Sea are the low-energy equivalents. The ephemeral sandbank islands of the meso- to macro-tidal Jade-Weser-Elbe region (Fig. 1) are covered by vegetation but do not have the potential to form larger coherent dunes.

In the past several hypotheses of barrier island formation have been developed (*e.g.* Penck 1894 sand spit hypothesis, Lüders 1953 beach ridge hypothesis, Barckhausen 1969 offshore sand shoal hypothesis) of which the latter is generally accepted today. According to Barckhausen (1969) all dune islands originate from offshore sand shoals deposited on Pleistocene ridges or heights during high energy events (*i.e.*, storms). Under moderate wave and wind conditions sediment accumulation continues, resulting in only episodic inundations during extreme high water events. On the sheltered side of the shoals, tidal flats can develop under low energy conditions. Additionally, primary dunes are formed by aeolian sediment transported from the backshore. First pioneer vegetation favours sediment accumulation by trapping and stabilizing the aeolian sediments. Under conditions of continuing transgressive sea level rise the entire sediment sequence migrates southward (landward) overrunning previous deposits of the back-barrier/dune island complex. Most of the West and East Frisian Islands originate from several dune ridges formerly separated by wash-over fans (‘sloops’). The wash-over fans are formed under extreme high water and energy conditions (storms). Today most of the wash-over fan related gaps have been closed due to coastal protection measures. The closure of dune ridge gaps as well as the decrease in tidal basin volume by a fixed coast/dike line causes the present elongated (drumstick) shape of the barrier islands.

Kachelotplate: the missing link in barrier island evolution

The sand shoal hypothesis of Barckhausen (1969) describes a geological process of which only the latest phase (the barrier islands) is well known. However, the initial and transitional stages are of a more or less theoretical nature. This knowledge gap can now be closed by an interdisciplinary study and a continuous survey running since 2007 on the Kachelotplate, an ephemeral sandbank island southwest of Juist Island. In contrast to the sandbank islands of the Jade-Weser-Elbe region, the Kachelotplate is situated within the stability field of barrier islands which limit tidal range and wave energy factors and it therefore has the potential to develop a continuous dune belt. Kachelotplate allows the study of all processes of initial barrier island evolution as postulated in Barckhausen’s hypothesis.

To define the status quo of the Kachelotplate a sedimentology-based field survey was conducted in 2007 (Wehrmann & Tilch 2008). Accordingly, numerous sedimentary structures and morphological units typical for barrier islands can be found (Fig. 2; for details see also atlas of sedimentary structures in Wehrmann & Tilch 2008). The exposed southwestern to northwestern part of the island is marked by a tide-influenced high (wave) energy beach whose foreshore shows a well developed ridge-and-runnel system running slightly oblique to the water line (Fig. 3a). The transition to the backshore is marked by drift lines as indicated by the characteristic pioneer vegetation dominated by *Cakile maritima*. The upper backshore and flat topped central part of the island are covered by aeolian sand and shell lag deposits (Fig. 3b). This area will not be submerged under ordinary tidal conditions and so allows the establishment of a scattered vegetation cover by *Elymus farctus* (Fig. 3c) which is well adapted to both strong sand accumulation and erosion down to its rootlet system. *Elymus farctus* sediment baffling and stabilizing traits as well as aeolian sediment support from the backshore favours the development of primary dunes up to 2.5m high during summer. Tops of highest dunes are covered by *Leymus arenarius* (Fig. 3d). Nevertheless, the semicircular belt of primary dunes will be inundated from western directions during extreme high water events as documented by shell lag deposits reaching far beyond the dune belt into the sheltered tidal flats. In most cases these winter storm related extreme high water events are associated with strong wave impact resulting in a more or less complete erosion of primary dunes (Fig. 3e). The sediment volume of the primary dunes will not be exported out of the system but will be extensively redistributed within the dune belt area and to a minor degree also in the easterly tidal flats (Schwartz 2013). Excavated rootlets of *Elymus farctus* are able to regenerate immediately after disturbance and therefore initiate formation of new primary dunes (Fig. 3f). Sources for nutrients are air (mainly for nitrogen), water and faeces from birds and seals. Erosion of subaquatic out-

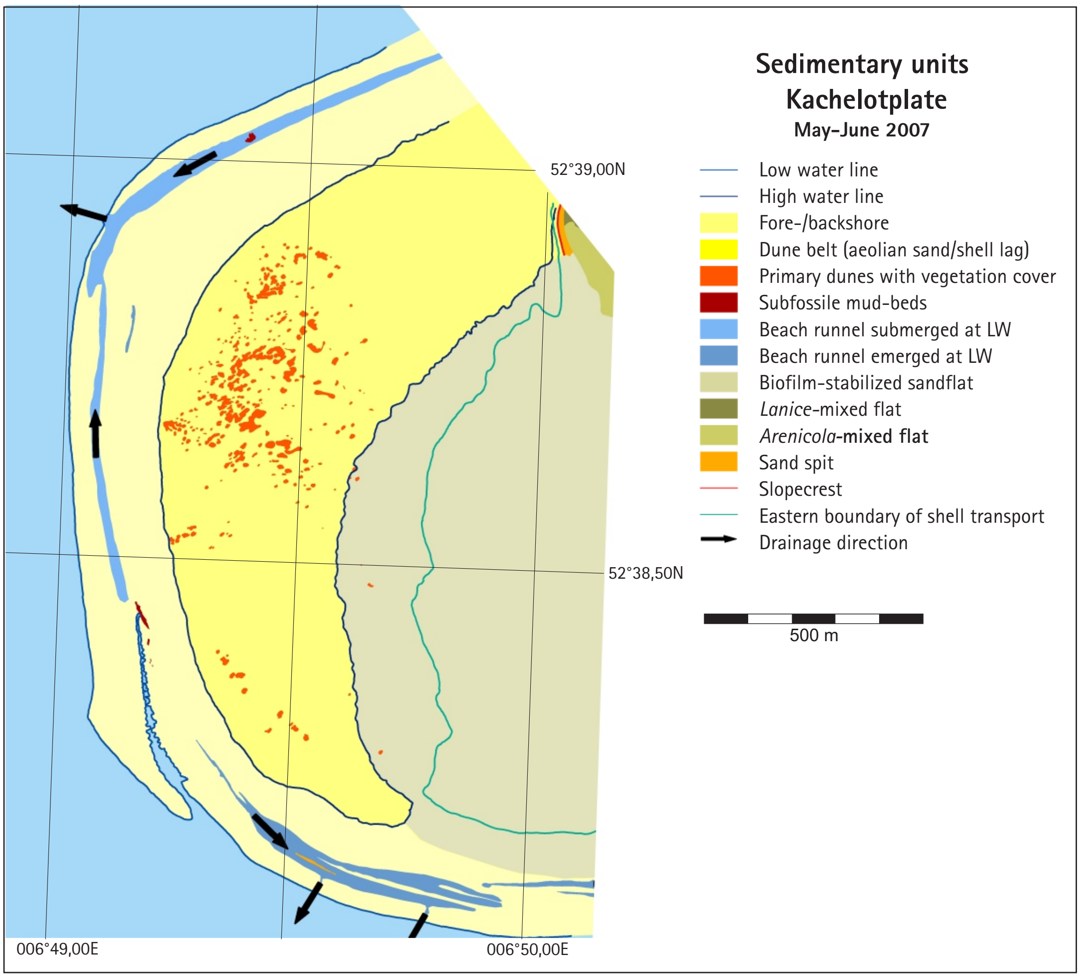


Fig. 2: Map of the Kachelotplate from surveys in May to June 2007 showing spatial distribution of principle sedimentary and morphological units, depositional sub-environments and benthic communities. Modified after Wehrmann & Tilch (2008).

cropping Holocene peat beds are a typical source for phosphate (Liebezeit *et al.* 2008).

The sheltered tidal sand flats east of the dune belt are characterized by a markedly even relief. Sedimentary structures as a typical indicator for sediment transport are missing. The same holds true for benthic organisms (*e.g.* polychaetes, endobenthic bivalves, *Peringia ulvae*) as known from adjacent sandy tidal flats. The tidal flats between the Kachelotplate and Memmert Island are unique in the Central Wadden Sea in that they are completely covered by microbial mats (Gerdes & Wehrmann 2008). The microbial mats trap and bind sediment particles and thus stabilize the sedimentary surface (Fig. 3g). The sheltered biofilm-stabilized sand flats are submerged only around high water. However, outcropping semi-consolidated mud beds (Fig. 3h) at the low water line of the exposed beach indicate contrasting conditions in the past. These sub-fossil mud beds contain an endobenthic bivalve fauna in growth position which is typical for muddy to mixed tidal flats of a back-barrier environment. Additionally, they also indicate the general southeastward migration of the barrier island chain.

Medium-term morphodynamics

During the survey period the northern sand spit of the Kachelotplate underwent the most obvious modification visible, with a strong clockwise rotation, whereas the central part only shows minor fluctuations caused by short-term disturbances, *i.e.* storms. Comparison of aerial photographs from 2006 and 2011 (Fig. 4) reveals the general southeastward migration of the entire system on short to mid-term scales. The biofilm-stabilized back-barrier sand flats between Memmert Island and the Kachelotplate are the most stable part of the entire system, showing slight but continuous sediment accumulation (for sediment erosion stick [SES] method see Wehrmann & Tilch 2008). Accumulation rates decrease with distance from the dune belt, the main source area. In parallel with the general accumulation trend in the central (dune belt) and eastern parts (biofilm stabilized sand flats) of the Kachelotplate, the frequency of inundation decreased (Schwartz 2013). The sedimentation base grew

Fig. 3a (left): Exposed high-energy beach at low tide with ridge-and-runnel system.

Fig. 3b (right): Flat topped central part of the island covered by aeolian sand and shell lag deposits sparsely vegetated by *Elymus farctus.*

Fig. 3c (left): Central dune belt with primary dunes (summer situation).

Fig. 3d (right): Top of the highest dunes covered by *Leymus arenarius.*

Fig. 3e (left): Strongly eroded central dune belt after storm inundation.

Fig. 3f (right): Excavated rootlets of *Elymus farctus* are able to regenerate immediately after disturbance.

Fig. 3g (left): Biofilm stabilized sheltered sand flat at the eastern side of the Kachelotplate. Windows with oscillation ripples mark spots where biofilm is disturbed.

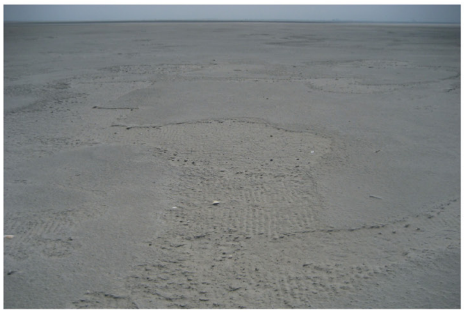


Fig. 3h (right): Semi-consolidated mudbeds of sub-fossil backbarrier tidal flat deposits indicating southward migration of the entire barrier island chain.

Fig. 3i: Aerial photograph of Kachelotplate (August 2012) with a clearly recognizable dune belt.

from 2.03m in 2007 to 2.45m in 2013 (highest value 2.53m in Nov 2012)(Fig. 5).

The westerly exposed beach migrated around 330m east between 2002 and 2012, a mean annual shift of 33m (Fig. 4). In the same period the outermost tip of the northern sand spit rotated clockwise by about 530 m. From 2004 to 2012 the western margin of the central dune belt (as indicated by *Elymus farctus* vegetation) shifted towards southeast. Since 2010 the western margin of the dune belt has been stable while the others have continued to grow, resulting in a strong increase in total area, i.e. despite the strong erosion in the western part of the Kachelotplate the area above mean high water level increased, indicating net accumulation (Fig. 6).

Between 2008 and 2012 significant morphodynamic processes were recorded on the intertidal sand bar west of the Kachelotplate, changing shape, size and orientation. The area of the sand bar fluctuates between 59 ha and 82 ha. In general the sand bar also migrates southeast, moving nearer to the Kachelotplate. It has to be assumed that the large sand bar is the main sediment source for the medium-term net accumulation of the dune belt and the sheltered tidal flats.

Seasonal dynamic of primary dunes was studied by the sediment erosion bar (SEB) method at 10 locations within the dune belt from 2008 to 2012. In general most of the dunes became more or less eroded during severe storm surges and washover events each winter, with decreasing intensity. During summer months primary dune formation recovers, primarily initiated by dense rootlets of *Elymus farctus* vegetation. As this vegetation type has increased both in lateral extension and abundance, the recovery process starts directly after disturbance, resulting in a continuous increase in mean primary dune height from year to year (Liebezeit *et al.* 2012).

Development of vegetation

The vegetation of the Kachelotplate was first investigated during a comprehensive mapping of the vegetation of the terrestrial area of the Lower Saxon Wadden Sea National Park in 2004. On the Kachelotplate, so far, only the TMAP - saltmarsh- and dune-vegetation type 'X.3.1 - *Elymus farctus* type' is established, which characterizes the primary dunes. The Lower Saxony mapping key for biotope types (Drachenfels 2011) refers to this type as 'Binsenquecken-Vordüne'. It is defined as the initial stage of dune development (primary dunes), usually only a few decimeters high, comprising calcareous and salty sand accumulations with strong sediment dynamics and sparse vegetation of *Elymus farctus*, and some *Leymus arenarius* or *Ammophila arenaria*. This vegetation type also includes the drift lines with growth of *Cakile maritima* and other associated plants.

The definition accurately describes the vegetation development on the Kachelotplate since 2004. Other vegetation types such as white dunes, salt marshes or *Salicornia/Spartina* tidal flats have not established to date. An incipient salt marsh development, however, is most likely to occur on the sheltered east side of the island. *Salicornia* tidal flats are missing due to the ab-

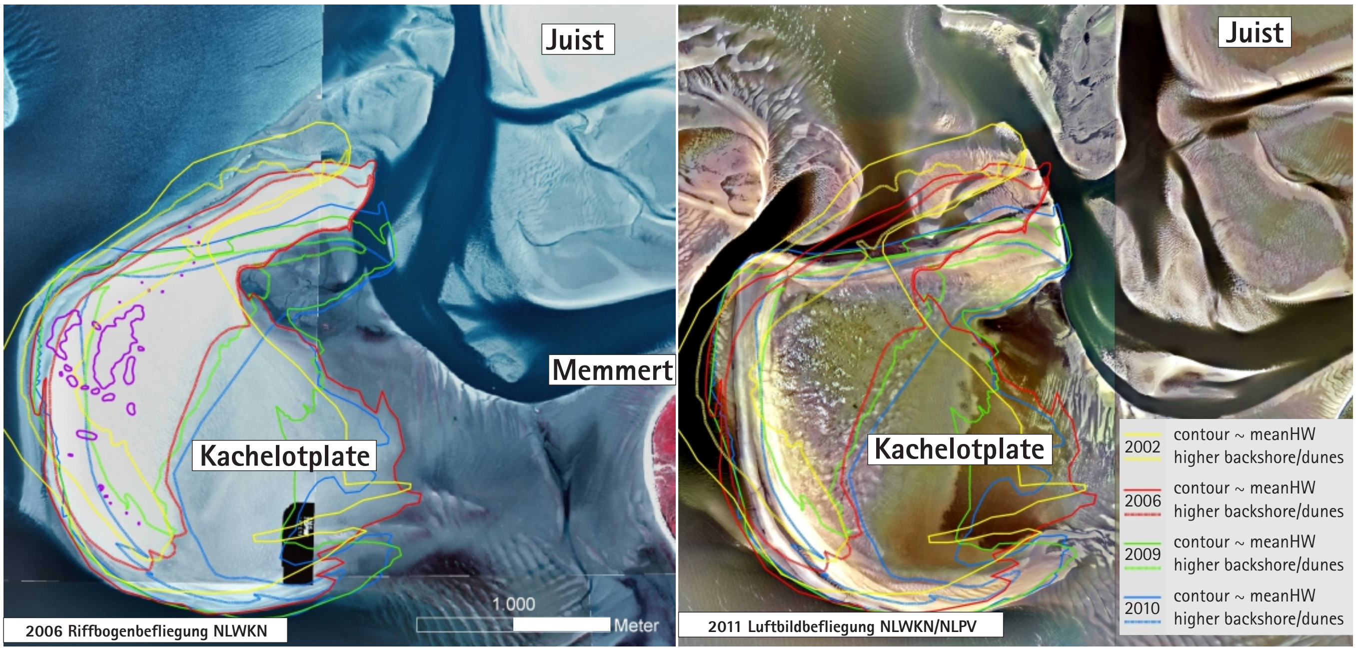


Fig. 4: Extension and lateral migration of the Kachelotplate from 2002 to 2011 by interpretation of aerial photos and ground surveys. Aerial photos from 2006 (data source NLWKN) and 2011 (data source NLWKN/NLPV).

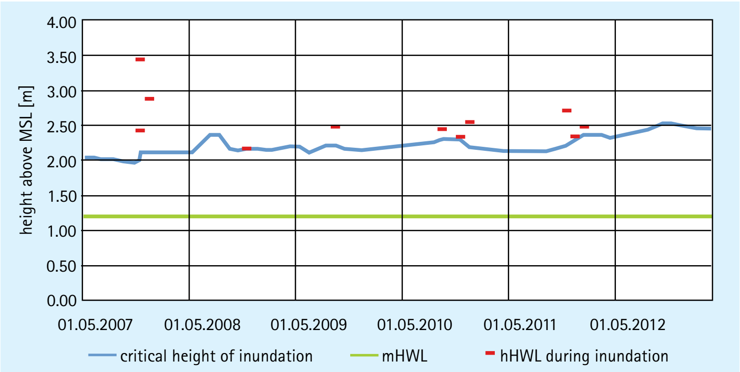


Fig. 5: Temporal development of the critical height of inundation (height of the sedimentation base) and highest highwater levels (hHWL) of episodic storm events. Top of primary dunes are up to 1.5 m above sedimentation base. Data source of gauge heights WSV/BfG.

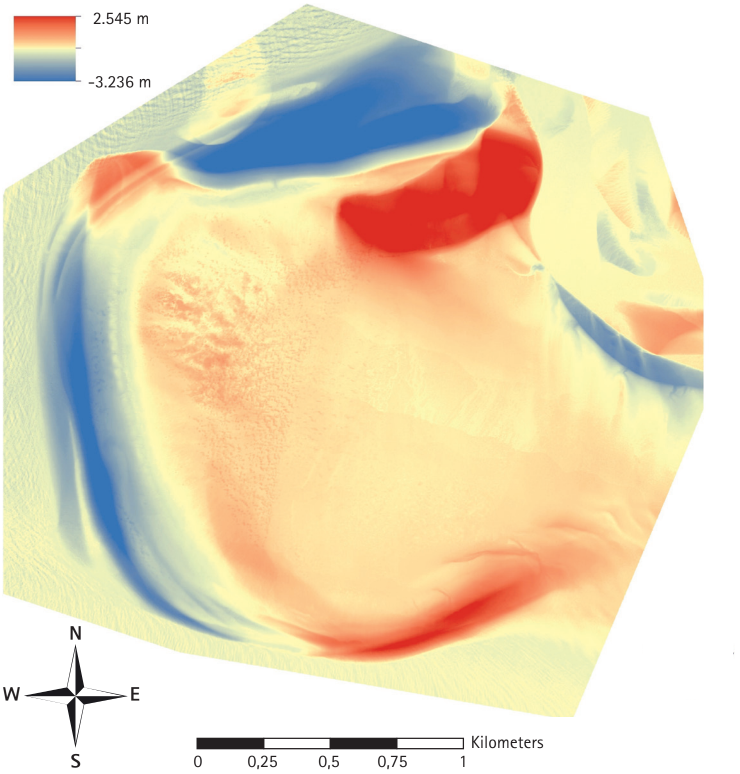


Fig. 6: Relative change in sediment budget from 2007 (=0 m) to 2012. Erosion (blue) significantly occurred at the western exposed beach. Clockwise rotation of the northern sand spit is clearly indicated by both adjoined strong erosion and strong accumulation (red). The central dune belt and the sheltered biofilm sand flats are characterized by slight accumulation. Raw data source NLWKN.

sence of fine grained muddy sediments.

After 2004, the spatial distribution of the primary dunes has been surveyed in November 2010, 2011 and 2012 at the end of the respective vegetation season (Fig. 7). Vegetation, dominated by *Elymus farctus,* covers a clearly defined area as well as some scattered plant clusters south of the area. Relatively abundant in 2012 was *Cakile maritima*, which was found (partly decayed) in both the inner dune belt and drift lines of the backshore. *Cakile maritima* also occurred in 2006, and has been found continuously since 2009. On the highest dune elevations of the central dune belt *Honckenya peploides* and *Leymus arenarius* occur.

Conclusions and perspectives

The continuous survey over more than six years revealed that the Kachelotplate is influenced by both small scale fluctuations and medium-term dynamics as typical for initial barrier island evolution. The quantification of principle sedimentary processes, *i.e.* erosion, transport and accumulation, has shown that high energy events (storm surges and related washover) are the most prominent drivers in barrier island evolution. Winter storms will erode the primary dunes which developed from continuous aeolian sand transport during summer and were stabilized by specific adapted dune vegetation. The strong erosion of primary dunes resulted in an extensive

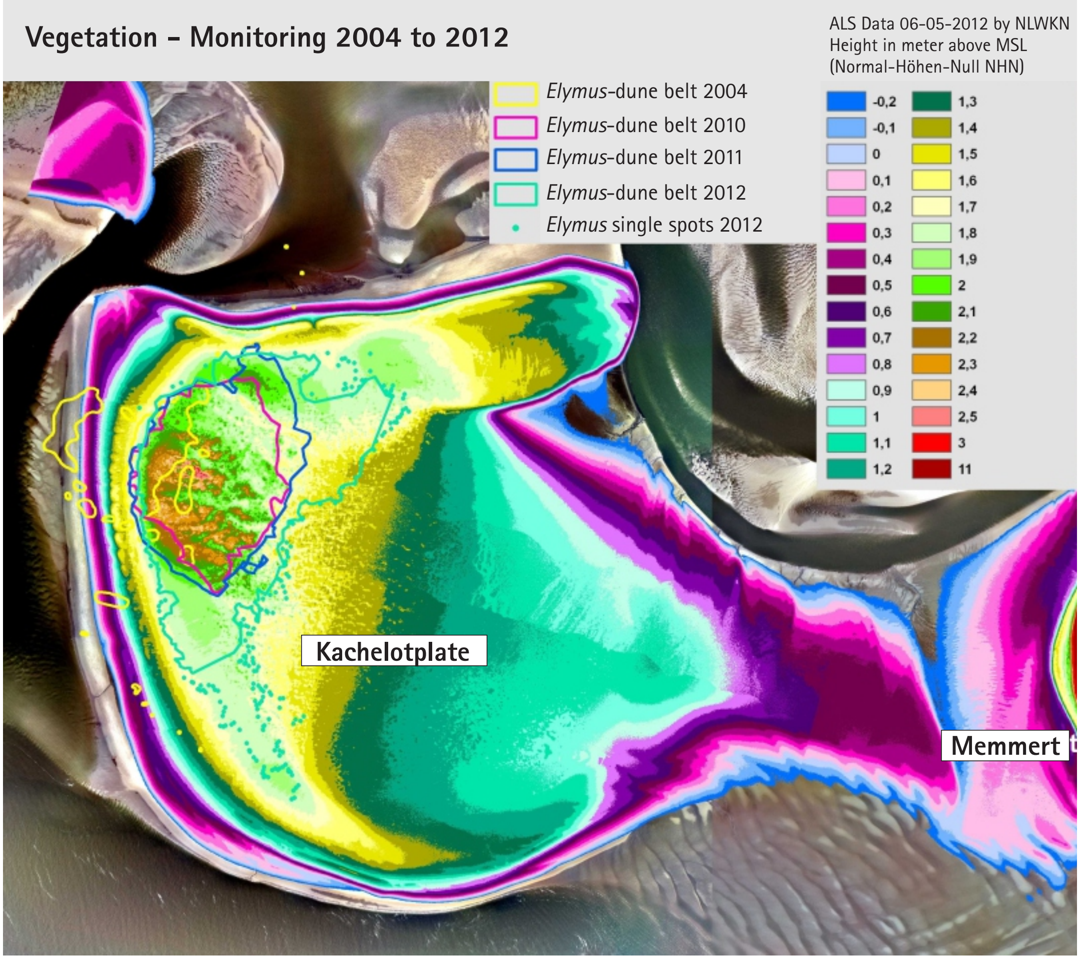


Fig. 7:
Distribution of *Elymus*-dune belt and *Elymus*-single spots between 2004 and 2012 based on vegetation monitoring. Digital elevation model generated from airborn laser scanning survey (data source NLWKN).

heightening of the sedimentary base as the sediment volume of the dunes could not be exported out of the system. This resulted in decreased inundations (Fig. 8), an essential step in the development of stable dunes (white and grey dunes) which are capable of resisting storm impacts. In recent years the sedimentary base (critical height of inundation) of the dune belt increased from 2.03m to 2.45m (above MSL). In the same time the frequency of inundations of the central dune belt decreased from 19 to three per year, in the eastern marginal dune belt from 37 to one per year and in the sheltered tidal flats from 87 to 19 per year. Continuous sediment supply for seasonal dune development is provided by the adjacent intertidal sand bars west of the Kachelotplate. As well as these principle morphodynamic processes, the strong interaction of sedimentation and vegetation favours the formation of barrier islands. The decay of organic material (algae, plant debris, peat debris) in drift lines causes local enrichment in nutrients and the establishment of pioneer vegetation. This pioneer vegetation often initiates growth of primary dunes. Baffling,

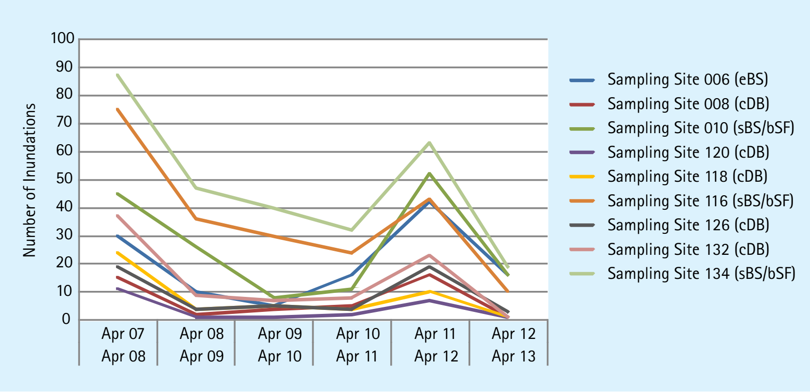


Fig. 8:
Yearly number of inundations per monitoring site from April 2007 to April 2013 calculated from tidal gauge data (WSA/BfG) and SES survey.

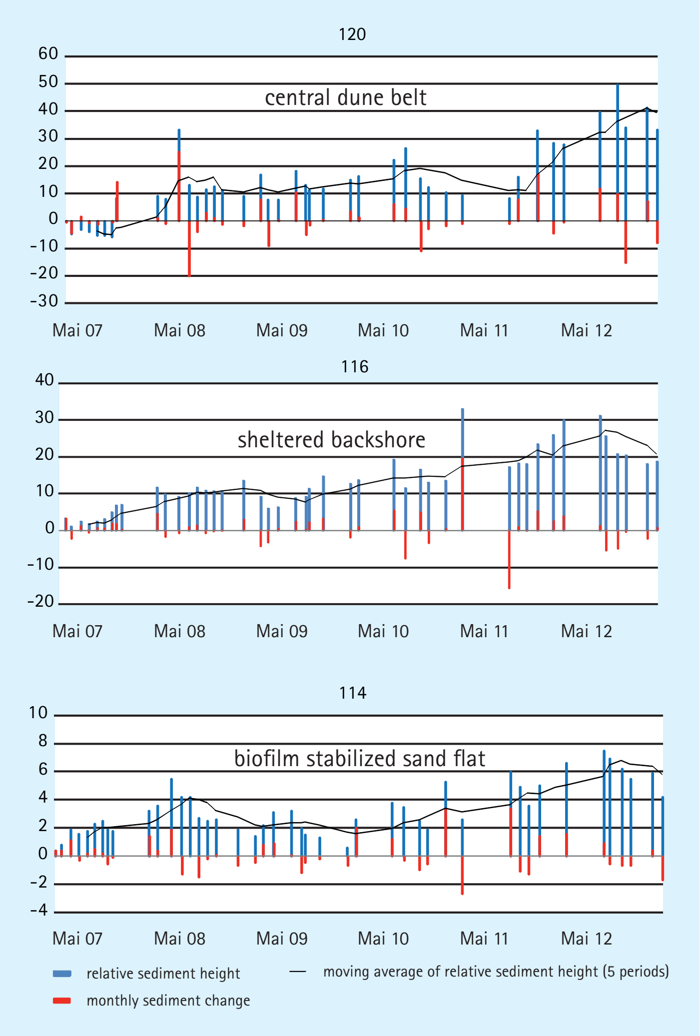


Fig. 9:
Monthly rate (in cm) of sediment accumulation (red +) or erosion (red -) and height of sedimentation base (blue) relative to April 2007 (= 0) for characteristic depositional sub-environments of the Kachelotplate. Moving average is calculated to the 5th period.

trapping and stabilization of aeolian transported sediment particles is an essential trait of the dune vegetation, initially represented by *Elymus farctus.* Furthermore, the sheltered sand flats east of the dune belt are stabilized by extended microbial mats resulting in a slight but continuous net accumulation (Fig. 9).

Despite the positive morphodynamic trends it is not expected that the Kachelotplate will become a separate island. It has to be assumed that it will merge with Memmert. So far, an aggregation of this complex with the island of Juist is improbable under the present drainage system of the back-barrier tidal flats via the Juister Balje and Haaksgat tidal channels.

Acknowledgements

We would like to to thank Holger Dirks (NLWKN) for providing ALS elevation data. Wilfried Wiechmann (BfG) is greatfully acknowledged for the provision of tidal gauge and water level data sets. We are indebted to Gerald Millat (NLPV Nieders. Wattenmeer) for his support in aerial photographs and GIS data.

Literature

Barckhausen, J. (1969): Entstehung und Entwicklung der Insel Langeoog. Beitrag zur Quartärgeologie und -paläogeographie eines ostfriesischen Küstenabschnittes. – Oldenburger Jahrb. 68: 239-281.

Drachenfels, O. v., (2011): Kartierschlüssel für Biotoptypen in Niedersachsen unter besonderer Berücksichtigung der gesetzlich geschützten Biotope sowie Lebensraumtypen von Anhang I der FFH-Richtlinie. Naturschutz Landschaftspfl. Niedersachsen, 327 S.

Freund, H. & Streif, H. (2000): Natürliche Pegelmarken für Meeresspiegelschwankungen der letzten 2000 Jahre im Bereich der Insel Juist. Petermanns Geogr. Mitt. 143: 34-45.

Gerdes, G. & Wehrmann, A. (2008): Biofilms in surface sediments of the ephemeral sand bank island Kachelotplate (southern North Sea). – Senckenberg. marit. 38: 173-183.

Hanisch, J. (1980): Neue Meeresspiegeldaten aus dem Raum Wangerooge. – Eiszeitalter u. Gegenwart, 30: 221-228.

Hayes, M. O. (1979): Barrier island morphology as a function of tidal and wave regime. – In: Leatherman, S. P. [Ed.]: Barrier Islands: 1-27; New York (Academic Press).

Liebezeit, G., Wöstmann, R., Wolters, S. (2008): Allochthonous organic matter as carbon, nitrogen and phosphorus source on a sandbank island (Kachelotplate, Lower Saxonian Wadden Sea, Germany). Senckenberg. marit. 38: 153-161.

Liebezeit, G. Wehrmann, A. Hecker, N. & Czeck, R. (2013): Die Kachelotplate – Einblicke in die Entstehung von Barriereinseln. – Natur und Umweltschutz, 12: 7-17.

Schwartz, M. (2013): The influence of storm surges on seasonal sediment budget and long-term evolution of the Kachelotplate from 2007 to 2013. BSc Thesis RWTH Aachen, 46 pp.

Streif, H. (1990): Das ostfriesische Küstengebiet. Nordsee, Inseln, Watten und Marschen. – Samml. geol. Führer, 57: 376 pp.; Berlin (Borntraeger).

Wehrmann, A. & Tilch, E. (2008): Sedimentary dynamics of an ephemeral sand bank island (Kachelotplate, German Wadden Sea): An atlas of sedimentary structures – Senckenberg. marit. 38: 185-198.

Wehrmann, A. (2014): Wadden Sea. In: Harff, J., Meschede, M., Petersen, S. & Thiede, J. [eds.], Encyclopedia of Marine Geosciences, 11 p., DOI 10.1007/978-94-007-6644-0_143-1

Authors

Achim Wehrmann
Senckenberg am Meer, Südstrand 40,
26382 Wilhelmshaven, Germany
e-mail: achim.wehrmann@senckenberg.de

Michael Schwartz
Senckenberg am Meer und RWTH Aachen
present address: Universität Bremen, FB Geowissenschaften,
28359 Bremen, Germany

Norbert Hecker
Nationalparkverwaltung Niedersächsisches Wattenmeer,
Virchowstraße 1,
26382 Wilhelmshaven, Germany

Gerd Liebezeit
Institut für Chemie und Biologie des Meeres, Schleusenstraße 1,
26382 Wilhelmshaven, Germany
present address: MarChemConsult, Altjührdener Straße 6,
26316 Varel, Germany

Mellum: a highly dynamic landscape, though not for plants

Michael Kleyer
Thorsten Balke
Vanessa Minden
Cord Peppler-Lisbach
Sarah Schoenmakers
Janina Spalke
Hanna Timmermann

Mellum: a highly dynamic landscape, though not for plants

Abstract

Many of the Wadden Sea's uninhabitated islands are characterized by strong geomorphological dynamics on multiple time scales. The salt marshes of Mellum, located beween the Weser and Jade estuaries on the Northwest-German coast, have made big increases in area during recent decades. Likewise, beaches, fore-dunes and pioneer zones of Mellum shifted in location, size and shape. Here we ask whether disturbances by geomorphological dynamics, *i.e.* burial and erosion, affect plant species distribution in a similar extent as salinity, groundwater depth, flood duration and soil nutrients. Sixty-six plots were established in 2006 on Mellum, covering most of the vegetation types occurring on Mellum. Species composition and surface elevation change were recorded during six consecutive years. Soil nutrients, groundwater depth, soil salinity, elevation and flooding duration could only be recorded in 2007. Species distribution models were fitted to the data, showing that surface elevation change had similar relevance in determining species frequencies than the other environmental parameters. Contrary to our assumptions, species turnover was strongest on sites with the lowest surface elevation change. We conclude that sedimentation and erosion represent strong selective forces, filtering a small subset of the total coastal species pool. These species exhibit specific traits allowing them to persist under a regime characterized by strong geomorphological dynamics.

Introduction

From a plant´s perspective, a landscape is dynamic, when habitat suitability shifts in time and space. Under such conditions, plant species can only persist when their population dynamics can keep pace with landscape dynamics (Kleyer *et al*. 2007). In principle, all landscapes are dynamic since habitat suitability is never constant. For instance, soil water availability and temperature show seasonal variability in many ecosystems. Stochastic climate extremes on longer time scales such as heavy rainfall or droughts are added to the seasonal variability. Many plant species maintain their reproductive capacity via seed banks or regenerative buds, to overcome such periods of unfavourable habitat conditions ("storage effects", Warner & Chesson 1985). This leads to habitats with strong variations in resource availability but stabilized plant communities, such as hardwood forests. Highly dynamic landscapes are those landscapes where destruction of plant biomass by stochastic disturbances is added to variations in resource availability on relatively short time scales, tearing apart established environment-plant-ecosystem relationships and even removing resident plant species from their habitats.

Wadden Sea islands are considered prime examples of highly dynamic landscapes as they are formed by sediments which are easily deposited and eroded again, depending on waves, currents and wind. The aeolian and coastal geomorphic features of the Wadden Sea islands are constantly changing. The barrier islands in the Wadden Sea feature an ever-changing beach side towards the open sea with fore-dunes and secondary dunes shaped by waves and wind. The tidal landscape at the back of the island towards the mainland features tidal flats, salt marshes and meandering creeks. Both landscapes intermingle on shoals where dunes and salt marshes occur in immediate vicinity.

Abiotic conditions and disturbance events vary on several temporal scales. Firstly, seasonal variations in resource availability interact with short-term variation in salinity as a strong non-consumable environmental factor. Secondly, the diurnal tidal rhythm is stochastically perturbed by storm surges and drift ice leading to prolonged periods of flooding, extreme sediment deposition or erosion, and hence burial or uprooting of plants. Thirdly, since some of the Wadden Sea islands are relatively young, they can still be colonized by newly arriving species from distant islands or the mainland, alongside with successions of salt marsh plants preferring clayey substrates over the former sandy substrates on the island´s slowly aging salt marshes.

Regarding plant-environment relationships, duration of tidal flooding (Wolters *et al.* 2008), soil aeration (Armstrong *et al.* 1985), soil salinity and waterlogging (Cooper 1982; Snow and Vince 1984), as well as physical disturbance (Wiehe 1935, Balke *et al.* 2014) are seen as the main environmental factors determining seaward limits of salt marsh species. In contrast, the landward boundary of the species niches is often attributed to competition (Pielou and Routledge 1976; Pennings and Callaway 1992; Bockelmann and Neuhaus 1999; Davy *et al.* 2000). According to Austin (1999), species niches in general are limited by physiological tolerances at the extremes of environmental gradients whereas competition controls the limits towards the centre of the gradient.

In contrast to salt marshes, beaches are exposed to stronger hydrodynamic and aerodynamic forces, leading to a sandy substrate and higher sediment transport rates (deposition, erosion). Consequently, beach sediments are also dryer and less anoxic than salt marsh soils although both ecosystems may have a similar flooding gradient. Sand can be redistributed by wind to form dunes where dune plants play a key role in binding the sediment. The dynamic biogeomorphic feedbacks between plants and sedimentation (Balke *et al.* 2014) have made dune plant communities and salt marshes model systems for the study of facilitation and succession (Cowles 1899; Olff *et al.* 1993; Franks & Peterson 2003). On the barrier islands of the Wadden Sea, stochastic extreme events such as major storm surges can set back dune formation by eroding and depositing dune sands in the adjacent salt marsh (Miller *et al.* 2010).

Here, we ask how these variations in environmental conditions affect coastal plant distributions and frequencies. Our study took place on the salt marshes and dunes of the island of Mellum, Germany. We assume that plant species respond differently to gradients in disturbance by burial and erosion on Mellum, and these responses interfere with responses to gradients in resources, tidal flooding, aeration, and salinity. Specifically, we hypothesize that fluctuations in species occurrences and frequencies increase with the magnitude of sediment deposition and erosion. Sedimentation and erosion are not mutually exclusive, both processes may occur at the same location at different points in time. Here, we use the term surface elevation change (SEC) to denote both sedimentation and erosion (Krauss *et al.* 2003; Nolte *et al.* 2013a). To study plant responses to variations in SEC, we conducted several years of continuous vegetation records together with measurement of SEC at the same plot, in order to capture effects of stochastic storm surges and ice winters. However, analyses of soil resources and groundwater variations could only be performed at the beginning of the study period.

Altogether, there are three interacting processes which we want to disentangle in this study: (i) plant responses to tidal inundation, as compared to other environmental factors such as nutrient supply, groundwater levels and soil salinity, (ii) plant responses to average SEC, as compared to all other environmental factors mentioned above, and (iii) effects of these environmental factors on the colonization-extinction rates and frequency variations of species over a time period of six years.

Material and methods

The island of Mellum (53°43'N, 8°08'E, Fig. 1) is located on the northern tip of the "Hohe Weg" tidal mudflats which are bordered by the outer Jade and Weser estuaries (Fig. 1). Mellum has a mean annual temperature of approx. 9°C and receives a precipitation of 830 mm per year (Deutscher Wetterdienst, 2009). Mellum covers approx. 555 ha, extending over 4 km in the east-west direction and 2.1 km north-south. The tidal regime near the island is macrotidal with a tidal range of approx. 3.2 m. The macrotidal zone of the German Bight is characterized by funnel-shaped estuaries and large tidal mudflats with extensive creeks. A few islands developed on these mudflats. They are however not as elongated as the East Frisean barrier islands, as the adjacent estuaries limit the eastward migration. Mellum developed with the formation of sandy shoals north-west of Mellum. With sand from these shoals, beach ridges were formed by the surf. Wash-overs and aeolian transport distributed the sand to form a flat sand bar, which eventually fell dry even at high tide. In contrast to the East Frisian islands, Mellum is not a barrier island and features only few, rather low embryonic dunes (Hartung 1975, Reineck 1987, Kuhbier 1975). Here, we denote these dunes collectively as fore-dunes, although some evolved into secondary dunes.

Mellum – a brief history

As early as 1410 AD, Mellum was mentioned as „Uppe de Mellem" in historic documents. By 1457, a first sea mark and shelter was erected on the island (Reineck 1987). From 1870 to 1890, a small part of the sandbar shielded by beach ridges on the northern part of the island was colonized by plants (Hartung 1975; Kuhbier 1975), leading to a salt marsh named „altes Grünland". Between the beach ridges and the marsh, a vast, flat sand bar prevailed, only covered with algae, diatoms and a few young dunes. Between 1910 and 1950, Mellum turned from an elongated shape with north-south orientation to a bean-shaped form in west-east extension. With further wave- and wind-driven supplies of sand, fore-dunes were formed in the north-west part of the island, in addition to the existing northern dunes, eventually shielding the sand bar from the surf. From approx. 1965 onwards, the sand bar became colonized by salt marsh plants, with occasional wash-overs leading to sand-covered upper marshes near the fore-dunes (Hartung 1975,

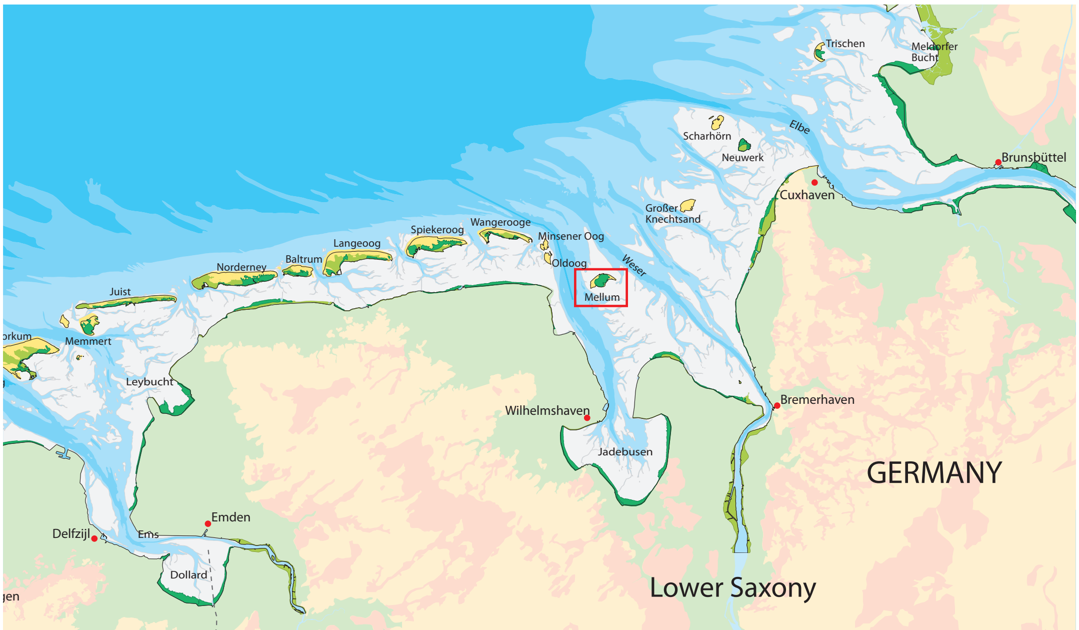


Fig. 1:
Location of Mellum.

Taux 1986). Heinrich Kuhbier, who observed the island for many years, saw a coincidence between the rapid colonization of the former sand bar and the invasion by *Spartina anglica*. According to his notes, the first plants occurred in 1954. Ten years later, he recorded 2000 tussocks (Kuhbier 1987). From personal observation and aerial photos, it appears that Mellum is still growing on its western part, forming a new salt marsh and new creeks behind embryonic dunes, whereas the north-eastern beach ridges are slowly eroding.

In summary, a core area of Mellum has been covered with vegetation for approx. 150 years, and the larger proportion of the island has been colonized for approx. the last 40 years. In the most recent years, the western shoals developed from sand bars to vegetated marshes, accompanied by slow deposition of clay. This leads to a change in nutrient and aeration conditions promoting further vegetation successions (Olff 1992; Olff *et al.* 1993).

Until the 1930s, Mellum was not used by humans at all. Neither groynes nor other constructions impeded or accelerated the evolution of the island (Taux 1986). During World War II, Mellum was considered strategically important to protect the naval port of Wilhelmshaven. In 1940, anti-aircraft guns and bunkers were installed on Mellum. To protect the garrison from storm surges, an area of approx. 4ha was enclosed by a circular dike which was planted with grass sods from the mainland and Wangerooge (Kuhbier 1975). Both the dike and the demolished military constructions are still in existence. All other parts of the island are free of any constructions or usage. In contrast to the mainland, there are no grazing animals on Mellum, apart from staging geese.

As early as 1921, the island was protected as a bird reserve and since 1925 managed as a nature reserve by an NGO, the "Mellumrat e.V." (Mellumrat 2008). Today, Mellum is part of the Wadden Sea National Park and strictly protected from human interference, together with the surrounding tidal mudflats (Nationalparkverwaltung 2008).

Sampling design

In 2006, we established 66 plots on the island of Mellum (4 m x 4 m each, Fig.2). Plots were chosen by random stratified sampling, based on elevation above sea level and marsh age. Approximately two thirds of the plots were established in the salt marshes and one third in the dune vegetation, proportionally to their spatial extent on the island. Plots were evenly distributed among older and younger salt marshes. A larger part of the island had to be excluded to protect breeding birds. However, according to our observations, the elevation map (NLWK 2004) and the TMAP map (PortalU 2014), conditions in the excluded island area were not substantially different from the sampled areas.

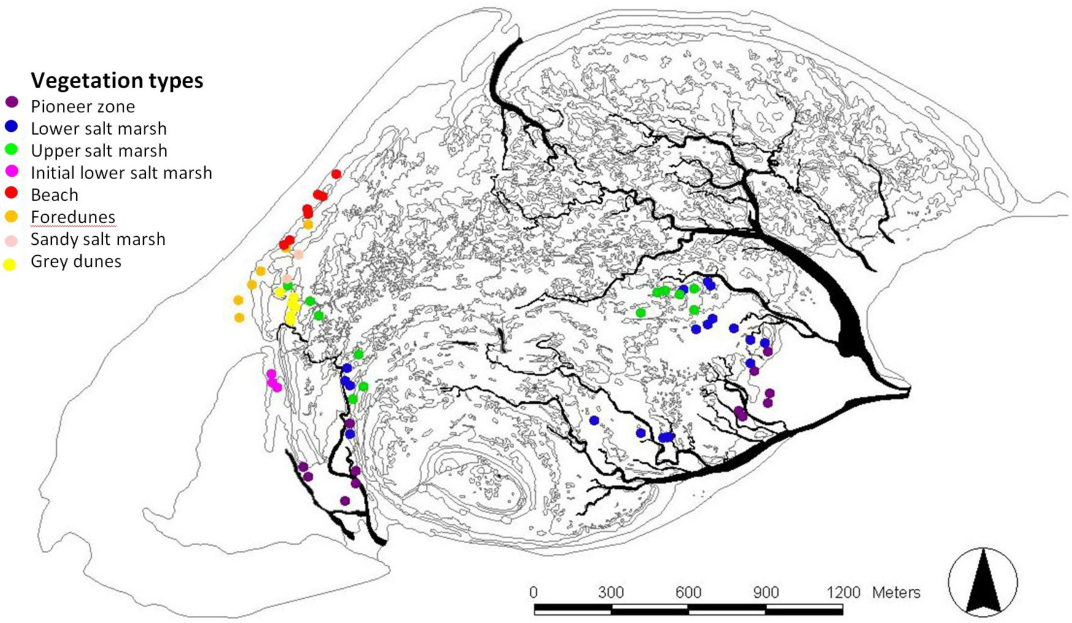


Fig. 2: Plot distribution on Mellum. Colours refer to different vegetation types (map provided by Lower Saxony Wadden Sea National Park Authority).

Field and laboratory measurements

Each plot was marked with two horizontally aligned poles to hold a sedimentation-erosion bar (SEB), orientated strictly in east-west direction. Recycled plastic poles, 2.25 m long were driven into the soil to a depth of 1.75 m. This depth served as a fixed benchmark to define surface elevation change (SEC, Cahoon *et al.* 2002a; Cahoon *et al.* 2002b; Krauss *et al.* 2003). To record SEC, an aluminium bar of 1.5 m length was placed on the two poles. The bar had 12 holes (diameter 0.01 m) with a distance of 0.1 m between each other. A measuring pin was inserted in each hole to measure the distance from the soil surface to the bar (Nolte *et al.* 2013a) and the average of the 12 distance values was used as the plot SEC value. These measurements were performed each year in late summer from 2006 to 2012. Over the years, many plots experienced alternating erosion and sedimentation rates so that gains and losses cancelled out. Therefore, we used the standard deviation of surface elevation change from 2006 to 2012 rather than the average.

Species composition and frequency was recorded by frequency analysis at each plot in August 2007, 2008, 2009, 2010, and 2012. In a sub-plot with the southern corners marked by two poles at 0.25 m distance, a 1 m x 1 m frame was laid out, sub-divided into 100 grid cells of 0.1 m x 0.1 m. In each grid cell, presence or absence of each rooted species was recorded and summed up as a measure of frequency.

The frequency records were ordered by manual tabular sorting and classified to eight vegetation units: Pioneer zone; initial lower salt marsh; lower salt marsh; upper salt marsh; sandy salt marsh, grey dune, foredune, and beach (Fig. 2). Sandy salt marshes were buried with sand from adjacent dunes by past storm surges ("washover"). This classification served as an assistance to visualize results, however, species-environment relationships were analysed unbiased of this categorization.

All environmental variables except SEC and species frequencies were recorded or measured in 2007. Soil samples were taken at each plot from each soil horizon to a depth of 60 cm in March and April 2007. Bulk density was evaluated from 200 cm^3 of soil. Soil samples were air dried, sieved through a 2 mm sieve and analysed for sand content (Ad-Hoc-AG Boden, 2005). Calcium carbonate ($CaCO_3$) was determined by adding 10 ml hydrochloric acid (dilution 1:3) to a 10 g soil sample and by measuring the carbon dioxide produced (gasometric technique, according to Scheibler in Schlichting *et al.* (1995). Plant available potassium and phosphorus were extracted with ammoniumlactate-acetic acid at pH 3 following Egnér *et al.* (1960) and analysed by AAS (Atomic Adsorption Spectroscopy) and CFA (Continous Flow Analyser, Murphy and Riley, 1962), respectively. Soil ph was measured in 0,01 M CaCl2-suspension and soil electric conductivity in a water suspension.

To record the temporal variation of the groundwater table, drainage pipes (6.5 cm diameter, 80 cm long) were installed vertically in the ground at 51 of the 66 plots. In these pipes the groundwater level was recorded biweekly from April to September 2007 at ebb tide, as well as the salinity content of the groundwater using a conductivity measurement device ('pH/Cond 340i' with measuring electrode 'Tetracon 325'). The 15 plots without groundwater measurements were located on dunes where groundwater below a depth of -0.8 m was not expected.

To assess tidal flooding duration, data loggers ('diver', ecoTech, Pegel-Datenlogger PDLA, calibrated for temperature fluctuations and salt water density) recorded the water column in 16 drainage pipes from May to September 2007 on an hourly basis. One additional data logger was placed near the study plots to record the pressure of the surrounding air, so that the relative pressure of water accumulating in the pipes could be calculated. Tidal flooding duration expressed in hours per recording period was calculated from the elevation of all adjacent plots relative to the water level measured by the data loggers. Plot elevation was determined by combining plot locations recorded by GPS with a 1x1 m resolution elevation map (via LIDAR, Light Detection and Ranging, NLWK 2004). As the elevation data was closer to normality than flooding duration data, we used elevation as the predictor variable.

Groundwater level was recorded during low tide and thus lacked information about tidal variation. Therefore, a regression was conducted with paired values of the hourly data produced by the loggers and the biweekly data of the groundwater levels at the 16 plots. Subsequently, the regression function was used to adjust values of mean groundwater level of all other plots to include information about high tide.

Statistical analysis

We used logistic regression, i.e. generalized linear models (GLMs) with a logit link function, to model the response of the species´ frequencies to the environmental predictors sampled in 2007 (Kleyer *et al.* 1999/2000; Guisan & Zimmermann 2000; Elith & Leathwick 2009). Standard deviations of SEC were averaged over the sampling period (2007-2012) and used as an additional predictor, assuming that these averages represented the long-term typical SEC at a given plot. Highly correlated environmental variables (R>0.55) were aggregated using the scores of the 1st axis of a principal components analysis (PCA). Variables only marginally correlated entered the statistical analysis directly, *i.e.* without aggregation.

Model averaging was used to avoid problems arising from variable selection and model overfitting (Burnham & Anderson 2002). The weights obtained in the averaging process indicate the relative importance of the environmental variables. To this end, for each species, separate multiple regression models were estimated for each possible combination of the environmental variables. An LR-test was used to check if one model performed better than other models. A model was considered adequate if the R^2 between predicted and observed values was >0.3 and the coefficients significantly different from zero ($p < 0.15$). In case several adequate models were obtained, the Akaike information criterion (AIC) indicated how well a model performed the trade-off between model fit and model complexity. Akaike weights were calculated from the AIC differences between each model and the AIC of the best model. Model coefficients were weighted with the corresponding model weight and the sum of all weighted coefficients for a given variable represented the averaged coefficient for this variable (Strauss & Biedermann 2006; Kattwinkel *et al.* 2009; Kattwinkel *et al.* 2011).

Community dynamics in response to environmental conditions

To quantify vegetation dynamics, we calculated a numerical variable d which summarized colonization and extinction events as well as distinct changes in species frequencies from 2007 to 2012.

$$d_{s,p,ij} = 0.3 \cdot c_{s,p,ij} + 0.3 \cdot e_{s,p,ij} + 0.07 \cdot rounddown\left(\frac{|n_{s,p,i} - n_{s,p,j}|}{10}\right)$$

$$C = \begin{cases} 1 & \text{when colonisation occurs,} \\ 0 & \text{without colonisation.} \end{cases}$$

$$e = \begin{cases} 1 & \text{when extinction occurs,} \\ 0 & \text{without extinction.} \end{cases}$$

$$\{n_{s,p,ij} \in N | 0 \leq n_{s,p,ij} \leq 100\}$$

d was calculated per occurring species (s), plot number (p) and year (i; j referring to the years). C indicates a colonisation event in the particular plot for the particular species and e indicates an extinction event. $n_{s;p;i}$ and $n_{s;p;j}$ refer to the species frequencies in two consecutive years. Thus, changes in species frequencies are weighted by the extent of the change. $d_{s;p;ij}$ equals 1, its maximum value, when frequencies change from 0 to 100 or from 100 to 0. $d_{s;p;ij}$ becomes 0 for small frequency changes < 10 without a colonisation or extinction event. Hence, dynamics involving colonization or extinctions of species received a higher weight than changes in frequencies alone. Eventually, $d_{s;p;ij}$ was averaged per plot over all species and the changes between years (2007-2012, or until the year a plot was destroyed). As a result, d_p is an indicator for plant dynamics in a certain plot. In order to select the best environmental predictor for d, the mreg function in R for Stepwise Multiple Regression was used (Bond & Farewell 2009).

Results

Plot permanence

The first SEB measurements were performed in September 2006. In November 2006 however, a storm surge (storm "Britta", extremely strong winds, offshore waves up to 17 m) flooded the island and led to the destruction of 10 plots located in the fore-dunes. Approx. 1 m of beach sediment was eroded and dune sediment was deposited on the upper salt marsh. As a consequence, the poles were driven out of the remaining soil and swept into the inner part of the island. In March 2007, these plots were re-established some metres further inland at similar abiotic conditions. During the following years, more plots were destroyed by removal of poles, due to meandering or newly developing creeks, drift ice or storm surges (2008: 1 plot; 2009: 2 plots; 2010: 6 plots; 2011: 6 plots; 2012: 4 plots). These plots were mainly located in the pioneer zone, lower salt marshes and fore-dunes. They could not be replaced in the following years as the times series depended on the exact spatial replication of measurements, regarding both, sedimentation / erosion and vegetation sampling. In 2009 and 2011, the poles marking three other dune plots were completely covered with sand so that the plots could not been found. In the following years, erosion exposed the poles again and measurements were resumed.

Abiotic gradients

Among the predictor variables, phosphorus, potassium, mean groundwater level, mean conductivity and sand content were all significantly and highly correlated ($R^2>0.5$) and were therefore aggregated to a single composite variable "saltprin1", using the scores of the first axis of a principal correspondence analysis which explained 74% of the variation of the correlated variables. Phosphorus, potassium, mean groundwater level, mean conductivity were negatively correlated with the first axis whereas sand content was positively correlated. Thus, saltprin1 became negative when groundwater levels, conductivity, and nutrients increased. SEC and elevation were correlated less than 0.5 with all other variables and used as single, independent variables in the statistical analysis. Variation in pH-values was very small so we omitted pH from any further analysis.

Boxplots of elevation per vegetation unit (Fig. 3b) show that grey dunes and most fore-dunes were almost never flooded during summer 2007. All other vegetation types were subject to tidal flooding ranging from 3,000 hours (beaches) to <20 hours (upper salt marsh; sandy salt marshes, recording period May to September 2007). Salt, groundwater and nutrients decreased from the pioneer zone to the dune communities whereas soil sand content increased (Fig. 1a).

From 2007 to 2012, the average yearly SEC values were: pioneer zone: -2.2 cm, lower salt marsh: 1.0 cm, initial lower salt marsh: 0.3 cm, upper salt marsh: 0.2 cm, sand-covered salt marsh: 11.4 cm, grey dune: 0.8 cm, fore-dune: 6.8 cm, beach: -0.4 cm. Beach and dune erosion by the storm surges in winter 2006/2007 were not included in these average values. Furthermore, SEC was presumably much larger on plots after events which destroyed sedimentation-erosion bars, such as ice drift or creek erosion. The variation in SEC was low on the salt marsh plots but increased strongly on beaches, fore-dunes and sandy salt marshes (Fig. 3c). Compared to the fore-dunes, grey dunes exhibited very low SEC due to their elevated position behind the pioneer dunes shielding them from the surf and tidal floodings. Altogether, the three predictor variables reflect the main environmental gradients on small, uninhabitated islands such as Mellum: (i) the nutrient, salt and aeration gradient distributing salt marsh plants; (ii) the tidal flooding gradient affecting salt marshes, beaches and pioneer dunes; and (iii) the SEC separating the plant communities exposed to the surf from the salt marshes which can only develop in the absence of strong wave energy.

Tab. 1: Environmental parameters used as predictors. Number of plots: 66.

Abbre-viation	Variable	Unit	Mini-mum	Maxi-mum	Mean	Sd	Transfor-mation
P	Available phosporous, calculated for 60 cm soil depth	kg/ha	20.79	395.48	124.91	79.97	Ln
K	Available potassium, calculated for 60 cm soil depth	kg/ha	354.53	2681.60	1098.46	580.20	Ln
Sand	Sand content	%	8.00	92.50	80.29	18.37	-
pH	pH		6.70	8.90	7.71	0.42	-
GW	Mean groundwater level	cm	-75.92	7.27	-37.55	28.26	-
EC	Soil root zone electric conductivity	mS/cm	0.29	16.68	3.96	3.30	Ln
Elevation	Elevation	m asl	0.60	3.20	1.64	0.55	Ln
Sd_SEC	Standard deviation in yearly surface elevation change 2007-2012	cm	0.38	70.41	10.13	16.42	Ln

Species response to environmental conditions

Several species did not respond significantly to any predictor variable (*Chenopodium album*, *Linaria vulgaris*, *Sagina nodosa*, *Sonchus asper*, *Trifolium arvense*, *Armeria maritima*). Furthermore, the models of *Leontodon saxatile*, *Carex extensa*, *Plantago coronopus*, *Sonchus arvensis*, and *Cochlearia danica* were discarded because of low agreements between observed and predicted values (R2 < 0.3). This was most often due to low prevalence, *i.e.* there were too few observations to obtain good models.

Elymus farctus x athericus and *Leymus arenaria* only responded to the variation in SEC (R2 = 0.4 and 0.9, respectively), *Sedum acre* only to elevation (R2=0.5) and *Salicornia brachystachia* to both gradients (R2=0.33), but not to saltprin1. Hence, these species could not be ordinated on the saltprin1 gradient in Fig. 4, although they produced fair to good models. Note that *Ammophila arenaria* was not very abundant on Mellum and did not occur in our plots.

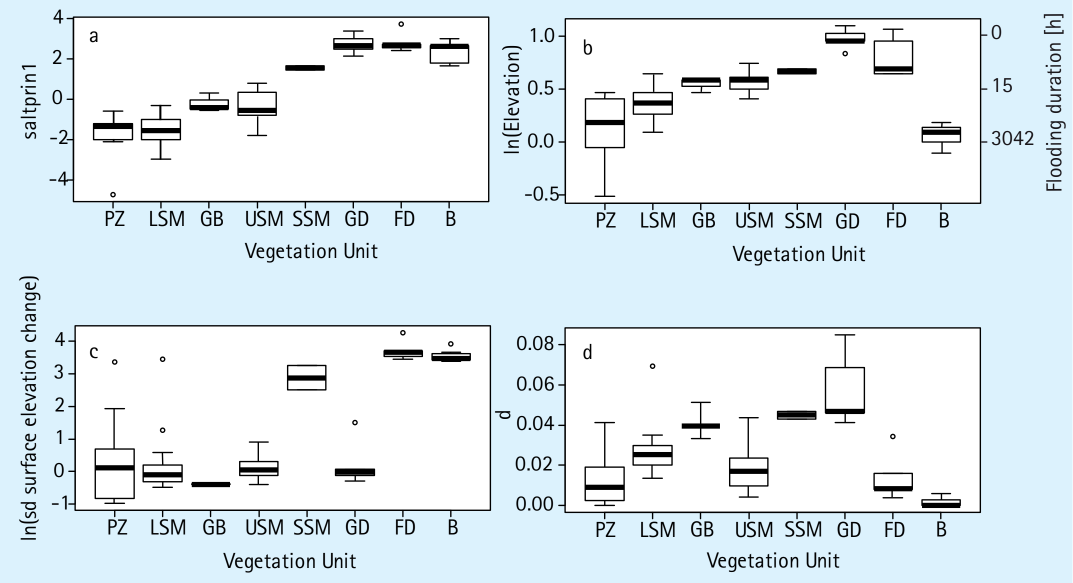


Fig. 3: Distribution of environmental parameters (a-c) and the species dynamics indicator dp (d) across vegetation units (d). PZ: pioneer zone, LSM: lower salt marsh, GB: green beach, USM: upper salt marsh, SSM: sandy salt marsh, GD: grey dune, FD: foredune, B: beach. Saltprin1 was the first principal component of five correlated parameters: available P, available K, mean groundwater level (GW), soil electric conductivity (EC), soil sand content (Sand). The correspondence between these parameters and the saltprin1 values indicated on the y-axis is as follows: -4 corresponds to 250 kg*ha-1 P, 2680 kg*ha^{-1} K, +3 cm GW, 16 mS*cm^{-1} EC, 10 % Sand; -2 corresponds to 390 kg*ha^{-1} P, 1650 kg*ha^{-1} K, -8 cm GW, 5 mS*cm^{-1} EC, 70 % Sand; 0 corresponds to 120 kg*ha^{-1} P, 900 kg*ha^{-1} K, -35 cm GW, 3 mS*cm^{-1} EC, 85 % Sand; +2 corresponds to 70 kg*ha^{-1} P, 540 kg*ha^{-1} K, -75 cm GW, 1 mS*cm^{-1} EC, 90 % Sand; +4 corresponds to 30 kg*ha^{-1} P, 350 kg*ha^{-1} K, -75 cm GW, 0.3 mS*cm^{-1} EC, 95 % Sand.

The response curves of the remaining species show typical patterns of species responses to "saltprin1", aggregated from available phosphorus, available potassium, mean groundwater table, mean soil conductivity and sand content (Fig. 4). When only comparing the response to saltprin1 at low and high elevation, constrained for low sedimentation rates (Fig. 4a and 4c), the species composition changed from pioneer and lower salt marsh species to upper salt marsh species, fore-dune and grey dune species. In both cases, species diversity was high. The distributions of a few lower salt marsh species at low elevation and low SEC were somehow unexpected (Fig. 4a). For instance, *Puccinellia maritima* showed a stronger tendency to high groundwa-

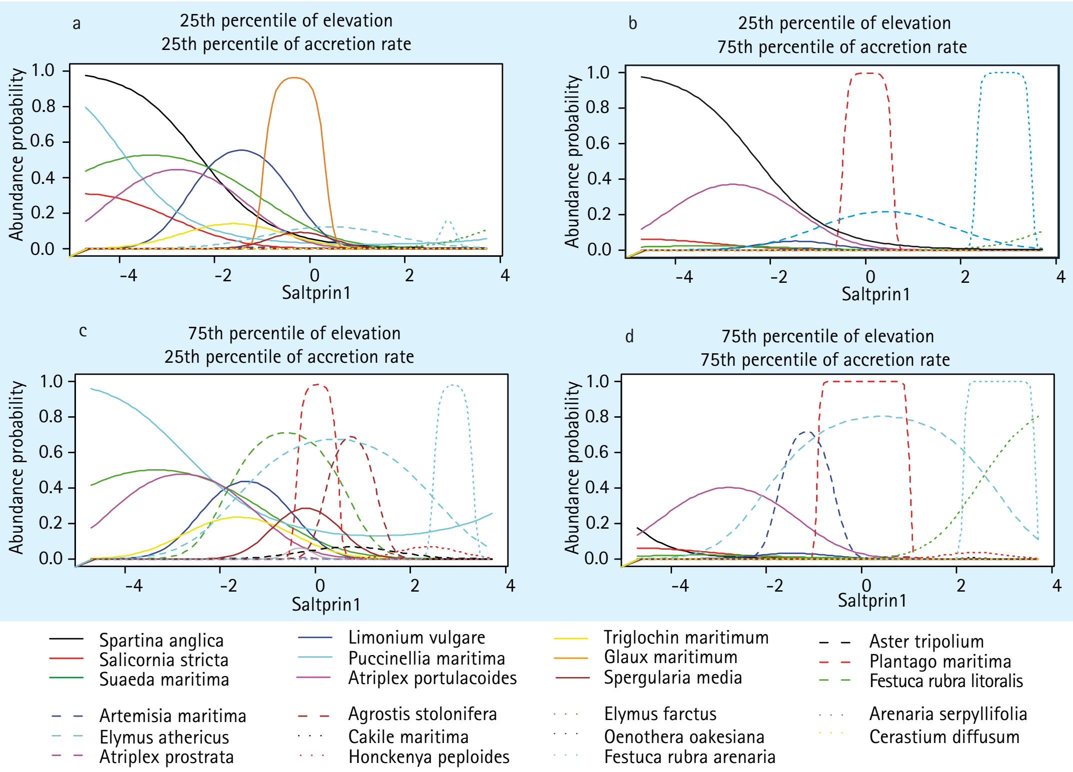


Fig. 4: Species niches on the saltprin1 gradient. Each niche model was calculated with fixed values of elevation and variation in surface elevation change. These values were the 25th percentile of ln(Elevation), corresponding to 1.2 m asl; the 75th percentile of ln(Elevation), corresponding to 1.9 m asl; the 25th percentile of ln(Sd_SEC), corresponding to a standard deviation of 0.85 cm; and the 75th percentile of ln(Sd_SEC), corresponding to a standard deviation of 6.8 cm.

ter tables, salinity and nutrients than *Spartina anglica*, although the latter is a typical species of the pioneer zone. On the other hand, increasing elevation strongly decreased the frequency probability of *Spartina anglica* whereas that of *Puccinellia maritima* increased, suggesting that tidal flooding duration was more relevant for *S. anglica*, whereas *P. maritima* responded more to the salinity and aeration gradient. Furthermore, the optimum of *Atriplex portulacoides* on the saltprin1 gradient was lower than that of *Limonium vulgare* (Fig. 4a). The reason for this pattern was that the saltprin1 gradient comprised not only nutrients, salinity, and aeration but also soil sand content, which, in contrast to the former parameters, increased with increasing values of saltprin1. *Limonium vulgare* was found on more sandy soils, whereas *Atriplex portulacoides* attained high dominance on the clay-rich soils of the older part of the island. Therefore, the response curve of *Limonium vulgare* was shifted to the centre of the saltprin1 gradient. At high elevations, *Festuca rubra* ssp. *litoralis* was found at higher salinities and lower aeration than *Elymus athericus*.

With high surface elevation changes, either at low or high elevation, the frequency probabilities were almost zero for many species. *Plantago maritima*, *Artemisia maritima*, *Elymus athericus*, *Elymus farctus* and *Festuca rubra* ssp. *arenaria* were among the few species increasing with SEC.

Note that *Spartina anglica*, *Artemisia maritima*, *Elymus farctus*, *Oenothera oakesiana*, *Arenaria serpyllifolia*, and *Cerastium diffusum* responded only to elevation and saltprin1, but not to SEC. Therefore, the response curves of these species did not differ between low and high SEC (*i.e.* between Fig. 4a and 4b, 4c and 4d). Likewise, *Salicornia stricta* did not respond to elevation (no change between Fig. 4a and 4c, 4b and 4d). For the remaining species, all three environmental gradients had the same weights (Tab. 2).

Plant community dynamics in response to the environment

According to our indicator dp, the 12 species with the highest dynamics were: *Atriplex portulacoides*, *Elymus athericus*, *Suaeda maritima*, *Salicornia stricta*, *Salicornia brachystachya*, *Puccinellia maritima*, *Limonium vulgare*, *Spergularia media*, *Elymus farctus x athericus*, *Triglochin maritima*, *Elymus farctus*, and *Festuca rubra* ssp. *litoralis* (in decreasing order, n=38).

In the final regression model with d_p as dependent variable, SEC and elevation remained as significant predictors while saltprin1 was removed ($d_p \sim 0.021-0.0014*\ln\_sd\_SEC^2+0.03*\ln\_elevation^3$, adjusted $R^2 = 0.4$). Variation in SEC was the main predictor of d_p. Contrary to our

Tab. 2: Akaike regression weights showing the relevance of each predictor for the species distribution models.

Species	ln(elevation)	ln(sd_SEC)	saltprin1	ln(elevation)^2	ln(sd_SEC)^2	saltprin1^2
Spartina anglica	25	0	25	25	0	25
Salicornia stricta	0	25	25	0	25	25
Suaeda maritima	16.67	16.67	16.67	16.67	16.67	16.67
Limonium vulgare	16.67	16.67	16.67	16.67	16.67	16.67
Puccinellia maritima	16.67	16.67	16.67	16.67	16.67	16.67
Atriplex portulacoides	16.67	16.67	16.67	16.67	16.67	16.67
Triglochin maritima	16.67	16.67	16.67	16.67	16.67	16.67
Glaux maritima	16.66	16.67	16.67	16.66	16.67	16.67
Spergularia media	16.67	16.67	16.67	16.67	16.67	16.67
Aster tripolium	14.39	17.81	17.81	14.39	17.81	17.81
Plantago maritima	16.67	16.67	16.67	16.67	16.67	16.67
Festuca rubra ssp. litoralis	16.67	16.67	16.67	16.67	16.67	16.67
Artemisia maritima	25	0	25	25	0	25
Elymus athericus	16.67	16.67	16.67	16.67	16.67	16.67
Atriplex prostrata	16.67	16.67	16.67	16.67	16.67	16.67
Agrostis stolonifera	16.67	16.67	16.67	16.67	16.67	16.67
Cakile maritima	16.67	16.67	16.67	16.67	16.67	16.67
Honckenya peploides	16.67	16.67	16.67	16.67	16.67	16.67
Elymus farctus	25	0	25	25	0	25
Oenothera oakesiana	25	0	25	25	0	25
Festuca rubra ssp. arenaria	16.67	16.67	16.67	16.67	16.67	16.67
Arenaria serpyllifolia	25	0	25	25	0	25
Cerastium diffusum	39.83	0	10.17	39.83	0	10.17

initial assumption, species dynamics increased with decreasing SEC. The vegetation units with highest dynamics were initial salt marshes, grey dunes and sandy salt marshes (Fig. 3d).

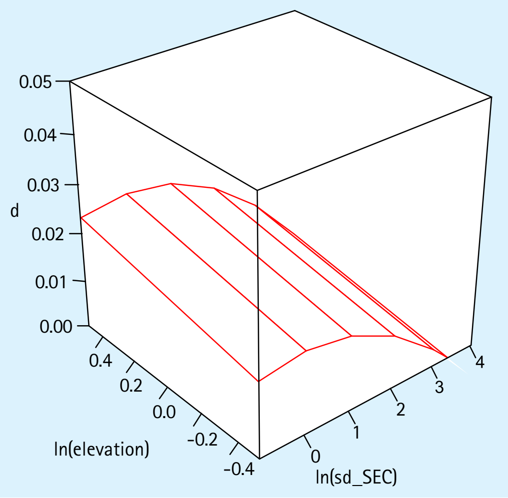


Fig. 5: Relationship between the plant dynamics indicator dp, elevation and variation in surface elevation change (SEC).

Discussion

In this study, we ordinated the plants species of all major habitats of Mellum on the most relevant environmental gradients, namely soil resources, aeration, salinity and groundwater level as well as accretion rates and elevation as a proxy for tidal flooding duration. We assumed surface elevation change (SEC) to be the master factor for creating dynamic conditions, by destruction or burial of plant biomass. According to our results, SEC played an equal role as the more "classical" environmental factors in explaining frequencies of the majority of the plant species, as shown by the regression weights. Beaches, fore-dunes and pioneer zones were the habitats with the highest variation in SEC. Plots in these habitats also experienced the highest destruction rates. Contrary to our initial assumptions, they exhibited the lowest species turn-over.

The role of sediment dynamics

Both historical accounts and our observations demonstrated the dynamic geomorphology of Mellum. On average, we found negative SEC on pioneer zone and beach plots, whereas sandy salt marshes and fore-dunes showed the highest positive SEC. Average SEC was lowest in the upper salt marsh, where sediment is deposited only during storm surges, whereas tidal flooding and storm surges both contribute to SEC in the pioneer zone and the lower salt marsh (Schuerch *et al.* 2012). Average SEC on Mellum was in line with long-term rates found by other studies along the North Sea coast (Nolte *et al.* 2013b). However, the variation in SEC on beaches, foredunes and sandy salt marshes was much larger than the average. Although SEC in pioneer zones was lower than in dunes, pioneer zones could also be considered highly dynamic habitats, as indicated by the high number of destroyed plots where SEC measurements were not possible any more. As a caveat, we note that our plots were not uniformly distributed over the island and surface elevation changes at the eastern side of Mellum were not considered.

Species responses to environmental conditions

Nutrients, groundwater level, soil salinity and soil sand content were all correlated and thus formed a common gradient (saltprin1) running from the pioneer zone with high salinity and waterlogged conditions to the grey dunes with low salinity, low nutrient supply, no groundwater within the root zone, and high sand content. Although the lower salt marsh was richer in nutrients than the upper salt marsh and the dunes (Adam 1990), most salt marshes on Mellum exhibited rather low nutrient contents as compared to mainland marshes (Minden *et al.* 2012). Mainland marshes of the Frisian coast mostly originate from land reclamation measures (Gray and Bunce 1972) rather than developing from sand bars. Therefore, they usually contain more silt and are thus richer in nutrients.

When variations in SEC were low, species niches were almost evenly distributed along the saltprin1 gradient. Likewise, they were strongly influenced by elevation and hence flooding duration. The continuous change of species optima imply rather gradual transitions of communities along the salinity, aeration, nutrient and inundation gradients corresponding to the classical "individualistic continuum concept" (Austin 1990, 2005), which states that species are continuously distributed on environmental gradients. However, other direct environmental factors such as pH and temperature can promote higher discontinuities in species distributions, due to buffered soil Al and H+ concentrations or frost (Peppler-Lisbach & Kleyer 2009).

Individualistic niche distributions of coastal plants were often explained by the 'physiological-ecological-amplitude' concept (Scholten *et al.* 1987; see also Cooper 1982; Snow & Vince 1984; Pielou & Routledge 1976; Pennings & Callaway 1992; Bockelmann & Neuhaus 1999; Davy *et al.* 2000). According to this concept, seaward niche boundaries are limited by species-specific physiological tolerances whereas the landward boundaries are determined by competition. Recently, empirical studies were conducted along the Frisian coast, including Mellum, to verify the concept using functional traits (Minden *et al.* 2012). The seaward species distributions could be well indicated by functional traits. For instance, plants actively diluting and excluding salt increased with increasing groundwater salinity. Succulence and dilution of salt in the vacuole increased specific leaf area by enlarging leaf area without increasing leaf dry weight. Moreover, decreasing plant tissue C:N ratios marked increasing synthesis of nitrogen-rich osmoprotectants with increasing salinity and waterlogged conditions (Minden *et al.* 2012; Eallonardo *et al.* 2013, Minden & Kleyer 2014). On the other hand, species occurring at lower values of salinity responded to osmotic stress by passive adaptations such as lignification of cell walls (Rozema *et al.* 1985), as indicated by increased leaf and stem dry matter contents. However, competition was less clearly indicated by traits in these studies. For instance, plant height, leaf area, as well as plant leaf, stem and root biomass are usually seen as indicators of competitive ability. Lower salt marsh plants did not exhibit higher values of these traits as compared to the pioneer species *Spartina anglica* (data not shown). Likewise, plant height and leaf area values of *Elymus athericus* were not significantly larger than those of lower salt marsh species. Rather, litter accumulation due to reduced decomposability as a result of high tissue C: N ratios was identified as a possible mechanism of *Elymus athericus* to monopolize upper salt marsh sites (Minden & Kleyer 2014)

For the majority of all modelled species, SEC was an equally important predictor as saltprin1 or elevation. High variation in SEC strongly decreased the modelled frequencies of many salt marsh species, leading to species-poor communities. Burial and erosion exerts a strong selective pressure on many coastal species (Wilson & Sykes 1999; Maun 2009). Species able to cope with this pressure are characterized by extended clonal networks of elongated rhizomes with regenerative buds and relatively large seeds (*e.g. Leymus arenarius*, *Elymus farctus x athericus*, *Elymus farctus*, *Festuca rubra arenaria*, *Spartina anglica*) or by an annual life cycle with abundant seed production (*e.g. Suaeda maritima*, *Salicornia* spp.). Like traits of weeds on arable fields (Froud-Williams *et al.* 1984), these trait syndromes facilitate rapid regeneration following below-ground disturbance or burial (Grace & Tilman 1990; Grime 2002; Garcia-Mora *et al.* 1999).

In contrast to our expectation, sites with high variation in SEC were characterized by low species turnover, as demonstrated by the negative relationship between the population dynamics indicator d and the variation in SEC. Neither saltprin1 nor elevation had a comparably strong effect on d. We found higher colonization and extinction rates and frequency changes on sites with low SEC, such as grey dunes and initial lower salt marshes, than on sites with high SEC (*e.g.* fore-dunes, pioneer zones). This result corroborates our interpretation that burial and erosion represent a strong filter, sieving only a small subset of species from the coastal species pool (Kleyer *et al.* 2012). The traits of these species provide a stabilizing mechanism (Chesson 2000) enabling them to prevail at sites with strong geomorphological dynamics (Franks & Peterson 2003).

Here, we interpreted the interplay between vegetation and SEC in a "classical" way, *i.e.* SEC was seen as an independent environmental factor to which species responded in occurrence and frequency probability. However, recent models and empirical investigations emphasize that sediment accretion is actively engineered by plant species so that competition between plants and sediment trapping create a dynamic feed-back system of multiple quasi-equilibrium states of which the zonation of plant communities are the observable results (Marani *et al.* 2013). Although plant responses to the ecosystem and effects on ecosystems were recently investigated on mainland salt marshes of Lower Saxony (Minden & Kleyer 2011), the emerging field of biogeomorphic dynamics requires more research to predict the evolution of coastal landscapes and their biodiversity.

Conclusion

Historical accounts and our data show that Mellum is a very dynamic landscape. First, the island has completely changed its shape on a centennial scale. Second, some sites of the island underwent vegetation successions on a decadal scale when these areas were elevated above tidal flooding thresholds by sedimentation. Third, within the yearly scale of our investigation, beaches, foredunes, pioneer zones and directly adjacent lower salt marsh communities were subjected either to strong erosion, wash-over effects or high aeolian sedimentation. However, these were not the sites experiencing the strongest vegetation dynamics. On the contrary, strong variations in SEC support a few plants well adapted to erosion and sedimentation. On Mellum, these species were *Leymus arenarius*, *Elymus farctus x athericus*, *Elymus athericus*, and *Festuca rubra* ssp. *arenaria*. They all feature an extended network of elongated rhizomes allowing rapid vegetative colonization of bare sediment. Many other species were suppressed by strong surface elevation changes. Conversely, the sites with lowest SEC exhibited the strongest vegetation dynamics. A time series of six years may not be long enough to disentangle vegetation successions from random fluctuations or neutral dynamics (Hubbell 2001) and short term variability in surface elevation from long term geomorphic evolution. Clearly, evolution and migration of islands at the scale of centuries is associated with strong shifts in community composition. However, our results demonstrate that yearly colonization and extinction rates are facilitated in the absence of strong surface elevation changes, which select for specific plant adaption strategies, such as rapid vegetative or generative regeneration. This study also shows that the geomorphological perspective of a "highly dynamic island" does not necessarily correspond to a plant´s perspective of a "highly dynamic island".

Acknowledgements

We thank "Der Mellumrat e.v." for supporting our research for many years, in particular Matthias Heckroth, Gregor Scheiffarth, Nadine Knipping, and Thomas Clemens. "Der Mellumrat" is a NGO founded in 1925 for the preservation of Mellum. We also thank Corinna Burkhart and Maria Schoenen for their assistance in the field.

Literature

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

Austin M.P. (1990). Community theory and competition in vegetation. In: Perspectives on plant competition. (eds. Grace JB & Tilman D). Academic Press San Diego, CA, USA, pp. 215–238.

Austin M.P. (2005). Vegetation and environment: discontinuities and continuities. In: Vegetation ecology. (ed. Van der Maarel E). Blackwell Publishing Malden, MA, USA, pp. 52–84.

Balke T., Herman P.M.J. & Bouma T.J. (2014). Critical transitions in disturbance-driven ecosystems: identifying Windows of Opportunity for recovery. Journal of Ecology, 102, 700–708.

Bockelmann A.C. & Neuhaus R. (1999). Competitive exclusion of *Elymus athericus* from a high stress habitat in a European salt marsh. Journal of Ecology, 87, 503-513.

Bond S.J. & Farewell V.T. (2009). Likelihood estimation for a longitudinal negative binomial regression model with missing outcomes. Journal of the Royal Statistical Society: Series C (Applied Statistics), 58, 369-382.

Burnham K.P. & Anderson D.R. (2002). Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach. 2nd ed. Springer, New York.

Cahoon D.R., Lynch J.C., Hensel P., Boumans R., Perez B.C., Segura B. & Day J.W. (2002a). High-precision measurements of wetland sediment elevation: I. Recent improvements to the sedimentation-erosion table. Journal of Sedimentary Research, 72, 730-733.

Cahoon D.R., Lynch J.C., Perez B.C., Segura B., Holland R.D., Stelly C., Stephenson G. & Hensel P. (2002b). High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. Journal of Sedimentary Research, 72, 734-739.

Chesson P. (2000). Mechanisms of maintenance of species diversity. Annual Review of Ecology and Systematics, 31, 343-366.

Cooper A. (1982). The effects of salinity and waterlogging on the growth and cation uptake of salt marsh plants. New Phytologist, 90, 263-275.

Cowles H.C. (1899). The ecological relations of the vegetation of the sand dunes of Lake Michigan. Botanical Gazette, 27, 95-391.

Davy A.J., Costa C.S.B., Yallop A.R., Proudfoot A.M. & Mohamed M.F. (2000). Biotic interactions in plant communities in saltmarshes. Linnean Society of London by Forrest Text, Tresaith, Ceridigion.

Diercke Weltatlas (1988), Braunschweig: Westermann.

Eallonardo A.S., Leopold D.J., Fridley J.D. & Stella J.C. (2013). Salinity tolerance and the decoupling of resource axis plant traits. Journal of Vegetation Science, 24, 365-374.

Elith J. & Leathwick J.R. (2009). Species distribution models: Ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics, 40, 677-697.

Franks S. & Peterson C. (2003). Burial disturbance leads to facilitation among coastal dune plants. Plant Ecology, 168, 13-21.

Froud-Williams R.J., Chancellor R.J. & Drennan D.S.H. (1984). The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. Journal of applied ecology, 21, 629-641.

Garcia-Mora M.R., Gallego-Fernandez J.B. & Garcia-Novo F. (1999). Plant functional types in coastal foredunes in relation to environmental stress and disturbance. Journal of Vegetation Science, 10, 27-34.

Grace J.B. & Tilman D. (1990). Perspectives on plant competition. 1st edn. Academic Press, San Diego.

Grime J.P. (2002). Plant strategies, vegetation processes, and ecosystem properties. . John Wiley and Sons, Chichester.

Guisan A. & Zimmermann N.E. (2000). Predictive habitat distribution models in ecology. Ecological Modelling, 135, 147-186.

Hartung W. (ed.) (1975). Mellum als eine werdende Nordseeinsel. Heinz Holzberg Verlag, Oldenburg.

Hubbell S.P. (2001). The unified theory of biogeography and biodiversity. Princeton University Press, Princeton.

Kattwinkel M., Biedermann R. & Kleyer M. (2011). Temporary conservation for urban biodiversity. Biological Conservation, 144, 2335-2343.

Kattwinkel M., Strauss B., Biedermann R. & Kleyer M. (2009). Modelling multi-species response to landscape dynamics: mosaic cycles support urban biodiversity. Landscape Ecology, 24, 929-941.

Kleyer M., Biedermann R., Henle K., Obermaier E., Poethke H.J., Poschlod P., Schroder B., Settele J. & Vetterlein D. (2007). Mosaic cycles in agricultural landscapes of Northwest Europe. Basic and Applied Ecology, 8, 295-309.

Kleyer M., Dray S., Bello F., Lepš J., Pakeman R.J., Strauss B., Thuiller W. & Lavorel S. (2012). Assessing species and community functional responses to environmental gradients: which multivariate methods? Journal of Vegetation Science, 23, 805-821.

Kleyer M., Kratz R., Lutze G. & Schröder B. (1999/2000). Habitatmodelle für Tierarten: Entwicklung, Methoden und Perspektiven für die Anwendung. Zeitschrift für Ökologie und Naturschutz, 8, 177-194.

Krauss K.W., Allen J.A. & Cahoon D.R. (2003). Differential rates of vertical accretion and elevation change among aerial root types in Micronesian mangrove forests. Estuarine Coastal and Shelf Science, 56, 251-259.

Kuhbier H. (ed.) (1975). Das Pflanzenkleid der Insel Mellum. Heinz Holzberg Verlag, Oldenburg.

Kuhbier H. (1987). Die Entwicklung des Grünlandes auf Mellum. In: MELLUM Portrait einer Insel (eds. Gerdes G, Krumbein WE & Reineck HE). Verlag Waldemar Kramer Frankfurt am Main, pp. 234-262.

Marani M., Da Lio C. & D'Alpaos A. (2013). Vegetation engineers marsh morphology through multiple competing stable states. Proceedings of the National Academy of Sciences, 110, 3259-3263.

Maun M.A. (2009). The biology of coastal sand dunes. Oxford University Press, Oxford.

Mellumrat (2008). Homepage des Mellumrat e.V. URL http://www.mellumrat.de/index3.htm

Miller T.E., Gornish E.S. & Buckley H.L. (2010). Climate and coastal dune vegetation: disturbance, recovery, and succession. Plant Ecology, 206, 97-104.

Minden V., Andratschke S., Spalke J., Timmermann H. & Kleyer M. (2012). Plant trait-environment relationships in salt marshes: Deviations from predictions by ecological concepts. Perspectives in Plant Ecology Evolution and Systematics, 14, 183-192.

Minden V. & Kleyer M. (2011). Testing the effect-response framework: key response and effect traits determining above-ground biomass of salt marshes. Journal of Vegetation Science, 22, 387-401.

Minden, V. & Kleyer, M. (2014). Internal and external regulation of plant organ stoichiometry. Plant Biology. DOI: 10.1111/plb.12155.

Nationalparkverwaltung (2008). URL http://www.nationalpark-wattenmeer.niedersachsen.de /master/ C24387843_N24389728_L20_D0_I5912119.html

NLWK. 2004. Niedersächsischer Landesbetrieb für Wasserwirtschaft und Küstenschutz, Laserscan-Befliegung Jadebusen, Bereich II.

Nolte S., Koppenaal E.C., Esselink P., Dijkema K.S., Schuerch M., Groot A.V., Bakker J.P. & Temmerman S. (2013a). Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. Journal of Coastal Conservation, 1-25.

Nolte S., Müller F., Schuerch M., Wanner A., Esselink P., Bakker J.P. & Jensen K. (2013b). Does livestock grazing affect sediment deposition and accretion rates in salt marshes? Estuarine, Coastal and Shelf Science, 135, 296-305.

Olff H. (1992). Effects of Light and Nutrient Availability on Dry-Matter and N-Allocation in 6 Successional Grassland Species - Testing for Resource Ratio Effects. Oecologia, 89, 412-421.

Olff H., Huisman J. & Vantooren B.F. (1993). Species Dynamics and Nutrient Accumulation During Early Primary Succession in Coastal Sand Dunes. Journal of Ecology, 81, 693-706.

Pennings S.C. & Callaway R.M. (1992). Salt marsh plant zonation: The relative importance of competition and physical factors. Ecology, 73, 681-690.

Peppler-Lisbach C. & Kleyer M. (2009). Patterns of species richness and turnover along the pH gradient in deciduous forests: testing the continuum hypothesis. Journal of Vegetation Science, 20, 984-995.

Pielou E.C. & Routledge R.D. (1976). Salt marsh vegetation: Latitudinal gradients in the zonation patterns. Oecologia, 24, 311-321.

PortalU K. (2014). Biotoptypen im Bereich Mellum. URL http://www.portalu.de/kartendienste? wms_url=http%3A%2F%2Fmdi.niedersachsen.de%2Fgeoserver%2FBiotoptypen%2Fwms%3FREQUEST%3DGetCapabilities%26SERVICE%3DWMS%26VERSION%3D1.1.1

Reineck H.-E. (ed.) (1987). Morphologische Entwicklung der Insel Mellum. Kramer, Frankfurt am Main.

Scholten M., Blaauw P.A., Stroetenga M. & Rozema J. (eds.) (1987). The impact of competitive interactions on the growth and distribution of plant species in salt marshes. Dr W. Junk Publishers, Dordrecht.

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. Estuaries and Coasts, 35, 486-500.

Snow A.A. & Vince S.W. (1984). Plant zonation in an Alaskan salt marsh. II. An experimental study on the role of edaphic conditions. Journal of Ecology, 72, 669-684.

Strauss B. & Biedermann R. (2006). Urban brownfields as temporary habitats: driving forces for the diversity of phytophagous insects. Ecography, 29, 928-940.

Streif H. (1990). Das ostfriesische Küstengebiet: Nordsee, Inseln, Watten und Marschen. Gebrüder Bornträger, Berlin - Stuttgart.

Taux K. (1986). Die Oldenburgischen Naturschutzgebiete. Heinz Holzberg Verlag, Oldenburg.

Warner R.R. & Chesson P.L. (1985). Coexistence Mediated by Recruitment Fluctuations - a Field Guide to the Storage Effect. American Naturalist, 125, 769-787.

Wilson J.B. & Sykes M.T. (1999). Is zonation on coastal sand dunes determined primarily by sand burial or by salt spray? A test in New Zealand dunes. Ecology Letters, 2, 233-236.

Authors

Michael Kleyer*, Thorsten Balke, Vanessa Minden, Cord Peppler-Lisbach, Landscape Ecology Group, Institute of Biology and Environmental Sciences, University of Oldenburg, D-26126 Oldenburg, Germany;

Sarah Schoenmakers, Heumarschstraße 30, D-28309 Bremen;

Janina Spalke, BioConsult SH GmbH & Co. KG, Schobüller Str. 36, D-25813 Husum;

Hanna Timmermann; ARSU, Escherweg 1, 26121 Oldenburg.

* Corresponding author: Fax: +49-441-7985659,
E-mail: michael.kleyer@uni-oldenburg.de

Dynamic patterns on Scharhörn-Sand

Ulrich Hellwig
Peter Körber
Jens Umland
Levinia Krüger-Hellwig

Aerial photo of Nigehörn during low tide, showing the wooded dune valley as well as the lagoon; in the background the island of Neuwerk, in the far back the mainland coast of Cuxhaven. Photo: Stock 2013

Fig. 1b:
Aerial photo of Scharhörn during low tide, showing mega ripples in (northern) front of the island and part of the gully system; the wadden way is distinguishable in the south; in right back the furthermost edge of Nigehörn is visible. Photo: Stock 2013

Dynamic patterns on Scharhörn-Sand

Abstract

Natural and undisturbed dynamics characterize the Scharhörn-sand in the Elbe estuary. While the sand has been known since the Middle Ages, the islands on it developed in the last century. The natural development of Scharhörn began around 1900 and Nigehörn was artificially created in 1989. Island development and bird populations have been monitored on Scharhörn since the early 1900s – after World War II this was done regularly by bird wardens of the Verein Jordsand, and since 1989 also for Nigehörn. After basic studies in 1997 the monitoring program for the Hamburg Wadden Sea National Park, in line with the Trilateral Monitoring and Assessment Program (TMAP), delivered data about the Scharhörn-sand and its islands since the year 2000.

Based on this data, this article presents an overview of island landscape developments. It demonstrates the significant shift of the islands and their expansion in the past 15 years. The subsequent development of a gully system in the elevated flats is an aspect of the last few years. Fast succession of the vegetation is illustrated with the results of permanent plot studies since the year 2000, with a special emphasis on salt marshes and dunes. In former times Scharhörn was known as a dune island. But nowadays the areas of salt marsh and increasing pioneer zones are much more dominant than the dune aspects. Some unexpected phenomena are also discussed, *e.g.* the growth of shrubs and trees in the salt marsh area of Nigehörn. The alteration of habitat structures was followed by a change of bird life; *e.g.* a shift from large tern colonies to an increased gull population. New breeding species, such as Cormorants, Spoonbills and Short-eared Owls, also arrived on the islands. The development of the vegetated sites (area and elevation) and the potential for new breeding grounds for birds will be of interest in the years to come.

Introduction

The high sand of Scharhörn ("Scharhörnplate") is situated at the south-western edge of the outer Elbe estuary. The meso-tidal regime is characterized by a mean tidal amplitude of about 3.1 m; the mean high water (MHW) is 1.4 m above sea level.

The elevation of the high sand areas varies from about 0.1 m to 0.6 m above mean high water (MHW), that is 1.5 m to 2.0 m above sea level. The highest dune ridges of Scharhörn rise to 6.0 m above MHW, those of Nigehörn up to 5.5 m above MHW.
Salinity in this region varies between 24-26 psu (Umweltbehörde Hamburg 2001, Siefert 1970).

Neighbouring islands are Neuwerk in the south-east, Trischen to the north-east and Mellum to the west.

Göhren (1970) explained the formation of the high sand and its shifting since 1868 as a comparatively new manifestation, as opposed to Linke (1969), who assumed the sand to have existet for at least for 3,500 to 4,000 years.

Since 1229 the sandbanks in the mouth of the river Elbe have been known because of the dangers they represented near the shipping lanes to the harbour of Hamburg. The name "Schaerhorne" was first mentioned in 1466. By 1594 Schroeter had published a map depicting sandbars north of Neuwerk. In 1868 exact outlines of the high sand were available (Schmid 1988). The first beacon was recorded in 1861.

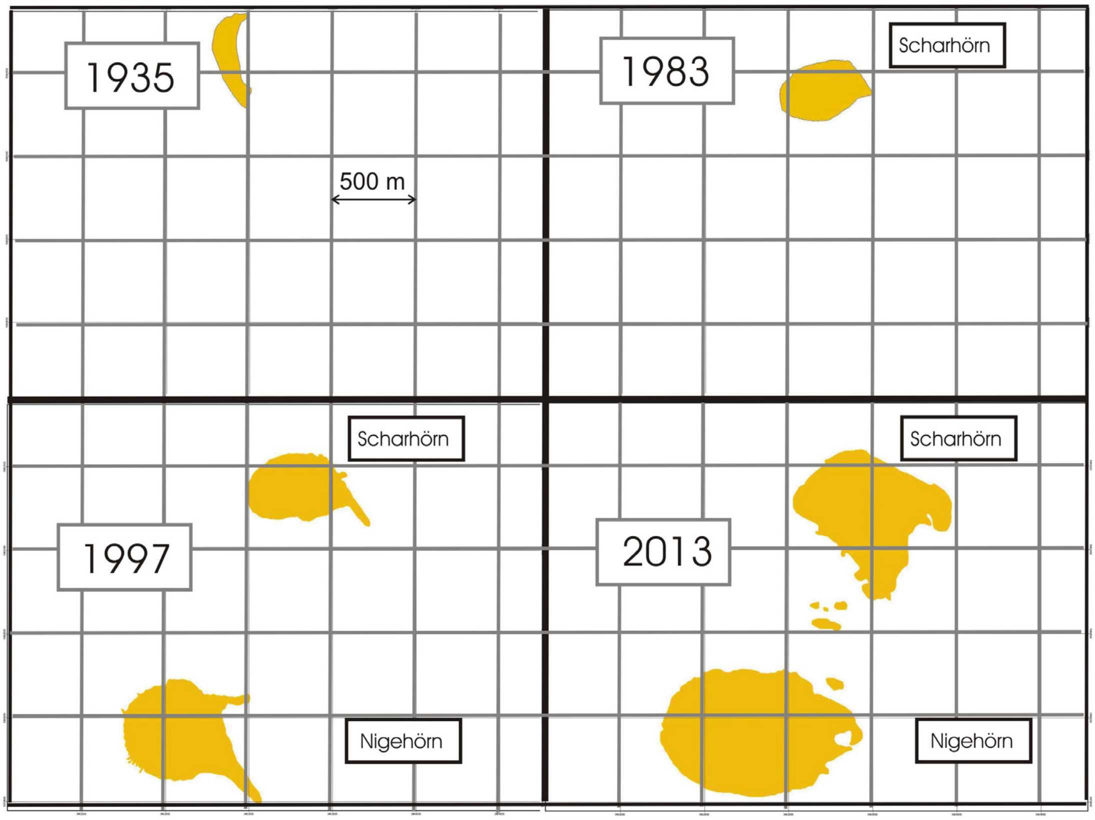
The islands on this sandbar – Scharhörn and especially Nigehörn – are comparatively new. Their history dates back to the beginning of the 20th century when the first pioneer vegetation and breeding attempts of terns and plovers on the high sand were observed. In the 1920s, following the proposition of conservation measures, the state of Hamburg successfully promoted and supported the development of the island of Scharhörn. By building brushwood groynes, seeding and planting, a primary dune island was established, and it prospered in the following decades (Wagner 1952). However, continued maintenance measures were necessary to stabilize the island. Storm surge events in 1936, 1962 and 1976 demolished wide parts of the dune barrier and repeated fires (1938, 1950, 1951, 1954) heavily damaged the vegetation (Schmid 1988), but the island continued to exist and even thrive.

Scharhörn increased in size and became famous for its large breeding colonies of terns.

But in the 1980s it became obvious that the island was in decline. The area decreased from 15.3 ha in 1977 to 13.7 ha in 1983 and a total loss of breeding grounds seemed to be possible (Schmid 1988). Maintenance measures which proved to be ineffective had been generally abandoned in 1975, although in 1987 and during late summer of 1991 the responsible authorities of Hamburg provided sand-nourishments (Janke & Glitz 1992).

In view of the seemingly inevitable loss of Scharhörn as a breeding site for coastal birds in the 1980s, a new island neighbouring Scharhörn was constructed and dedicated to nature and

Fig. 2: Development of islands on the high sand, Nigehörn was built in 1989; vegetation of annuals is not shown.



natural processes (Janke & Glitz 1992).

The dune island Nigehörn was created in 1989, a few hundred meters south-west of Scharhörn on a stable, high area of the Scharhörn-sand. During one of the largest projects in nature conservation in the Wadden Sea so far, 1.2 million m³ sand were deposited. Dunes were landscaped by Caterpillars and subsequently fixed by planting and sowing. Brushwood groynes were erected to accelerate sedimentation. In 1991, all actions were completed. Since then natural dynamics have been allowed to prevail, with any other actions banned, even access for visitors.

A monitoring project undertaken in the early years (1989-1994) confirmed positive developments of breeding and roosting sites for seabirds as well as the establishment of typical biotopes and characteristic plant species (INUF 1995). In spite of severe winter storms losses of island area to erosion were smaller than expected. At the end of the initial monitoring period in 1994, the artificial island was considered to be a successful nature conservation project. This early history of Nigehörn is very well documented by publications in the early 1990s (Fiedler & Glitz 1991, Glitz 1991, Janke & Glitz 1992, Janke & Piper 1992, Piper & Hartwig 1994).

The next survey in 1997 showed only small changes on Nigehörn. Some large erosion areas had isolated outlying dunes on the north-western edge and it was presumed that these areas would be eroded. Other than that, a dune bow complex and an island tail, consisting of embryonic dunes and pioneer zone respectively, had established on the eastern and southern borders.

The history of the islands is tightly linked with their function as a nature reserve. In 1939 solely the vegetation covered island Scharhörn was designated as bird sanctuary. However, since 1967 the whole sand was designated as nature reserve and this was extended in 1986. Since 1990 the nature reserve has been part of the Hamburg Wadden Sea National Park.

Since 1948 bird wardens stayed on Scharhörn each season, from April to October. Nowadays they are the only inhabitants, but in former times the little island occasionally hosted lots of people. Working crews lived there each summer from 1929 to develop the island. During World War II military personnel were stationed there, and from 1964 to the late 1970s a research team was there to investigate the feasibility of constructing a deep water harbour at Scharhörn. All that activity resulted in many different lodgings being built. However, they have disappeared due to erosion and the island's shifting location. Today the hut for bird wardens is the only building on Scharhörn.

The development of both islands is well documented. The sand, and especially the islands, are examples of changing aspects of the landscape. Figure 2 represents four development stages over the last 80 years. Spatial data of the sandbank itself are not available for each stage, but both increase and shift of the islands become obvious. Human interference becomes apparent by adding the new island Nigehörn in 1989.

Scharhörn and Nigehörn present a unique opportunity to study and analyse how natural processes affect the development of islands and habitats after their artificial creation. It will be instructive to compare their development to those of the neighbouring islands Trischen and Mellum (also in this issue).

In this publication we will concentrate on developments between 2000 and 2013, since standardised data on biology and geomorphology are available for these years. We aim to describe possible interactions of ongoing geological, ecological and biological processes. Previous publications included long-term studies with a main focus on bird communities, but they did not consider bio-geomorphological interactions in a comparable way.

Methods and data sources

Scharhörn belongs to the best documented breeding and roosting sites for birds in Germany. Since 1948 yearly reports on bird life have been produced by „Vogelwarte Helgoland" or „Verein Jordsand". Since 1989 the reports have also included the new island Nigehörn. Those data have been published continuously in the journal „Seevögel".

Since 2000 the methods to record all data concerning breeding and roosting birds have been standardized (see below).

Schmid (1988) published a monograph concerning Scharhörn including detailed data about vegetation, flora and a multitude of fauna groups. From 1989 to 1994 an extensive monitoring project documented the first years of Nigehörn (INUF 1995).

Tüxen und Böckelmann (1957) and Grossmann (1988) published results of vegetation relevees and floristic overviews. Mang (1982) made up a flora of Scharhörn and Neuwerk. Kuhbier (1993) documented first floristic aspects of Nigehörn. The most recent publications concerning the flora of Scharhörn and Nigehörn were published 14 years ago (Hellwig & Kuhbier (2000) and Umweltbehörde Hamburg (2001)).

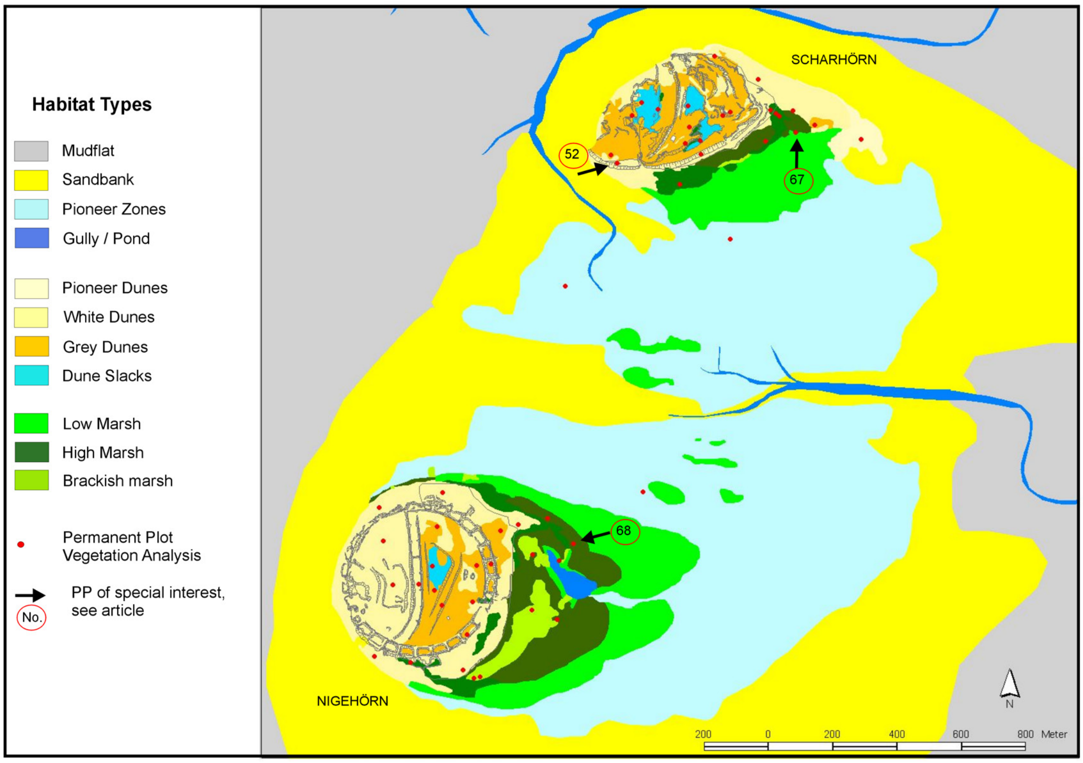


Fig. 3: Habitat types (survey 2009) of Scharhörn-sand and permanent plots for vegetation analysis (in this article represented permanent plots are marked by arrows).

However, most of the recent data have not yet been published (*e.g.* IfAUM 2005, 2011), while Hellwig (2006) and Piper (2007a, b) produced the most recent overviews.

In 2000, the monitoring programme within the National Park Wadden Sea of Hamburg started in line with the Trilateral Monitoring and Assessment Program (TMAP).

Based on the vegetation map of 1997, 52 permanent plots with a size of 4 m² each were established in 2000, located in different habitats on Scharhörn and Nigehörn . All relevant habitat types were covered to document the succession of the vegetation (see fig. 3). The plots were investigated annually during the first days of August. Plant cover of different species is estimated by means of Londo (1976). Nomenclature of plant species follows Wisskirchen & Haeupler (1998).

In this article we have chosen graphs to represent the development of specific permanent plots. Species with less than 5% coverage are not presented; therefore the graphs do not completely reflect species richness of the plots.

Complete biotope mappings were carried out in 1997, 2004 and 2009, combining aerial survey and terrestrial analysis. All surveys were transferred into vegetation types according to the TMAP classification (Petersen *et al.* 2014). A new survey, celebrating the 25th anniversary of Nigehörn, is planned in 2014.

Since 2000, annual surveys of the outline boundaries (= perimeter) of Scharhörn and Nigehörn have been carried out. We measured the vegetation border by means of a standard GPS-device around the vegetation covered areas of both islands. At the northern, western and eastern sides we defined the vegetation of primary dunes as island boundary (therefore neglecting driftline vegetation). Ont the south side we determined two boundaries:

(1) (the border between salt marsh and pioneer zone; and
(2) the border between pioneer zone (> 5 % coverage) and bare sand.

To analyse the shifting of the islands we defined three transects (N-S, NW-SE, W-E) which intersect nearly at the centre point of Scharhörn as well as Nigehörn and determined the yearly changes at the points of intersection with the vegetation boundaries.

The imaginary centre point of the islands was also determined annually by using the relevant function of ArcGis.

Observed developments

Island size and location

Following the successful establishment of Scharhörn its area increased until 1973 with a calculated average growth of about 4.7 %/year. Schmid (1988) reported a decrease of nearly 2.7 %/year in the period 1977–1983. However, the following surveys revealed an increase of the area with a burst of growth in the period 1997–2004 with an average progress of 7.2 %/year (Fig. 4 & 5). This expansion rate seems to continue as the perimeter mapping in 2013 revealed an all-time maximum area of about 43.2 ha for salt marshes and dunes.

In the time between its establishment and the surveys in 1997, the much younger island Nigehörn suffered from significant erosion at the sea-exposed boundaries and mirrored the general development of Scharhörn.

However, the survey in 2004 showed a near-doubling of vegetation covered area. The former erosion zones were covered by white dunes, al-

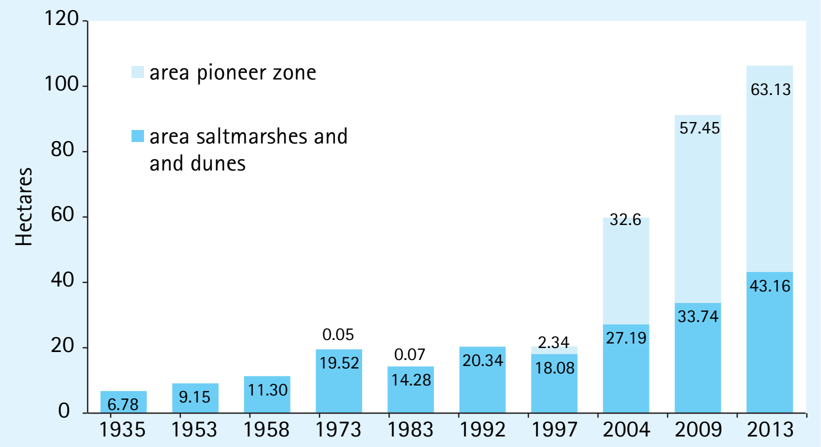


Fig. 4:
Increasing area of Scharhörn; in 1992 no details to pioneer zones were available; (compilation from Kraus 1995, Schmid 1988, own surveys).

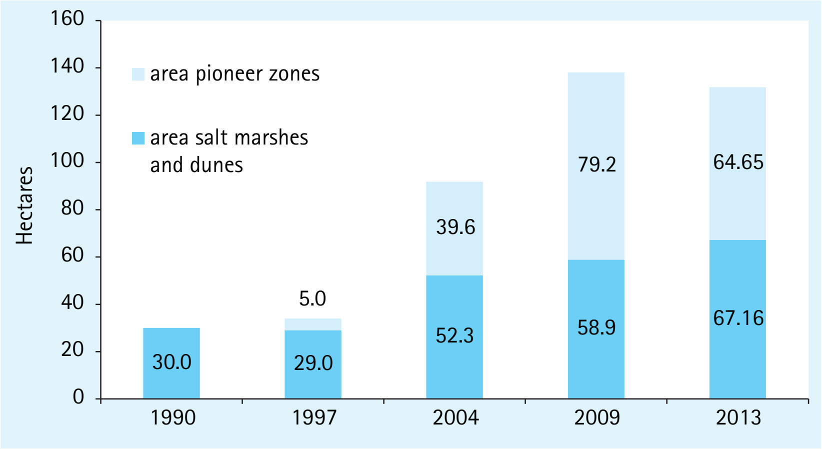


Fig. 5:
Increasing area of Nigehörn; area 1990 is an educated guess (from 1989 to 1994 no reliable data are available).

though on a very low elevation, and exceptional salt marsh growth had quite changed the overall aspect of the island.

The survey in 2009 and continuous monitoring of the perimeter since 2000 confirmed that the north-western edges remain nearly stable. Due to significant growth at the southern and eastern boundaries Nigehörn increased constantly.

Scharhörn is continuously shifting its position. In 1997, only a very small area in the north-west could be traced back to 1953 and this had altogether vanished in 2009 (Fig 6).

The island shift, expressed as south-east movement of the island boundaries (salt marshes as well as dunes), differs substantially between Scharhörn and Nigehörn. There is also a clear difference between the amount of relocation of vegetation boundaries between the sea-exposed and sea-sheltered parts of the islands (Tab. 1).

Tab. 1:
Shift of vegetation boundaries of Scharhörn and Nigehörn, 2000-2013 (negative values indicate erosion; for further explanations see text).

	Situation of vegetation border	**Annual mean drift (m/a)**	**Total shift from 2000-2013 (m)**
Scharhörn	N	-0.7	-8.1
	NW	-2.8	-33.9
	W	-3.9	-47.7
	S	17.7	212.3
	SE	8.9	106.2
	E	22.1	265.5
	Centre point		173.7
Nigehörn	N	1.3	16.4
	NW	-0.6	-7.9
	W	2.6	33.2
	S	12.1	156.8
	SE	5.2	62.4
	E	41.9	502.6
	Centre point		233.9

We could observe three main lines of development:

(1) Main feature is the average regression of the seaward vegetation line of Scharhörn to 2.8 m/year in the north-west (NW) and 3.9 m/year in west (W). Schmid (1988) reported different values. Between 1953-1983 the NW boundary has relocated about 9.8m/year, while the eastern border has progressed at about 15m/year. Detailed analysis of our data (not presented in this article) shows that yearly changes differ substantially. Maximum regression was up to 15.4 m (2006-2007) in the NW, in other years the island boundaries were stable or progressed (2003-2004, 2008-2009)

(2) The regression is collectively much more distinct on Scharhörn than on Nigehörn, where only the NW transect has given way to erosion. The other sea-exposed vegetation lines remain stable or even show progress. But the range of data [max. regression 29.1m (2007-2008), max. progression 27.9m (2012-2013)] is much more prominent on Nigehörn.

(3) In southern and eastern directions the vegetation boundaries have grown at a scale 10-times greater than the observed regression. This therefore represents an enlargement of the islands.

In consequence to the observed processes, up to now, both islands increased in area. Furthermore, the islands relocate, which is also demonstrated by shifting of their imaginary centres about 200 metres from 2000 to 2013 in south-eastern to eastern direction. The dune centre of Nigehörn remains comparatively stable, whereas Scharhörn shows shifting and eroding phenomena.

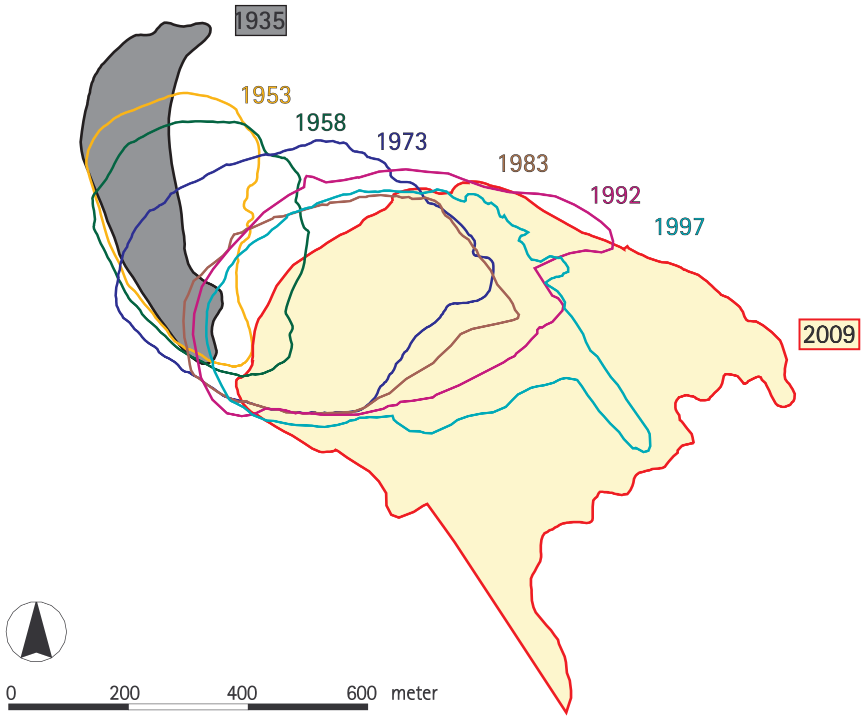


Fig. 6:
Shift of Scharhörn-island (Kraus 1995, Schmid 1988, own surveys).

However, these results do not take into account the ever increasing pioneer zones. Considering these annual biotopes, the centre points and the southern and eastern edges of Scharhörn would have shifted about 400 metres since 2001, the borders of Nigehörn about 600 metres.

As the decreasing biotopes consist of high dunes whereas the increasing areas are of comparatively low elevated salt marshes and primary dunes, the mass balance seems to be much more complicated. Therefore we hesitate to proclaim an overall gain to the island.

It has to be noted that shift and increasing area of Scharhörn up to the 21th century is mainly due to erosion and wind-induced sedimentation which would result in dune succession. During the last decades, however, water-induced sedimentation became the defining main factor in accelerating growth of salt marshes.

Habitats

Some significant changes in the structure of the sand took place in the last 15 years. Compared to 1997 (Tab. 2) vegetation coverage on the sand has increased by up to 433%. A large percentage is pioneer zone plants with *Salicornia stricta* and *S. procumbens*, *Spartina anglica* and *Suaeda maritima*. The pioneer zones are extending significantly in a south-eastern direction but are also covering nearly the whole area between the islands. Although built by annual vegetation growth these biotopes seem to be very persistent and do function as starting points for salt marsh succession. These succession lines can be determined not only at the salt marsh edges of the islands but also between the islands (chapter vegetation, Fig. 3) with no contact to existing salt marshes. Generally salt marshes have increased considerably and are nowadays a main feature. While areas of low marshes increased significantly, some low marsh aged and underwent succession to high marsh. From 2004 to 2009 a considerable part of the high marsh developed into brackish marsh dominated by reed beds.

Embryonic dunes have declined and are nowadays absent on Nigehörn, whereas Scharhörn has grown a considerable and increasing amount of primary dunes during the last three years (not shown in Tab. 2). White dunes, eutrophic dunes and dune grassland (= grey dunes) are fluctuating in size while the overall area is slightly increasing.

Typical dune slack units are deficient on both islands. On Scharhörn two comparatively large depressions are covered by *Phragmites*-reedbeds, other dune slack communities like *Agrostis*-dominated marshes and *Bolboschoenus*-reedbeds are sparse. Nigehörn presents a windblown depression with a low-growing *Centaurium littorale*/ *Sagina nodosa*/ *Juncus articulatus* vegetation which develops into a dune slack willow shrubbery.

Habitats changed over the years, but development of some very new habitats and structures have also been observed. Extensive develop-

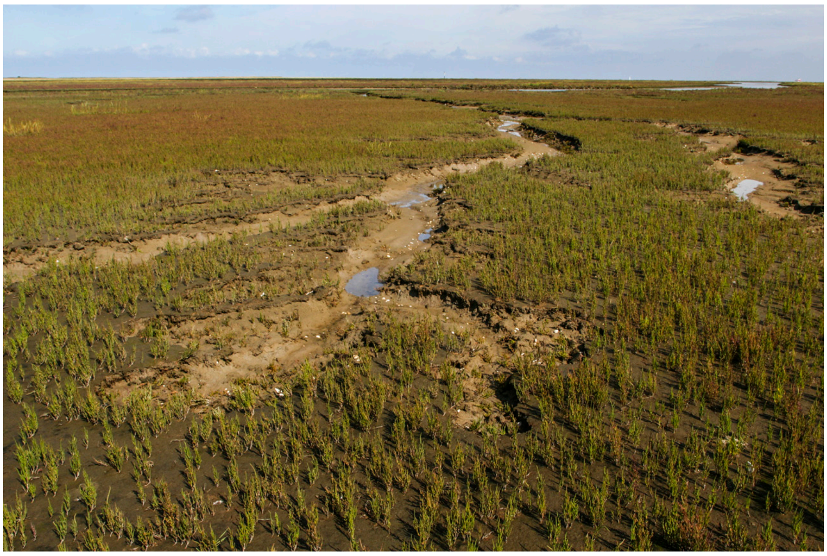


Fig. 7:
Development of gullies on Scharhörn-sand.
Photo: Körber 2012

ments of gullies in what were initially plain areas (Fig. 7), occurrence of salt marshes between the islands, and the recently possible passage from Scharhörn to Nigehörn during high tide, hint at considerable changes; *e.g.* an overall elevation of the plate. Detailed elevation data of the whole sand are only available for the year 1999. In other years only line transect data were provided by Hamburg Port Authority. These data demonstrate increasing elevation from 1999 to 2007 (from 1.5 m to 1.8 m above sea level). However, the elevation in the 1980s seemed to be significantly higher, rising to 2.1 m above sea level (Schmid 1988).

Tab. 2:
Development of biotopes on the sand (concerning only vegetation-covered areas and open areas inside the dunes, the vegetation-free sand and other biotopes like gullies are not considered).

(area in ha)	1997	2004	2009
Pioneer zone	6.34	72.17	140.32
Low marsh	0.42	10.64	26.84
High marsh	0.85	15.75	4.63
Brackish marsh	0	3.21	14.72
Embryonic dunes	4.00	4.12	1.94
White dunes	16.66	13.79	26.56
Dune grassland	18.40	20.99	14.07
Eutrophic dunes	2.44	6.58	3.99
Dune slacks	0.30	2.95	1.75
Other biotopes	4.98	1.43	0.97
Total	**54.39**	**151.63**	**235.79**

In 2001 we first noticed a lagoon in the salt marsh zone south of Nigehörn. It has persisted at a comparatively stable size of about 2,000 m^2 but water levels have varied each year. Its connection to the daily flooding regime nearly disappeared as primary salt marshes began to develop at its outer edges. In 2012 a primary pond also established itself on Scharhörn, duplicating the site on Nigehörn.

On Nigehörn scrubs and trees have developed. *Salix* species, *Juniperus communis*, *Rosa canina*, *Alnus glutinosa*, *Fraxinus excelsior*, *Hippophae rhamnoides* are only to be found on Nigehörn, while *Rosa rugosa* is much more common on Scharhörn. In a windblown depression in the interior of Nigehörn *Salix* species invaded the area. During the last decade this area changed nearly completely into a dune slack willow shrubbery. *Pinus nigra*, *Betula pubescens*, *Alnus glutinosa* and *Fraxinus excelsior* show a possible further development to dune slack woodland. Furthermore willows, Common Alder and Seabuckthorn have invaded the salt marshes outside the dune ridge.

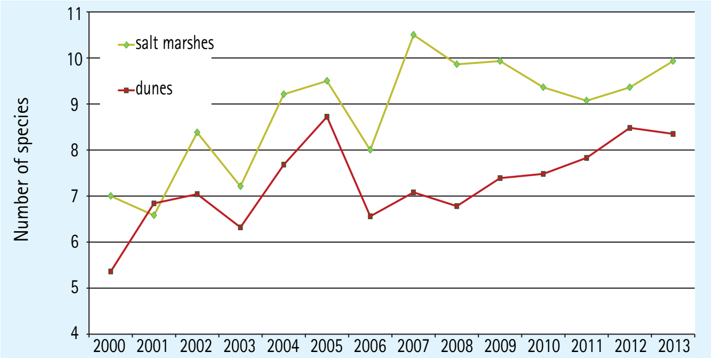
Vegetation

In contrast to birds, detailed information on both plants and vegetation has not been published since Grossmann (1988).

We define species richness as number of plant species per plot. Species richness was low in the pioneer zone (2-3 species) and white dunes (5-7 species). Highest values in salt marshes were found in high marshes in transition to brackish marshes (vegetation types of *Carex extensa* and *Plantago coronopus*/*Centaurium littorale*, see following chapter). Grey and white dunes influenced by storm surges presented the highest species richness in dunes (dune slack communities were not considered).

Overall species richness has been increasing in both dunes and salt marshes with two depressions in 2002/2003 and 2005/2006 (Fig 8).

Fig. 8:
Mean species richness of permanent plots (dunes = 25 sites, salt marshes = 14 sites)



However, highly significant changes from year to year can only be confirmed in dunes from 2005 to 2006, with less significant changes ($\alpha/2 = 2.5\%$) in dunes 2000/2001 and 2003/2004 as well as in salt marshes 2006/2007.

The increase of species diversity may represent a maturing of habitats from 2000 to 2013, especially in salt marshes as spreading of species poor *Elymus athericus* stands only occurred in two plots.

Singular events, *e.g.* the hurricane "Kyrill" (Jan 18, 2007) which represented one of the strongest in north-west Germany in recent centuries, did not cause a decrease in species richness. On the contrary, the species diversity in the salt marshes increased but this was mainly due to drift and litter species which had been transported into the salt marsh area.

Salt marshes

One of the most surprising developments on the sand was the continuing increase of salt marsh areas and their very rapid succession. Such large salt marshes with such quality and diversity as we observed seemed unlikely to develop on Scharhörn and Nigehörn.

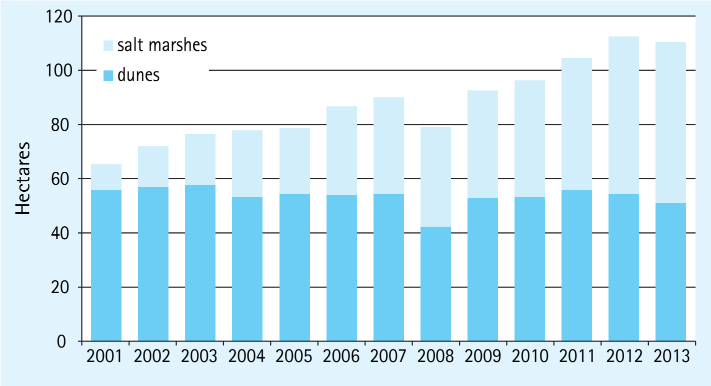
Since 2001 salt marshes have increased at an average rate of 4.15 ha y^{-1}, thus constituting nearly half of the island's area. The last biotope and vegetation survey in 2009 showed a comparatively wide array of vegetation types but clearly nutrient poor, sand dominated salt marshes prevail. And nowadays, in the large pioneer zone areas it is expected that the salt marshes will increase much more in the future (Fig 9).

Especially noteworthy are high to brackish marshes with *Carex extensa* and/or *Juncus maritima* and reedbeds with *Phragmites australis* and *Bolboschoenus maritimus*. The extent of primary dune slacks featuring mixed vegetation units [with *Parapholis strigosa* (*Saginetea maritimae* = type of *Plantago coronopus* / *Centaurium littorale*) as well as transitions to nearly glycophytic vegetation units] are remarkable whereas species poor, but highly competitive units (*Elymus athericus*-type) cover only small areas.

Fortunately, we defined locations for permanent plots (Fig. 3) from the outset, so we were able to follow the succession of salt marshes from the very start.

In 2000 some of our permanent plots showed only low vegetation coverage, less than 1% (with *Salicornia decumbens*, and/or *S. stricta* and/or *Suaeda maritima*). However, they developed steadily into mature salt marshes (Fig. 10). This permanent plot for example displayed, after a few years covered with pioneer vegetation, a rapid and clear succession via a lower salt

Fig.9:
Area of salt marshes and dunes on the Scharhörn-highsand (without pioneer sites)



	Type of	Area (ha)
S.1.1.	*Spartina anglica*	2.8
S.1.2	*Salicornia*	137.5
S.2.1	*Puccinellia maritima*	26.5
S.2.4	*Atriplex portulacoides*	0.3
S.3.6	*Juncus maritimus*	0.1
S.3.7	*Elymus athericus*	2.1
S.3.8.	*Carex arenaria*	8.6
S.3.9	*Atriplex prostrata/A. littoralis*	0.1
S.3.10	*Agrostis stolonifera/ Trifolium fragiferum*	1.6
S.3.11	*Plantago coronopus/ Centaurium littorale*	0.8
S.5.1	*Bolboschoenus/Schoenoplectus*	0.5
S.5.2	*Phragmites australis*	3.2
S.5.3	Brackish flooded grassland type	2.4

marsh stage with *Puccinellia maritima*, *Agrostis stolonifera* and *Aster tripolium* to high/brackish marshes dominated by *Carex extensa*. The development of the brackish marshes was completed within six years. Other plots imply that these high to brackish marshes will evolve further into brackish reed beds with *Phragmites australis* and *Bolboschoenus maritimus*.

Other salt marshes have developed from primary dunes. Permanent plot No. 68 (Fig. 11) shows an existing primary dune (the dunes had already risen up to 25 cm above surface level) which has, via *Agrostis stolonifera* dominated communities, evolved to salt marsh. Thus the very pronounced micro-topography has resulted in a mosaic of different vegetation units. Brackish marshes with *Carex extensa* and high marshes which show succession to glycophytic meadows dominated by *Festuca rubra* and *Trifolium pratense* as well as dune slack communities with *Parapholis strigosa*, *Plantago coronopus* and *Centaurium pulchellum* alternate in scale of decimeters. The different vegetation units indicate very differing habitat qualities.

We were further able to determine locations with a rapid development of *Elymus athericus*. After only six years of *Agrostis* dominated salt marsh, *Elymus* gained dominance and in following years it covered nearly 80%. However, storm surge events and presumably differing levels of

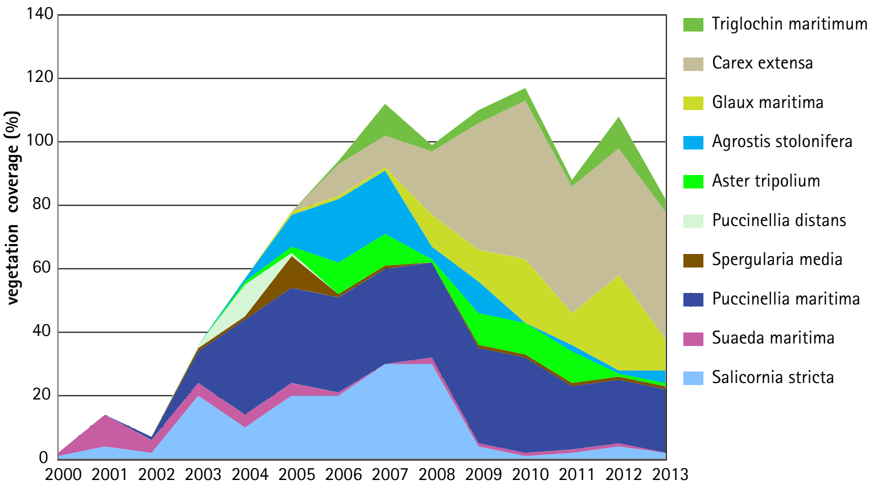


Fig. 10: Development of permanent plot No 67 on Scharhörn from 2000 to 2013; only species with vegetation coverages > 5% are represented

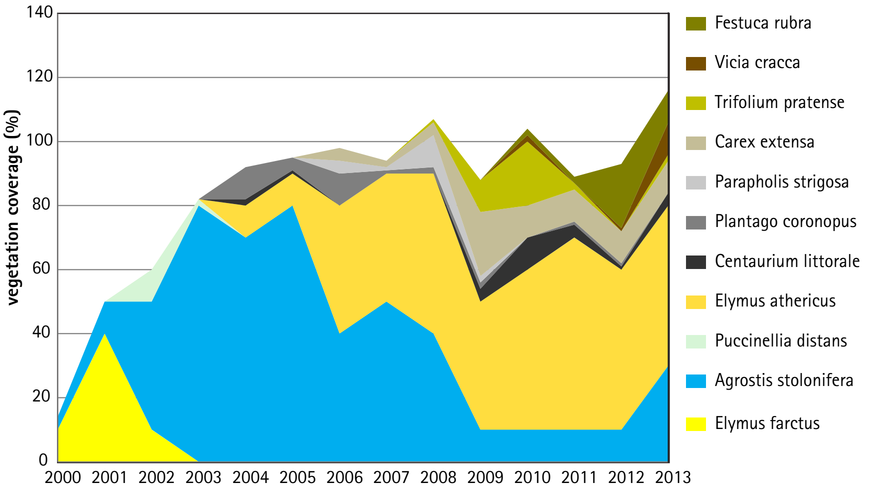


Fig. 11: Development of permanent plot No 68 on Nigehörn from 2000 to 2013; only species with vegetation coverages > 5% are represented

ground water led to the establishment of *Atriplex littoralis* and *Atriplex prostrata* stands with a co-dominance of reedbeds. Dense coverage of *Elymus*-dominated vegetation was found in less than 5% of all salt marshes. The situation suggests that these stands will remain confined to small areas.

However, it is not predictable in this particular case how and when a specific location will start to develop, but generally the primary salt marshes are evolving towards comparatively nutrient poor salt marshes on sand with transitions to vegetation units related to dune habitats.

Dunes

Scharhörn had always been a dune island. Other biotopes were not considered worth mentioning. But it soon became obvious that, due to rapid turnover, mature dunes could not develop. Grossmann (1988) reported grey dunes in rudimentary development and very confined areas (1977 = 0.17 ha, 1983 = 0.24 ha) which would only exist for up to six years before they underwent regression. Dune shrubs or dune woodlands (= brown dunes) never existed on Scharhörn, although the authorities originally had planned for forest plantations (Schmid 1988).

Nigehörn was planned as a dune island and all preparations were aimed at developing dunes in order to promote possible breeding places for birds. In the beginning the island was dominated by artificial white dunes with planted *Leymus arenarius* and *Ammophila arenaria* as well as artificial grey dunes after seeding different grasses (partly not indigenous to dune islands). These nearly immobile dunes became common in the interior of the island and have developed substantially since 2000. Due to disturbances by wind and also by breeding and roosting birds the persistent moss and lichen canopies of the artificially grey dunes have given way to more diverse vegetation, partly also with varying coverage of ruderal species like *Senecio inaequidens* and *Epilobium angustifolium*.

Also, natural white and grey dunes have developed outside the artificially formed dune circle. They have remained comparatively stable in the course of monitoring since 2000. Other dune areas in the interior protected by north-south extending dune ridges did not show any significant changes but a gradual development to grey dunes.

The dunes located on the periphery of the islands were repeatedly influenced by storm surge events. Erosion, sedimentation and input of seeds and litter determine the further fate of the sites. Besides macroalgae-litter, plastic wastes, refrigerators, ship equipment and much more besides can be found on the islands. In the last century Tüxen designated so-called "Spülsaum-Dünen" (= driftline dunes) on Scharhörn (Tüxen & Böckelmann 1957, Grossmann 1988) which described dune vegetation heavily influenced and partly buried by litter, not only on the periphery but also in the centre of Scharhörn. In scientific literature these types were not accepted because they did not represent characteristic vegetation succession but demonstrated short-lived superimposed abiotic factors. While these effects can be demonstrated repeatedly on Scharhörn and Nigehörn, the original vegetation (mainly white dunes) emerges again after a few years.

In winter 2006/2007 the north-westerly edge of Scharhörn retreated by about 15 metres due to heavy winter storms (notably the storm "Kyrill" from Jan 18, 2007). In this year we lost two permanent plots by erosion. In the following winter nearly identical erosion was noted.

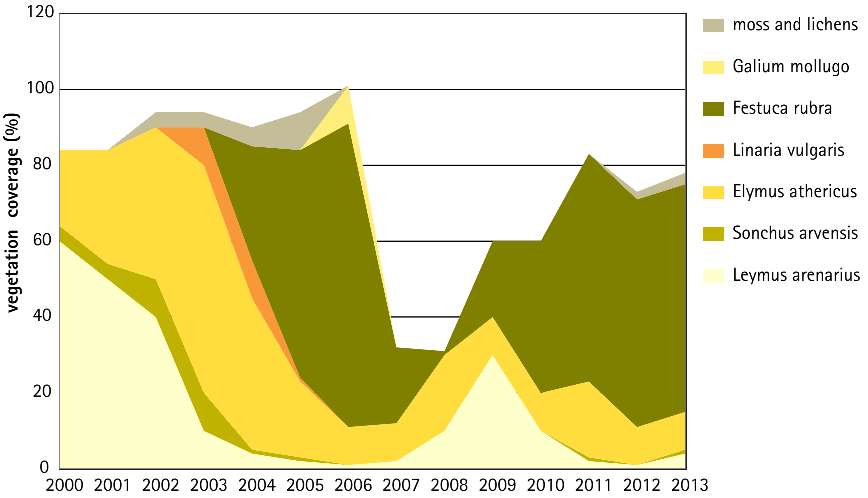


Fig. 12: Development of permanent plot No 52 on Scharhörn from 2000 to 2013; only species with vegetation coverages > 5% are represented

The slightly less exposed dunes in the northeast of Scharhörn as well as north and south of Nigehörn were also affected by the fierceness of the flooding. We saw a relevant turnover of vegetation but up to 2013 most of the biotopes showed a more or less elastic stability. But the storms caused not only loss of area, but they also deposited new sand in the lee of the islands as well as on less exposed sites. Some permanent plots (*e.g.* PP 52, Fig. 12) showed remarkable accumulations of sand (up to 15 cm y^{-1}) which forced these comparatively stable dunes to regress to white dunes.

Birds

Developments of bird colonization on Scharhörn and Nigehörn are well documented (Schmid 1988, Piper 2000, Umweltbehörde Hamburg 2001, Piper 2007a,b) and therefore will not be presented here in detail. Furthermore, actual numbers and relevant occurrences are recently published in the journal "Seevögel".

Since the late 1940s Scharhörn has been characterized by colonies of Common, Arctic and Sandwich Terns, which populated the island with up to 8,100 pairs in 1982 (Glitz 1991). After previous denser colonization in the 1930-40s with up to 500 pairs of Herring Gulls, the larger gull species were nearly absent. Since the mid-1980s the numbers of the larger gull species increased on Scharhörn as well as on Nigehörn. The population of Common and Arctic Terns decreased and since 2001 only small numbers have bred occasionally on Scharhörn. The last breeding Sandwich Terns were noted in 2005 with 95 pairs on Scharhörn. Nowadays the islands´ bird populations are characterized by gulls, which breed on both islands.

Among waders the Oystercatcher is the dominant species, Redshank and Plovers breed regularly with a few pairs on the high sand. Ground

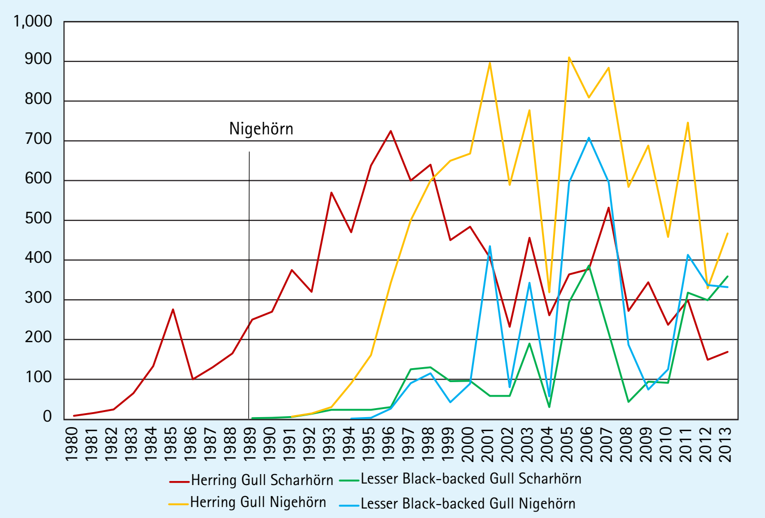


Fig. 13: Population-development [number of pairs] of Herring and Lesser Black-backed Gull on Scharhörn and Nigehörn.

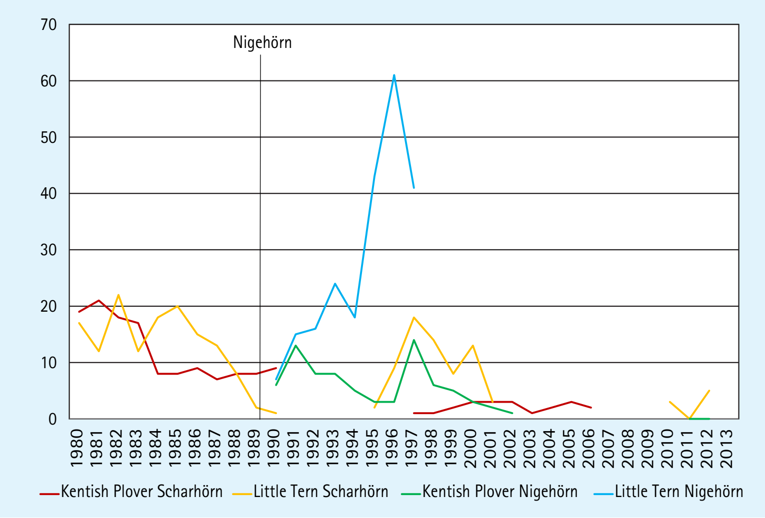


Fig. 14: Population-development [number of pairs] of Kentish Plover and Little Tern on Scharhörn and Nigehörn.

Fig. 15: Population-development [number of pairs] of Oystercatcher and Redshank on Scharhörn and Nigehörn.

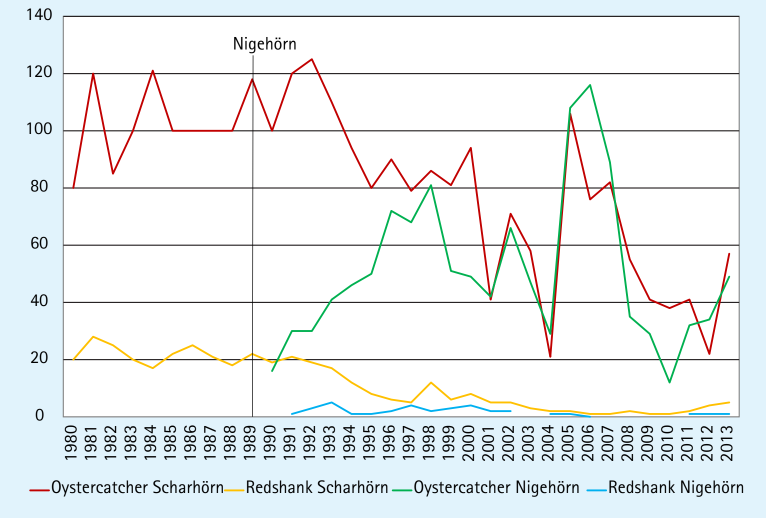
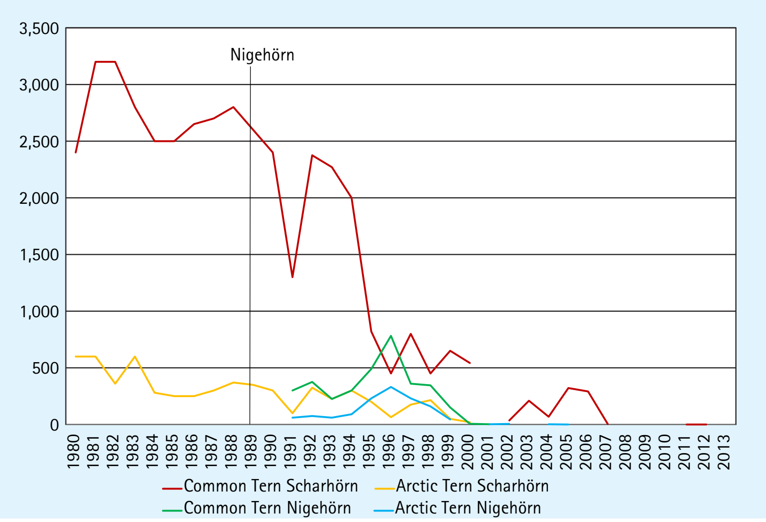


Fig. 16: Population-development [number of pairs] of Terns on Scharhörn and Nigehörnd.



breeding Cormorants (only Nigehörn), a few species of ducks, Short-eared Owls and a small number of passerines like Meadow Pipits and Skylarks are regular breeding birds on the islands. Occasionally Peregrine Falcon and Eurasian Spoonbill have been reported as breeding birds.

The numbers of larger gulls (Herring and Lesser Black-backed Gull) have increased since 1986, presumably because of availability of suitable breeding grounds in comparatively high locations (fig. 13). On Nigehörn we also noticed this rapid development following the establishment of attractive vegetation structures (dune grassland and artificially grey dunes). The local population of Herring Gulls has decreased since 2007. Lesser Black-backed Gulls have been breeding on the islands since 1978. In both populations we could discern major fluctuations. Since 2011 the gull population on the islands numbers just over 1200 pairs, with more or less equal proportions of both species.

The breeding birds of the open beaches, sands and embryonic dunes (Kentish Plover and Little Tern) reacted with a rise in numbers to the newly formed Nigehörn and the availability of suitable habitats (Fig. 14). However, since 1989 both species have decreased. Kentish Plover bred until 2008 and Little Tern breeds only sporadically since 2000.

In the Wadden Sea area loss of primary habitats as well as disturbances during the breeding period are presumed responsible for the decline of these highly endangered species. However, on Scharhörn-sand human interference is negligible due to restrictive management. Appropriate primary habitats are still present and even expanding and predation pressure is considerably reduced due to decreasing gull populations.

The local Oystercatcher population increased steadily from 1947 and achieved a significant growth to about 50% in context to the additional area after the formation of Nigehörn (Fig. 15).

Since 2000 the population has shown a negative trend on the high sand with steep population drops in 2001 and 2004. Since 2010 the short-term trend is positive again.

The Redshank population shows no corresponding development to any changes on Scharhörn-sand. Enlargement of vegetation covered areas and succession to mature salt marshes and older dune stages did not result in increased numbers of breeding birds. Probably the development of suitable feeding habitats for the Redshank (and to a lesser extent Oystercatcher) did not keep pace with the growth of acceptable breeding grounds in salt marshes and dunes. Scharhörn-sand is characterized by comparatively coarse sandy sediments, lacking the fine sediments that would be the preferred feeding sites of Redshank and (to a lesser extent) Oystercatcher. Changes that have resulted in a higher proportion of fine sediments mainly to the west of Scharhörn in recent years could provide more feeding grounds for waders.

Arctic and Common Terns (*Sterna paradisaea* and *Sterna hirundo*) populated Scharhörn from 1947 to 1989 with large fluctuations to an average local population size of about 2,500 breeding pairs. A decline could be observed since 1987 but was seemingly compensated by the formation of Nigehörn because Common Terns and, to a lesser extent, Arctic Terns settled on the new island (Fig. 16).

Since 1995 a rapid decline of tern numbers on the sand has been observed.

Apart from a few isolated breeding pairs until 2004, the Arctic Tern had its last small colony of 20 pairs in 2000 on Scharhörn. The Common Tern abandoned Nigehörn in 2000 and bred only in low numbers on Scharhörn until 2007.

The decline of the "Commic Terns" is only partly understood. Succession leading to less suitable breeding habitats and/or the increased population of Herring and Lesser Black-backed Gull possibly made the islands less attractive to the terns.

Although the terrestrial area, especially of salt marshes, increased on the sand since the 1990s, the changes have not benefited all species. Some new breeding species (like Greylag Goose and Spoonbill) may benefit from altered habitat qualities and hint at a change of species composition, but most of the established and valued Wadden Sea species did not prosper. More salt marshes could clearly not provide the requisite habitat qualities for Redshank and Oystercatcher. The increase of ostensibly suitable breeding habitats on Scharhörn and Nigehörn has not ensured the growth or stabilization of bird populations yet. The reason for this may be that the the habitats are not yet high enough above sea level for successful breeding; but with rising elevation due to sedimentation conditions, this may improve. But it remains to be seen whether surface elevation changes can keep up with sea level rise. Investigations of sedimentation rates only started in 2011.

Conclusion and perspectives

With interest we are looking forward to further developments on both islands on Scharhörn-sand.

By increasing vegetation coverage (pioneer zones and salt marshes) between the islands we anticipate an eventual fusion of the islands, which are likely to be separated only by a gully system. Storm surge events like the recent hurricanes "Christian" in October 2013 and "Xaver" in December 2013 have had significant influences which are not predictable. These storms led again to large losses at the north-western edge of Scharhörn. In the immediate future we expect further erosion of the north-western dunes of Scharhörn, resulting in a loss of significant parts of the island as well as a temporary increase of primary dunes at the south-eastern edge.

Particular questions may mark the course of future studies. Further investigations of the habitat conditions that allowed the establishment and distribution of the extraordinary woods and reeds that currently populate the typical salt marsh and beach area of Nigehörn are necessary. The establishment of trees and scrub in the area and the elevated levels of salt marshes are not yet completely understood. A freshwater lens might explain these phenomena, but even if we consider a freshwater source as an important factor to promote woody plants, we have to take into account the high salinity that is associated with regular flooding of the respective sites. There is also no reason why an underground freshwater lens could not equally develop on Scharhörn, presumably with the same results.

We have noticed a slight but distinct difference to the flora of both islands. Some years ago Nigehörn presented more calcium-dependant species like *Koeleria arenaria* or *Filago minima*, which have already perished. This could be related to deposited sediments which may have been more calcareous. Some species occurring on Nigehörn are due to sowing and planting (like *Rosa spinosissima*, *Poa compressa*, *Festuca*

Fig. 17: View from Nigehörn to Scharhörn in August 2012; note the high vegetation coverage between the islands, also the gully-system.
Photo: Körber 2012

arundinacea, and maybe some willow species); other species were probably imported by birds or flooding (like *Senecio inaequidens* and most of above mentioned scrub plants and trees). Why the latter have not yet invaded Scharhörn remains unknown.

The structures of the grey dunes differ between Scharhörn and Nigehörn. The dunes of the older island are nearly devoid of mosses and lichens whereas Nigehörn hosts a large flora of *cryptogamae*.

The study of these two islands in comparison to the other islands will further improve the understanding of development of islands in the Wadden Sea and the interactions between geomorphology, biology and ecology.

Acknowledgements

The data were collected by different people. We acknowledge their help in long-term field work, especially the bird wardens of Scharhörn and the responsible persons at the Verein Jordsand. Furthermore we want to acknowledge the support of the State Ministry of Urban Development and Environment of the City of Hamburg which financed most of the studies. We are grateful to Dr. Klaus Janke, head of the National Park Administration Hamburg Wadden Sea for his continuous support and his helpful comments on this paper. Julia Baer kindly corrected the English, Martin Stock provided the aerial photos.

Literature

FIEDLER, R. & D. GLITZ, 1991. Errichtung und Sicherung schutzwürdiger Teile von Natur und Landschaft mit gesamtstaatlich repräsentativer Bedeutung - Projekt Nigehörn - Hamburgs neue Vogelschutzinsel im Watt. Natur und Landschaft 66: 20-23.

GLITZ, D., 1991. Vogelparadies an der Elbmündung. Nationalpark 2/91: 64-67.

GÖHREN, H., 1970. Studien zur morphologischen Entwicklung des Elbmündungsgebietes. Hamburger Küstenforschung 14.

GÖHREN, H., 1971. Untersuchungen über die Sandbewegung im Elbmündungsgebiet. Hamburger Küstenforschung 19.

GROSSMANN, A., 1988. Die Vegetation der Insel und ihre Dynamik. In: Schmid, U., 1988. Vogelinsel Scharhörn. Niederelbe-Verlag, Cuxhaven (= Jordsand-Buch Nr. 7). p 38-80.

HELLWIG, U. 2006. Nigehörn – An artificial island goes natural. Wadden Sea News Letter 32(1): 22-24.

HELLWIG, U. & L. KRÜGER-HELLWIG, 2000. Entwicklung der Biotope auf Nigehörn – eine Zwischenbilanz. Seevögel 21: 26-31.

HELLWIG, U. & H. KUHBIER, 2000. Flora der Farn- und Blütenpflanzen von Scharhörn und Nigehörn. Seevögel 21: 19-25.

IFAUM (Institut f. Angew. Umweltbiologie u. Monitoring), 1997. Nationalparkplan Hamburgisches Wattenmeer. - Arbeitsabschnitt 1997. Unveröff. Gutachten i. A. der Umweltbehörde der Freien u. Hansestadt Hamburg, Naturschutzamt. 87 S.

IFAUM (Institut f. Angew. Umweltbiologie u. Monitoring), 2005. Biotopkartierung auf den Inseln Neuwerk, Scharhörn und Nigehörn. Unveröff. Gutachten i.A. der Behörde für Stadtentwicklung u. Umwelt der Freien u. Hansestadt Hamburg, Naturschutzamt. 46 S.

IFAUM (Institut f. Angew. Umweltbiologie u. Monitoring), 2011. Biotopkartierung auf den Inseln Neuwerk, Scharhörn und Nigehörn 2009. Unveröff. Gutachten i.A. der Behörde für Stadtentwicklung u. Umwelt der Freien u. Hansestadt Hamburg Nationalparkplan Hamburgisches Wattenmeer. Naturschutzamt. 69 S.

INUF (Institut für Naturschutz- und Umweltschutzforschung), 1995. Begleitendes faunistisches (unter besonderer Berücksichtigung der Vögel) und vegetationskundliches Forschungsprogramm für die durch Sandaufspülung bei Scharhörn neu geschaffene Insel "Nigehörn". Unveröff. Gutachten i.A. der Umweltbehörde der Freien u. Hansestadt Hamburg, Naturschutzamt. 61 S.

JANKE, K & D. GLITZ, 1992. The story of Nigehorn. WSNL 1: 8-12.

JANKE, K. & W. PIPER, 1992. Errichtung und Sicherung schutzwürdiger Teile von Natur und Landschaft mit gesamtstaatlich repräsentativer Bedeutung - Projekt: Nigehörn - Hamburgs neue Vogelschutzinsel im Watt. Natur und Landschaft 67: 340-343.

KUHBIER, H, 1993. Zur Flora der neuen Watteninsel Nigehörn. Ber.Bot.Ver. Hamburg 13: 111-112.

LINKE, G., 1969. Die Entstehung der Insel Scharhörn und ihre Bedeutung für die Überlegungen zur Sandbewegung in der deutschen Bucht. Hamburger Küstenforschung 11: 45 – 84.

LONDO, G., 1976. The decimal scale for releves of permanent quadrats. – Vegetatio 33: 61-64.

MANG, F.W.C., 1982. Alphabetisches Verzeichnis der wildwachsenden Farn- und Blütenpflanzen von Neuwerk und Scharhörn. Hamburger Küstenforschung 41: 43-95.

PETERSEN, J., B. KERS & M. STOCK, 2014. TMAP-Typology of coastal vegetation in the Wadden Sea area. Wadden Sea Ecosystem (in press)

PIPER, W., 2000. Die Brutvogelwelt Scharhörns – ein Überblick. Seevögel 21: 5-9.

PIPER, W. 2007a. Die Vogelinsel Scharhörn im Nationalpark Hamburgisches Wattenmeer. Seevögel: 28: 134-140.

PIPER, W. 2007b. Die Vogelinsel Nigehörn im Nationalpark Hamburgisches Wattenmeer. Seevögel: 28: 142-147.

PIPER, W. & E. HARTWIG 1994, Nigehörn, eine neue Insel im Nationalpark „Hamburgisches Wattenmeer". Seevögel 15(3): 45-49.

POTT, R., 1995. Die Pflanzengesellschaften Deutschlands. 2. überarb. Aufl., Ulmer-Verlag, Stuttgart.

PREISING, E., H.-C. VAHLE, D. BRANDES, H. HOFMEISTER, J. TÜXEN & H.E. WEBER, 1990. Salzpflanzengesellschaften der Meeresküste und des Binnenlandes. Naturschutz Landschaftspfl. Niedersachs. Heft 20/7.

SCHMID, U., 1988. Vogelinsel Scharhörn. Niederelbe-Verlag, Cuxhaven (= Jordsand-Buch Nr. 7).

SIEFERT, W, 1970. Die Salzgehaltsverhältnisse im Elbmündungsgebiet. Hamburger Küstenforschung 15.

TÜXEN, R. & W. BÖCKELMANN, 1957. Scharhörn - Die Vegetation einer jungen ostfriesischen Vogelinsel. in: Mitt. Flor. soziol.Arb.Gem. NF 6/7: 183-204.

UMWELTBEHÖRDE HAMBURG (Hrsg.), 2001. Nationalpark-Atlas Hamburgisches Wattenmeer. Naturschutz und Landschaftspflege in Hamburg. Schr.-Reihe Umweltbehörde Heft 50.

WAGNER, P., 1952. Scharhörn. Seine Entwicklung vom Sand zur Düneninsel. in: Dannmeyer, F., E.v. Lehe & H. Rüther (Hrsg.): Ein Turm und seine Insel.- Verlag Rauschenplat, Cuxhaven: 163-164.

WISSKIRCHEN, R. & H. HAEUPLER, 1998. Standardliste der Farn- und Blütenpflanzen Deutschlands. Ulmer, Stuttgart.

Authors

Ulrich Hellwig & Levinia Krüger-Hellwig
Institute for applied environmental biology and Monitoring (IfAUM)
Wurster Landstraße 11
D-27638 Wremen
ifaum@ewe.net & levinia.krueger@ewetel.net

Peter Körber
Administration Hamburg National Park Wadden Sea
c/o Free and Hanseatic City of Hamburg
State Ministry for Urban Development and Environment
Neuenfelder Straße 19
D-21109 Hamburg, Germany
peter.koerber@bsu.hamburg.de

Jens Umland
Schleswiger Damm 143
D-22457 Hamburg
Jens.Umland@t-online.de

Trischen – wax and wane of a Wadden Sea island

Martin Stock
Julia Baer
Moritz Mercker

Trischen - wax and wane of a Wadden Sea island

Abstract

Trischen is situated off the coast of Dithmarschen in the German Bight. The island has one of the longest track-records of breeding bird observations, spanning the past 100 years. In this publication we focus on recent developments since the turn of the century and discuss all major aspects concerning island ecology such as climate, geomorphology, vegetation, breeding and migrating birds.

In recent years the island continued to decrease in size due to erosion processes at the western shoreline and insufficient land formation in the east; however the rate of long-term land loss appears to have decelerated. The overall vegetation cover increased while plant species diversity decreased significantly over the past five years. The results on sedimentation rates showed an average surface elevation change of + 3.74 (± 2.47 S.E.) mm y^{-1}, which only just keeps pace with the local rise in sea level of 3.6mm y^{-1}. The majority of permanent plots showed a sedimentation rate significantly lower than the current sea level rise.

The breeding bird population decreased rapidly between 2000 and 2007 and has since levelled out at about 5,000 breeding pairs. Frequent flooding events during the breeding season are one of the major threats to breeding waders and terns, both of which continue to decline. After a steep increase in the gull population during the turn of the century, gull species are now experiencing the most drastic reduction in numbers. Recent arrivals such as Spoonbill, Cormorant and Barnacle Geese are the only species with an upward population trend.

The numbers of resting waders decreased significantly during the past decade, beyond generally observed declines in the Wadden Sea area. Whether this is caused by lack of prey availability or disturbance due to the resident Peregrine Falcon remains unclear. Records on passerine numbers also showed downward trends, possibly as a result of changing wind patterns, but further research is needed to verify this assumption.

Introduction

Trischen has a long history. As early as 1610 an island-like elevation with spare vegetation, situated south-west off Büsum, was mentioned in a case record about the “beach-rights” of the so-called “Buschsand”. More than 100 years later the island firstly appeared on the oldest map of the Elbe mouth in 1721 (Göhren 1975). The island was named as “Busch- or Rischen- Sand”. Later maps depicted three sandbanks on the same location with a first record of a beacon in 1840 on the westernmost sandbank, now called “Boschsand”. The westernmost sand eroded and the other two grew together and formed the foundation of “Trieschen”. In 1866 this sand was blown up to two metres above mean sea level. Already in the 18th century the sandbanks were covered with salt-marsh vegetation which vanished at the end of the century. In the middle of the 19th century salt-marsh growth started again and the vegetated area expannded. Dunes appeared at a later stage on Trischen. During the second half of the 19th century reclamation works started and more than 100 hectares of marshes was reclaimed in the shelter of the dune-ridge. At the end of the 19th century the height of the dunes was measured at more than 4.9 m above mean high tide line. These dunes had grown to more than 8 m by the 1950s (Wieland 2000; Wohlenberg 1950).

In 1895 a first farmer settled on Trischen to graze the marsh with his sheep. Two years later a dike was built to protect the house and drinking place for the livestock. A series of three severe storms in autumn and winter 1899 caused a breach of the dune ridge and resulted in a huge loss of the marsh area used for grazing due to silting up with a thick sand layer. In consequence the farmer had to leave the island. Due to protection works in the dunes and further reclamation works in the marshes the island started to grow again in eastward direction. At the end of the First World War the marshland increased once more and covered about 90 hectares. In 1922 a constructor from the city of Rendsburg leased the island, raised a new ring-dike, built a farm house of stately size, called “Luisenhof”, and put up stables and a windmill. In the following years the farmer grew cereals, potatoes and swedes and grazed the marshland with cattle and sheep.

Five years later the island was taken over by the city of Altona and a large barn was constructed. During these years the island was used as farmland and later turned into a holiday residence for school children and an artists’ colony. In 1934 the last farmer relocated to Trischen and stayed there until 1943 when several severe storms led to a massive breaching of the dike (Trende 2003). In the autumn of that year the farmer was forced to leave the island. Further storms in the coming years demolished the buildings. In 1950 the last lease of the island ended and Trischen started to move again in eastward direction.

This eventful past is hard to believe when visiting the island these days. Only long-lasting remains of the old settlement appear from time to time on the beach and old clay layers on the west side of the island give a reference to historic reclamation work on the former east side salt marshes of Trischen.

Beside its cultural history, Trischen has a long-standing reputation as a bird reserve. As early as 1909 a bird sanctuary was establish on Trischen by a statutory order. Since then, the protection of this island has been continually intensified, leading to a highly protected and naturally developing island, without any artificial structures or maintained coastal protection works. In 1934 Trischen was designated as a nature reserve and since 1985 the island has been part of the National Park and sits within the Wadden Sea World Heritage Site.

Since 1948 solely a warden has lived on Trischen for seven months per year. His main task is to secure a disturbance-free island and to monitor the flora and fauna, to count the breeding, resting and migrating birds and to document changes in biology and geomorphology. This work led to a long-term series of data, some of which reaches back for more than 100 years (Kempf *et al.* 2000).

Due to its natural development and the availability of various biological and geomorphological data, Trischen constitutes a prime example to study and analyse natural developments on a continuously moving and changing island. This publication is aimed to provide insights into recent developments and possible interactions between environmental factors on Trischen. We touch briefly on the long-term data of the 19th century, but our main focus is on data obtained in the current millennium, which has been collected using standardised methods. The data on birds provided here represents the period from 15th March to 15th October, which is the length of time the warden is stationed on the island. Previous publications on long-term island development and breeding bird diversity include Kempf *et al.* (2000) and Oppel (2005).

With this investigation we want to

(1) describe and analyse the geomorphological development of the island;
(2) analyse the changes in relation to geomorphological conditions, hydrodynamics and history of the island;
(3) evaluate breeding bird population changes, species composition and factors influencing breeding success;
(4) document and discuss temporal population changes in resting birds and birds on migration passage on and around Trischen; and
(5) discuss bird population changes in relation to geomorphological and hydrodynamic changes, such as the predicted sea-level rise.

The publication is organized as follows (*c.f.* Fig.1.1): After a general overview of the island Trischen, we firstly describe changes in climate and hydrology primarily focussing on flooding events and wind patterns. This is followed by a

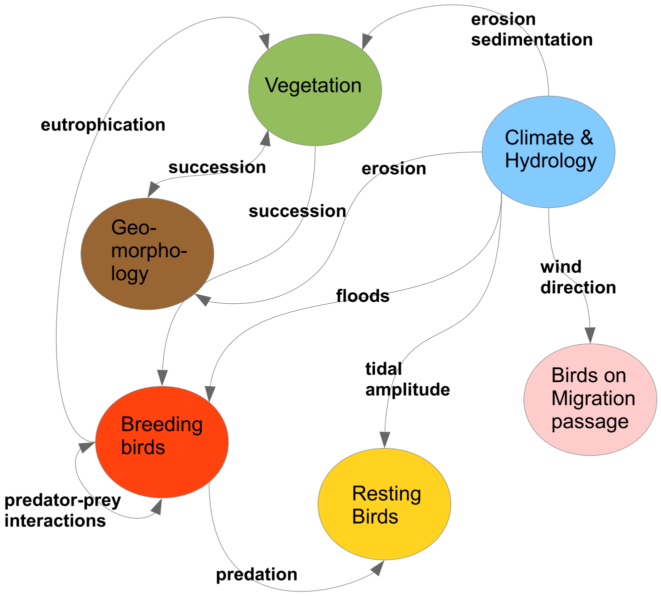


Fig. 1.1: Main chapters and some of the interconnections discussed within this article.

chapter in which we cover various aspects of geomorphology and vegetation of Trischen, *e.g.* changes in island size, location and habitats as well as flora composition and diversity. Finally, we focus on the avifauna of Trischen, documenting and discussing developments for several bird population complexes: breeding bird population trends and productivity are documented and discussed first, whereas population developments of resting birds and birds on migration passage are analysed and discussed at the end of the article.

Study area

The island Trischen is located in the German Bight within the outer Elbe estuary, German Wadden Sea (Coordinates: 54° 30' N, 8° 41' E). The tidal regime is meso-tidal with mean tidal amplitude of about 3.0 m. The hydrodynamic conditions in the area are dominated by strong currents associated with semidiurnal tides. Tidal flood-currents in the Flakstrom peak at 1.8 m/s. The ebb-current is slower at 1.2 m/s. Similar values occur during ebb- and flood-currents in the southern Neufahrwasser (Siefert *et al.* 1980). The actual size of the island above mean high tide in spring 2014 was about 187 ha. The island and the surrounding tidal area is part of the core zone of the "Schleswig-Holstein Wadden Sea National Park".

Calculated on the basis of the tide gauges of Cuxhaven the area has experienced a relative mean sea-level rise (SLR) of about 2.1 mm yr^{-1} during the period 1937-2008, but on a shorter time scale (1971-2008) the SLR is as high as 3.6 mm yr-1 (Jensen *et al.* 2010). The local mean high water level has increased from 1965-2001 at a rate of 4.2 mm yr^{-1}. Jensen and Mudersbach 2004a calculated an increase of mean high water in the summer months at a rate of 3 to 8 mm yr^{-1} from tidal gauges nearby over a time-span from 1971 until 2008.

The island represents a natural beach, beach-ridge, dune and salt marsh complex without any human interference for more than 70 years. The island is of alluvial origin. Trischen is half-moon-shaped with two tidal inlets north and south of it. The island was moving in an easterly direction over many years. This movement has decelerated over the last years and the island is now eroding on the exposed west side without growing further on the eastern parts.

Trischen harbours the typical habitats of a natural island. A narrow beach plain can be found on the seaward side and on the northern and southern island tips. The dune ridge of the island is characterized by white dunes with a small belt of embryonic shifting dunes in front of it. On some locations an annual vegetation of drift lines is present. In the northern-most part of the island an expanse of primary dune field is growing and increasing in size. To the east the yellow dune system changes into grey dunes with herbaceous vegetation. Dune heath, dunes slacks and dune scrub plants are not present. In a few places, isolated scrub plants like the invasive *Rosa rugosa* or the native *Sambucus nigra* are growing. A small lagoon is also present. The dunes change into sandy or clay-rich salt marsh vegetation. On the eastern end, as early as 1928, *Spartina townsendii* was planted for coastal protection (König 1948). In the same year, large *Spartina*-fields were also planted on the Marner Plate but this measure failed (König 1948). The island is bordered by extended muddy tidal flats in the east. Trischen is free of herbivores and mammalian predators.

According to the classification of Dijkema, 1987, the marshes belong to allochthonous barrier-connected salt marshes in the interior of the island and to foreland salt marshes in the eastern part. The latter is characterized by a thicker and more clayish sediment layer while the first has only a thin cover of clay-containing layers and is characterized as a sandy salt marsh rich in plant species.

2. Climate and hydrology

Low-lying sandy islands such as Trischen are especially vulnerable to changes in climate and sea levels. About half of the island land area rises no higher than 50 cm above sea level. The island is also intersected by a complex system of tidal streams which frequently flood the surrounding salt marshes during spring tides. Consequently about two thirds of the island area consists of salt marsh habitat. An increase in mean sea level (MSL) has far-reaching consequences for the flora and fauna on an island like Trischen.

The southern North Sea is influenced by isostatic and eustatic processes, both resulting in a rise in sea level. Tectonic sinking rates of 10-15 cm per century have been leading to increased sea levels ever since the post-glacial period (Streif 1993). Generally, salt marshes are able to react to an increased sea-level by sediment accumulation and vertical land growth, therefore maintaining an elevation in equilibrium with sea level rise (Redfield 1965). However, climate-induced eustatic processes are predicted to cause an increase in sea level of 0.28 - 0.98 m by 2100 (IPCC 2013) and simulation models suggest that soil accretion in salt marshes cannot keep up with the worst-case scenarios of sea level rise (French 2006; Simas *et al.* 2001). Global warming can affect coastal habitats such as salt marshes in two broad ways, through change in the climate and by sea-level rise. A rise in temperature and precipitation rates may lead to changes in soil salinity (Bertness and Pennings 2000), while a rise in sea level can affect the size and biodiversity of salt marshes, also known as 'coastal squeeze' (Hughes 2004). Coastal squeeze will not only reduce the total area of salt marsh, but also reduce primary productivity and reduce the time that is available to birds for feeding, roosting and nesting (Hughes 2004). Associated with the global sea-level rise is an increase in the number and scale of local flooding incidences, (Van De Pol *et. al.* 2010), which will also become more severe with a predicted increase in storm frequencies.

Data on temperature, precipitation and wind speed are recorded daily on Trischen, however the records cover an insufficient length of time to allow conclusions on a changing climate. Instead, we focused our analysis on possible changes in flooding frequencies since the turn of the century, especially since flooding events have such a direct and devastating effect on the majority of breeding birds on Trischen. We also plotted a graphic simulation model, comparing the level of land submergence during normal high tide scenarios and increased water levels.

Secondly, we analysed the changes in wind speed pattern, which has been shown to affect number and composition of staging, breeding and migrating birds (Bonter *et al.* 2014; Dierschke 2001). Especially on Trischen a change in the ratio of westerly to easterly wind directions may influence the number of migratory (*i.e.* passerine) birds, as Trischen is located west of the coastline and an east wind may drift birds off the line leading towards the island.

Flooding events & wind patterns

Methods

The Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation (LKN-SH) deploys stationary data loggers that monitor the daily maximum high and low tidal elevation relative to mean high water (MHW) at various locations in the German Bight. Since 1999 one such logger near Trischen measures the peak tidal water levels between March and October. This data can yield useful information on the development of high tide levels over time and in quantifying the number and severity of flooding incidences on the island during the breeding period. As high tide levels of > 40 cm above MHW begin to cause widespread flooding of breeding sites, we pooled all tide events of > 40 cm each year to see if the overall number of flooding incidences affecting breeding birds increased during the study period (1999-2012). The breeding season was defined as the period between 1st April to 31st of July, core autumn migration from 1st September to 31st October.

We also analysed the amount and location of island land loss during an average high tide compared to flooding incidences commonly experienced during the breeding period. Trischen land elevation contour data, which had been obtained in 2010 during a LIDAR aerial laser analysis, was used as baseline elevation data for tidal simulation models. The vector lines were projected and smoothed prior to calculations, using ArcGIS (Esri 2009). Dry land area and volume was plotted and calculated for a) an average tidal height (MHW = 150 cm above mean sea level) and b) a flooding scenario of 50cm above MHW.

Average and maximum wind speed as well as wind direction is measured each season three times daily, using a portable anemometer. To examine the development of the dominant wind direction during bird migration on Trischen, we calculated its percentage distribution for the months September-October for each season from 2005-2013. Based on this, we evaluated changes in D_wind for each season, which is the difference between the percentage of eastern winds (NE,E,SE) and western winds (NW,W,SW). Changes in wind patterns were compared to passerine migration events and potential wind drift.

Results

The results of the flooding data showed that the average high tide deviation above MHW remained at a similar level between 1999 and 2012, with no significant trends or changes. During the breeding seasons the deviation averaged 20.85 cm (± 16.91 S.D.) above MHW between the study years (Fig. 2.1), during autumn migration

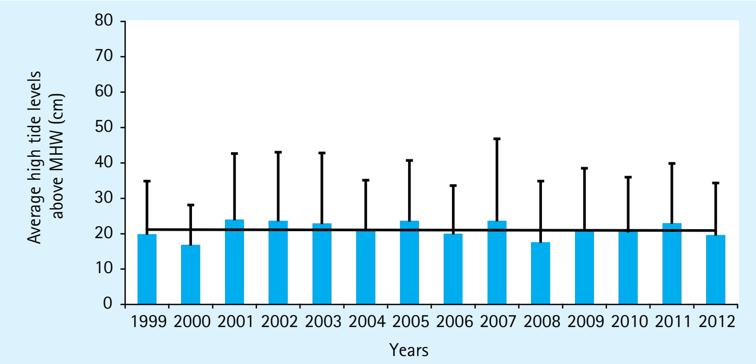


Fig. 2.1:
Yearly average of high tide deviation from mean high water (MHW) from 1999 to 2012 during the breeding period (1st April to 31st July). Error bars show Standard Deviation (S.D.). Linear regression y= -0.018x + 20.99

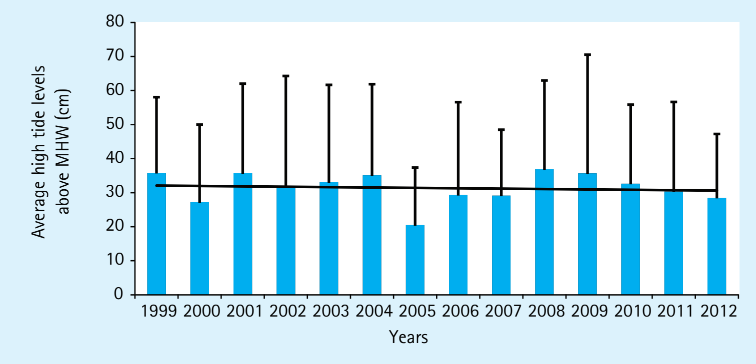


Fig. 2.2:
Yearly average of high tide deviation from mean high water (MHW) from 1999 to 2012 during autumn migration (1st September to 31st October). Error bars show Standard Deviation (S.D.). Linear regression y=-0.1125x + 32.037.

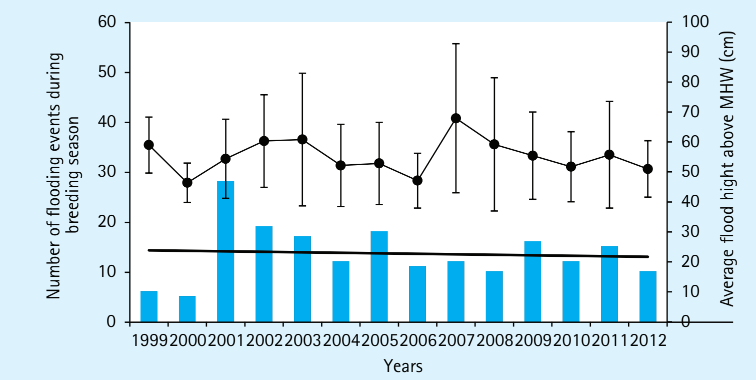


Fig. 2.3:
Bars: Number of flooding events (high tide >40cm above MHW) during the breeding season (1st April to 31st July) between 1999 and 2012. Linear regression y= - 0.0989x + 14.385.
Line: Average high tide level for all flooding events during the breeding season between 1999 and 2012 (± S.D.)

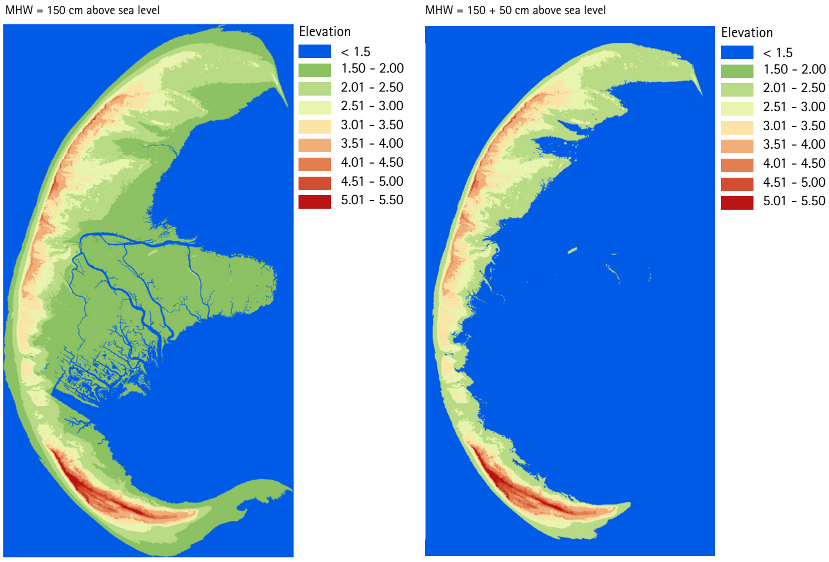


Fig. 2.4:
Left: Map showing Trischen at an average high tide (MHW 150cm above sea level).
Right: Trischen with an additional 50cm above MHW (150 cm above sea level). Shaded areas show elevation contours in metres, based on a LIDAR aerial laser scan from 2010.

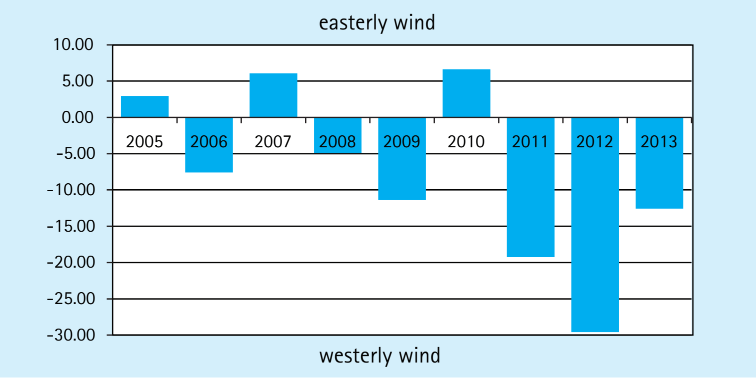


Fig. 2.5: Average changes of westerly in relation to easterly wind in September-October on Trischen (2005-2013). D_wind = (% easterly wind - % westerly wind) / season. i.e. positive values of D_wind represent predominant easterly winds, negative values are connected to predominant westerly winds.

the deviation average 31.19 cm (± 25.31 S.D.) above MHW (Fig. 2.2).

The analysis on flooding incidences of > 40 cm above MHW showed that, while the years 1999 and 2000 had only 5-6 such incidences, all other years experienced on average 14 such flooding events during the breeding season. Those flooding events between 1999 and 2013 ranged from 40 cm to 115 cm and averaged at 55 cm (±5.8). Again, long-term conclusions on the number and severity of floods cannot be drawn due to the short time frame (Fig. 2.3).

The simulation model of land area affected during flooding showed that a sea level of 50 cm above MHW leaves 55.3 % of the island submerged (Fig. 2.4). Only the dune chains spanning the length of the exposed westerly side of the island remain above water, while the entire salt marsh areas and sandy spits in north and south are flooded. In terms of land volume, the dry land mass reduced from 1.23 Mio m3 during a 'normal' high tide to 0.59 Mio m3 during a + 50 cm high tide.

The analysis of D_wind (which is the percentage of westerly winds in proportion to easterly winds during September-October on Trischen) reveals that the amount of westerly winds decreased in favour of easterly winds between 2005 and 2013 (Fig. 2.5).

Discussion

Salt marshes are important to birds as they provide sites for feeding, breeding and roosting (Hughes 2004). There are a number of ways in which climate change can affect salt marshes; one of the key issues is the effect of sea-level rise. The salt marshes on Trischen are populated by breeding birds such as Redshank, Oystercatcher, Black-headed Gull and, at the outer fringes, Common and Arctic Tern. In spring, several hundred Brent Geese use the salt marsh areas for feeding and roosting. In autumn these areas are important feeding and staging grounds for passerines such as Snow Bunting, Skylark and Twite. In theory, sea-level rise should lead to accelerated rates of sedimentation due to deeper water and a longer residence time, maintaining a dynamic equilibrium of elevation relative to sea-level, which has been confirmed for some areas. (Cahoon *et al.* 2000). Studies in the Wadden Sea estuary by Van De Pol *et al.* (2010) found that MHT levels in May-June increase at a rate of 3-8 mm year^{-1} between 1971 and 2008. They also found that between 1990 and 2008 extreme tides became more common and occurred throughout the breeding season, especially in the second half of June when most eggs hatch.

Soil accretion on Trischen has been monitored since 2004 and the results show average soil accumulation rates of 3.74 ± 2.47 S.E. mm y^{-1} in the salt marsh areas (see chapter 'Vegetation and Geomorphology'). It appears that the sediment supply on Trischen may be insufficient to counterbalance a rise in sea-level in the long run. A MHW level of + 50 cm submerges 55 % of nesting habitat on Trischen which is a common occurrence each breeding season; a flooding level of about + 55 cm occurred on average 14 times each season since 2001. Already, the majority of breeding seabirds on Trischen experience high losses due to flooding and in most years entire colonies fail for this reason (see chapter 'Breeding Birds' for details). This scenario is likely to get worse with additional pressures linked to climate change, such as increased wave action, tidal currents, precipitation and wind speeds (Hughes 2004).

For the discussion regarding the influence of wind direction on migrating (passerine) birds, we kindly refer the reader to the section 'Migrating birds'.

3. Geomorphology and vegetation methods

A first terrestrial survey of the island in 2001 measured the vegetation border, which is in line with a normal MHW-level on the east side, by means of a standard GPS-device. The determined area describes the vegetated part of the island. To estimate the island size, which is defined by the area above MHW, a further GPS measurement was taken along the MHW drift line and combined with the measurement of the vegetation border from the east side of Trischen. These surveys were repeated annually from 2006 onwards. To analyse the moving of the island the differences between the outlines of the island and the vegetation were measured between 2001 and 2013 in three sections (north, middle, and east). Terrestrial surveys were analysed by means of ArcGIS Software (Esri 2009).

The entire vegetation of Trischen was mapped in 2002 by Gettner *et al.* (2003). This survey was repeated in 2007 and 2012 with the method described by Petersen *et al.* (2010); Petersen *et al.* (2008). All three surveys were transferred into a vegetation typology according to the TMAP classification Petersen *et al.* (2014).

Based on the first vegetation map, 14 permanent plots each sized 4 m^2 were established in 2002 in different vegetation types on the island to follow succession in salt marsh vegetation. Due to rapid succession of some plots on sandy beach ridges a further plot was established in 2009. Plot elevation differed widely. Measurements in 2012 revealed a range from 1 to 93 cm above MHW (Tab. 3.2). All plots are used for yearly vegetation measurements and are part of the TMAP vegetation database Stock (2012b). Plant cover of different species was estimated by means of the Londo (1976) scale. Nomenclature of plant species follows Wisskirchen and Haeupler (1998).

As part of every permanent plot sedimentation erosion bars (SEB) were established in 2005 according to van Duin *et al.* (1997). Measurements took place annually in August and are part of the TMAP sedimentation database Stock (2012a). Year to year differences are expressed as surface elevation change (SEC), which is the net result of accretion and subsidence processes. Following Nolte *et al.* (2013) accretion is defined as the increase in marsh surface elevation as a result of deposition and erosion on the marsh surface. Subsidence is the decrease of the marsh surface due to shrinkage or compaction of deeper sediment layers. An elevation deficit occurs when the increase of the marsh surface elevation is lower than sea-level rise.

The elevation of the SEBs was measured with an optical levelling-instrument to the nearest millimetre in 2005. The measurements were repeated in 2012 to check for height changes. Differences between consecutive measurements were within measuring accuracy. Based on the height of the sedimentation poles the elevation of the permanent plots was calculated. Hydrological data were taken from the nearest tidal gauges west of Trischen and close to Büsum.

Data on vegetation mapping, permanent plot surveys and SEB measurements were analysed either by means of PASW Statistics (SPSS 2009) or by ArcGIS Software (Esri 2009).

Results

Island size and location

Trischen is moving eastwards and decreasing in size since the first record of the vegetated island. Figure 3.1 shows the replacement in five timesteps from 1885 to the survey in 2013. During this time span of 128 years the island has decreased in size from 1,140 ha to less than 200 ha today.

Wieland (2000) calculated from his measurements (1885-1996) an annual rate of decline in the order of 8.5 ha y^{-1}. Our first measurement is from 2001. In this year the island was somewhat larger than shown by Wieland (2000) five years before. Figure 3.2a shows the change in island size due to our surveys from 2001 to 2013. Within these years the area decreased further over time but the calculated annual loss was much lower than reported by Wieland 2000 and had a value of 2.6 ha y^{-1}. While the island is decreasing in size the vegetated proportion has increased (Fig. 3.2b). A step increase in plant covered area occurred from 2001 to 2006. Between the latter two surveys this increase was much less.

The island shift, expressed as eastward movement of the island boundary (mean high tide MHW line), was 10.6 m y^{-1} in the last 12 years. There was a clear difference between the amount of relocation between the northern (12.8 m y^{-1}), the central (9.9 m y^{-1}) and the southern part (9.7 m y^{-1}) of the island. The differences between the northern and the central part, as well as the difference between the northern and the southern part were significant (U-Test, $p < 0.05$; Fig. 3.3).

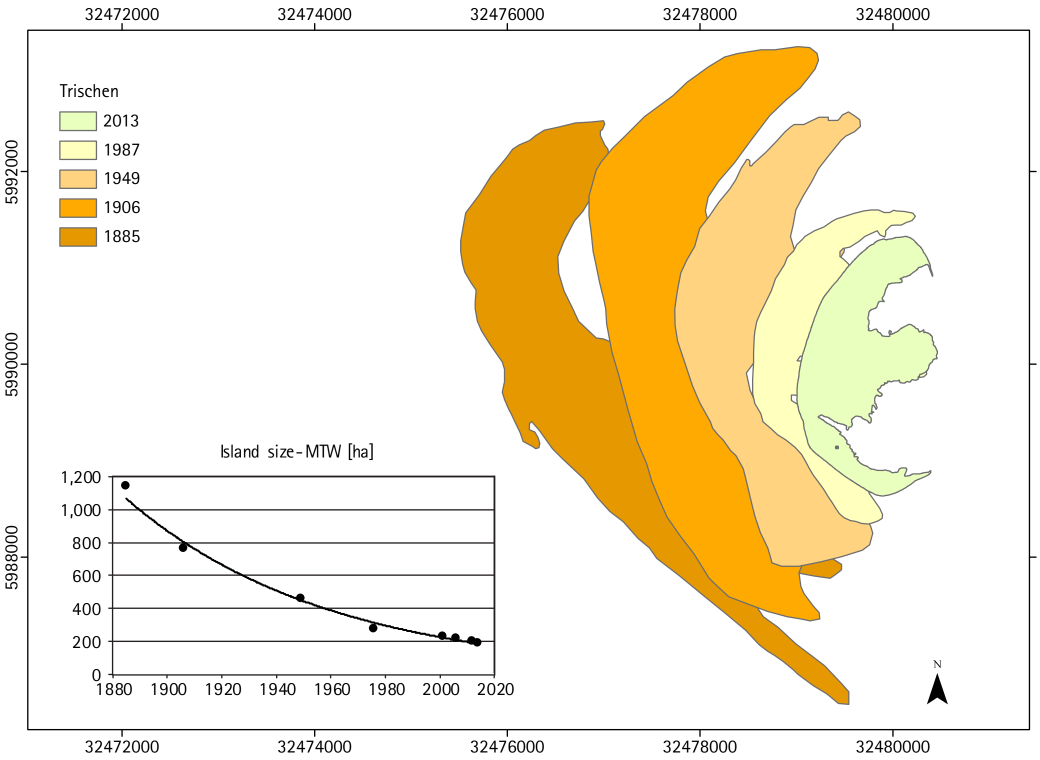
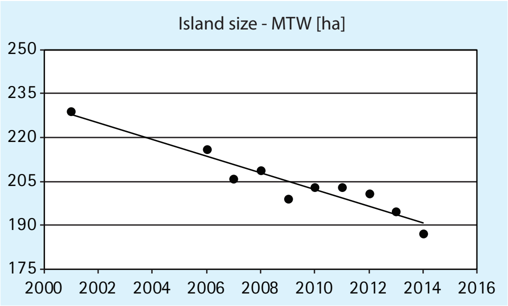


Fig. 3.1: Location and size of Trischen from 1885 until 2013.



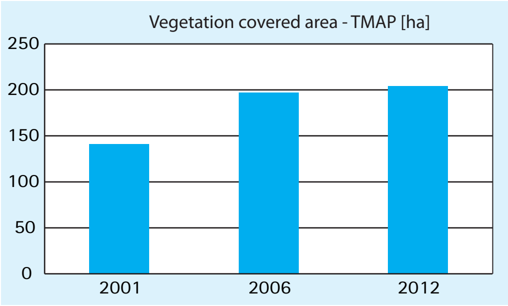


Fig. 3.2a (left): Change in island size during the last 13 years according to own measurements by GPS.

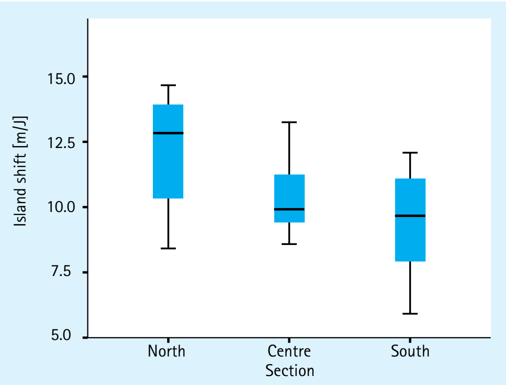
Fig. 3.2b (right): Change in vegetation covered area based on TMAP vegetation mapping.

The shift of the seaward vegetation line was lower than the shift of the island itself (8.8 m y^{-1}). The differences in relocation of the vegetation border between the northern (9.5 mm y^{-1}) and central part (10.5 m y^{-1}) in relation to the southern part (6.1 m y^{-1}) of the island were significant (U-Test, $p < 0.05$; Fig. 3.4).

In consequence of the described changes the island got smaller in the northern and southern ends and the beach plain nearly vanished at these locations. At the same time the shape of Trischen changed from an elongated island into a half-moon shaped topography, becoming more and more rounded on the exposed side. The relocation and the reshaping of the island are visible on the vegetation maps (Fig. 3.5). The reshaping is mainly due to the fact that both gully systems, “Flakstrom” in the north, and “Neufahrwasser” in the south, showed a gradual relocation over the last decades. Their position converged over time east of Trischen and both tidal inlets narrowed considerably on the “Marner Plate”, the watershed in the mainland direction. The position on Trischen in relation to the main gully systems and the tidal flat “Marner Plate” is shown in an aerial image from August 2003 (Fig. 3.6 – XPAN image).

Habitat changes

Typical habitat types of the island change over time. The results are summarized in table 3.1. The pioneer zone has slightly decreased in size whereas the low marsh has increased. The high marsh shows a similar increase as the low marsh, which is mainly driven by aging and by an expansion in the more sandy parts close to the dune ridge of the island. Brackish marsh vegetation is dominated by some reed beds growing in the dunes. Yellow dune habitats generally change size each year. This is the fact for both, embryonic and white dunes, with a higher incidence during the last survey for the embryonic dunes and



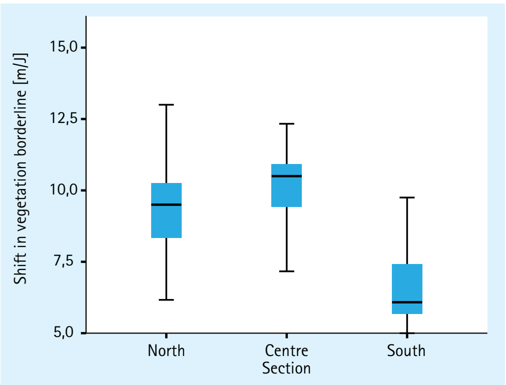


Fig. 3.3 (left): Mean annual island shift, measured as change in MHW-line in three different sections.

Fig. 3.4 (right): Mean annual shift in vegetation boarder in three different sections.

a maximum value for white dunes in 2006. Grey dunes only have a very small incidence while wet dune valleys are entirely missing on Trischen. In the northern part of the island a lagoon is present.

In autumn 2013 two severe winter gales passes the North Sea, namely "Christian" on 28th October and "Xaver" on 5th-6th December 2013. While the first gale reached a wind speed of 172 km/h in St. Peter-Ording and passed by very fast, the second gale was characterised by both strong winds and three consecutive storm surges during a spring tide (Deutschländer *et al.* 2013; Haeseler and Lefebvre 2013) with water levels 3 m above MHW. These two storm events caused very severe habitat changes. The former dune chain, visible on the 2010 LIDAR survey, was presumably destroyed by the storm surges. Only the highest dunes in the southwest still exist. Figure 3.7 shows the vegetation border and the MHW-line from spring 2014 in relation to the digital terrain model from 2010.

The appearance of the island has changed drastically. Trischen has become a flat plateau-like vegetated island with only one visible small dune remaining. Most of the dunes are eroded

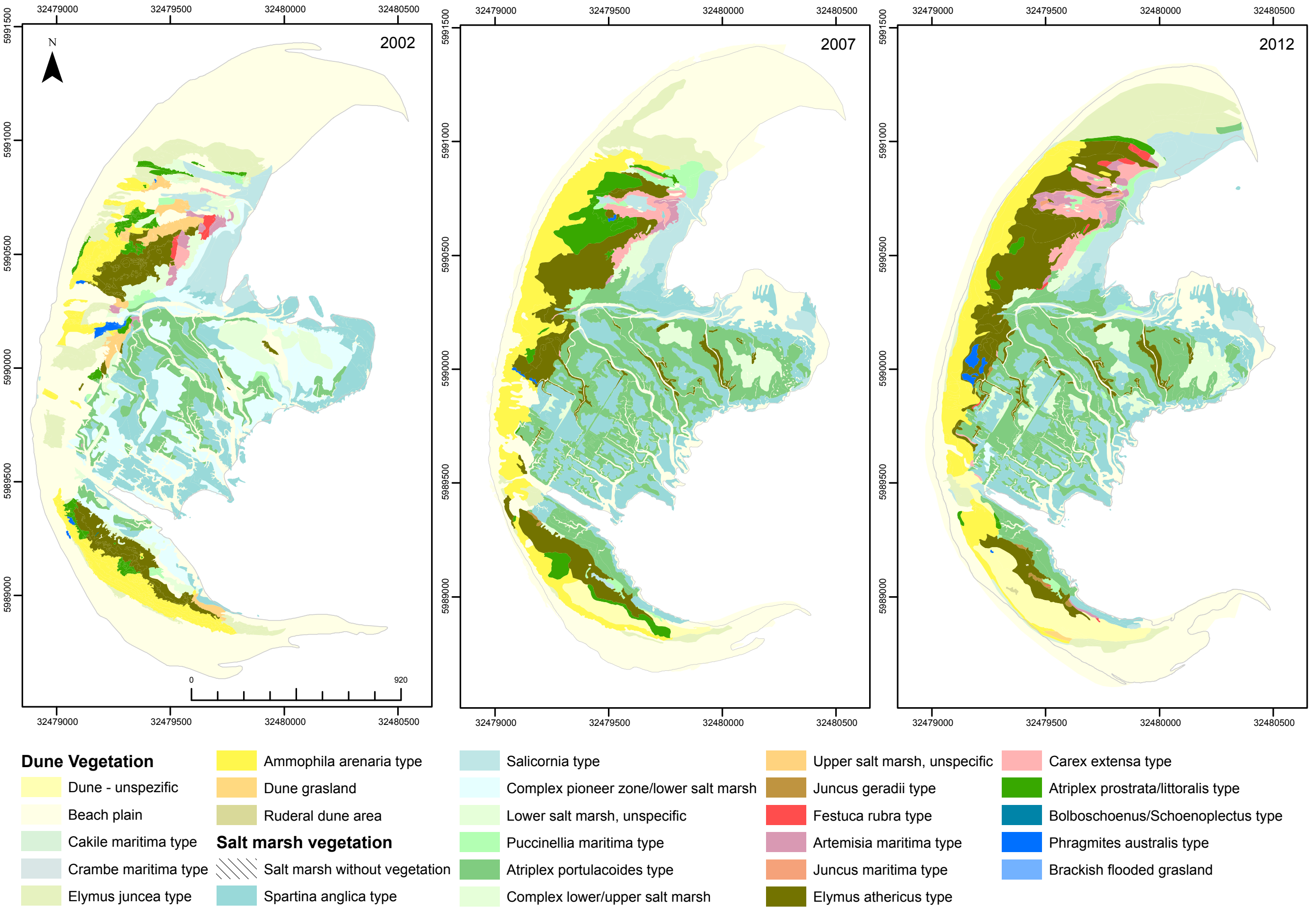


Fig. 3.5: Vegetation maps of Trischen in relation to TMAP-typology. Note the shift and the reshaping of the island during the different surveys.

Fig. 3.6: Aerial photo of Trischen during low tide, showing the two gully systems "Neufahrwasser" and "Flakstrom" as well as the "Marner Plate", the narrow tidal flat between the two tidal inlets. Foto: M. Stock

and the sand was washed over the island to a width of about 50-100 m. Behind this sand covered area a similarly broad band of mussel shells on sand can be found today, with a width of between 50-100 m. The embryonic shifting dunes disappeared totally although rhizomes of species like *Elymus farctus* and *Honckenia peploides* are still alive and sprouting. The three washover areas of the island were hardly affected. We guess, this is due to the high water levels during the storm surges.

Tab. 3.1: Occurrence of habitat types on Trischen (ha). n.m. = not mapped.

Habitat	**2002**	**2007**	**2012**
Pioneer zone	60.3	47.4	51.7
Low marsh	28.2	40.2	40.6
High marsh	28.1	31.5	37.2
Brackish marsh	0.6	0.2	0.7
Embryonic dunes	11.6	8.2	20.8
White + eutrophic dunes	12.3	69.8	53
Grey dunes	0	0	0.2
Lagoon	n.m.	n.m.	0.04

Vegetation changes

The island vegetation changed considerably over time. This is demonstrated by results of regular area-wide mapping of Trischen according to TMAP-Standard (Fig. 3.8 left). Three main developments can be described. First: a succession from younger to older vegetation stages, mainly in the salt marsh; second, an increase in the dune-covered parts of the island, especially at the northern island tip; and third, an increase in *Elymus athericus* vegetation on the lee side of the dune ridge and on the beach-barrier system. The latter developments mainly took place at the northern part of the island. In general these changes coincided with an increase of total vegetation coverage of the island. From 141 ha in

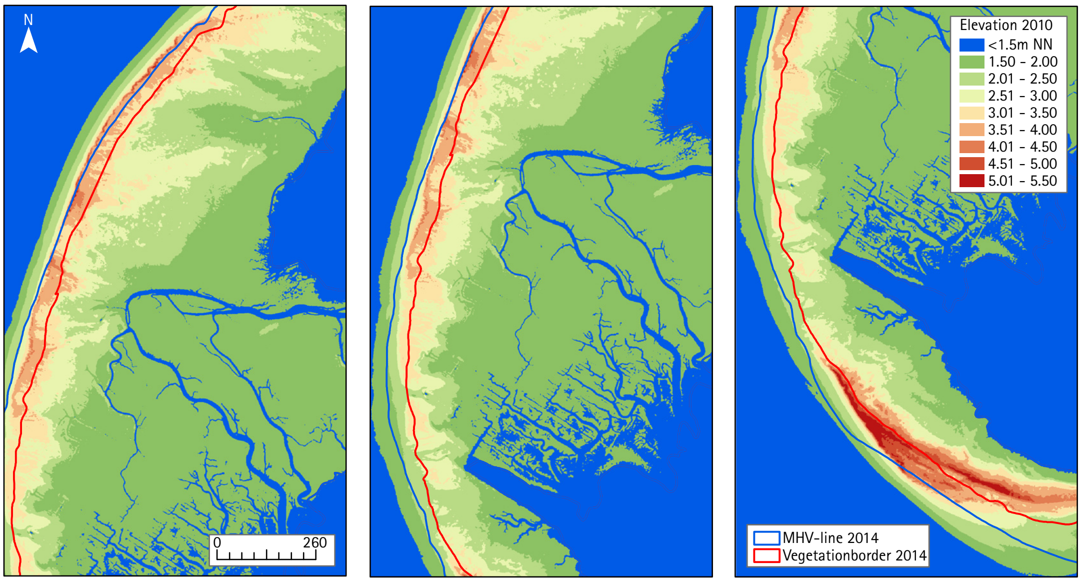


Fig. 3.7: Mean high water line and vegetation boarder on Trischen in spring 2014 in relation to the digital terrain model from 2010.

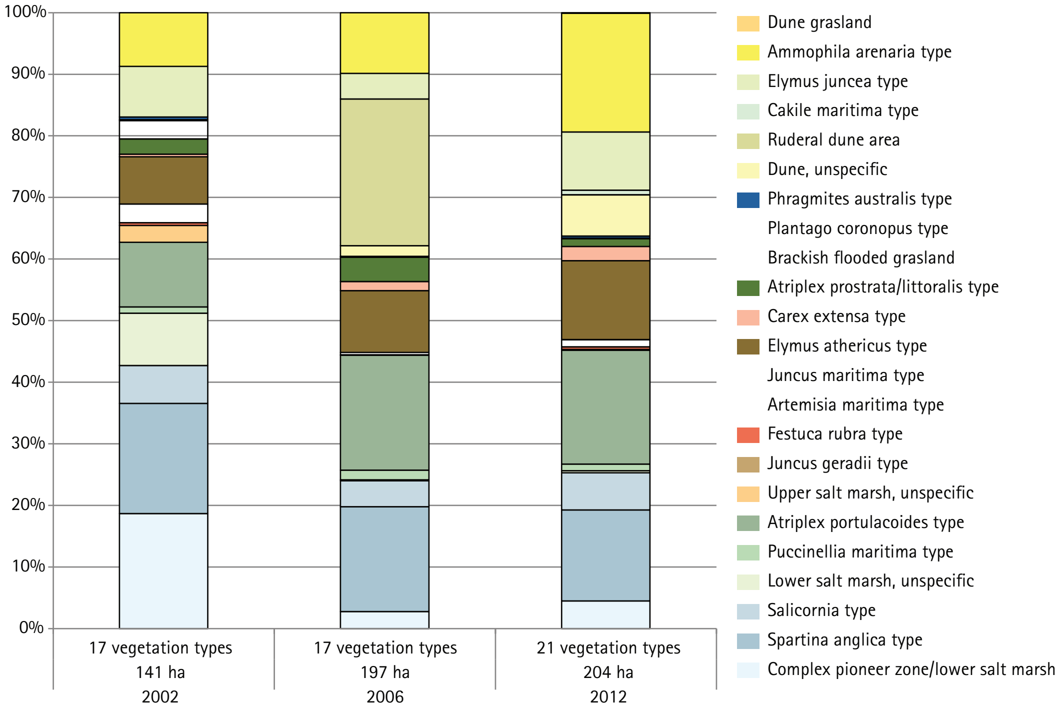


Fig. 3.8: Incidence of main vegetation types in relation to TMAP-typology for the three surveys in 2002, 2007 and 2012. The numbers below the graph show the total number of vegetation types mapped.

2002 it grew to over 197 ha in 2007 and 204 ha in 2012. This development is mainly due to the broadening of the dune belt and the spreading of the primary dunes in the northern part. In line with this development is the increase of the total number of mapped vegetation types from 17 in 2002 and 2007 to 21 in 2012. The highest variety of vegetation types occurs in the high marsh. Six vegetation types within the different vegetation zones show an incidence of more than 5 % vegetation cover in at least two of the three mapping years. These are the *Spartina anglica* (S.1.1), the *Salicornia* (S.1.2), the *Atriplex portulacoides* (S.2.4), the *Elymus athericus* (S.3.7), the *Elymus farctus* (X.2.1) and the *Ammophila arenaria* (X.4.1) type. All other vegetation types show very low incidences (Fig. 3.8).

Species richness and evenness

We define "species richness" as number of species per plot. In general, species richness was higher in the upper and lower salt marsh compared to the pioneer zone (ANOVA, F = 20.27, p = 0.001, n = 172). Highest species numbers (15-18 species per plot) were found in the sandy upper salt marshes on former dune ridges in the north of the island. Low numbers occurred in the pioneer zone with 3-5 species per plot (Tab. 3.2).

Based on all data collected within the 15 permanent plots a steady decrease in the overall species richness is evident during the last 12 years (Fig. 3.9a). The mean number of species decreased from 10.6 (± 0.9 S.E.) in 2002 to 6.5 (± 0.5 S.E.) in 2013 ($r^2 = 0.826$, F = 47.5, p = 0.001). This decrease was highest in plots from the upper marsh zone. As shown in figure 3.9a a drop in species richness occurred after 2008. We thus compared species richness from 2002-2008 (n = 7 years) with 2009-2013 (n = 5 years). Species richness dropped significantly (T-Test, F = 6.75, p = 0.001) from 10.4 ± 3.7 species in the first interval to 7.7 ± 2.8 species in the second interval.

DQ	Vegetation 2002	Domin	Elev	SEC	Delta
1	*Limonium* type	*Festuca*	24	1.92	-10
2	*Carex extensa* type	*Elymus*	50	2.1	-7
3	*Elymus* type	*none*	93	0.29	0
4	Complex pioneer/lower marsh	*Festuca*	32	4.51	-5
5	*Salicornia* type	*Spartina*	1	9.24	2
6	Complex lower marsh	*none*	18	5.26	0
7	*Spartina* type	*Festuca*	32	7.71	-4
8	*Agrostis* type / beach ridge	*Elymus*	57	1.57	-6
9	*Atriplex*/*Artemisia* type	*Festuca*	30	2.57	-4
10	*Atriplex*/*Artemisia* type	*Elymus*	23	2.97	-7
11	*Agrostis* type	*Elymus*	67	2.8	-3
12	Upper marsh, unspecific	*Elymus*	73	2.07	-3
13	*Atriplex* type	*Atriplex*	13	17.9	2
14	*Puccinellia* type	*Elymus*	63	5.82	-8
15	Not specified	*Elymus*	43	3.31	-2

Tab. 3.2: Permanent plot characteristics. Domin = dominant species in 2013, Elev = plot elevation above MHW [cm], SEC = surface elevation change [mm y^{-1}], Delta = Species difference between 2002 and 2013.

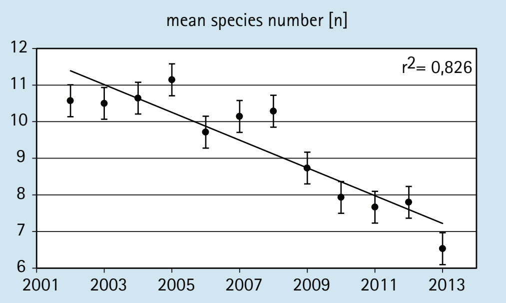


Fig. 3.9a: Change in mean species number n (+/- S.E.) of the permanent plots over the last 13 years.

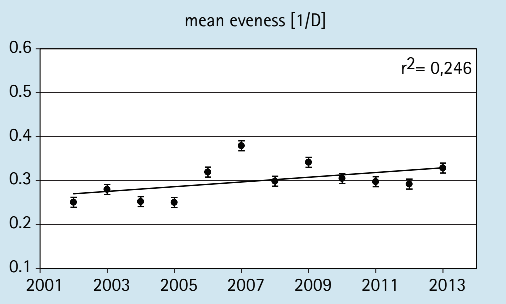


Fig. 3.9b: Change in mean evenness [1/D] (+/- S.E.) of the permanent plots over the last 13 years.

Compared to species richness the mean evenness increased slightly but was non-significant ($r^2 = 0.246$, $F = 3.26$, $p = 0.101$) over time. Values are low and span from 0.25 (± 0.03 S.E.) in 2002 to 0.38 (± 0.04 S.E.) in 2007 (Fig. 3.9b).

Surface elevation change (SEC)

Mean annual SEC on Trischen varies between 0.29 mm y^{-1} at the highest plot (DQ 3) in the upper salt marsh to 17.98 mm y^{-1} at a low-lying plot (DQ 13) in the lower marsh close to a gully. There is a negative correlation between mean annual SEC and the elevation of the plots above mean high tide ($r^2 = 0.512$, $p = 0.001$).

With the exception of permanent plot DQ 13 the mean SEC for Trischen is 3.74 (± 2.47 S.E.) mm y^{-1}. Four plots at the north-eastern part of the island show a mean annual SEC with a range of 4.51 to 9.24 mm y^{-1}. Apart from one plot close to the large gully in the south of the island all nine other plots show a mean annual SEC of 2.50 (± 1.39 S.E.) mm y^{-1} and are thus lower than the local MHW level rise for the Cuxhaven tidal gauge with a rate of 3.6 mm y^{-1} since 1970 (Wahl *et al.* 2011).

Discussion

General morphological changes

Trischen is known as a moving and ever changing island in the river Elbe estuary (Göhren 1975). Over the past 400 years the island has grown and been shifted by natural forces from its original location, the Buschsand, to its position of today. In conjunction with this development the shape of the island has changed from a long, thin outline to a crescent-shaped island.

Doing (1983) describes Trischen as a type III island which is characterised by relative fast movement, gradually being swallowed by the current in a deep tidal inlet. Wadden Sea islands of this type are often located in a meso-tidal river mouth like Trischen, Memmert, Mellum, Scharhörn, and even Lütje Hörn. Those islands show in the beginning a shape as a crescent dune, rounded towards the attacking waves and currents and have two island tips curved inwards in the direction the system is moving in. On the lee side a sheltered salt marsh of simple structure often exists. This island type varies in area and height from an embryonic island, which may be completely flooded during extreme tides, to stable islands with parabolic dune systems and a salt marsh complex. The central area of this island type, and other areas exposed to strong-flowing currents, are often characterised by the sea breaking through the dunes to connect with the tidal creek system of the salt marsh.

The eastward shift of Trischen is a well-known and documented feature. Wohlenberg (1950) presented first profile measurements of the west-exposed dunes and found a mean retreat of the white dunes of 40 m y^{-1} within five years between 1937-1942 whereas the MHW line proceeded about 30 m y^{-1}. In the same timespan the height of the dunes decreased from 8 to 4 m but Wieland (2000) could show that they grew again to a similar size of 8.4 m in 1949, with fluctuating but overall decreasing values since then. The width of the beach decreased from 1898 to 1924 with an annual decline of 35 m y^{-1} (Wohlenberg 1950). The measurements by Wieland (2000) between 1885 and 1990 revealed an island shift of 40.9 m y^{-1} in the north, 26.0 m y^{-1} in the centre and 28.7 m y^{-1} in the south. These values were much higher than those we obtained for the movement of the eastern border of Trischen, measured as a shift of the MHW line, during the last decade. Our mean value was 10.6 m y^{-1} with a larger spatial shift of the island in the north than in the centre and the south. Unfortunately Wieland (2000) gave no separate data or measurements about the shift of the eastern island border. Our recent data showed that Trischen is eroding on the sea side but not simultaneously growing in the east. We conclude that the strong shift of the island has weakened noticeably during the last decades and that the decrease of the island size has gradually attenuated.

Although both the reduction in island size and the speed of island movement have decelerated over the last decades (Fig 3.1) we assume in accordance with Wieland 2000 that the fate of Trischen is determined by two main factors. One is the development of the tidal flats and sandbanks west of Trischen. As long as they stay high enough and provide a shelter against incoming waves and currents Trischen will continuously but slowly moving further to the east. This will lead to a continuing reduction in size since there is very little growth on the east side of Trischen. This assumption is in line with the general tendency of the morphological development of the entire tidal flat and sandbank system in the Wadden Sea area of Dithmarschen coast with a general landward shift (Ricklefs and Asp Neto 2005). The speed of this progress is mainly forced by the development of the second main factor, the influence of two large tidal inlet systems, namely the "Flakstrom" north of Trischen and the "Neufahrwasser" south of the island. Both gully systems are known to erode on their Trischen allocated side (Wilkens and Mayerle 2005) although the erosion processes in the region are depth-limited by early Holocene deposits in the subsurface, namely the "Dithmarscher Klei" (Ricklefs and Asp Neto 2005). But nevertheless, both gullies have been approaching each other for years, resulting in vanished space for the island. East of Trischen, along the "Marner Plate", the meander of the two gullies is getting closer over time. Wieland (2000) reported a width of 500 m at the narrowest point between the gullies in 1996. In 2013 this distance was reduced to 350 m. The outcome of these changes in the future will ultimately determine the fate of the entire tidal system and that of Trischen. If the morphodynamic processes continue, it is probable the Trischen will be squeezed between the approaching gullies in the decades to come (Fig 3.6).

Washover complexes

Washovers were a frequent phenomenon during violent storm surges on all Wadden Sea islands in former centuries. Due to a fixation of the dune ridge on many island tails a washover is nowadays a rare event and occurs only on islands with an active regeneration of old washover complexes or on young, entirely unprotected islands. Washover is listed as an endangered biotope within the Wadden Sea (Ssymank and Dankers 1996) and restoration of this habitat type is a focus of dune management. Restoration is mainly done by removing or opening former drift dikes on island tails. This stimulates a rejuvenation of the entire dune complex with the salt marshes behind them and the beach plains (Arens *et al.* 2013; De Jong *et al.* 2014).

Fig. 3.10:
Mussel shell fields cover the former dune ridges and salt marshes on the seaward side of Trischen after a severe storm surge in Dezember 2013.
Photo: M. Stock

On Trischen washovers occur regularly during extreme high tides at several locations. The vegetation at these spots is generally highly diverse, consisting of pioneer species from beaches, drift lines, primary dunes and salt marshes (Pott and Peters 1997). If a series of calm winters with little storm activity prevails, the washovers rapidly recover and primary dune formation starts. This can lead to a temporary closure of the dune belt but due to the continuous loss of the beach and the exposed dunes, the island substance on the west side fades away. One large washover on Trischen thus recently broke into a large gully called "Hafenpriel" on the east side of the island (Fig. 3.10: Foto Washover). In consequence of these naturally occurring morphological changes some further washover may create a gully connection between the west and the east side of the island. This may lead to Trischen being broken into two parts but it can also function as a sediment source for salt marsh growth in the future.

Vegetation changes

Growth and erosion of an island as well as succession and ageing of the vegetation may cause changes in habitats. Data on habitats are available from three successive mapping surveys. According to these two-thirds of the island is covered by salt marsh vegetation. While the proportion of the pioneer zone and of the brackish marsh varies between surveys the proportion of low and high marsh has increased over time.

The other third of Trischen is covered by dune habitats. Embryonic dune proportion varies between and 8.2 and 20.8 %. Differences in the occurrence of this dune type between the first two surveys are mainly based on the potential of building up dunes on the beach or within washover areas in a certain year. The doubling of embryonic dune occurrence during the last surveys is caused by a large expansion of this dune type in the northern part of the island (Fig. 3.5).

Based on the continuous eastward move of Trischen in the past, direct comparisons with older mapping data are impossible. A GIS-based approach thus failed. The comparison is only possible through description. The oldest available maps of the vegetation on Trischen are from Dirksen (1968) and Schwabe (1972). Between these two maps large differences in vegetation cover and vegetation composition are visible. Dirksen (1968) described embryonic dunes, growing on the western island side and on the fringes of the washover areas, as characteristic for Trischen in 1966. Only some scattered white dunes could be mapped during his survey. East of the dune ridge he found an extended *Puccinellia maritima* dominated vegetation zone. The "*Spartina*-field" more to the east was dominated by a complex of glasswort, common cord-grass and common salt-marsh grass vegetation.

Five years later, in summer 1970 and 1971, Schwabe (1972) has mapped a more closed dune ridge without further differentiation in embryonic or white dunes along the west exposed side of Trischen. She also mapped a new dune complex more to the north on the beach plain of the island. In two existing washover areas *Puccinellia distantis* dominated vegetation was recorded. The former *Puccinellia maritima* dominated vegetation zone has developed into different associations of the upper salt marsh zone with *Juncus geradii*, *Parapholis strigosa* or *Odontitis rubra* as characteristic species. *Elymus athericus* vegetation was scare. Brackish communities with *Phragmites australis* or *Scirpus maritimus* were mapped only on some spots. The gullies were fringed by *Atriplex portulacoides* vegetation. The former "*Spartina*-field" was mainly covered by common cord-grass with bands of *Aster tripolium* or *Triglochin maritimum* aspects. The elevated gully banks were dominated by *Atriplex portulacoides* vegetation.

Most of the previously mapped parts had already sanded up and were overgrown when the next survey was done in 2002 by Gettner *et al.* (2003). In this year the dune ridge was elongated and the vegetation much denser than during the mapping 30 years before. The embryonic dunes had changed to white dunes and were partly covered with upper salt marsh vegetation. The central part of the dune belt was noticeably open and showed three large washover complexes dotted with vegetation patches, either remains of dunes or build up from pioneer vegetation. In the north two chains of dunes were visible. The southern chain was already mapped in 1971, indicating the northeast directed growth of the dunes on the beach plain. The vegetation of the dry dune valleys was scarce and characterised by species-rich vegetation of the upper salt marsh. On the leeward side of the dunes in the north and south a long ribbon of vegetation dominated by *Elymus athericus* had already established in 2002. The "*Spartina*-field" was dominated by *Spartina* only in the wet parts. The more elevated parts showed a mixture of vegetation of the lower and the upper salt marsh.

During the next two surveys in 2007 and 2012 the dune belt was close to continuous but still showing signs of older washovers. The steep increase in vegetation cover could be observed between 2002 and 2007 with a clear north-east spread. From 2007 to 2012 a third dune chain built up and the embryonic dunes noticeably spread on the northern beach plain. In parallel with the increase of the vegetated part of the island an ageing of the vegetation on the leeside of the dunes became obvious. The incidence of *Elymus*-dominated vegetation had increased in the northern part of the island and succession from *Agrostis*-dominated vegetation to *Elymus* progressed fast. This spreading is a phenomenon of natural succession on natural ungrazed backbarrier marshes (Veeneklaas *et al*. 2013a). Some of the higher elevated parts showed reed vegetation spreading. The dune ridges – the older ones as well as the newly developed valley - showed a species-rich vegetation on sandy soil. East of this belt a pioneer zone became established and increased in size. The southern beach barrier and the dune ridge have suffered from strong erosion in recent years leading to an invasion of the former upper marsh vegetation by *Elymus athericus*.

The former "*Spartina*-field" revealed a clear change in vegetation composition during the last years. The marshes grew up along the gullies and the plant cover changed more and more into *Atriplex portulacoides*-dominated vegetation. During the last two surveys it became obvious that the gully banks increased steadily in elevation and are nowadays fringed by *Elymus athericus*. *Spartina* is still dominating in the wet depressions between the gully branches. This part of Trischen is a good example of the dependency on certain abiotic factors for different vegetation types to occur (Davy *et al.* 2011; van Wijnen and Bakker 1997).

Salt marsh growth was recorded on the northeast side of the "island spit" with a spreading of Spartina on the tidal flats in a northerly direction (Fig. 3.5). This is probably the only location on Trischen where new marshes can establish in the near future.

The described phenomena in vegetation succession are typical for beach-barrier islands with dynamic dune-bow and washover complexes and more sheltered island-tails with salt marshes. They are also described from similar islands like Memmert (Oltmanns 1996), Mellum (Gerdes *et al.* 1987) or Scharhörn (Hellwig *et al.* 2014). An initial dune formation also started some years ago on the Kachelotplate (Liebezeit *et al.* 2013; Wehrmann *et al.* 2014), where the young island on the Norderoogsand already formed an initial dune bow and salt marshes (Padlat *et al.* 2014; Stock *et al.* 2013).

A general increase in numbers of vegetation types on the island scale (Fig. 3.8) coincides with a decrease in species richness on the small scale (Fig. 3.9a). This general trend is in line with similar scale-dependent findings for ungrazed mainland salt marshes, especially on *Elymus*-dominated plots (Kiehl *et al.* 2007; Wanner *et al.* 2014). Species losses in our study area occurred mainly in the plots on the dune ridges while these were overgrown by *Elymus athericus*, especially in the second half of the study period. Species like *Sagina nodosa*, *Odontites litoralis*, *Puccinellia distans*, *Parapholis strigosa*, *Centaurium pulchellum* and *Centaurium littorale* disappeared from those plots, although they still can be found in low numbers in close vicinity.

The most conspicuous reason for a decrease in species richness was a rapid spreading of *Elymus athericus* (8 out of 15 plots) or an increase of grass mats, caused by a spreading of *Festuca rubra* (2 out of 15 plots) over the last years. The negative influence of *Elymus athericus* dominance on species diversity is well known (Kiehl *et al.* 2007; Wanner *et al.* 2014).

The spread of *Elymus* on the higher elevated and sandy plots close to or in the dune ridge was also influenced by gulls breeding at those locations. Sometimes gull nests were found directly within the plots, indicating eutrophication. *Elymus* is known as a species reacting directly to nitrogen content, especially at young and elevated back-barrier marshes (Van Wijnen and Bakker 1999).

Seabird colonies are likely to have important consequences for plant species composition on islands, while smaller islands appear to be more affected than large ones (Vidal *et al.* 1998). In a review article Ellis (2005) stated that in most studies analysed the plant species composition in seabird colonies had an increased proportion of annual, rural and cosmopolitan species. This shift in species composition resulted mainly from altered soil nutrient concentration, pH value, increased physical disturbance and seed dispersal by the birds. The latter factor frequently leads to an invasion of cosmopolitan species and a decline of native species, especially in gull colonies. The general described change was also found on Wadden Sea islands, *e.g.* by Runge (1977).

Elevation changes and sea level rise

Measurements of surface elevation changes over the last decade revealed very little vertical growth at our permanent plots. The mean of all measured locations is just in balance with the mean SLR of 3.6 mm y^{-1} since 1970 for the tidal gauge in Cuxhaven (Wahl *et al.* 2011). Only one low-laying plot on a creek near a large washover showed high values, typical for clay-rich marshes close to the sediment source (Stock 2011). Four plots located on a northwest-southeast transect within the slow growing and more clay-rich part of the salt marsh had annual SEC values that exceeded the above mentioned mean sea level rise of 3.6 mm y^{-1} and thus will be able to keep pace with a SLR.

Trischen is continuously eroding on the west side. The locally reworked sediment seems not be deposited on the back-barrier marsh itself and sediment supply for the marsh is thus in deficit. Active washover complexes on the island may play an important role in sediment supply in the years to come. As has been shown on the Skallingen peninsula in Denmark storm surges caused breaches in the dune ridge and created large washover complexes. This process results in local gains of sediment (Christiansen *et al.* 2004; Nielsen and Nielsen 2006). Initial and future flooding events may thus bring sediment into the system via the washover as does the aeolian sand drift and sand transport across the island. This process may stimulate further aggradation on the island marshes (Oost *et al.* 2012) to keep pace with further sea level rise.

4. Breeding birds

A glimpse in the past: breeding bird records on Trischen since 1910

Breeding bird activities are extremely well documented on Trischen. Continuous records are available for the past 100 years, with short interruptions during both world wars (Fig. 4.1).

The early interest in the island and resulting wealth of annual bird data is mainly due to the high number of breeding terns, which also gained the island its formal protection status in 1934. At this point up to 9500 pairs of Common and Arctic Tern - nearly half of the total population of the German west coast - occupied the island (Kempf *et al.* 2000). In 1955 the tern population was joined by a new species, the Sandwich Tern, which also began to breed in high numbers of between 3000- 4000 pairs (Kempf *et al.* 2000). Signs of change in breeding bird composition became apparent with the cessation of active gull persecution in the 1980's, which resulted in a rapid increase of gull numbers. In terms of overall breeding bird numbers Trischen reached its heydays in the early 1990's, when 15,000 – 20, 000 pairs populated the island, which represented 20% of the total seabird breeding population of the Schleswig-Holstein Wadden Sea (Kempf *et al.* 2000). However, this high number was mainly due to the increase in breeding gulls, while the tern population started to dwindle. Common and Arctic Tern numbers crashed in 1995 and up to now continue to breed only occasionally and in low numbers of 100-200 pairs. Sandwich Terns remained in relatively high numbers of about 2500 pairs until 2001, but abandoned the island shortly after and have not attempted to breed since 2006.

Trischen has one of the highest breeding bird densities on the German west coast (Kempf *et al.* 2000). This, combined with a strict ban on visitors, has given the island a somewhat mythical status in the public eye, a bird's paradise that many people would love to visit once in their life time.

In this chapter we begin with a brief overview of long-term records from 1910 onwards, followed by a focus on recent breeding bird trends (population and productivity) since the turn of the century. In the discussion we highlight potential causal relationships between population trends, breeding success and environmental changes.

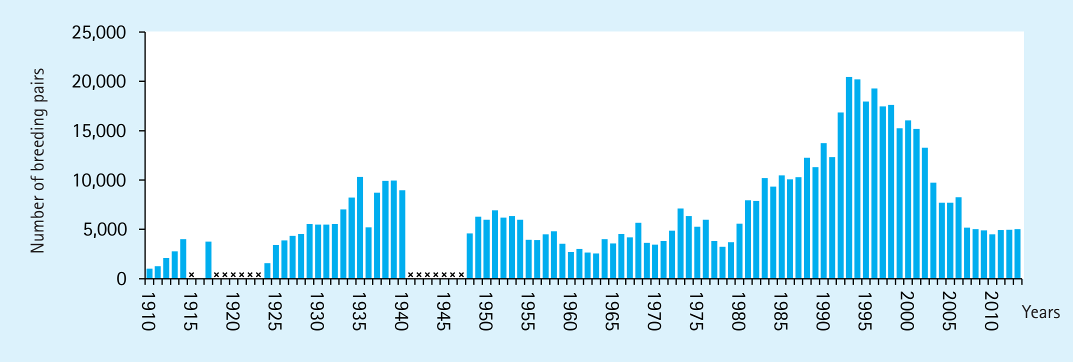


Fig. 4.1: Overview of total number of breeding pairs on Trischen since 1910. In years without bars counting of birds was not possible

Bird Population Trends and Productivity 2000–2013

Methods

Numbers of breeding birds are recorded annually by the resident warden, using standardized species-specific methods that are applied along the entire German coast (Hälterlein *et al.* 1995). Keeping disturbance to a minimum is a priority throughout the breeding period, hence the breeding grounds are rarely directly accessed and breeding numbers are usually counted from distant vantage points. The extensive salt marsh areas are monitored three times a season by walking along transect lines and counting the presence of breeding pairs / individuals. Only in the case of the Spoonbill are nests counted individually and the position recorded. The number of breeding Cormorants is assessed by aerial photography.

Population trends are shown in both absolute and relative values. Total breeding pair number per year was plotted for each species from 2000 to 2013, followed by a linear regression analysis. The slope of the regression equation indicated the average annual change in breeding pair numbers. Secondly, relative changes (%)

were calculated by checking four different regression curves (linear, logarithmic, exponential and potential) for the best fit (r^2). The 14-year trends (%) were calculated based on the values of corresponding regression functions for the years 2000 and 2013. In the case of Spoonbill and Barnacle Goose, which started to populate the island in 2002, the trend was evaluated for the 12-year period.

A feasibility test for productivity monitoring of Herring Gull and Lesser Black-backed Gulls was carried out on Trischen in 2009 (Spalke 2009). Productivity results for both species are available from 2010. The methods follow a protocol established by Exo *et al.* 1996 and Koffijberg and Schrader 2010. Both species breed in mixed colonies all over the island. Up to 80 nests are fenced with chicken wire shortly before the first chicks hatch. Each nest is individually marked and observed to establish the species identity for as many study nests as possible. Young chicks are marked with metal and plastic rings. The colony is visited by the warden every 3-4 days throughout the breeding period and records on clutch/brood size, chick survival and possible reasons for failure are noted.

Chick survival of other species is not followed as intensely to avoid disturbance. However observational data can provide a rough estimate on the number of fledged young, at least for some species. This data is likely to be more accurate for large fledglings such as Spoonbill, Cormorant and Barnacle Goose, while young Redshanks and Oystercatchers are generally harder to spot in the high island vegetation. Results for these less visible wader species therefore represent lowest estimates. The breeding success of the only resident bird of prey, the Peregrine, is determined by the ringing of nestlings and follow-up observations.

Results

A steady decline of the breeding bird population on Trischen began in the late 1990's and continues to this day. Between 2000 and 2007 the total population decreased by about two thirds (Fig. 4.2). The biggest losses within that time frame have been with the gull species, especially Black-headed Gulls and Herring Gulls have decreased dramatically since 2000 (Fig. 4.3). However, Herring Gulls and Lesser Black-backed Gulls continue to contribute the majority towards the breeding bird number, averaging about 3,500 pairs. Since 2007 the total bird population has remained relatively stable at around 5,000 breeding pairs.

A total of 30 breeding bird species have been recorded on Trischen since 2000 (Tab. 4.1). Of these, 17 non-passerine and three passerine species have been regular breeders, *i.e.* species that have bred in 11 or more years since 2000. Species diversity within the 13-year time frame appears stable as several new species colonized the island, namely Spoonbill (2002), Barnacle Goose (2002), Pintail (2002) and Greylag (2012). Species that ceased to be regular breeders are Kentish Plover and Sandwich Tern; other species are traditionally rare breeders such as Water Rail and Mediterranean Gull.

A comparison of population trends in the past 13 years shows that of the 19 regular breeding species only four show positive population developments in terms of both absolute and relative values (Fig. 4.3 and Fig. 4.4). Most of these successful species have colonized the island in the recent past. The Cormorant started breeding on Trischen in 1997 and increased its colony substantially by on average 19 breeding pairs per year. The Spoonbill, also a recent addition to the island, has been increasing by five pairs

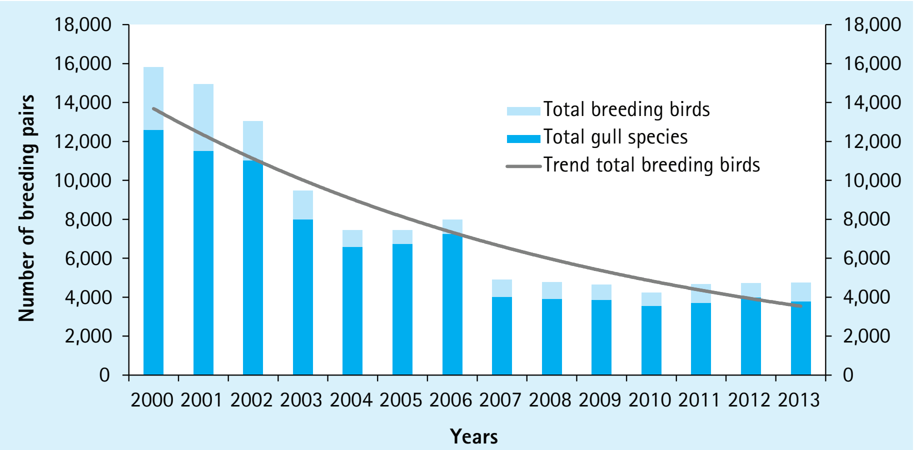


Fig. 4.2:
Total number of breeding pairs in relation to gull population 2000-2013. Trend as exponential regression for all breeding birds $y= -15{,}184e^{-0.1041x}$.

Tab. 4.1: Species list of breeding birds showing presence (%) between 2000 – 2013 and number of breeding pairs (2013).

	Species	Latin name	% presence 2000–2013	Number of breeding pairs 2013
1	Lesser Black-backed Gull	*Larus fuscus*	100	1838
2	Herring Gull	*Larus argentatus*	100	1781
3	Cormorant	*Phalacrocorax carbo*	100	394
4	Common Tern	*Sterna hirundo*	100	210
5	Black-headed Gull	*Larus ridibundus*	100	118
6	Oystercatcher	*Haematopus ostralegus*	100	91
7	Spoonbill	*Platalea leucorodia*	86	89
8	Shelduck	*Tadorna tadorna*	100	67
9	Redshank	*Tringa tetanus*	100	53
10	Common Gull	*Larus canus*	100	34
11	Meadow Pipit	*Anthus pratensis*	100	24
12	Mallard	*Anas platyrhynchos*	100	16
13	Barnacle Goose	*Branta leucopsis*	86	13
14	Little Tern	*Sterna albifrons*	79	9
15	Ringed Plover	*Charadrius hiaticula*	100	4
16	Skylark	*Alauda arvensis*	100	4
17	Greylag	*Anser anser*	14	2
18	Great Black-backed Gull	*Larurs marinus*	100	2
19	Wagtail	*Motacilla alba*	100	2
20	Pintail	*Anas acuta*	14	1
21	Peregrine	*Falco peregrinus*	100	1
22	Arctic Tern	*Sterna paradisea*	100	1
23	Barn Swallow	*Hirundo rustica*	7	1
24	Water Rail	*Rallus aquaticus*	14	0
25	Lapwing	*Vanellus vanellus*	7	0
26	Kentish Plover	*Charadrius alexandrinus*	7	0
27	Mediterranean Gull	*Larus melanocephalus*	29	0
28	Sandwich Tern	*Sterna sandvicensis*	43	0
29	Yellow Wagtail	*Motacilla flava*	7	0
30	Reed Bunting	*Emberiza schoeniclus*	14	0

per year since its arrival in 2002. The Barnacle Goose, a breeding bird since 2002, is on the increase, by one pair per year. Little Tern numbers increased on average by 0.5 pairs per year, but the population fluctuates markedly between 0 and 14 breeding pairs; hence the average increase of 265% between 2000 and 2013 is misleading. Passerines such as Wagtail and Skylark remain stable. All the remaining species show strong downward population trends. Gull species and Oystercatcher are worst affected, followed by Common and Arctic Tern (Fig. 4.3). Sandwich Tern and Kentish Plover are no longer breeding on the island (Fig. 4.4).

Productivity has been consistently low for both Lesser Black-backed Gull and Herring Gull since 2010, with an average fledging success of 0.32 (± 0.14 S.D.) chicks per pair and 0.26 (± 0.12 S.D.) chicks per pair respectively (Tab. 4.2).

Spoonbill, Cormorant and Barnacle Goose have a consistently higher breeding success than all other breeding species (Tab. 4.3). Spoonbills for example managed to raise an average of 2.08 (± 0.27 S.D.) young per pair over the past four years, Cormorants raised 0.96 (± 0.73 S.D.) and Barnacle Geese 3.50 (± 1.53 S.D.) young per pair.

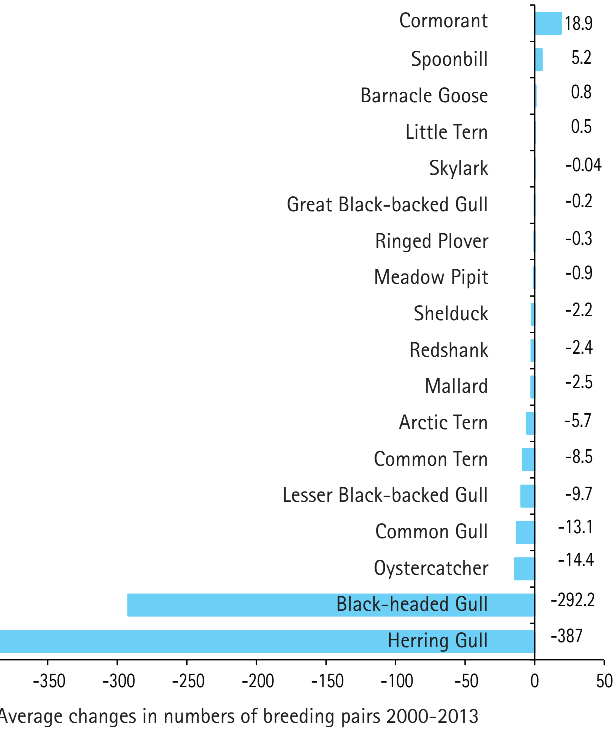
Productivity estimates for the wader species are vague, but sightings of fledged Redshanks suggest a breeding success of < 0.1 young per pair during the past four years, while Oystercatcher sightings are even lower with < 0.04 fledged young per pair.

Sightings of Shelduck fledglings were also low, translating into an average breeding success of < 0.09 since 2010.

The Peregrine breeding success averaged at two fledglings per year, with an increase of +1.3 fledglings within the study period.

% changes in numbers of breeding pairs 2000-2013

Fig. 4.4 (left): Species trends, showing % population changes between 2000 and 2013. Spoonbill and Barnacle Goose are breeding birds since 2002.



Average changes in numbers of breeding pairs 2000-2013

Fig. 4.3 (right): Species population trends 2000–2013, showing average annual changes in breeding pair numbers.

Breeding success of the tern species fluctuates between total colony loss and years of relatively high breeding success. Arctic Terns had a good breeding year in 2011, with 0.57 fledged per pair; Little Terns achieved a breeding success of 2.25 fledged per pair in 2013, and Common Terns had 0.5 fledged young per pair in 2010. In all other years the tern species showed a total productivity of 0 to <0.14.

	Lesser Black-backed Gull		**Herring Gull**	
	fledged pair $^{-1}$		fledged pair $^{-1}$	
2010	0.2	n=10	0.43	n=14
2011	0.3	n=18	0.25	n=21
2012	0.26	n=31	0.18	n=34
2013	0.52	n=33	0.18	n=40

Tab. 4.2: Number of fledged chicks/ pair for Lesser Black-backed Gull and Herring Gull, 2010–2013.

	Spoonbill	**Cormorant**	**Barnacle Goose**
2010	1.71	0.35	1.5
2011	2.04	0.41	5
2012	2.3	1.18	3.2
2013	2.26	1.9	4.3

Tab. 4.3: Number of fledged chicks/ pair for Spoonbill, Cormorant and Barnacle Goose, 2010–2013.

Discussion

Natural island succession caused Trischen to decrease in size to less than a quarter since 1906, yet by the 1990's species diversity and number of breeding pairs had reached values three to five times higher than at the beginning of the century (Oppel 2005). Gull and tern populations increased between 1970 and 1990 in the entire Wadden Sea region, most likely due to the cessation of gull persecution (Südbeck *et al.* 2000), reduced contamination by toxic chemicals (Becker and Cifuentes 2004), protection of breeding grounds and increased food availability (Garthe *et al.* 2000; Spaans 1998). On Trischen this positive trend started to level out by the late 1990's and the start of the new century was marked by a steep decline in breeding bird numbers. Especially species groups such as tern and wader declined dramatically, gull numbers are down to a third of the population since 2000.

The question remains as to why the majority of species are struggling, except for the most recent arrivals. After all, Trischen is one of the few remaining pristine places on the German coast, human disturbance is negligible and habitat alterations have not been carried out for the past 60–70 years. A mosaic of breeding sites is available that is rarely found elsewhere. Salt marshes, dune systems and large sparsely vegetated sandy spits provide perfect breeding habitat for waders, gulls and terns. Yet, none of these species groups are thriving. This is also the case in a wider regional context, the entire Wadden Sea area. From 1997 to 2001, strongest declines were shown by gulls and waders, *i.e.* Oystercatcher, Black-headed Gull, Ringed Plover, Kentish Plover and Herring Gull. Cormorant, Spoonbill, Barnacle Goose and Greylag Goose showed the highest increases within this timeframe; in particular Cormorant and Spoonbill increased their European breeding range (for species details see reviews by Koffijberg and Südbeck 2006 and Hötker *et al.* 2010a). Regional differences aside, the homogeny of species trends across large spatial scales suggests that population levels on Trischen are also subject to changes in the wider environmental landscape. Like many other islands in the Wadden Sea region, Trischen changed from an island dominated by terns to an island dominated by gulls over the past 15-20 years (Kempf *et al.* 2000). However, productivity monitoring has shown that breeding success is extremely low not just for terns and waders, but also for large gulls such as Herring Gulls and Lesser Black-backed Gulls. Consequently, the large gull population on Trischen has experienced a drastic decline, mainly driven by a pronounced reduction in Herring Gull numbers while Lesser Black-backed Gulls decreased only slightly.

The reasons for this are varied. Some are species-specific while others affect most seabird populations in the Wadden Sea area. Some factors are particularly evident on, or possibly even unique to, Trischen. A number of factors such as food availability, flooding events, succession and predation are discussed in the following sections.

Flooding & breeding habitat

One major reason why species such as Spoonbill, Cormorant and Barnacle Goose are doing better in terms of population increase and productivity than most other species on Trischen is rooted in their choice of breeding habitat. They all breed inland and / or in elevated areas, which means they are not threatened by flooding during the breeding period. This is one big advantage that they share only with the large gull species that colonize dunes; all other species breed on grounds equal at, or only slightly higher than sea level.

The difficulty of providing flood resistant breeding grounds for future bird generations is not unique to Trischen. In fact, most of the Wadden Sea, which is Europe's largest wetland and core breeding area for many coastal species (Koffijberg *et al.* 2006), has experienced an increased sea level rise (SLR) from 3.6 mm y^{-1} to 4.2 mm y^{-1} in the second half of the 20th century (Jensen and Mudersbach 2004b; Jensen *et al.* 2010). While mainland salt marshes can keep pace with a SLR of about 6-8 mm y^{-1} (Dijkema 1997; Suchrow *et al.* 2012), island salt marshes are at risk of drowning with an increase larger than about four mm y^{-1} (Bartholdy *et al.* 2010).

In the 'Climate and Hydrology' chapter we showed that multiple flooding events each breeding season leave over 50 % of the island submerged, resulting in a lack of safe breeding habitat and consequently low productivity rates. This affects all species that breed in the salt marshes such as Black-headed Gull, Redshank, Oystercatcher, occasionally Common and Arctic Terns, and species colonizing the lower dunes and beaches, i.e. Ringed Plover, Little Tern and Common/Arctic Tern. These flooding events are probably the most destructive forces these breeding birds have to deal with on Trischen. Depending on the timing of flooding incidences and energetic condition of the females, second broods are attempted by some individuals, but the majority of failed pairs usually abandon the breeding grounds.

Van De Pol *et al.* (2010) have shown that previously rare events such as extreme summer flooding of > 50 cm above MHT have become more frequent and occur increasingly at a crucial time of hatching, severely reducing population viability of species such as Oystercatcher. The phrase 'ecological trap' has been applied to breeding areas of high flooding risk to which birds are unable to adapt in time, mainly because the environmental cues are too hard to predict in order to alter behaviour, such as the choosing of higher nest sites (Van De Pol *et al.* 2010). To some extend this phrase also describes the situation on Trischen, which attracts a high number of breeding birds by apparently providing safe breeding spots in natural habitat with low disturbance. That over 50 % of the island's main breeding habitats are prone to flooding is a fact that many breeding birds such as Oystercatcher, Ringed Plover and Common Tern discover at a high cost – a cost which is especially detrimental for species already vulnerable due to widespread population declines (Koffijberg *et al.* 2009; Koffijberg and Südbeck 2006).

As regards to species such as Herring Gull, Lesser Black-backed Gull, Common Gull and Shelduck, which all tend to breed in elevated areas not prone to flooding, other factors seem to be causing the decline, some of which are discussed in the following sections.

Food availability & predation

Because large gulls have been shown to influence species composition and population size (Becker *et al.* 1997; Finney *et al.* 2003), studying gull populations can provide some key insights into species dynamics. On Trischen, the breeding success of Herring Gulls and Lesser Black-backed Gulls has been very low, also as it has internationally. A productivity protocol that aims to allow comparisons across larger geographical scales has been introduced by the World Seabird Union (Irons *et al.* 2011). The productivity index (PI) (PI= fledglings / clutch size * 100) facilitates the classification of breeding success into different categories, with a productivity index of < 10 % classified as poor, 10-50 % as moderate and > 50 % as good productivity. With a four-year average PI of 9.8 % for Herring Gulls and 11.9 % for Lesser Black-backed Gulls, the breeding success has shown to be rather poor on Trischen during the past years.

On an island where 76 % of all breeding birds are constituted by large gulls, the effect of gull predation on eggs and chicks is an important issue. The population dynamics on Trischen appear to follow a typical predator-prey pattern. This is characterised by an initial steep increase in gull numbers, followed by a decline in the overall breeding bird population, which in turn results in a population drop of large gulls (Mercker and Baer 2013). A diet analysis in 2013 found that 3.7% of gull pellets contained chicks or eggs which, extrapolated for a gull population of about 4000 breeding pairs, translates into a potential of >1t chicks/ fertilised eggs on the island during the breeding season (Mercker and Baer 2013).

High levels of chick predation and poor reproductive output are important indicators of food limitation in seabird colonies as illustrated by Martin (1987). In terms of large gulls such as Herring Gull and Lesser Black-backed Gull, this also includes intra- and interspecific predation. For example on the island of Texel, cannibalism rates exceeded 60% of predated hatchlings in Lesser Black-backed Gulls, which is probably linked to food shortage (Camphuysen and Gronert 2012). Food availability for gulls has gone through some changes in the recent past, especially as gulls are an opportunistic species that benefit greatly from human activities and are able to shift their choice of prey depending on availability (Camphuysen 2013). Two of those key human activities affecting gulls are the closure of refuse dumps and changes in the commercial fisheries sector. While the closure of refuse dumps resulted in a pronounced population decline (Hötker *et al.* 2010b; Kilpi and Öst 1998), increases in fisheries activities and associated discards during the past century generally facilitated seabird population growth. In particular Herring Gull and Black-headed Gull were found to utilize shrimp trawler by-catch in inshore Wadden Sea areas (Walter and Becker 1997), while Lesser Black-backed Gulls were mainly found following trawlers further offshore (Camphuysen 1993; Garthe *et al.* 1996). Since the early 1990's however, fishing effort in the Wadden Sea area declined steadily (Camphuysen 1995), resulting in increased intra- and inter-specific foraging competition (Camphuysen 2013). Recent studies highlighted the strong link between gull productivity and fisheries activities, as reduced amount of available prey during times of low fishing activities caused starvation periods for chicks of both Herring Gull and Lesser Black-backed Gull (Camphuysen 2013).

On the island of Trischen, boating traffic is recorded three times a day between March and October. The data on shrimp trawler activities, which trawl the tidal channels in the immediate vicinity to the island, shows that the number of sightings fluctuated strongly over the past 14 years, but an overall declining trend is apparent (Fig. 4.5).

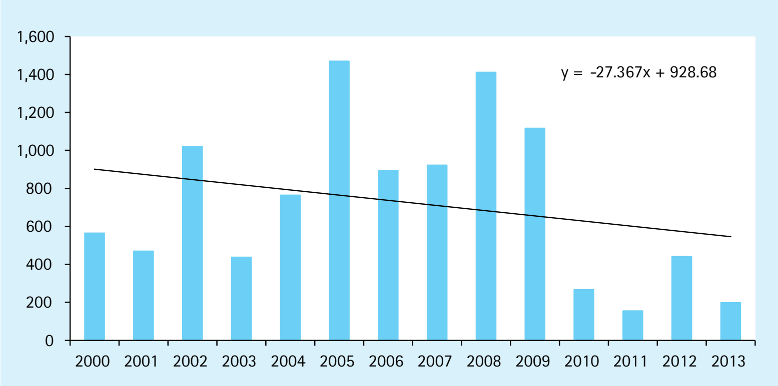


Fig. 4.5:
Number of shrimp cutters on Trischen 2000-2013.

Shrimp cutters have the highest by-catch rate of any fishery with 70-90% of total landed catch being discarded (Walter 1997). Both Herring Gull and Lesser Black-backed Gull are likely to benefit from this food source so close to their breeding grounds. The level of dependency on this food source during chick-rearing is not clear, however in the light of the very low breeding success of both species, a reduction in local shrimp trawlers will have an additional negative impact. A consequence of reduced prey availability could be a further increase in predation rates, which has been noted previously on Trischen during times of low fishing activities (Kempf *et al.* 2000; Baer pers. obs.).

The second local bird species that may impact other birds breeding on the island is the Peregrine Falcon, which has successfully bred there since 1999. The Peregrine inhabits the northern part of the island where activities are difficult to observe as the area is visited infrequently. All Peregrine prey items are recorded when found; frequently encountered food items include species such as Oystercatcher, Knot, Woodcock, pigeons and small gulls. As Peregrines specialize in catching adult birds, the population viability of some island species is likely to be impacted, however the extent of the impact is extremely hard to quantify, leave alone to predict.

Vegetation Succession

Seabirds have a capacity to introduce large amounts of marine-derived nutrients to land and are known to impact island vegetation in terms of nutrient supply, physical disturbance and seed dispersal. The review by Ellis (2005) on the impact by seabirds on island vegetation showed that plant diversity usually declined within dense colonies; however the effect varied with island size and the degree of seabird disturbance. Gulls have been described as important drivers of these processes (Becker and Erdelen 1987) and the steep increase in gull numbers during 1970-1990 on Trischen is likely to have had important consequences for the plant community on the island. The vegetation development within permanent plots between 2002 and 2013 showed a decrease in plant species richness from 10.6 (± 0.94 S.E.) to 6.5 (± 0.52 S.E.) species while at the same time there was an increase in overall vegetated area (see the chapter "Vegetation Changes" for details). Most notably the native perennial grass *Elymus athericus* has increased its range over the past 12 years from 7.7 ha to 12.8 ha, a development similar to that taking place at many salt marsh sites in the Wadden Sea and across Europe (Bockelmann and Neuhaus 1999; Valéry *et al.* 2004; Veeneklaas *et al.* 2013a; Veeneklaas *et al.* 2013b). What role the increase in gull numbers had in plant succession on Trischen is not clear, especially as many of these processes are also found elsewhere, where no large gull colonies influence vegetation developments. However, the recent changes from habitats characterised by salt marsh vegetation to habitats that are increasingly dominated by *Elymus athericus* favour breeding birds such as gulls, which generally prefer breeding sites with tall vegetation (Bezzel 1985). Oppel 2005 argued that, after a steady increase in overall bird numbers and species diversity on Trischen, a level was reached by the turn of the century that indicated a limitation in resource availability such as a lack of suitable and flood resistant breeding sites. Consequently, island succession can be regarded as another key element shaping future breeding bird dynamics on Trischen.

Ants on Trischen

Ants play a large role in ecosystems as they act as predators, scavengers and herbivores and constitute a great part of the overall animal biomass (Holway *et al.* 2002). On islands where ants have been accidentally introduced the effect is often one of widespread ecological damage (McGlynn

Fig. 4.5a-b:
Herring Gull chicks swarmed by ants (Myrmica rubra), Trischen June 2013.
Photos: J. Baer.

1999; Rabitsch 2011), including damage to breeding seabirds through reduced chick survival (Feare 1999; Lockley 1995; Nisbet and Welton 1984; Plentovich *et al*. 2009; Safina *et al*. 1994).

Trischen is home to a large ant population which can be found in all island habitats and is especially abundant in the dunes and grass-covered areas. The ant species has been identified as *Myrmica rubra* or European Ruby Ant, which is known to be a highly aggressive ant that stings painfully and may form supercolonies (Seifert 2007). *Myrmica rubra* is one of the most abundant native ant species in Europe, extending from Ireland and Portugal in the west to central Asia and eastern Siberia (Wetterer and Radchenko 2011). In America *Myrmica rubra* is a non-native species which was first recorded in 1970 and recent studies suggest detrimental effects on Herring Gull reproduction due to ant predation (DeFisher and Bonter 2013). They showed that nest sites infested by *Myrmica rubra* caused erratic incubation behaviour in Herring Gulls, possibly affecting embryonic development. DeFisher and Bonter (2013) also found that Herring Gull chicks swarmed by *Myrmica rubra* either died rapidly or showed slower growth rates.

So far most cases of ants affecting seabird reproduction are reported from outside of Europe. In Germany one incident was mentioned in 1938, where ants (species unknown) caused distress to seabird chicks on the island of Amrum (Schulz 1947). A negative effect of ants on seabird reproduction can be difficult to detect, as the mere presence of ants cannot automatically be attributed to the cause of chick death. Consequently gull chick predation by ants was first noticed on Trischen with the onset of intensive gull productivity monitoring and frequent colony visits. Philipps (2011) was the first to report ants entering pipped eggs and attacking living chicks, apparently resulting in the death of both Herring Gull and Lesser Black-backed Gull chicks. Following reported ant attacks on gull chicks in 2012 (Mercker pers. com), a further investigation was carried out during the 2013 season (Baer 2014). Herring Gull and Lesser Black-backed Gull nest sites with living chicks that were obviously suffering from attacks by *Myrmica rubra* were noted (Fig. 4.5a-b). This was the case for 8.3 % of the nest sites, where all of the chicks (n=29) died before the age of 4 d (± 2 d), reflecting a chick loss of 14.5 % within the colony. These ant infested nest sites showed a 12-fold higher ant density in comparison to nests with successful fledglings. A distinctive ant density pattern within the colony was also found, suggesting that location of nesting sites strongly affected chick survival. The relatively small number of nests infested by ants (n=10) does not allow a distinction between gull species, however chick losses in the region of 11 % as found in 2011 (Philipps 2011) and 14.5 % in 2013 (Baer 2014) highlight the potential level of impact by *Myrmica rubra* on the overall gull productivity on Trischen. This is particularly salient when bearing in mind that these figures represent the lowest estimates as only chicks found alive were included in the analysis, and exclude all chicks that died prior to detection.

5. Migratory birds

5.1 Resting birds

The Wadden Sea provides an important resting, feeding and breeding area for many migratory waterbirds: at least 52 populations of 41 species regularly use the Wadden Sea in internationally important numbers (Meltofte *et al.* 1994). Although the "Joint Monitoring of Migratory Birds" project regularly coordinates resting bird counts within the Wadden Sea at several places in Denmark, Germany and The Netherlands (van Roomen *et al*. 2012), Trischen occupies a special role in two respects:

On the one hand, Trischen is largely unaffected by direct human disturbance or development. Hence, the island provides a suitable area to study resting bird populations depending on local natural factors, such as appropriate resting areas, food availability or climate/hydrology.

On the other hand, the role of Trischen as a resting and feeding area for waterbirds has decreased significantly over the past decades, even surpassing the average decline of resting birds in the wider Wadden Sea region. Moreover, both resting and breeding waterbird populations are affected (Mercker and Baer 2013). These combined findings suggest that (mainly still unknown) factors causing a general decline in waterbird populations could have an intensified effect on Trischen.

In this section, we will document and discuss (mainly waterbird) population developments in a 13 year period (2000-2012) on Trischen.

Methods

In order to monitor resting birds (non-passerines) on and around Trischen, regular counts took place every 15 days (close to spring tide), following methods of the Joint Monitoring of Migratory Birds (JMMB), a project of the Trilateral Monitoring and Assessment Program (TMAP). These counts, including data collection and management, have been coordinated by K. Günther from the 'Schutzstation Wattenmeer' on behalf of the Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation. In the context of this monitoring all resting/swimming birds are counted, including birds belonging to local breeding populations (Günther 2009). Hence, in the case of several species, bird numbers are influenced (sometimes mainly composed of) Trischen breeding populations. However, if not otherwise stated within this section, all birds counted in the context of the TMAP are termed as "resting birds".

To visualize population developments of resting birds on Trischen, the maximum counts of resting individuals per season (2000-2012) were plotted for each species. These maximum numbers were subsequently summarized to study species complexes. Temporal trends in resting birds were plotted using regression functions. These trends were tested with four different regression curves (linear, logarithmic, exponential and potential), finally using the regression curve with the highest coefficient of determination R². Furthermore, percentage 13-year trends were evaluated based on the values of corresponding regression functions at the year 2000 and 2012 respectively.

Results

If we look at the interspecies development of the 29 most common resting bird species (including breeding birds) on Trischen, an average decrease of approximately 30 % since the turn of the millennium becomes apparent (Fig. 5.1a). This decrease affects most (non-passerines) resting species on Trischen: only eight of the most common 29 species show a positive trend (corresponding diagrams not for each species shown), namely: Cormorant, Spoonbill, Brent Goose, Eider, Whimbrel, Lesser Black-backed Gull, Arctic Tern and Little Tern. This interspecies decrease becomes even more pronounced if we take into account that four of these eight positive trends reflect an increase in Trischen breeding populations, rather than in resting migrants (*c.f.* "Breeding birds" chapter).

To work out the role of Trischen as a resting/feeding area for migratory birds, we evaluated resting data for the 10 most frequent non-breeding waders (Fig. 5.2). Here, the negative trend is even more pronounced and averages

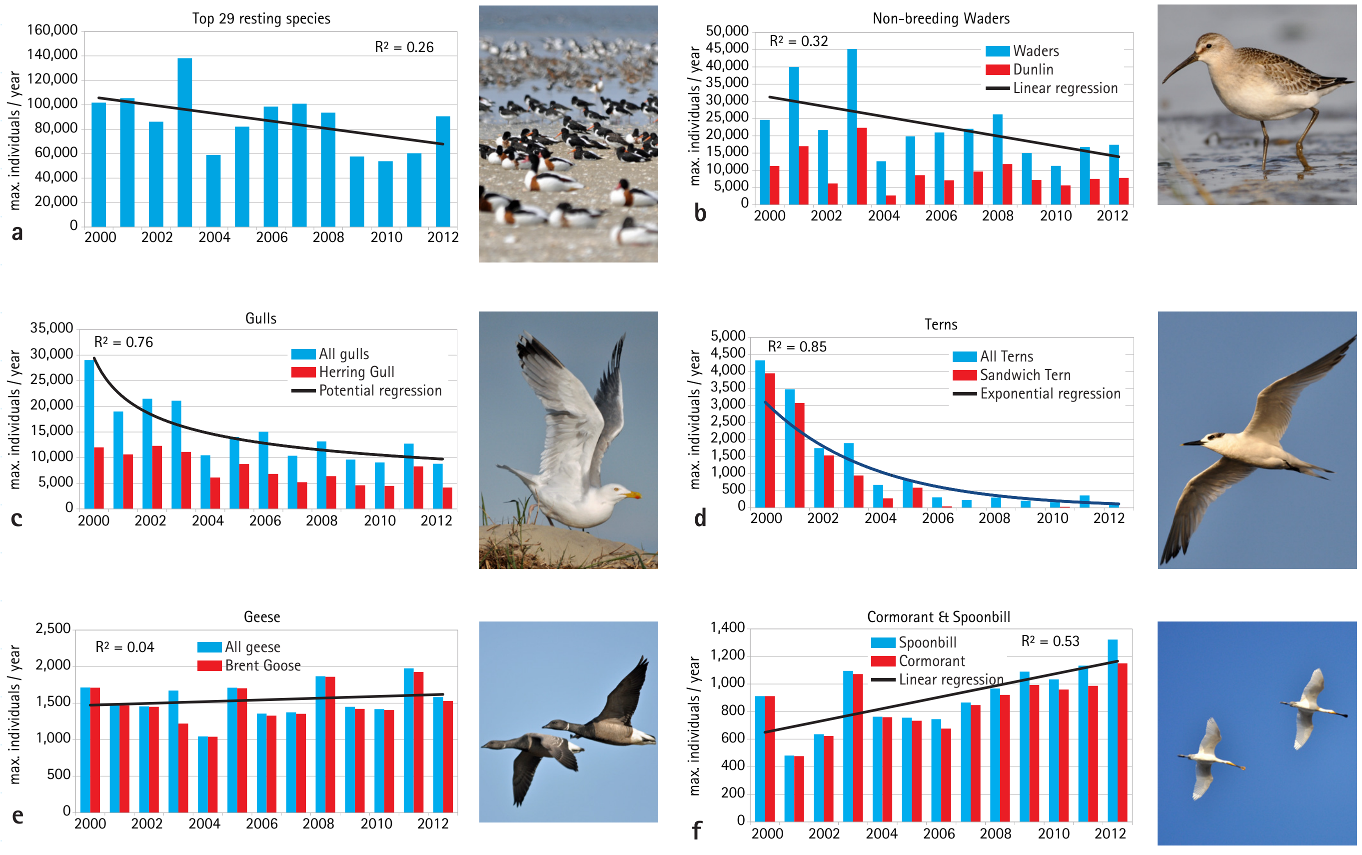


Fig. 5.1: Temporal development of resting birds on Trischen 2000-2012, based on maximal counted numbers for each species and year.

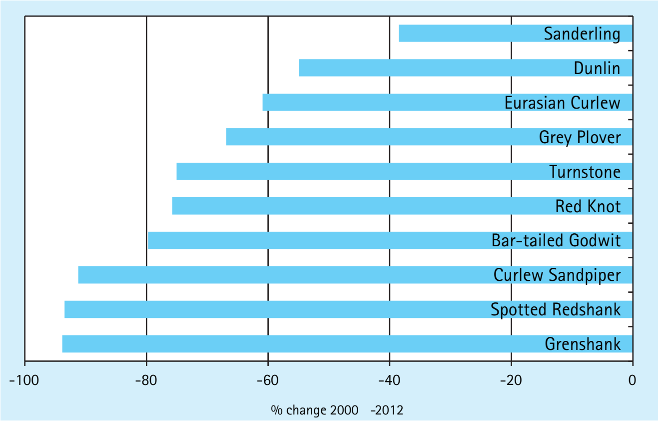


Fig. 5.2: 13-year trend for the 10 most frequent non-breeding waders on Trischen.

just under 60 % (Fig. 5.1b). All 10 wader species show strong negative trends without exception. However, illustrated strong negative trends in gull and tern populations (*c.f.* Fig. 5.1c-d) as well as positive developments of Cormorants and Spoonbills (*c.f.* Fig. 5.1f) are strongly influenced by local breeding populations, and hence are unsuitable to characterize the suitability of Trischen as a resting/feeding area. Finally, the amount of resting (Brent) geese on Trischen appears to have been nearly constant during the past decade (Fig. 5.1e).

Discussion

The decrease in most resting bird species (especially waders) on Trischen has not happened only since the beginning of this millennium (Fig. 5.1 a-b), but is a trend that has been observed over the past 25 years (Mercker 2012; Oppel 2005). However, a local decrease of resting birds on and around Trischen has to be discussed in the context of two distinctly different possible processes: 1) a change in resting bird populations throughout the entire Wadden Sea, and 2) a possible local change in relative "attractiveness" of Trischen as a resting or feeding site, causing local population shifts as opposed to declines across the whole Wadden Sea area. In the following, we will briefly discuss these two possibilities regarding Trischen. Thereby, we will focus on the decline of resting (non-breeding) waders (Fig. 5.1b), representing a typical migrant species complex for Trischen and the Wadden Sea.

Population changes in the entire Wadden Sea

Population declines of water birds within the last two decades have been shown to dominate not only on Trischen, but for most other species and regions of the Wadden Sea as well (Blew and Südbeck 2005; Günther 2009; van Roomen *et al.* 2012). Comparing the trends in the Wadden Sea with corresponding entire flyway populations, van Roomen *et al.* (2012) suggested that changes in resting bird populations are predominantly caused by factors involved in the Wadden Sea ecosystem itself. However, some of these bird population trends do not affect all tidal basins within the Wadden Sea to the same degree but dominate in the German Bight, especially in the regions surrounding Trischen (van Roomen *et al.* 2012). This indicates that responsible factors for these declines are non-homogeneously distributed within the Wadden Sea and that particular factors may lead to a reduced local attractiveness of Trischen and surrounding tidal basins. In the following, we discuss several possible causes.

Local Population shifts

Especially in a highly dynamic ecosystem such as the Wadden Sea, many factors can potentially change the local attractiveness of a feeding/resting/breeding area for birds within a few decades. Examples include geomorphological changes or coastal protection (Schekkerman *et al.* 1994), disturbance due to humans or predators (Lindstrom 1990; Madsen 1998; Smit and Visser 1993), natural succession (Oppel 2005), food availability [*e.g.* influence of invasive alien species (Nehring *et al.* 2009)], eutrophication, fishery or changes in climate/hydrology (Bonter *et al.* 2014; Marencic and de Vlas 2009; Van Eerden *et al.* 2005; van Roomen *et al.* 2012). However, many of these factors can be quickly ruled out for Trischen: *e.g.* it has been recently argued that some of these factors are probably not major influences in the centre of the German Bight, where the strongest resting bird declines have been observed. These factors include declining phytoplankton levels as well as patterns in bivalve stocks, invasive species, temperature and shellfish fisheries, which are not as pronounced in the German Bight – in comparison to Dutch and Danish Wadden Sea (van Roomen *et al.* 2012). Other possible reasons for a decline in resting populations mentioned above have been shown to be either absent or on the decrease during recent decades on Trischen. These include costal management or disturbance due to tourists, ships, low-flying helicopters and aeroplanes (evaluated from Trischenberichte 2000-2013, data not shown). In the following, we will briefly discuss possible remaining causes for resting bird declines on Trischen.

Geomorphology and succession

Trischen is a highly dynamic island continuously changing its size, shape and vegetation (Gettner *et al*. 2003; Kempf *et al*. 2000). However, the total loss of area is 15 % from 2001-2013 (*c.f.* "Island size and location" section) which probably does not influence surrounding resting habitats very much. The same holds for vegetation changes: although the vegetation of Trischen changed considerably during this period (*c.f.* "Vegetation changes" section), most of these changes affect areas only rarely used as resting or feeding sites for waders. Hence, changes in island size and vegetation may have affected resting bird declines to only a small degree, if at all.

Predation

Due to the lack of mammalian predators on Trischen, the only disturbance due to predation takes place by raptors. Especially the Peregrine Falcon (*Falco peregrinus*) is as a breeding bird a regular predator of the island. It has been discussed recently that the increasing number of Peregrine Falcons within the Wadden Sea region may be one cause for decreases in resting waders. Avian raptor densities have been shown to locally influence migrant numbers (van den Hout 2009; Ydenberg *et al*. 2007) and Peregrine Falcon densities within the Wadden Sea may spatially coincide with the recent reductions in resting birds (van Roomen *et al*. 2012). Indeed, the Peregrine Falcon is a relatively new breeding bird on Trischen (since 1999) and has experienced increasingly successful breeding years since then (*c.f.* "Breeding Birds" chapter). Hence, and beside other causes discussed within this section, an increased disturbance regime due to Peregrine Falcons could be a factor negatively influencing the resting bird numbers on Trischen, especially in regards to small waders.

Tidal flats and food availability

The question of changes in local food availability is highly complex, species dependent and due to the lack of corresponding data hard to quantify for small scale island regions. Interestingly, recent studies showed that local population changes within the Wadden Sea could be coupled to the strength of tidal amplitude: regions with large tidal amplitudes (such as the inner part of the German Bight) predominately show negative trends of benthiovorous waterbirds in contrast to regions with small tidal amplitudes, where bird numbers have mainly increased (Laursen *et al*. 2010; van Roomen *et al*. 2012). One hypothesis is that the coarsening of the sediment due to increased hydrodynamic forces in areas of high tidal amplitude could lead to a reduction of the stocks of benthic invertebrates (Dolch and Reise 2010). Since Trischen is situated in a region with high tidal amplitudes, this factor could be linked to its above-averaged population decline. However, biological causes for this relationship are still under discussion (van Roomen *et al*. 2012; van Roomen *et al*, 2012).

Hydrology

Since Trischen is located in the centre of the German Bight, changes in tidal amplitude over time could have an effect on the foraging and resting habitat available to resting waders on and around the island. To further investigate this hypothesis, we calculated annual average high tide deviations from the MHW during the peak of bird migration (1st September - 31st October). However, there appear to be no visible trends over the 14 year study period, ruling out a corresponding correlation with resting bird declines on Trischen.

Summary

In summary, resting birds on Trischen experienced drastic declines across a number of species groups during the study period, with waders being worst affected. Even in comparison to generally declining population trends in the Wadden Sea region, the reductions in resting bird numbers on Trischen are above average. Possible causes are extremely hard to ascertain as the processes involved are large-scale and varied. Causal effects specific to Trischen and immediate surroundings remain vague. Future analysis on benthic prey availability and on predation or disturbance pressure due to falcon activities is needed to arrive at more conclusive answers.

5.2 Birds on migration passage

Shorelines have been shown to have a strong bundling / leading line effects on bird migration (Perdeck 1970), a factor that also holds for the North and Baltic Sea shorelines of Schleswig-Holstein (Koop 2010). Since Trischen is close to the shoreline of the German Bight (ca. 12 km offshore), it is not only resting and feeding species that accumulate during spring and autumn, several other bird species regularly cross the island during migration, such as passerines and geese. The migration of the Barnacle Goose in spring is a particularly impressive spectacle on Trischen, when tens of thousands of geese cross the island within a few days.

In this section we will document and discuss changes in the yearly amount of migrating birds passing Trischen, focusing particularly on passerines and geese.

Methods

Migrating birds on Trischen (mainly passerines and geese) have been regularly counted by the warden, based on calls and sight-observations. In spring and autumn, counts have been performed at least one hour per pentad, less often during the summer months. Between the years 2005-2013 a total of 333,078 migrating birds have been counted within 1,369 hours of observation. All counts included detailed data considering weather/wind, duration of data logging as well as height and direction of passing birds. The project was initiated and standardized within the context of the OAG project “Bird Migration over Schleswig-Holstein”, coordinated by B. Koop.

To visualize the seasonal intensity of bird migration on Trischen, we calculated the bird numbers/hour for each daily decade, averaged over the years 2005-2013 (Fig. 5.3a,c). Temporal trends over the past nine years were plotted by calculating the average number of birds/hour for each season, additionally using regression functions and corresponding coefficients of determination R^2 (Fig. 5.3b,d). As a nine-year period is a relatively short time for data evaluation using this method, averaged values in terms of individuals/hour are consequently not very robust, to the effect that yearly (personal) differences in daily and monthly monitoring (length of time spent counting, time of day, *etc.*) affect these values. However, we assume that these individual differences are averaged out over the considered time period and do not significantly influence evaluated trends.

Results

The seasonal intensity of migrating passerines over Trischen differs distinctly between spring and autumn (Fig. 5.3a). In spring, passerine migration appears to be very weak (with a peak on the 11-12th daily decade) in contrast to the autumn, when migration flux is on average nine times higher, with a maximum of 45 individuals/hour in the 29th daily decade (the last cycle of data collection before the warden leaves the island). However, the average number of counted passerines/hour per season decreased during the past decade (Fig. 5.3b). The most common passerine is the Meadow Pipit, constituting more

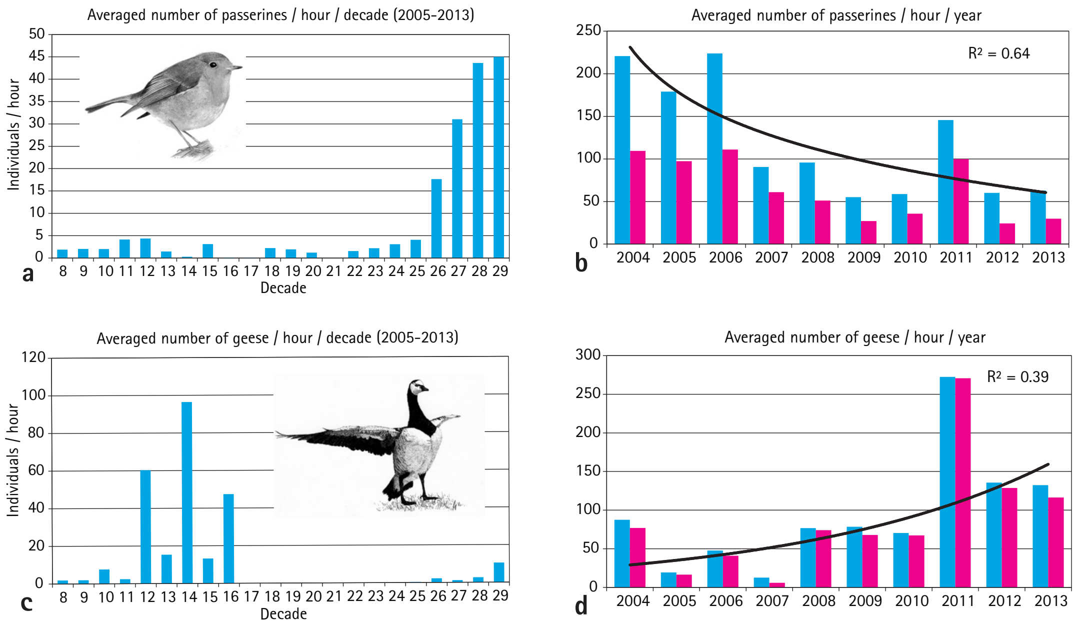


Fig. 5.3: Saisonal and temporal development of migrating passerines (a-b) and geese (c-d) over Trischen.

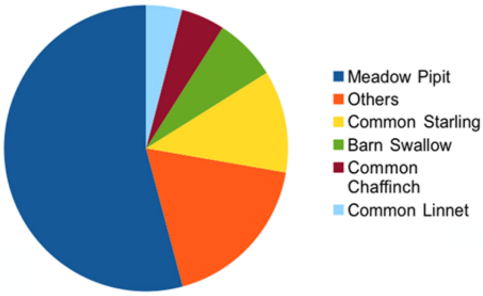


Fig. 5.4: Occurrence (%) of main passerine species on migration over Trischen 2005-2013.

than 50% of migrating passerines on Trischen, followed by the Common Starling and the Barn Swallow (Fig. 5.4).

In contrast to passerines, the main concentration of migrating geese occurs during spring on Trischen (Fig. 5.3c). The average number of counted geese / hour per season has increased during the past nine years (Fig. 5.3c). Interestingly, geese migration during spring shows three distinct different peaks (12th, 14th and 16th daily decade).

Discussion

The significantly more pronounced migration of passerines in autumn compared to spring (Fig. 5.4a) is a typical phenomenon observed on the west coast of Germany. The Meadow Pipit – the most common migrating passerine on Trischen – constitutes a typical example. Most of them breed in fell regions of Scandinavia (Hagemeijer and Blair 1997) and especially Norwegian populations are assumed to use the German North Sea coastline as a leading line. This results in higher autumn concentrations at the western compared to the eastern coastline of Schleswig-Holstein (Koop 2002). However, during spring migration, this ratio is the other way round, since the birds favour other locations, *e.g.* the eastern (Baltic Sea) shoreline of Schleswig-Holstein (Koop 2002). Furthermore, the enhanced autumn migration on Trischen is additionally influenced by the typically higher amount of juvenile birds during autumn (Hüppop and Hüppop 2007).

The decline of passing passerines on Trischen (Fig. 5.4b) could have several causes, such as changes in corresponding (mainly Scandinavian) breeding populations and a local shift of migrants, *e.g.* due to changes in migration routes or drifting intensity.

Although the overall Meadow Pipit population shows on average a weak decline, at least from 1990-2003, its Norwegian breeding populations were stable (BirdLife International 2014). Furthermore, the number of migrating Meadow Pipits/hour over Schleswig-Holstein during the autumn migration (averaged over 2005-2012) is nearly constant (evaluated from data published in Koop 2012). Hence, declines in counted Meadow Pipits on Trischen must be explained by other factors that may be shifting migration routes away from Trischen. An increasing amount of westerly winds in relation to easterly winds would be a likely reason, since wind from the east probably blows the birds away from the coastline and onto Trischen, located to the the west. Similar observations have been recently described for different raptor species on the (far more westerly) island Helgoland (Dierschke 2001).

Indeed, our calculations show that western winds increasingly prevail in the period under consideration on Trischen. Certainly, a yearly correlation between D_wind and the intensity of passerine migration on Trischen is not given. However, wind direction is only one of many different possible influences on migration routes (Berthold 2000; Koop 2002) and a deeper analysis of possible reasons is beyond the scope of this paper.

The impressive amount of Barnacle Geese crossing Trischen in spring is caused by the fact that Trischen is situated directly on their flyway route and close to the Eider estuary, a gateway crossing Schleswig-Holstein (Koop 2002). Furthermore, the three distinct "migration waves" in spring (Fig. 5.4c) are most likely connected to differences in resting areas and age patterns of arriving geese (Koop, oral communication). The low numbers of migrating geese in autumn are based on the fact than Barnacle geese usually do not leave the west coast of Schleswig-Holstein until November (Koop, oral communication), when the warden has already left Trischen.

The average increase of Barnacle Geese crossing Trischen (Fig. 5.4d) reflects a general increase in Barnacle Goose breeding population. The numbers of migrating Barnacle Geese over the entire Schleswig-Holstein have increased hugely (evaluated from autumn migration data 2005-2012 published in Koop 2012), in line with other breeding populations in several regions of western Europe (Fox *et al.* 2010; Van Eerden *et al.* 2005). Interestingly, this trend is also reflected in the breeding pair numbers on Trischen.

Acknowledgements

The data were collected by different people. We acknowledge their long-term help in field work, especially the wardens of Trischen and the colleagues from the LKN for performing the levelling of the permanent plots. Bernd Koop and Klaus Günther gave valuable comments to improve the manuscript.

Literature

Arens, S.M., Slings, Q.L., Geelen, L.H.W.T., Hagen, H.G.J.M., 2013. Restoration of Dune Mobility in The Netherlands, In Restoration of Coastal Dunes. eds M.L. Martínez, J.B. Gallego-Fernández, P.A. Hesp, pp. 107-124. Springer Berlin Heidelberg.

Baer, J., 2014. Native ant species Myrmica rubra affect Herring Gull (Larus argentatus) and Lesser Black-backed Gull (Larus fucus) chick survival at a North Sea island. Seabirds 27, 87-97.

Bartholdy, A.T., Bartholdy, J., Kroon, A., 2010. Salt marsh stability and patterns of sedimentation across a backbarrier platform. Marine Geology.

Becker, P., Brenninkmeijer, A., Frank, D., Stienen, E.W.M., Todt, P., 1997. The reproductive sucess of Common Terns as an important tool for monitoring the state of the Wadden Sea. Wadden Sea Newletter 1997-1, 37–41.

Becker, P.H., Cifuentes, J.M., 2004. Contaminants in bird eggs. Wadden Sea Quality Status Report, 123-134.

Becker, P.H., Erdelen, M., 1987. Die Bestandsentwicklung von Brutvögeln an der deutschen Nordseeküste 1950-1979. J. Orn 128, 1–32.

Berthold, P., 2000. Vogelzug - eine aktuelle Gesamtübersicht. Wiss. Buchges., Darmstadt.

Bertness, M.D., Pennings, S.C., 2000. Spatial variation in process and pattern in salt marsh plant communities in eastern North America, In Concepts and controversies in tidal marsh ecology. pp. 39-57. Springer.

Bezzel, E., 1985. Kompendium der Vögel Mitteleuropas.

BirdLife International, 2014. Species Factsheet: Anthus pratensis Population 19 (2000): 11.

Blew, J.K.G., Südbeck, P., 2005. Bestandsertwicklung der im deutschen Wattenmeer rastenden Wat- und Wasservögel von 1987/1988 bis 2001/2002. Vogelwelt 126, 99–125.

Bockelmann, A.-C., Neuhaus, R., 1999. Competitive exclusion of *Elymus athericus* from a high-stress habitat in a European salt marsh. Journal of Ecology 87, 503–513.

Bonter, D., MacLean, S., Shah, S., Moglia, M., 2014. Storm-induced shifts in optimal nesting sites: a potential effect of climate change. Journal of Ornithology, 1-8.

Cahoon, D.R., French, J.R., Spencer, T., Reed, D., Möller, I., 2000. Vertical accretion versus elevational adjustment in UK saltmarshes: an evaluation of alternative methodologies. Geological Society, London, Special Publications 175, 223-238.

Camphuysen, C., Gronert, A., 2012. Apparent survival and fecundity of sympatric Lesser Black-backed Gulls and Herring Gulls with contrasting population trends. Ardea 100, 113-122.

Camphuysen, C.J., 1993. Feeding opportunities for seabirds in beamtrawl fisheries: a pilot study. Sula 7, 81-104.

Camphuysen, C.J., 1995. Herring gull Larus argentatus and Lesser Black-backed gull Larus fuscus feeding at fishing vessels in the breeding season: competition versus efficient flying. Ardea 83, 365–380.

Camphuysen, C.J., 2013. A historical ecology of two closely related gull species (Laridae) - Multiple adaptations to a man-made environment., p. 421. University Groningen, Groningen.

Christiansen, C., Aagaard, T., Bartholdy, J., Christiansen, M., Nielsen, J., Nielsen, N., Pedersen, J.B.T., N., V., 2004. Total sediment budget of a transgressive barrier-spit, Skallingen, SW Denmark: A review. Danish Journal of Geography 104, 107-126.

Davy, A.J., Brown, M.J.H., Mossman, H.L., Grant, A., 2011. Colonization of a newly developing salt marsh: disentangling independent effects of elevation and redox potential on halophytes. Journal of Ecology 99, 1350-1357.

De Jong, B., Keijsers, J.G.S., Riksen, M.J.P.M., Krol, J., Slim, P.A., 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.

DeFisher, L.E., Bonter, D.N., 2013. Effects of Invasive European Fire Ants (Myrmica rubra) on Herring Gull (Larus argentatus) Reproduction. PLoS ONE 8, e64185.

Deutschländer, T., Friedrich, K., Haeseler, S., Lebfebvre, C., 2013. Orkantief XAVER über Nordeuropa vom 5. bis 7. Dezember 2013, p. 19.

Dierschke, V., 2001. Das Vorkommen von Greifvögeln auf Helgoland: regulärer Zug oder Winddrift? Vogelwelt 122, 247-256.

Dijkema, K.S., 1987. Geography of salt marshes in Europe. Zeitschrift für Geomorphologie 31, 489-499.

Dijkema, K.S., 1997. Impact prognosis for salt marshes from subsidence by gas extraction in the Wadden Sea. J. Coastal Res 13, 1294–1304.

Dirksen, J., 1968. Die wichtigsten Pflanzengesellschaften der Insel Trischen. Natur und Heimat 28, 184–190.

Doing, H., 1983. Geomorphology and soil of dunes., In Ecology of the Wadden Sea. ed. W.J. Wolff, pp. 12-26. BalkmeA, Rotterdam.

Dolch, T., Reise, K., 2010. Long-term displacement of intertidal seagrass and mussel beds by expanding large sandy bedforms in the northern Wadden Sea. Journal of Sea Research 63, 93-101.

Ellis, J.C., 2005. Marine Birds on Land: A Review of Plant Biomass, Species Richness, and Community Composition in Seabird Colonies. Plant Ecology 181, 227-241.

Esri, 2009. ArcGIS Desktop: Release 9. Environmental Systems Research Institute.

Exo, K.-M., Becker, P.H., Scheufler, H., Steifel, A., Thorup, O., Hötker, H., Stock, M., Südbeck, P., 1996. Empfehlungen zum Bruterfolgsmonitoring bei Küstenvögeln. Vogelwelt 117, 287–293.

Feare, C., 1999. Ants take over from rats on Bird Island, Seychelles. Bird Conservation International 9, 95-96.

Finney, S., Harris, M., Keller, L., Elston, D., Monaghan, P., Wanless, S., 2003. Reducing the density of breeding gulls influences the pattern of recruitment of immature Atlantic puffins Fratercula arctica to a breeding colony. Journal of Applied Ecology 40, 545-552.

Fox, A.D., Ebbinge, B.S., Mitchell, C., Heinicke, T., Aarvak, T., Colhoun, K., Clausen, P., Dereliev, S., Faragó, S., Koffijberg, K., 2010. Current estimates of goose population sizes in western Europe, a gap analysis and an assessment of trends. Ornis Svecica 20, 115-127.

French, P.W., 2006. Managed realignment - the developing story of a comparatively new approach to soft engineering. Estuarine, Coastal and Shelf Science 67, 409–423.

Garthe, S., Camphuysen, K., Furness, R., 1996. Amounts of discards by commercial fisheries and their significance as food for seabirds in the North Sea. Marine ecology progress series. Oldendorf 136, 1-11.

Garthe, S., Flore, B.-O., Hälterlein, B., Hüppop, O., Kubetzki, U., Südbeck, P., 2000. Brutbestandsentwicklung der Mowen (Laridae) an der deutschen Nordseekuste in der zweiten Halfte des 20 Jahrhunderts. Vogelwelt 121, 1-13.

Gerdes, G., Krumbein, W.E., Reineck, H.-E., Ziegler, W., 1987. Mellum: Portrait einer Insel. W. Kramer.

Gettner, S., Heinzel, K., Dierssen, K., 2003. Kartierung der realen Vegetation der Vorländer von St. Peter-Ording, Amrum, Sylt, Föhr, Pellworm, Nordstrandischmoor, Hooge und Gröde sowie der Insel Trsichen und der Halligen Habel, Südfall, Süderoog und Norderoog.

Göhren, H., 1975. Zur Dynamik und Morphologie der hohen Sandbänke im Wattenmeer zwischen Jade und Eider. Küste 27, 28-49.

Günther, K., 2009. Rastvogel-Monitoring im Schleswig-Holsteinischen Wattenmeer, 1987-2008., In unveröffentlichter Bericht. Husum.

Haeseler, S., Lefebvre, C., 2013. Orkantief CHRISTIAN am 28. Oktober 2013, p. 20.

Hagemeijer, W.J., Blair, M.J., 1997. The EBCC atlas of European breeding birds: their distribution and abundance. Poyser London.

Hälterlein, B., Fleet, D.M., Henneberg, H.R., Mennebäck, T., Rasmussen, L.M., Südbec, k.P., Thorup, O., Vogel, R., 1995. Anleitung zur Brutbestandserfassung von Küstenvögeln im Wattenmeerbereich. Seevögel 16, 3–24.

Hellwig, U., Körber, P., Umland, J., Krüger-Hellwig, L., 2014. Dynamic patterns on the Scharhörn-highsand. Wadden Sea Ecosystem.

Holway, D.A., Lach, L., Suarez, A.V., Tsutsui, N.D., Case, T.J., 2002. The causes and consequences of ant invasions. Annual review of ecology and systematics 33, 181-233.

Hötker, H., Schrader, S., Schwemmer, P., Oberdiek, N., Blew, J., 2010a. Status, threats and conservation of birds in the German Wadden Sea, p. 116, Berlin.

Hughes, R.G., 2004. Climate change and loss of saltmarshes: consequences for birds. Ibis (Suppl.) 146, 21–28.

Hüppop, K., Hüppop, O., 2007. Atlas zur Vogelberingung auf Helgoland: Teil 4: Fangzahlen im Fanggarten von 1960 bis 2004. Vogelwarte 45, 145-207.

IPCC, 2013. Climate Change 2013 - The physical science basis - Summary for Policymakers., Bern.

Irons, D.B., Svoboda, M., Gill, M., Petersen, A., 2011. Seabird information Network (SIN): Concept Paper CAFFs Circumpolar Seabird expert group (CBird). In CAFF Strategy Series Report. Akureyri.

Jensen, J., Mudersbach, C., 2014a. Zeitliche Änderungen in den Wasserstandszeitreihen an den Deutschen Küsten., In Klimaänderung und Küstenschutz. eds G. Gönnert, H. Grassl, D. Kelletat, H. Kunz, B. Probst, H. von Storch, J. Sündermann, pp. 1-15. Proc. Uni Hamburg, Hamburg.

Jensen, J., Wahl, T., Frank, T., 2010. Improved estimates of mean sea level changes in the south-eastern North Sea since 1843. Proc. Coastal Engineering 2010.

Kempf, N., Tod, P., Hälterlein, B., Eskildsen, K., 2000. Trischen - Perle im Wattenmeer. Schriftenreihe des Nationalparks Schleswig-Holsteinisches Wattenmeer 13, 22.

Kiehl, K., Schröder, H., Stock, M., 2007. Long-term vegetation dynamics after land-use changes in Wadden Sea Salt marshes. Coastline Report 7, 17-24.

Kilpi, M., Öst, M., 1998. Reduced availability of refuse and breeding output in a herring gull (Larus argentatus) colony, In Annales Zoologici Fennici. pp. 37-42. Helsinki: Suomen Biologian Seura Vanamo, 1964-.

Koffijberg, K., Dijksen, L., Hälterlein, B., Laursen, K., Potel, P., Südbeck, P., 2006. Breeding Birds in the Wadden Sea in 2001 - Results of the total survey in 2001 and trends in numbers between 1991-2001. CWSS, Wilhelmshaven.

Koffijberg, K., Dijksen, L., Hälterlein, B., Laursen, K., Potel, P., Schrader, S., 2009. Wadden Sea Quality Status Report - Breeding birds. Wadden Sea Ecosystem 25, 15.

Koffijberg, K., Schrader, S., 2010. Monitoring breeding success of coastal birds in the Wadden Sea - Methodological guidelines and field work mannual., In Unpublished manuscript on behalf of the JMBB joint monitoring.

Koffijberg, K., Südbeck, P., 2006. Breeding Birds in the Wadden Sea in 2001 - Results of the total survey in 2001 and trends in numbers between 1991-2001. CWSS, Wilhelmshaven.

König, D., 1948. Spartina townsendii an der Westküste von Schleswig-Holstein. Planta 36, 34–70.

Koop, B., 2002. Vogelzug über Schleswig-Holstein. Räumlicher und zeitlicher Ablauf des sichtbaren Vogelzugs nach archivierten Daten 1950-2002, In Unveröffentlichtes Manuskript. Kiel.

Koop, B., 2010. Schleswig-Holstein: Kreuzung internationaler Zugwege - die Erfassung von Zugvögeln. Falke 57, 51-54.

Koop, B., 2012. Vogelzug über Schleswig-Holstein 2012, In unveröffentliches Manuskript. Kiel.

Laursen, K., Blew, J., Eskildsen, K., Günther, K., Hälterlein, B., Kleefstra, R., Lüerßen, G., Potel, P., Schrader, S., 2010. Migratory Waterbirds in the Wadden Sea 1987-2008. Trend, Phenology, Distribution and Climate Aspects. Wadden Sea Ecosystem 30, 5-165.

Liebezeit, G., Wehrmann, A., Hecker, N., Czeck, R., 2013. Die Kachelotplate - Einblicke in die Entstehung von Barriereinseln. Natur und Umweltschutz 12, 7-17.

Lindstrom, Å., 1990. The role of predation risk in stopover habitat selection in migrating bramblings, Fringilla montifringilla. Behavioral Ecology 1, 102-106.

Lockley, T.C., 1995. Effect of imported fire ant predation on a population of the Least Tern: an endangered species. Southwestern Entomologist 20, 53-60.

Londo, G., 1976. The decimal scale for relevés of permanent quadrats. Vegetation 33, 61-64.

Madsen, J., 1998. Changing trade-offs between predation risk and food intake. Norsk Polarinst. Skrifter 200, 303–311.

Marencic, H., de Vlas, J., 2009. Wadden Sea Quality Status Report 2009. Wadden Sea Ecosystem 25.

Martin, T.E., 1987. Food as a limit on breeding birds: a life-history perspective. Annual review of ecology and systematics, 453-487.

McGlynn, T.P., 1999. The worldwide transfer of ants: geographical distribution and ecological invasions. Journal of Biogeography 26, 535-548.

Meltofte, H., Blew, J., Frikke, J., Rösner, H.-U., Smit, C.J., 1994. Numbers and distribution of waterbirds in the Wadden Sea. IWRB Publication 34. Wader Study Group Bulletin 74, 1–192.

Mercker, M., Baer, J., 2013. Räuber-Beute-Interaktionen als mögliche Erklärung für aktuelle Brutbestandsabnahmen von See- und Küstenvögeln am Beispiel der Wattenmeerinsel Trischen. Vogelwelt 134, 115-127.

Nehring, S., Reise, K., Dankers, N., Kristensen, P.S., 2009. Wadden Sea Quality Status Report 2009 - Alien species. Wadden Sea Ecosystem 25, 3-28.

Nielsen, N., Nielsen, J., 2006. Development of a washover fan on a transgressive barrier, Skallingen, Denmark. Journal of Coastal Research, Special, 107-111.

Nisbet, I.C., Welton, M.J., 1984. Seasonal variations in breeding success of Common Terns: consequences of predation. Condor, 53-60.

Nolte, S., Koppenaal, E.C., Esselink, P., Dijkema, K.S., Schuerch, M., Groot, A.V., Bakker, J.P., Temmerman, S., 2013. Measuring sedimentation in tidal marshes: a review on methods and their applicability in biogeomorphological studies. Journal of Coastal Conservation, 1-25.

Oltmanns, B., 1996. Untersuchungen zu Vegetationsveränderungen auf der Insel Memmert. Hamburger Vegetationsgeographische Mitteilungen, H 9, 52–107.

Oost, A.P., Hoekstra, P., Wiersma, A., Flemming, B., Lammerts, E.J., Pejrup, M., Hofstede, J., van der Valk, B., Kiden, P., Bartholdy, J., van der Berg, M.W., Vos, P.C., de Vries, S., Wang, Z.B., 2012. Barrier island management: Lessons from the past and directions for the future. Ocean & Coastal Management 68, 18-38.

Oppel, S., 2005. Long-Term Changes of a Coastal Bird Breeding Community on a Small Island – Does Natural Succession Compromise Conservation Values? Biodiversity and Conservation 14, 3407-3422.

Padlat, M., Stock, M., Dolch, T., 2014. Norderoogsand. Wadden Sea Ecosystem this issue.

Perdeck, A.C., 1970. Standard direction of scandinavian Chaffinch during autumn migration throughout its area of passage. Ardea 58, 142-&.

Petersen, J., Dassau, O., Dauck, H.-P., Janinhoff, N., 2010. Applied vegetation mapping of large-scale areas based on high resolution aerial photographs - a combined method of remote sensing, GIS and near comprehensive field verification. Wadden Sea Ecosystem 26, 75-79.

Petersen, J., Dassau, O., Dauck, H.P., Janinhoff, N., 2008. Angewandte Vegetationskartierung großräumiger Projektgebiete auf Basis digitaler Luftbilddaten - eine kombinierte Methode aus Fernerkundung, GIS und nahezuh flächendeckender Verifizierung im Gelände., In Angewandte Geoinformatik 2008 - AGIT-Symposium eds S. Strobel, T. Blaschke, G. Griesebner, pp. 584-594. Wichmann Verlag, Salzburg.

Petersen, J., Kers, B., Stock, M., 2014. TMAP-Typology of coastal vegetation in the Wadden Sea area. Wadden Sea Ecosystem (in press).

Philipps, B.M., 2011. Trischenbericht 2011, p. 206. NABU Schleswig-Holstein.

Plentovich, S., Hebshi, A., Conant, S., 2009. Detrimental effects of two widespread invasive ant species on weight and survival of colonial nesting seabirds in the Hawaiian Islands. Biological Invasions 11, 289-298.

Pott, R., Peters, M., 1997. Dünendurchbrüche und ihre Bedeutung für die Vegetations- und Landschaftsdynamik. Raumzeitliche Diversität am Beispiel der Nordseeinsel Norderney. - Naturschutz und Landschaftsplanung 29, 69–74.

Rabitsch, W., 2011. The hitchhiker's guide to alien ant invasions. BioControl 56, 551-572.

Redfield, A.C., 1965. Ontogeny of a salt marsh estuary. Science 147, 50-55.

Ricklefs, K., Asp Neto, N., 2005. Geology and Morphodynamics of a Tidal Flat Area Along the German North Sea Coast. Die Küste 69, 93-127.

Runge, F., 1977. Die Vegetation der Langeooger und Baltrumer Silbermöwenkolonien., In Berichte der Internationalen Symposien der internationalen Vereinigung für Vegetationskunde., pp. 295-307. J. Cramer.

Safina, C., Burger, J., Gochfeld, M., 1994. Occurrence of Ants in Nests of Roseate Terns and Common Terns at Cedar Beach, New York. Colonial Waterbirds, 91-94.

Schekkerman, H., Meininger, P.L., Meire, P.M., 1994. Changes in the waterbird populations of the Oosterschelde (SW Netherlands) as a result of large-scale coastal engineering works. Hydrobiologia 282, 509-524.

Schulz, H., 1947. Die Welt der Seevögel - Ein Führer durch die Vogelbrutstätten der deutschen Küsten. Verlag Anton Lettenbauer, Hamburg.

Schwabe, A., 1972. Vegetationsuntersuchungen in den Salzwiesen der Nordseeinsel Trischen. Abh. Landesmuseum Naturkd. Münster 34, 9–22.

Seifert, B., 2007. Die Ameisen Mittel-und Nordeuropas. Lutra Verlags-und Vertriebsgesellschaft Tauer.

Siefert, W., Miessner, F., Richter, H.-H., Taubert, A., Wieland, P., 1980. Die Strömungsverhältnisse vor der Westküste Schleswig-Holsteins. Ergebnisse eines KFKI-Messprogramms. Küste 35.

Simas, T., Nunes, J., Ferreira, J., 2001. Effects of global climate change on coastal salt marshes. Ecological Modelling 139, 1-15.

Smit, C.J., Visser, G.J.M., 1993. Effects of disturbance on shorebirds: a summary of existing knowledge from the Dutch Wadden Sea and Delta area. WSG Bull 68, 6–19.

Spaans, A.L., 1998. The Herring Gull Larus argentatus as a breeding bird in the Netherlands during the 20th century. Sula 12, 183-196.

Spalke, J., 2009. Trischenbericht 2009, p. 201.

SPSS, 2009. PASW Statistics for Windows, Version 18.0. SPSS.

Ssymank, A., Dankers, N., 1996. II. Red list of Biotopes and Biotop Complexes of the Wadden Sea Area. Helgoländer Meeresunters 50, 9-37.

Stock, M., 2011. Patterns in surface elevation change across a temperate salt marsh platform in relation to sea level rise. Coastline Report 17, 33-48.

Stock, M., 2012a. TMAP Wadden Sea Sedimentation Database, In Vegetation databases for the 21st century. eds J. Dengler, J. Oldeland, F. Jansen, M. Chytry, J. Ewald, M. Finckh, F. Glöckler, G. Lopez-Gonzales, R.K. Peet, J.H.J. Schaminée, p. 372. Biodiversity and Ecology.

Stock, M., 2012b. TMAP Wadden Sea Vegetation Database., In Vegetation databases for the 21st century. eds J. Dengler, J. Oldeland, F. Jansen, M. Chytry, J. Ewald, M. Finckh, F. Glöckler, G. Lopez-Gonzales, R.K. Peet, J.H.J. Schaminée, p. 373. Biodiversity and Ecology.

Stock, M., Braun, M., Fleet, D.M., Hellfritz, K.-P., Hälterlein, B., Knopp, L., Levsen, E.-J., 2013. Norderoogsand - vom Sand zur Insel? Falke 60, 321-324.

Suchrow, S., Pohlmann, N., Stock, M., Jensen, K., 2012. Long-term surface elevation changes in German North Sea salt marshes. Estuarine, Coastal and Shelf Science 98, 71-83.

Südbeck, P., Hälterlein, B., Knief, W., Köppen, U., 2000. Bestandsentwicklung von Fluß- Sterna hirundo und Küstenseeschwalben Sterna paradisaea an den deutschen Küsten. Vogelwelt 119, 147-163.

Trende, F., 2003. Versunkene Welt und literarische Landschaft: Erinnerungen an die Insel Trischen. Schleswig-Holstein 3, 1-5.

Valéry, L., Bouchard, V., Lefeuvre, J.-C., 2004. Impact of the invasive native species *Elymus athericus* on carbon pools in a salt marsh. Wetlands 24, 268-276.

Van De Pol, M., Ens, B.J., Heg, D., Brouwer, L., Krol, J., Maier, M., Exo, K.-M., Oosterbeek, K., Lok, T., Eising, C.M., Koffijberg, K., 2010. Do changes in the frequency, magnitude and timing of extreme climatic events threaten the population viability of coastal birds? Journal of Applied Ecology 47, 720-730.

van den Hout, P., 2009. Mortality is the tip of an iceberg of fear: peregrins Falco peregrinus and shorebirds in the Wadden Sea. Limosa 82, 122-133.

van Duin, W.E., Dijkema, K., Zegers, J., 1997. Verandering in bodemhoogte (opslipping. erosie en inklink) in de Peazemerlaan. IBN-Rapport 326, 104 p.

Van Eerden, M.R., Drent, R.H., Stahl, J., Bakker, J.P., 2005. Connecting seas: western Palaearctic continental flyway for water birds in the perspective of changing land use and climate. Global Change Biology 11, 894-908.

van Roomen, M., Laursen, K., van Turnhout, C., van Winden, E., Blew, J., Eskildsen, K., Günther, K., Hälterlein, B., Kleefstra, R., Potel, P., Schrader, S., Luerssen, G., Ens, B.J., 2012. Signals from the Wadden sea: Population declines dominate among waterbirds depending on intertidal mudflats. Ocean & Coastal Management 68, 79-88.

Van Wijnen, H., Bakker, J., 1999. Nitrogen and phosphorus limitation in a coastal barrier salt marsh: the implications for vegetation succession. Journal of Ecology 87, 265-272.

van Wijnen, H.J., Bakker, J.P., 1997. Nitrogen accumulation and plant species replacement in three salt marsh systems in the Wadden Sea. J. Coastal Conservation 3, 19–26.

Veeneklaas, R.M., Dijkema, K.S., Hecker, N., Bakker, J.P., 2013a. Spatio-temporal dynamics of the invasive species Elytrigia atherica on natural salt marshes. Applied Veg. Science 16, 202-216.

Veeneklaas, R.M., Dijkema, K.S., Stock, M., Bakker, J.P., 2013b. Elytrigia atherica invasion of mainland marshes depends on abiotics and management. Journal of Coastal Conservation.

Vidal, E., Medail, F., Tatoni, T., Roche, P., Vidal, P., 1998. Impact of gull colonies on the flora of the Riou archipelago (Mediterranean islands of south-east France). Biological Conservation 84, 235-243.

Wahl, T., Jensen, J., Frank, T., Haigh, I., 2011. Improved estimates of mean sea level changes in the German Bight over the last 166 years. Ocean Dynamics 61, 701-715.

Walter, U., 1997 Quantitative analysis of discards from brown shrimp trawlers in the coastal area of the East Frisian islands. Archive of Fisheries and Marine Research 45, 61-76.

Walter, U., Becker, P.H., 1997. Occurence and consumption of seabirds scavening on shrimp trawler discard in the Wadden Sea. ICES J. Mar.. Sci 54, 684–694.

Wanner, A., Suchrow, S., Kiehl, K., Meyer, W., Pohlmann, N., Stock, M., Jensen, K., 2014. Scale matters: Impact of management regime on plant species richness and vegetation type diversity in Wadden Sea salt marshes. Agriculture, Ecosystems & Environment 182, 69-79.

Wehrmann, A., Schwartz, M., Hecker, N., Liebezeit, G., 2014. Initial barrier island evolution (Kachelotplate, Central Wadden Sea): sediment-vegetation interaction. Wadden Sea Ecosystem this issue.

Wetterer, J.K., Radchenko, A.G., 2011. Worldwide spread of the ruby ant, Myrmica rubra (Hymenoptera: Formicidae). Myrmecological News 14, 87-96.

Wieland, P., 2000. Trischen - die Geschichte einer alluvialen Insel im Dithmarscher Wattenmeer. Küste 62, 101–140.

Wieland, T., von Bargen, U., 2008. Großräumige Kompensation an der Unterweser - Ausführungsplanung für den 4. Bauabschnitt des Contaiernterminals CT4 im Weser-Ästuar bei Bremerhaven. Naturschutz und Landschaftsplanung 40, 393-402.

Wilkens, J., Mayerle, R., 2005. Morphodynamic Response to Natural and Anthropogenic Influences in the Dithmarschen Bight. Die Küste, 311-337.

Wisskirchen, R., Haeupler, H., 1998. Standardliste der Farn- und Blütenpflanzen Deutschlands. Ulmer.

Wohlenberg, E., 1950. Entstehung und Untergang der Insel Trischen. Mitteilungen der Geografischen Gesellschaft in Hamburg. 49, 158-187.

Ydenberg, R.C., Butler, R.W., Lank, D.B., 2007. Effects of predator landscapes on the evolutionary ecology of routing, timing and molt by long-distance migrants. Journal of Avian Biology 38, 523-529.

Addresses

Dr. Martin Stock, The Schleswig-Holstein Agency for Coastal
Defence, National Park and Marine Conservation, National
Park Authority, Schlossgarten 1, 25832 Tönning.
martin.stock@lkn.landsh.de

Julia Baer, BioConsult SH, Schobüller Str. 36, 25813 Husum.
j.baer@bioconsult-sh.de

Dr. Moritz Mercker, Universität Heidelberg, Institut für
Angewandte Mathematik, AG Marciniak-Czochra, BioQuant,
INF 267, D_69120 Heidelberg.
mmercker_bioscience@gmx.de

An emerging island in the Wadden Sea – the spatial past and present of a sandy barrier

Moritz Padlat

An emerging island in the Wadden Sea – the spatial past and present of a sandy barrier

Abstract

Norderoogsand is a supratidal barrier sandbank on the western side of the central North Frisian Wadden Sea. It shelters the back barrier tidal flats from the open North Sea and is a valuable, remote habitat for numerous sea birds and a resting place for large groups of seals. The sandbank covers an area of 8.5 km² and is around 5.3 km long and 2.5 km wide. Reconstructed coastlines show that Norderoogsand is highly dynamic and had retreated some 1050 m in a landward, eastern direction from 1947 to 2010. The landward rollover of Norderoogsand is due to its exposure to wind, waves/currents, the tidal cycle and a rising sea level. It has constantly reshaped, yet retained a stable base contour as well as a constant base area. Volumetric measurements from 2001 to 2010 show that area and volume of Norderoogsand have developed proportionally. Additionally to the landward retreat Norderoogsand has rotated 18.5 degrees clockwise between 1947 and 2010. The erosion and sedimentation on the sandbank are governed by erosional processes on the seaward side and washover and aeolian transport of sediments in an easterly direction across the sandbank. Sediments are redistributed internally.

In the early 2000s a dune island emerged in the very north of Norderoogsand. Starting with the formation of small embryonic dunes, it has developed into a coherent system of dunes. The dune complex has become densely vegetated with dune vegetation and salt marshes starting to form in the shelter of the dune bow. The island shows several characteristics of a barrier island and its dunes reach 3.5 m above the mean high water level. In recent years a stable dune structure has formed on the island, making it a persistent new structure in the Central North Frisian Wadden Sea.

Introduction

The Wadden Sea, stretching along the coast of Denmark, Germany and The Netherlands, is the world´s largest coherent area of tidal flats. Its sand- and mud-flats form the near-shore area of the shelf coast within the German Bight. Around 500 km of coast are comprised of this unique ecosystem with a total area of around 4,700 km² of tidal flats and a total area of around 9,700 km². The Wadden Sea is the sheltered habitat for an estimated 10,000 different species of phototrophic plants, macrofungi and animals (Reise *et al.*, 2010; CWSS, 2008). In the steady cycle of high tide and low tide, the tidal flats are exposed and again covered with water twice a day. Within the German borders, the Wadden Sea is protected as a national park and as a UNESCO World Heritage Site. Each of the federal states bordering the Wadden Sea governs the respective area along its coast. The North Frisian Wadden Sea lies within the federal state of Schleswig-Holstein and reaches from the German-Danish border in the north to the Eiderstedt peninsula in the south (Fig. 1). Within this area several small and bigger islands characterize the coastal area. On the seaward outer rim of the tidal flats a series of barrier islands and sandy barriers separates the open North Sea from the back-barrier tidal flats.

The supratidal barriers and islands shelter the tidal flats and the Wadden Sea and diminish the energy of incoming waves from the open North Sea. The barriers are highly dynamic and are being shaped and altered by waves and currents, the tidal influence and the wind (Hayes 1979; Ehlers, 1988; Tillmann *et al.* 2013). There are three barriers in the central North Frisian Wadden Sea. Japsand, westerly to the island of Hooge, Norderoogsand, westerly to the small island of Norderoog and Süderoogsand, southwesterly to the small island of Süderoog (Fig. 1). Furthermore the barriers provide a habitat and resting place for numerous birds, mammals, plant species and other organisms (Oost and De Boer, 1994; Hofstede, 1997, 1999; Oost *et al.*, 2012). Due to their exposure to water and wind the sediments of the barriers are being relocated constantly. Since there is no significant sedimentary input from the open sea (Ahrendt, 2005), the barriers reshape in a process of constant internal sediment distribution. The constant reshaping and landward movement is also triggered by a rising sea level (Carter *et al.*, 1989; Eitner, 1996).

The Norderoogsand is the central barrier of the three North Frisian sandbanks on the edge of the Wadden Sea. It is an area of strictly restricted access within the national park. The sandy barrier Norderoogsand is under the stewardship of the Jordsand Ornithological and Nature Conservation Society and the small island of Norderoog is the private property of the Jordsand Society (Jordsand, 2014) (Fig. 1). Between 2001 and 2010 the area of Norderoogsand above mean high water (MHW) was around 5.3 km long and around 2.5 km wide at its broadest. The constant changes in shape and the gradual movement of Norderoogsand have been investigated between 1947 and 2013.

Since the early 2000s the north of Norderoogsand had gradually developed into a growing system of primary dunes with associated vegetation.

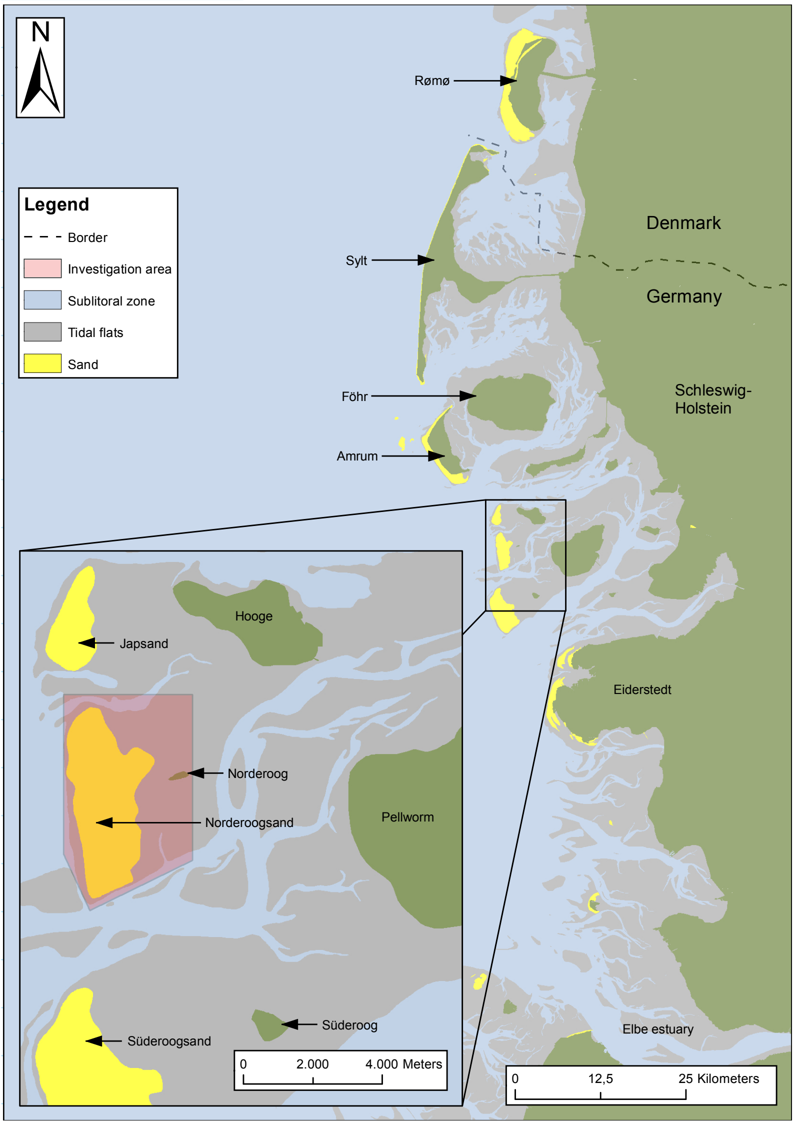


Fig. 1:
The Wadden Sea in Schleswig-Holstein and the survey area.

A new island had emerged in the central North Frisian Wadden Sea.

Starting with a small system of primary dunes, it has developed into a coherent, densely vegetated island of around 0.18 km² with single dunes rising 3.4 m above the MHW level (Stock *et al.*, 2013). Storm surges, which tend to level the terrain on the barriers (Hofstede, 1997) have so far not washed away the dune island. Furthermore the dune island has become a shelter for numerous birds and other animals. In 2012, 239 breeding pairs of birds were counted (Stock *et al.*, 2013). Its remote and protected situation also promoted the growth of a critically endangered species in Germany. In 2013, the frosted orache *Atriplex laciniata* was found on the dune island, as well as the sea spurge, *Euphorbia paralias* (Stock, 2013). These plants highlight the exceptional habitat on the new dune island.

In this paper, the development of the sandy barrier Norderoogsand over the last 66 years will be explained. The processes which shape and transform this sandy barrier will be highlighted with special regard to the formation of the new island. The focus will be on the questions: How has the sandbank changed in shape and position? How did the total area and the volume of the Norderoogsand develop? What makes the coherent system of dunes in the north of the sandbank an island and when did it start to emerge? To answer these questions the geomorphological history of the sandbank from 1947 to 2013 will be reconstructed with the aid of maps, nautical surveys and high resolution spatial data. Furthermore, findings from the field campaign will be used to find out whether the new island will be a persistent structure within the North Frisian Wadden Sea and what importance it has within its surrounding environment.

Material and methods

In order to determine the former development of the Norderoogsand, its current situation and especially the formation of the northern dune island, several methods were used. During a field campaign in 2013 elevation measurements, as well as a vegetation assessment and soil investigations were carried out. Furthermore certain geomorphological features like washovers and embryonic dunes were recorded to identify characteristic features of dynamic islands.

The historic development of the sandbank and its movement has been investigated by comparing coastlines of Norderoogsand from 1947 to 2010.

From 2001 onwards, high resolution spatial data has been used for volumetric measurements of the sandbank as well as the display of the erosion/accumulation regime.

Investigation area

The investigation area lies in the central part of the North Frisian Wadden Sea (Fig. 2). The present landscape started forming after the last Ice Age around 8000 years ago, when the sea level rise after the glaciation started to slow down.

A landscape with islands and sandy barriers on the western side and vast tidal flats and salt marshes stretching in the eastern, landward direction had formed. The barrier islands and sandy barriers we know today are sedimentary remainders from the last glaciation. The larger islands Sylt, Amrum and Föhr contain the cores of moraines, while the island of Amrum and the sandy barriers up to the Eiderstedt Peninsula are built up from sandy Geest-sediments (Ahrendt, 2005; Reise *et al.*, 2010).

Within the circle of tides the sandy barriers and the tidal flats are being formed and re-formed constantly. The wind, waves and currents, the rising sea level and extreme events such as storm surges reshape the landscape over and over. The survey area is predominantly under the influence of westerly winds (Fig. 3).

The Wadden Sea in the survey area is a habitat with many different characteristic features. It is comprised of sandy barriers and barrier islands, a vast area of tidal sand- and mud-flats with seagrass beds and mussel beds as well as salt marshes on the islands, Halligen and on the mainland shores. Furthermore beaches and dune systems can be found on the islands and barriers (Reise *et al.* 2010).

Norderoogsand is the central sandbank of the three North Frisian sandy barriers. The Japsand lies around 1 km in northern direction, while the Süderoogsand lies around 2.5 km south of Norderoogsand (Fig. 2).

Right at the eastern shore of Norderoogsand lies the small island of Norderoog. It is not permanently inhabited, but has two houses on stilts which provide shelter to ornithological wardens during certain times of the year. North-east of Norderoogsand and Norderoog lies the island of Hooge. It is the main municipality of Norderoog. In the very south of the displayed area lies the Süderoogsand and its adjacent island Süderoog. In the very west lies the island of Pellworm. The tidal flats that surround the Norderoogsand are bordered by two major tidal inlets. In the south and in the east the Rummelloch drains the tidal flats during low tide, in the north the Hoogeloch cuts between the Norderoogsand and Japsand and drains the area westerly, towards the open sea. During low tide the tidal flats connect the Norderoogsand and the islands of Norderoog and Hooge.

Vast parts of the Norderoogsand stay dry during high tide and only a rather small and shallow tidal inlet separates it from the island of Norderoog. In 2010 the Norderoogsand had an area above mean high water of around 8.6 km². In the very north of the sandbank a dune island had formed in past years. It was clearly visible from the islands of Hooge and Norderoog.

Norderoogsand and especially its northern dune island are a resting and breeding place for numerous seabirds and large groups of seals gather there during low tide.

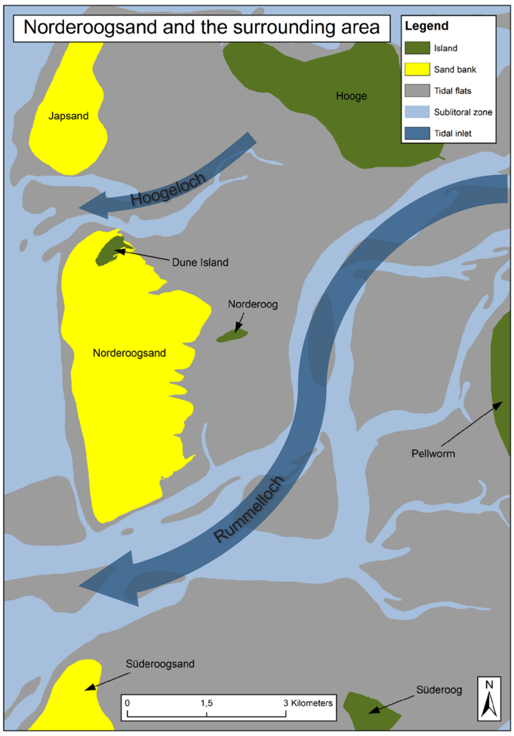
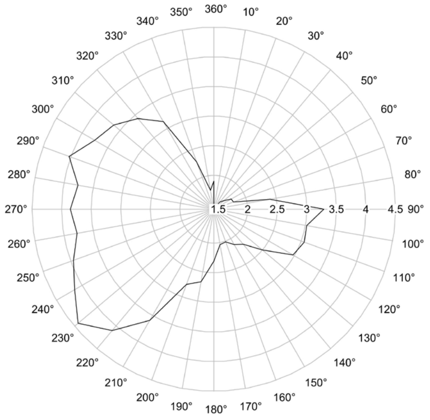


Fig. 2:
The Norderoogsand area.

Wind directions on Hallig Hooge

Graph shows hourly wind direction and abundance of the direction in percent between 01/01/2000 and 18/05/ 2014.



Data Source: Germany's National Meteorological Service (DWD), 2014

Fig. 3:
Wind directions in the survey area.

Gathering field data

The field data was gathered from 17th–19th August 2013. With a team of five scientists several investigations have been carried out on the sandbank Norderoogsand and on its northern dune island.

The elevation measurements were carried out with a Leica GPS 1200 differential GPS (DGPS) from Leica Geosystems. This system consists of a calibrated reference station, a rover system with GPS and radio antenna and a hand held device for operating the DGPS. The range for real time communication between the reference station and the rover can be up to 10 km, depending on the landscape's topography (Leica, 2005). During the research the reference station had been calibrated on a height measuring point, the LKN installed on the island of Norderoog, around 2.6 km from the westernmost side of the sandbank. The GPS antenna of the rover system was mounted on a flat aluminium sleigh, which was pulled behind the measuring scientist. The DGPS rover was set to a logging interval of one second, measuring x-, y- and z-coordinates constantly. Besides the coordinates, every measured triplet recorded a numeric quality indicator. This 3D coordinate quality shows the accuracy of a measuring point in metres. With a probability of 2/3 the measured positional value deviates less than the measured coordinate quality from the actual position. All measured values show a coordinate quality of less than 0.03 m. With the logging interval set to one second an average point distance from 1.4 m was achieved, making the field data comparable to the other acquired data sets. Nevertheless the distance between each measuring point depends on the terrain and walkability. On even, more solid surfaces the point distance is a little above 1.4 m, on steeper dunes the point distance can be significantly less than 1 m. (Fig. 4).

In order to create a time series of elevation profiles across the Norderoogsand two measuring transects have been created, one in the very dynamic northern part of the sandy barrier and one in the less dynamic central part (Fig. 4). These profiles were chosen to facilitate comparison with high resolution data from 2001, 2005 and 2010 and to highlight the movement and sediment accretion of the Norderoogsand. To measure an elevation profile across the sandbank, the rover was moved across the sandbank in two main transect lines.

One transect led from the western tip of Norderoog in a straight, westerly direction to the westernmost rim of the sandbank. The other transect led from the open tidal flats north of Norderoog in a westerly direction through the dune island at the northern tip of the sandbank. The slight change in direction on the northern measuring transect was due to water coverage west of the barrier beach of the dune island.

In addition to the transects, the dune island at the northern tip of Norderoogsand was measured with north-south oriented lines every 30 m, resulting in a dense pattern of measuring points (Fig. 5).

To determine the freshwater influence and rooting depths of the on-site vegetation, soil profiles were dug at three different locations in the investigation area. One profile is located on the western side of the sandbank at the level of the island of Norderoog, while the other two profile pits have been dug on the northern dune island. These two pits represent a cross section through one of the higher dunes in the north, as well as a profile at the southern slope of the dune island´s lee side. The profiles were dug until a few centimetres of ground water covered the bottom of each pit. The water level was recorded in comparison to DGPS height measurement at the top of the pits. Furthermore rooting depths of vegetation were recorded.

Salinity was tested with a sample from each

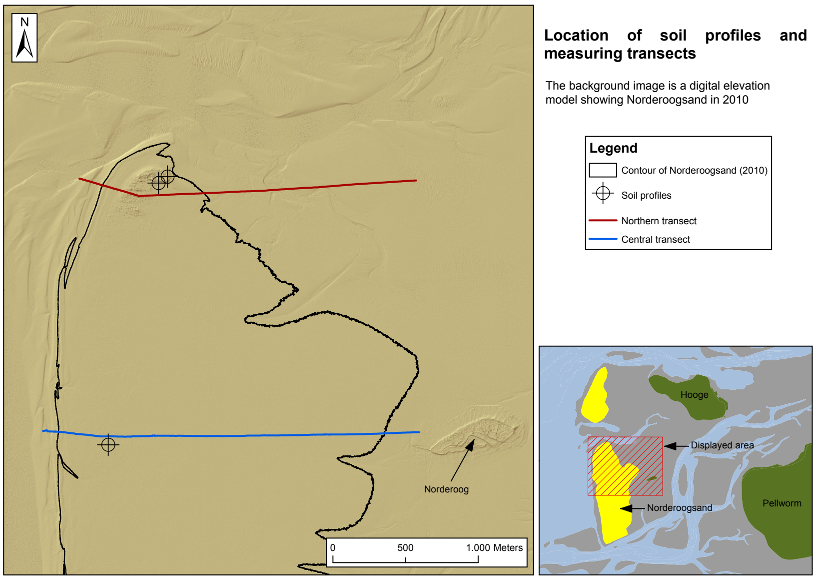


Fig. 4:
Measuring transects and sample locations.

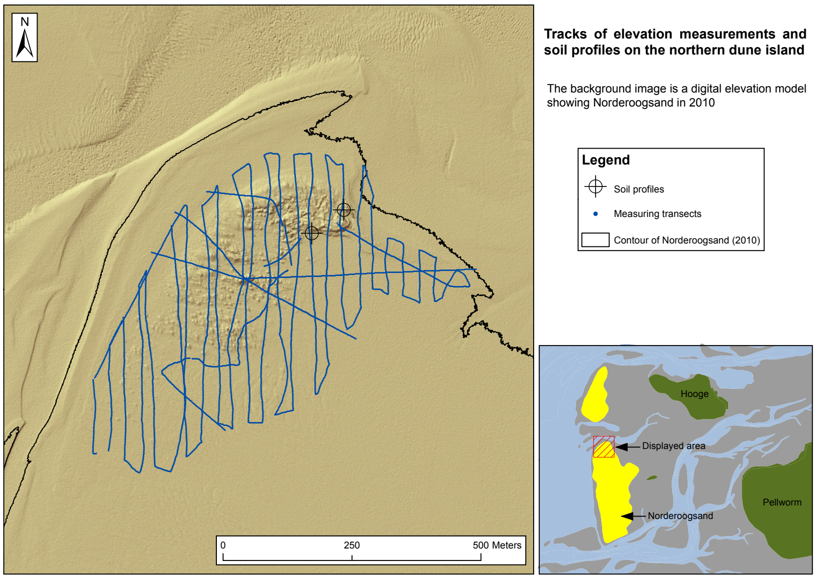


Fig. 5:
Elevation measurements on the dune island.

puddle at the bottom of a pit, using a traditional hand held refractometer. Additionally the salinity was tested at an adjacent spot with direct saltwater influence.

To determine the extent of a more or less dense layer of vegetation on the dune island two different classes of vegetation density were mapped. The denser part was defined as the area with 20% or more coverage of vegetation, the less dense part was defined as at least 5% of vegetation cover. The vegetation density was mapped with GeoXT hand held GPS units that provide a positional submeter accuracy (Trimble, 2014). While mapping, the researcher estimated the current vegetation density and walked around the perimeter of the covered area. At the same time the GPS unit recorded one node every five seconds, creating a polygon of the desired vegetational density. To ensure a consistent data quality the researchers were trained in estimating vegetation densities. In addition to the density estimates, several spots on the lee side of the dune island were mapped for plant species composition and abundance, using the Londo scale for vegetation assessment.

On the western side of the dune island distinct washover events could be identified on different years of aerial images, as well as during the field research. All washovers on the western side of the dune island, which could be identified from the ground, have been mapped using the same GPS units described in the vegetational mapping above. The washovers were clearly visible within the dune belt as eroded, unvegetated channels, widely covered with shell debris. The washover areas were recorded with the same handheld GPS units and settings that were used for the vegetation mapping.

Coastline contours

The shorelines of Norderoogsand have been calculated for the years 1947, 1965, 1974, 1977, 1981, 1991, 2001, 2005 and 2010. Due to the larger time span, the data sources from which the contours have been derived vary, and so does the data quality. All calculations have been performed with the educational version of ArcGIS 10.0 and the extensions Spatial Analyst, Geostatistical Analyst and 3D Analyst.

Generally the base data has been obtained from two different sources: Schleswig-Holstein's Government-Owned Company for Coastal Protection, National Parks and Ocean Protection (henceforth referred to as LKN) and the Federal Maritime and Hydrographic Agency of Germany (henceforth referred to as BSH) (Tab. 1).

Contour lines for the years 1947, 1965 and 1981 have been calculated from LKN-elevation-data-sets. These are coordinate triplets which are distributed along the former coastline of the sandbank as well as irregularly throughout the investigation area. The measuring points vary from 9800 to 12000 in each of the years. The positional accuracy is within a few metres, the elevation accuracy is within a few decimetres (pers. comm. Hinrichsen, LKN). These clouds of coordinate triplets have been interpolated into digital elevation models for each year. A radial basis function was used to transform the point data into raster images with a cell size of 10*10 m. Afterwards the annual mean high water level was determined from measurements of the tidal gauge in Wittdün (Amrum) and the values were used within the Contour tool to create coastline shapes.

Nautical charts from the BSH have been used a base of calculations for the years 1974, 1977 and 1991. The maps have been obtained from the agency as raster images in Tiff-files. As scans from German nautical charts they have been georeferenced by using the Gauss-Krüger grids on the maps. The digitized contour of the sandbank has been saved as shape files in Gauss-Krüger coordinate format. For easier comparison of all data sets they were subsequently transformed into ETRS89 coordinate format by the LKN.

The data for the years 2001, 2005 and 2010 were provided by the LKN. The three datasets are high-resolution LiDAR images with a positional accuracy of ≈30 cm and an elevation accuracy of ≈15 cm. The grid size is 1*1 m and each grid contains three to four measuring points (LKN, 2014).

Due to the dynamic environment of the tidal flats it can be hard to distinguish areas with water coverage and areas which have been exposed during low tide on a raster image (Brzank *et al.*, 2008). Within the three used datasets there were only a few areas that were classified as NoData-Values. The Focal Statistics tool has been used to replace the NoData-Values with mean values from the surrounding cells. Contour lines were identified with the Spatial Analyst-Contour tool, using annual MHW levels from the Wittdün tidal gauge (Amrum).

Geometric calculations and elevation profiles

All areas were calculated in square kilometres. Furthermore the x- and y- coordinates of the centre point (centroid) of each shoreline were computed. These points were used as the bases to identify the annual movement rates, as well as the major movement direction of Norderoogsand.

To identify the longitudinal axis of each contour the Minimum Bounding Geometry tool was used. By creating a convex hull around each contour, regular polygons with a shorter and longer side resulted. The length and orientation within the contour polygon resulted as the longitudinal axis of the sandbank.

Elevation profiles were calculated for 2001, 2005, 2010 and 2013. As described in the field data section two measuring transects were established across the sandbank in a west/east direction. These measuring transects from the field research were used as the profile lines to extract comparable data from the digital elevation models of 2001-2010. The extracted data were presented in two graphs. One graph displayed the northern transect, the other the central transect across the sandbank (Fig. 9, 10). The profile originates around the MHW shoreline in 2001. Both graphs additionally contain the average annual MHW from the period 2001-2012 as a reference height. The high water levels have been taken from the tidal gauge Wittdün (Amrum).

Three dimensional analysis

The scope of the three dimensional analysis incorporated the calculation of volumes for the Norderoogsand, the identification of erosive and accumulative zones of the sandbank and in particular, the spatial development of the northern dune island.

The volumetric calculations were based on the digital elevation models from 2001, 2005 and 2010. As they were gathered with the same methods and they fulfil certain standards in data

Tab. 1:
Sources of spatial data (1947-2013).
LKN = Schleswig-Holstein's Government-Owned Company for Coastal Protection, National Parks and Ocean Protection
BSH = Federal Maritime and Hydrographic Agency of Germany.

Year	**Data source**	**Data type**	**Positional accuracy**	**Elevation accuracy**
1947	LKN	Irregular elevation points	few metres	few decimetres
1965	LKN	Irregular elevation points		
1974	BSH	Nautical charts		
1977	BSH	Nautical charts		
1981	LKN	Irregular elevation points		
1991	BSH	Nautical charts		
2001	LKN	Laser scan data sets	≈30 centimetres	≈15 centimetres
2005	LKN	Laser scan data sets		
2010	LKN	Laser scan data sets		
2013	Own survey	DGPS measurements	≈3 centimetres	≈3 centimetres

accuracy they can be compared directly. The base for the calculations of the sandbank´s volumes was the raster data sets of the whole investigation area. As described in the section Coastline Contours, the areas with NoData-Values had been interpolated with mean elevation values from the surrounding raster cells before the calculations. To identify the volumes of the sandbank the raster files of each year were cut out at the perimeter of the coastline shapes from the corresponding year, thus creating an elevation model for each year depicting the steady area above MHW for the whole sandbank. Due to the different resolution of the coastline shapes and the digital elevation raster files there was a small variance between the calculated area of an annual coastline shape and its corresponding, clipped elevation model. The difference, however was significantly below 1% of the total volume. Furthermore the volume of the area above MHW level had been calculated.

To identify the zones of Norderoogsand that showed distinct surface erosion or accumulation, the years 2001, 2005 and 2010 have been used as base data for calculations. To display the change in surface elevation and thus show erosive and accumulative areas the digital elevation models have been subtracted from each other. To show the changes in surface elevation between 2001 and 2005 the raster data set from 2001 was subtracted from the data set of 2005. To show the elevation changes between 2005 and 2010, the data from 2005 was subtracted from the data of 2010.

As there are some areas within the digital elevation models that had not fallen dry during the low tide of the survey, the resulting raster images were not usable for the whole investigation area. Some tidal inlets that were flooded during low tide, for example, could not be assessed for surface change. The entire area of the sandbank, however could be compared in the periods from 2001-2005 and 2005-2010. To highlight the distinct changes in elevation, the values of the raster images were categorized into eight classes, each representing a change of 50 centimetres in surface elevation.

Furthermore coordinate quadrants were placed within the erosion/accumulation maps to show the morphological dynamics by reference to a fixed grid.

The third part of the three dimensional analysis was the development of the dune island in the north of the sandbank. The basis of this analysis is the LiDAR scan raster images from 2001, 2005 and 2010 as well as the measuring grids from the field survey of August 2013. As described in the Gathering Field Data section, the elevation of the dune island was measured in regular, parallel transects with a differential GPS rover. In order to compare the development over the defined period of time, the raw coordinate triplets from 2013 were interpolated into a digital elevation model. This operation was carried out by using the Natural Neighbour interpolation from the 3D Analyst section. The cell size was set to 1*1 m, as it was defined in the raster images of 2001, 2005 and 2010. To analyse the dune island, a section was extracted from the raster images of 2001, 2005 and 2010. The elevation values were classified along a stretched colour ramp from green over yellow towards red. In this symbology the darkest green was defined as the most elevated surface and the darkest red as the least elevated surface (Fig. 15). Furthermore the coastlines from 2001 and 2010, as well as a fixed coordinate grid of 300*300 m, were added to illustrate the morphological dynamics within the highlighted area.

Results

The results from the acquired data are presented in different thematic categories. Firstly the two-dimensional movements of the Norderoogsand are displayed. Secondly the elevation profiles, volumetric calculations and erosion and accumulation patterns are displayed in the three-dimensional analysis. Furthermore the newly formed island, as well as its vegetation densities and certain geomorphological features are presented.

Coastline, movement, area and rotation

During the reviewed years the shoreline of the Norderoogsand changed in both shape and position. The coastal outline retained a roughly similar base shape over the years. The most distinct changes were seen on the landward, eastern side (Fig. 6). While the western shore of Norderoogsand shows a rather steep profile, the eastern side of the sandbank was reshaped with accumulated sediments and with tidal inlets cutting into its structure.

Figure 6 shows the calculated shorelines of Norderoogsand for the years 1947, 1965, 1974, 1977, 1981, 1991, 2001, 2005 and 2010. The shoreline was defined as the area above MHW for each observed year. The seaward, western shore of the sandbank remained relatively straight, on an approximately south/north orientated line. Since the shorelines of the years 1947, 1965 and 1981 have been interpolated from rather dense point values and the years 2001, 2005 and 2010 resulted from high resolution spatial data, the outlines of these years showed more detailed, rippled contours. The shorelines from the years 1974, 1977 and 1991 however, were rather smooth, as they resulted from generalized maps. The years with the more detailed shoreline showed distinct spits of sand on the northernmost part of the sandbank and in 1947 and the 2000s these were also evident in the southernmost part. Furthermore the eastern part of the shorelines displayed distinct bulges from the tidal channels draining the tidal flats during low tide. The years 2001, 2005 and 2010 showed this pattern of tidal inlets on the eastern side of the sandbank very clearly. These years also showed the erosive inlets on the seaward western side of the sandbank (Fig. 6).

Over the displayed years the sandbank constantly moved, mainly in an easterly and slightly northerly direction. Figure 7 shows the movement rates and directions of the whole sandbank.

The displayed crosses in figure 7 represent the centre of the Norderoogsand. Between 1947 and 2010 the sandbank moved around 880 m east and 240 m north. The whole movement distance amounted to 1048 m over the 63 years. This leads to an annual movement of 17 m. However the movement of the Norderoogsand over the years was not regular. Between the shapes of 1977 and 1981 for example, the movement rate was 5 m per year whereas the movement rate between the shapes of 1991 and 2001 was 36 m per year. Since the centre points have been calculated from the coastline contours, they were most accurate in the 2000s and less accurate in the previous years. Furthermore the movement was dependent on natural, coastal processes. Therefore, while a movement trend was identified, there no uniform movement between the years.

The shapes of the coastline had been used to calculate the total area above MHW level each year.

Figure 8 shows the area for each investigated year between 1947 and 2010 in square kilometres. The area varied between 9.65 km² in 1974 and 7.66 km² in 1974. The mean area of all investigated years was 8.49 km². There was a deviation of around 20% between the smallest and the largest area in the investigated time.

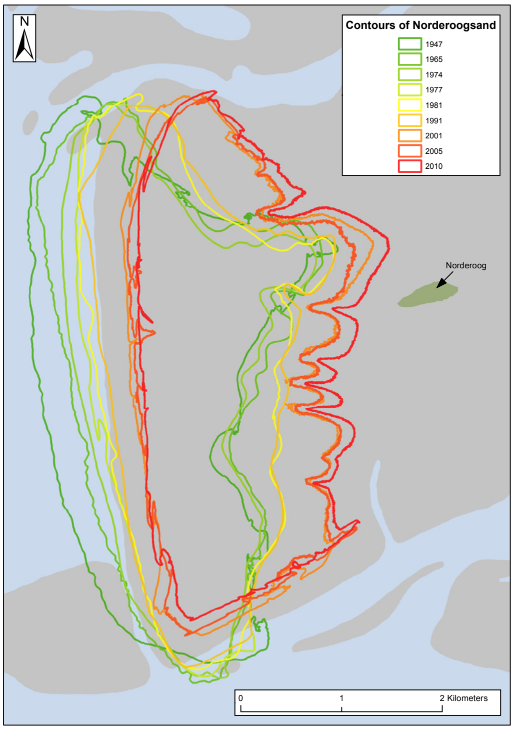
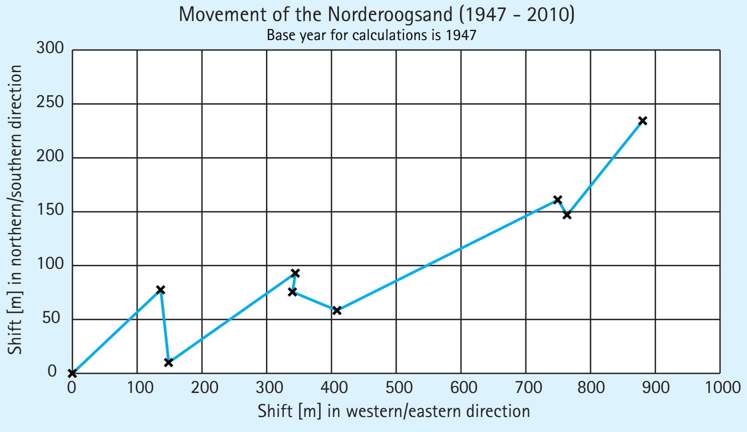


Fig. 6: Shorelines of Norderoogsand (1947-2010).



Years	Movement [m]
1947-1965	157
1965-1974	69
1974-1977	212
1977-1981	18
1981-1991	71
1991-2001	356
2001-2005	20
2005-2010	146
Sum	1048
[m]/[year] average	17

Fig. 7: Movement directions and movement rates of Norderoogsand (1947-2010).

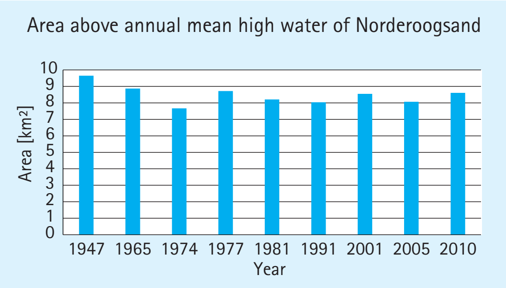


Fig. 8:
Area of Norderoogsand (1947-2010).

Within this development of the sandbank's size, there was a slight trend towards the shrinking of Norderoogsand. This did not take the overall volume of the sandbank into account, only the base area. However, if the large deviation of area size in 1947 was not taken into account, the trend of shrinking could not be established.

As figure 6 already showed, the sandbank, besides constantly moving eastward, seems to rotate in a clockwise direction over time. This slight turn had been evaluated by constructing longitudinal axes of every annual position of the sandbank. Figure 9 shows the bearing of each axis on a 360 degree scale. The sandbank continuously rotated clockwise. However, between 1947 and 1977 the rotation was calculated as being counter-clockwise. Between 1947 and 2010 the sandbank rotated a total of 18.5 degrees. The mean annual turn of the whole sandbank amounted to 2.05 degrees.

Elevation profiles, volumes and erosion regime

Two elevation profiles were established across the sandbank on a west/east axis. One was in the very north, crossing the dune island on Norderoogsand and one in the centre at the level of the island of Norderoog. Elevation profiles were generated for the years 2001, 2005, 2010 and 2013.

Figure 10 shows the northern elevation profile. The westernmost part of the elevation in 2001 showed the beach face and the transition into the berm and dune system. The dune island was clearly visible in the profile, but hardly exceeded 1.5 m in height. To the east the dune island constantly decreased in elevation. A spit with increasing elevation was visible at the eastern end of the dune island. Right after the spit a significant depression marked a tidal inlet. Going east from this tidal inlet the tidal flats continued with a slightly decreasing height. The slight elevation at around 1,450 m from the profile origin resulted from an isolated spit of sand within the tidal flats.

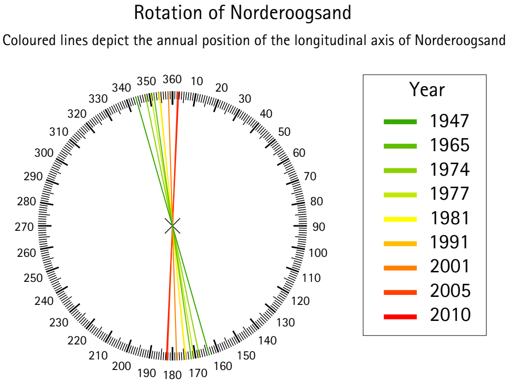
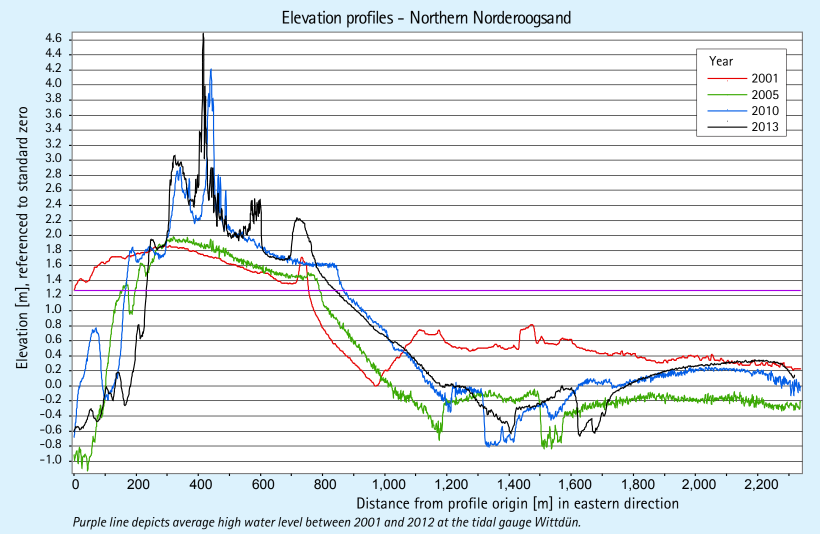


Fig. 9:
Rotation of Norderoogsand over time.

The profile from 2005 showed the eastward shift of the whole sandbank. The beach face started at around 150 m from the profile origin and transitioned into the berm and dunes to the west. The dune system reached an elevation of around 2 m and was clearly distinct from 2001. The spit on the westernmost end of the dune is-



Purple line depicts average high water level between 2001 and 2012 at the tidal gauge Wittdün.

Fig. 10:
Elevation of the northern Norderoogsand (2001-2013).

land was slightly visible at around 800 m from the profile origin. East from this spit the elevation declined into a tidal inlet, which increased in depth in comparison to 2001, but decreased in width. From the eastern bank of the tidal inlet the profile transitioned into low-lying tidal flats that were around 0.6 m below the surface of 2001. Another tidal inlet cut into the tidal flat further to the east. A sandy ridge marks the surface from the inlet in an easterly direction.

The profile line from 2010 showed that the sandbank has shifted east. In comparison to 2005 the beach face was steeper and transitioned quickly into the berm zone with small dunes. The dune island was significantly higher than in the preceding years with dunes up to around 4.2 m high. Most dunes on the small northern island however, were no higher than 2.8 m. To the east the dunes declined gradually up to the spit of sand on the westernmost part of the dune island. The spit had decreased in height compared to the two years before and was hardly visible. The eastern slope from the spit again clearly showed how the sandbank had shifted. The eastern slope from the dune island towards the tidal flats declined into a tidal inlet that seemed to have decreased in width and increased in height compared to 2005. This inlet was the western shore of a broader inlet that stretched from around 1,150 m to 1,550 m from the profile origin. The third small depression at 1,700 m from the profile origin resulted from a meander of the forementioned tidal inlet (Fig. 10). From this depression onwards a sandy ridge stretched east. This ridge had grown around 0.4 m in comparison to 2005.

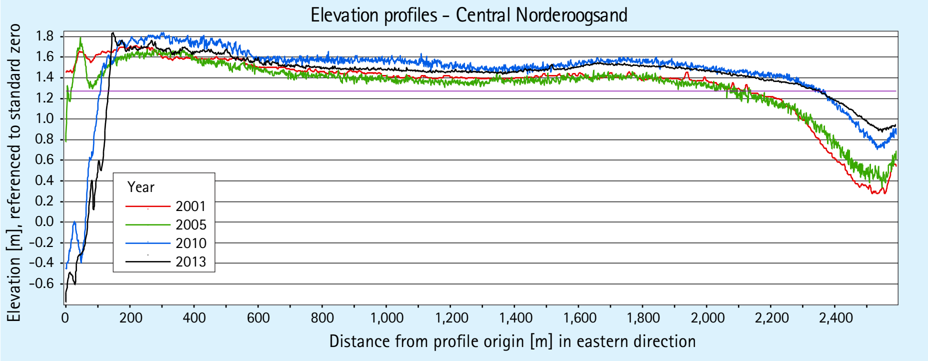
The profile from 2013 shows the shift east. It shows a rather steep beach face in the west and a quick transition into the berm. The dunes island grew in height to around 4.5 m at its highest point. Furthermore the dune system had grown wider easterly. The spit of sand which had almost vanished in 2010 became clearly visible again in the easternmost part of the dune island. From the spit on the terrain declined continuously towards the tidal flats. The two depressions marked a tidal inlet that had also been visible in the years before. The sandy ridge that had developed east of the tidal inlet grew in height and showed a distinct decline in the very east of the profile (Fig. 11).

The second elevation profile, which had been measured in the central part of Norderoogsand originated on the very western shore and proceeded east across the sandbank. The profiles were measured at the level of the island of Norderoog.

Figure 11 shows all elevation profiles within the central part. On the very western shore the movement of the sandbank was clearly visible. The sandbank constantly shifted east. Though the changes in terrain elevation were quite severe in the north of the sandbank, those in the central part were significantly smaller. Generally the relief consisted of a beach with a berm zone in the very west and a subsequent, prominent sandy ridge. At around 550 m from the profile origin the ridge declined into a spacious depression in the middle part of the sandbank. At around 1,600 m from profile origin the depression turned into a slight ridge and declined again at around 1,800 m. The immersion on the very eastern side of the sandbank resulted from a tidal inlet between the eastern shore of Norderoogsand and the island of Norderoog.

In 2001 the profile did not contain the steep slope at the western shore of the sandbank. It started with a small berm and continued in the above mentioned manner. The elevation profile of 2005 showed a similar progression, although the profile of 2001 was slightly more elevated than the profile of 2005. In the very east, the tidal inlet was some 15 cm deeper than in 2005. The years 2010 and 2013 showed a similar progression. In the west the slope of the beach was very steep and there was no distinct berm in 2010. The profiles proceeded accordingly in an

Fig. 11:
Elevation of the central Norderoogsand (2001-2013).



Purple line depicts average high water level between 2001 and 2012 at the tidal gauge Wittdün.

easterly direction, the terrain in 2010 being some 10 cm more elevated than in 2013. Near the eastern tidal inlet, however the terrain in 2013 was found to be more elevated than in 2010. Generally 2005 appeared to be the year with the least elevation, followed by 2001 and 2013. In 2010 the sandbank reached its highest elevation within the surveyed time span.

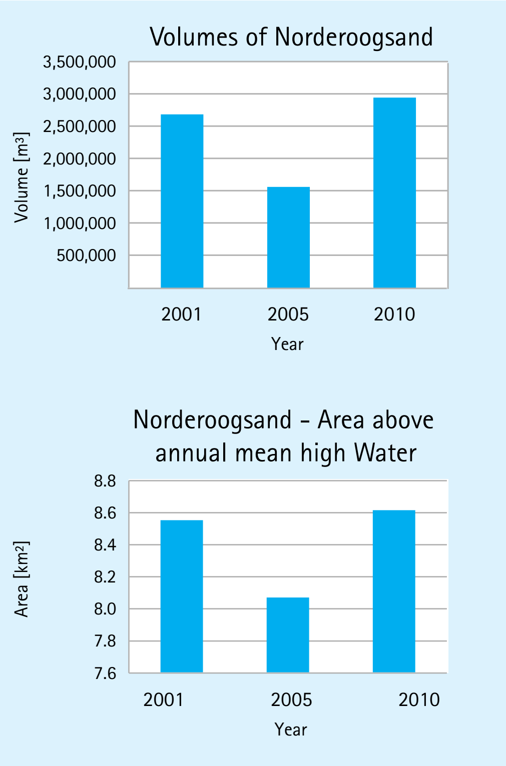


Fig. 12: Volumes and correspondent areas of the Norderoogsand (2001-2010).

The volumes of the whole Norderoogsand have been calculated for the years 2001, 2005 and 2010. They represent the volume of the sandbank above the annual MHW in cubic metres. In figure 12 the volumes and total areas are displayed together. The volumes and areas seem to develop accordingly. In 2001 the volume amounted to 2.7 million m³, in 2005 the volume decreased to 1.57 million m³. The highest volume of 2.95 million m³ was measured in 2010. Due to a lack of high-resolution spatial data only these three years could be calculated properly.

In order to determine areas of erosion an accumulation on the whole sandbank, high-resolution LiDAR images were used as a bases for calculations. Figure 13 shows areas of sediment erosion and accumulation between 2001 and 2005. The western shoreline of Norderoogsand was the major sediment erosion zone. Apart from small, isolated spits of sand in the northern part of the western shore, the whole western side was eroded. Generally the erosion on the western shore of the sandbank seemed to be strongest on the westernmost side and gradually declined across the beach structure. In the central parts four distinct eroded pools were detected. To the west, berms of sandy sediment had accumulated on a north/south axis. Right behind the berms in eastern direction smaller spots of accumulation had formed. The major centre part of the sandbank was dominated by sediment erosion within the elevation range of 0.5 m.

On the very north of the sandbank, where the dune island had built up, accumulation predominated over erosion. The spit of sand of the dune island could be identified by a small erosive stripe followed by a small zone of north-east sediment accumulation.

Apart from the northern dune island, sediment accumulation occurred on the southern and central lee side of the sandbank, reaching as far as the island of Norderoog. Within the accumulative area on the eastern shore, small east/west oriented structures were visible. They originated from the small tidal streams draining the

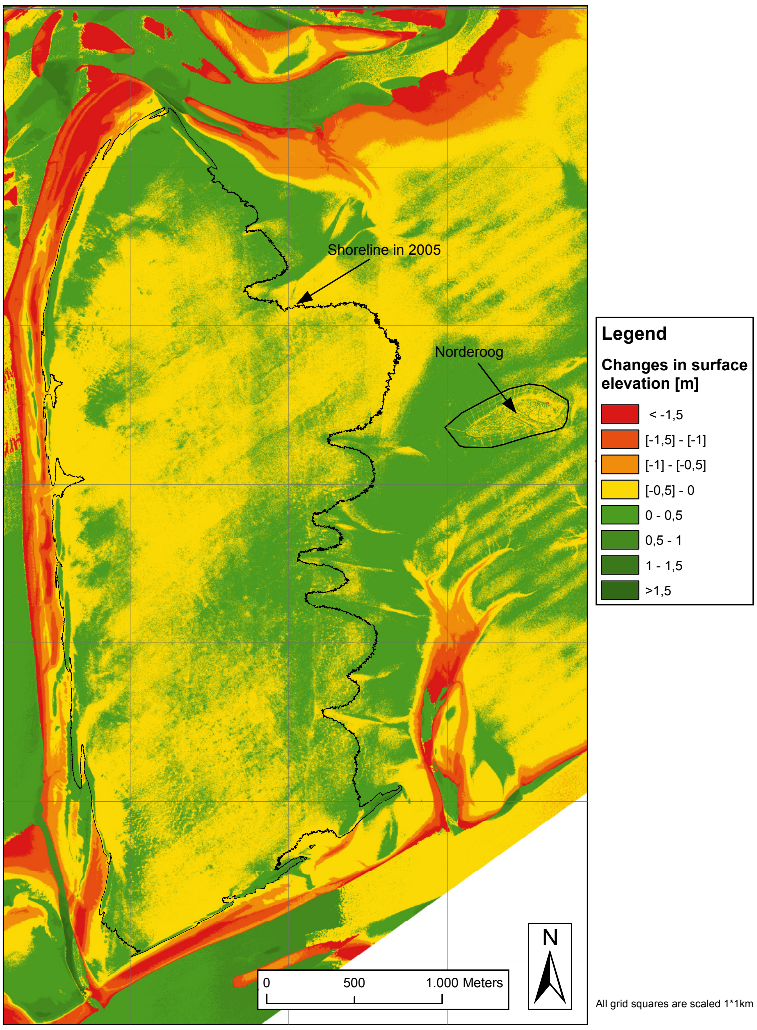


Fig. 13: Changes in surface elevation between 2001 and 2005.

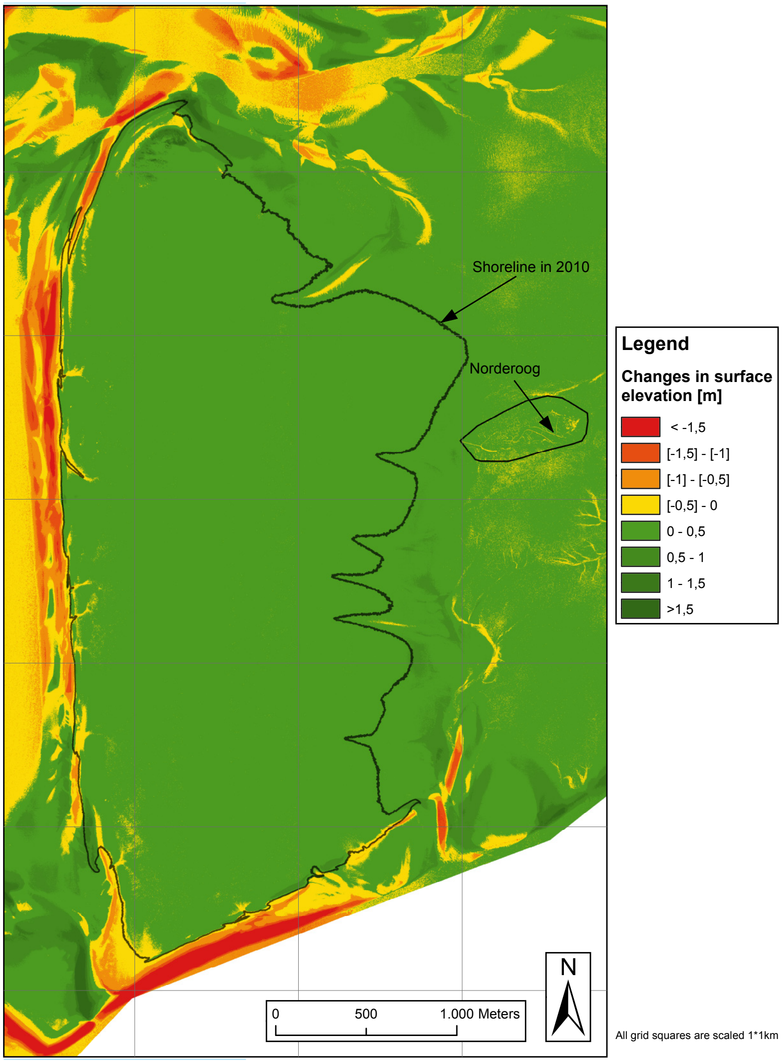
tidal flats during low tide into the larger tidal inlet in the south-east.

The regular, diagonal stripes visible all over the figure resulted from the LiDAR recording technique.

Figure 14 shows the changes in surface elevation between 2005 and 2010. The main area of erosion was on the western shore of the sandbank. The distinct pool identified in figure 13 had gathered large quantities of sediments between 2005 and 2010. Furthermore the berms on the western shore were no longer detectable. They had merged with the rising elevation of the whole sandbank. The gradual change from strong erosion to slight accumulation on the western shore between 2001 and 2005 changed into a more marked progression between 2005 and 2010. Almost the whole area of Norderoogsand showed a positive change in surface elevation within the range of 0.5 m.

The northern dune island accumulated large quantities of sandy sediments between 2005 and 2010. The shaping of dune systems had become visible, as had the eastern shift of the whole dune island.

Fig. 14: Changes in surface elevation between 2005 and 2010.



On the sheltered lee side of Norderoogsand sediments had also accumulated. In the south-east, where the large tidal inlet drained the tidal flats during low tide, the banks of the tidal inlet had risen significantly (Fig. 14).

The northern dune island

In the very north of the sandbank of Norderoogsand a dune island developed within recent years. Figure 15 shows coloured images, indicating the changes in elevation between 2001 and 2013. Furthermore the shorelines of the sandbank in 2001 and 2010 are displayed. The year 2001 was determined as the base year for this time line of terrain development (Fig. 15).

In 2001, differences in elevation on the dune island were minimal. A diagonal sandy ridge decreased gradually from north-west to south-east. In the north-west and west the beach gradually declined into the area of permanent water coverage, forming large ripples running parallel to the shore. In the north-east, adjacent to the shore line, a small spit of sand had formed on a north-west/south-east axis. The overall changes in surface elevation remained within the range of 0.5m. The island was confined by a large tidal inlet in the north and the open North Sea in the west.

In 2005 the shoreline of the whole northern tip had moved eastwards. The western beach declined into the open water, forming a single berm oriented in coastal direction. The sandy ridge across the northern tip of the sandbank had accumulated more sediments and the formation of a coherent dune system had progressed. On the western and southern side of the dunes a slight gain in surface elevation became visible. Between the dune system and the beach a series of small north-east/south-west orientated barrier dunes had formed. The area between the spit of sand in the north-east and the higher dunes had accumulated sandy sediments.

The shift of the sandbank was also visible in 2010. Along the shoreline in the north-west a sandy berm bordered the MHW line. West of this berm the beach gradually declined and formed a single berm parallel to the coast, as in 2005. The dune system had grown in size and became denser. To analyse the dune island, a section was extracted from the raster images of 2001, 2005 and 2010. On the western side of the dune

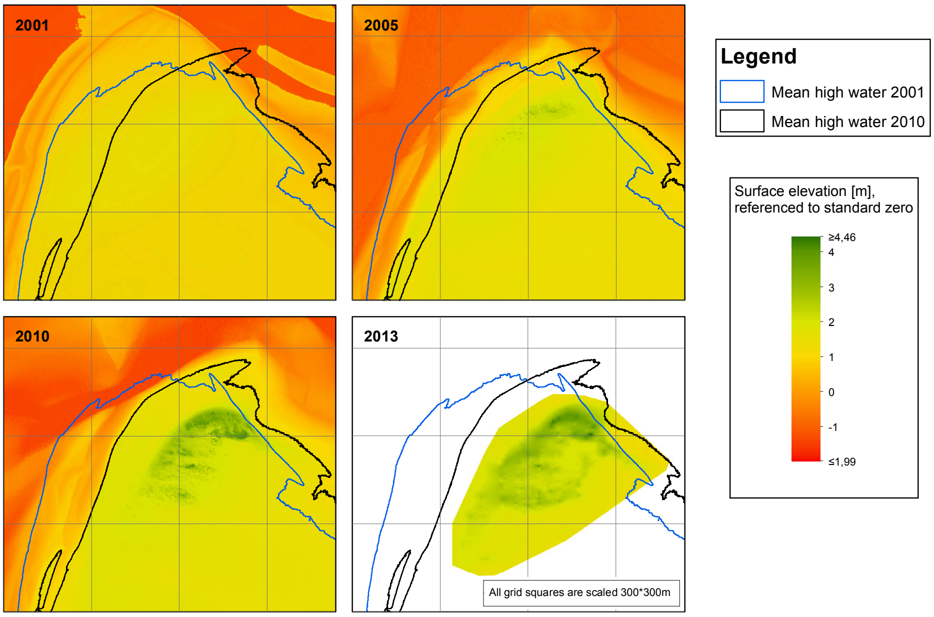


Fig. 15: Different stages of terrain development on the dune island between 2001 and 2013.

system, several smaller inlets indicate washover events. The spit of sand on the north-east side of the dune island, which had been also visible in the years before, had grown slightly in height. Furthermore the shoreline in the very north seemed to form another spit of sand in 2010.

The elevation model from 2013 was created from field data, and therefore has a lower resolution than the other observed years. During 2010 and 2013 the dune island had shifted in eastern direction. The dunes on the sheltered side in the south-east had grown and new ones had developed, especially in the south of the dune island. The spit of sand in the north-east, which had formerly been the boundary of the dune island had moved southwards and a small embayment had formed north of it. At the very north-east tip of the island a new spit of sand had started to form (Fig. 16).

Vegetation, washovers and eoil profiles

In order to determine the current state of the dune complex in the north of Norderoogsand, certain characteristics were recorded. Vegetation, as well as the salinity of the ground water are used as indicators for the formation of an island. The washover complexes were mapped as geomorphological characteristics of a dynamic island as well as indicators for sedimentation processes.

In 2013 the vegetation on the dune island in the very north of Norderoogsand was mapped. Figure 16 shows the extent of vegetation on the dune island, as well as the extent of the saltmarsh vegetation in the dune valley and the washovers on the western shore. The vegetation was mapped by estimating its density on the ground. The core area of the dune island was completely covered with vegetation above 20% density. The dense vegetation also covered the spits of sand in the north-east. A small, isolated field of dunes in the south-west was also densely covered. The vegetation borders were quite distinct in the core part of the dune island. The western and northern coast showed a particularly clear boundary from rather dense vegetation to bare sand. To the south the vegetation density decreased and fell below 20%. This part of the island had small, isolated primary dunes that did not constitute a consistent dune system. The vegetation border in the southern part was thus less marked than the western and northern shore. At the edge of its 5% coverage, the vegetation did not stop growing, but gradually tailed off to below 5%.

The saltmarsh vegetation was mainly found in the dune valley in the sheltered part between the higher northern and western dunes. Two isolated spots of saltmarsh vegetation were growing south of the dune valley and a little to the east.

The washovers were distributed all along the west of the island, where the dunes were higher and formerly coherent. The biggest washover area in the south reached up to 180 m into the dunes. The other washovers were smaller, but quite equally distributed along the western shore.

The locations of the soil profiles are displayed in the figures 4 and 5. One was in the higher dunes in the very north-east of the dune island,

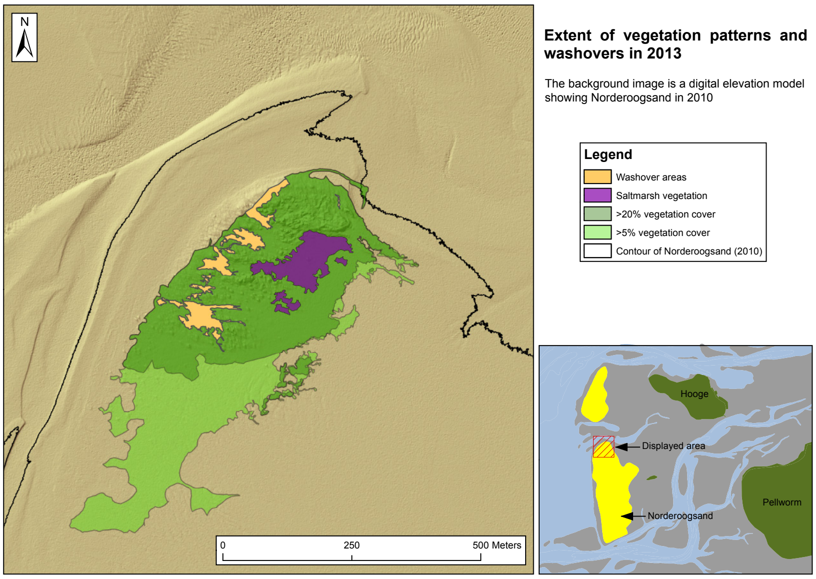


Fig. 16:
Vegetation density and washovers on the dune island.

another was in the valley at the foot of the higher dunes. The third profile was in the central part of the sandbank, at the western shore on the level of the island of Norderoog. The soil profile in the central part of Norderoogsand had been dug to a depth of 60 cm below the surface. It was located next to a small primary dune with the sand couch-grass *Elymus farctus* growing on it. The rooting depth of the grass was 80 cm. Within the ground water in the profile pit the salinity was measured at 23 ‰. The sea water at the near shore had a salinity of 30‰.

The soil profile in the dune valley was dug to a depth of 66 cm. The roots of the saltmarsh vegetation reached up to 33 cm into the ground. There was a distinct soil horizon with shell debris at 25 cm. The ground water built up at a depth of 55 cm and had a salinity of 16‰. The seawater at the nearest shore had a salinity of 30‰. The top of the soil profile was completely covered with vegetation and litter from dead plant parts. The third profile was dug in the higher dunes in the north of the dune island. The profile pit had a depth of 3.5 m. The top of the dunes was vegetated with E. farctus and its roots reached 1.2 m into the sediment. Single roots and rhizomes reached even deeper. The groundwater built up at 3.45 m. Here a salinity of 6‰ was measured. Water at the nearest shore had a salinity of 32‰.

Discussion

The development of the sandy barrier Norderoogsand has been reviewed from 1947 to 2013. Within those 66 years the island had constantly reshaped and moved, yet retained its overall shape. The sandbank moved some 1050 m in an easterly, landward direction and around 230 m north. These values are based on the centre of the sandbank. The landward retreat is most distinct on the western shoreline. The calculated movement north is not due to an actual migration, but rather to a shortening of the sandbank in the very south (Fig. 6). The lengthening of Norderoogsand described by Hofstede (1997) seems to have become a broadening in recent years. Apart from the landward rollover, the steep, western shore of the sandbank remained in a very similar state, while the eastern side had reshaped and grown under the influence of aeolian sedimentation. Moreover, the Norderoogsand had rotated 18.5 degrees clockwise between 1947 and 2010. The rotation is clearly visible on the western shoreline (Fig. 6) but apart from the actual rotation, slight changes in the sandbank's shape have in effect meant it has turned clockwise. The total area of Norderoogsand remained pretty constant between 8 and 9 km² between 1947 and 2010. Only 1947 and 1974 show slightly larger (1947) and smaller (1974) values. Overall there has been little change in Norderoogsand's size. However, marginal changes in size were reflected within the volumetric analysis. Whereas between 2001 and 2005 large parts of Norderoogsand had been slightly eroded (Fig. 13), between 2005 and 2010 almost the whole area above mean high water had accreted sediments. This decline of volume between 2001 and 2005 and the phase of accretion between 2005 and 2010 was observed for volume and area size accordingly (Fig. 12).

The movement of Norderoogsand and associated processes

Accordingly to Intergovernmental Panel on Climate Change (IPPC) estimates, the mean sea level rise, depending on different development scenarios, will amount to between 0.26 and 0.82 m within the base time span of calculations (1986-2005) and the end of this century (2081-2100) (Church *et al.*, 2013). While this is a very general projection, it shows the likely severity of sea level rise in the future. Within the local environment of the North Frisian Wadden Sea Jensen *et al.* (2011) identified a mean sea level rise of 2.3 mm/a as well as a rise in MHW levels of 4.4 mm/a between the years 1937-2008 for the tidal gauge Wittdün on the island of Amrum.

Hofstede (1997) suggested that Norderoogsand had constantly moved landward in response to a constant rise in MHW. He furthermore stated that the eroded sediments formed the seaward side and their deposition on the sandbank could balance out the sea level rise and maintain the volume of the sandbank. In addition it can be assumed that sandy sediments will not be transported towards the sandbank from the open North Sea (Ahrendt, 2005), but will come only from internal erosion and accumulation processes of the local tidal basins. This local erosion/accumulation regime transports sandy sediments from the foreshore and adjacent subtidal zone of Norderoogsand in a landward direction, where it is being accumulated on the sandbank and on its sheltered lee side. As the huge tidal stream Rummelloch borders the eastern and southern side of Norderoogsand, eroded sediments from the sandbank might also be transported into the tidal stream. During low tide and water draining into western direction, these sediments could be accumulated within the ebb-delta in the very southwest of the sandbank.

The movement of the Norderoogsand was tracked from shorelines of different years between 1947 and 2010. Since the movement between two years had been calculated from centre points of the irregular shaped shorelines, the movement rate of the whole sandbank has not only been affected by the shift of the shoreline, but also by the shape itself. The shape of Norderoogsand changed significantly between 1947 and 2010. This was partly due to an actual change of shape, but also resulted in the data quality. The years 1974, 1977 as well as 1991 were taken from nautical charts. The shoreline on theses maps does not represent the actual shoreline at MHW level, but rather a shoreline during lowest astronomical tide. Therefore the forementioned years have the strong tendency to display the Norderoogsand as being larger than it actually was. The shoreline of the years 2001, 2005 and 2010 resulted from high resolution data and therefore gives a much more detailed image of the actual shape of Norderoogsand at those times. The data source for the remaining shoreline contours was interpolated from measuring points which have a very high positional accuracy, but an elevation accuracy within a few decimetres. Therefore the calculated movement rates (Fig. 7) have to be interpreted with caution. Only the years 2001, 2005 and 2010 provide a high, consistent precision.

Generally Norderoogsand has retreated constantly in an easterly direction. Additionally, it had shifted some 230 m to the north. Figure 7 shows three depressions within the whole time (1974, 1991 and 2005). Around these three points in time the northward movement of Norderoogsand had reversed into a southward movement. Furthermore the eastward movement had substantially decreased around the three depressions. The depressions could relate to a periodical pattern of the sandbanks movement, to extreme events such as storm surges, or they could originate from data inaccuracy. Since Norderoogsand is located within a highly dynamic and changeable environment a periodic pattern within such a time span seems unlikely. Hofstede (1997) and Christiansen *et al.* (2004) suggest that high water events and the associated overwash are the driving process in sediment accumulation on barriers. However, strong storm surges can also lead to inundation and the erosion of sediments (Anthony, 2013). Two periods of increased storminess in the German Bight could be identified, one in the late 1940s and one in the 1990s. However there seems to be no evidence for a trend of increasing storminess (Rosenhagen and Schatzmann, 2011). The storm index from Rosenhagen and Schatzmann (2011) furthermore does not explain the depressions in the movement pattern of Norderoogsand. The first depression was developing from 1965 to 1974. These two years originate in different data sources and might therefore cause a depression in the movement pattern. The second depression started from 1977 and continued in 1981 until 1991. Again the data source changed between 1977 and 1981/1991. Thus, the depressions might originate in the data quality and chosen methodology.

Generally, overwash governs the sedimentation regime on the sandbank of Norderoogsand (Hofstede, 1997). Additionally, the overwashed sandy sediments are transported by the wind. The prevailing wind direction between 2000 and 2014 was west, which leads to a sediment transport across the sandbank in an easterly direction. The three main factors for the transport of sandy sediments are the availability of sediments, the wind speed and the wind direction. In addition, the topography and moisture content of the sand determine how the sediments are being transported (Anthony *et al.*, 2009). The sandbank and the dune island in the north of Norderoogsand have developed a different morphological structure within the last 14 years. Whereas the central and southern part of Norderoogsand was a sandy barrier, in the north a coherent dune system has developed. Therefore different processes for the erosion and accretion of sediments can be assumed. Whereas overwash and aeolian transport of sediments dominate on the sandy barrier, the dune island also accumulated sediments within its vegetation. The vegetation on the dune island also traps sediments during extreme events (De Groot *et al.*, 2011). Due to these different morphological structures, different rates of movement may result. As figure 9 shows, Norderoogsand has gradually rotated clockwise. Between 1974 and 1977 the rotation was counter-clockwise and between 1981 and 1991 the rotation had almost stopped. Between 2005 and 2010 the rotation was reduced to 0.4 degrees. This could be in response to a slower landward retreat of the northern dune island and a faster retreat of the rest of the Norderoogsand.

Regarding the movement of the Norderoogsand, the findings of Hofstede (1997) were very similar to the present investigation. He stated that the Norderoogsand had moved some 700 m landward between 1947 and 1991. This movement rate has been derived from comparing cross sections of the Norderoogsand. Therefore the movement rate is based on the retreat of the western shoreline. In the present survey, however the base of the movement rates was not the western shoreline, but the centre of the sandbank. This leads to a movement rate of some 523 m. Therefore the small discrepancy between both surveys is of methodological origin.

The northern dune island

Since the early 2000s a small island has developed in the north of Norderoogsand. Beginning with only a few embryonic dunes along a north-east/south-west oriented berm structure in 2001, a coherent system of densely vegetated dunes had developed by 2010. In 2013 single dunes were rising around 3.5 m above MHW level. Between 2001 and 2010 the island was shifting accordingly to the whole Norderoogsand. Figure 17 shows the elevation of the dune island and the areas which remain dry during times of exceptionally high water (Fig. 17).

When water is 1 m above MHW, the whole dune bow, as well as separated smaller dune fields in the south, remain dry. When water rises to 2 m above MHW most of the dune complex is covered, leaving only the higher dune ridges above water level.

The dune complex of the island was densely covered with the associated dune vegetation. On the sheltered eastern side a spot with distinct salt marsh vegetation had formed. Water samples from soil profiles dug in 2013 showed a salinity of 6‰ in the dune bow complex and 16‰ in the salt marsh in the dune valley. This indicates the formation of a fresh water aquifer with a brackish outer zone underneath the dune island.

The distinct elevation above MHW and the coherent, densely vegetated dune complex with an associated freshwater aquifer clearly show that since the early 2000s a new island has emerged in the north of Norderoogsand.

Island components on Norderoogsand

The northern dune island showed several distinct geomorphological features, such as the formation of dunes, the spit of sand in the north or the washovers in the western dune belt. Lammerts *et al.* (2009) published a synthesis of three reports, describing a model barrier island and its geomorphological features. Though the model was based on barrier islands of the Dutch Wadden Sea and German North Sea coast of Lower-Saxony, similarities to the Norderoogsand area could be found

Figure 18 shows the model island and its specific elements, as well as the dune island on northern Norderoogsand and the complementary model elements. Generally, the dune island is significantly smaller than the model island, therefore the components are in different stages of development and differently located. On the dune island the whole structure is somewhat compacted.

Number one indicates the island head and the associated processes of sedimentation and accumulation. Lammerts *et al.* (2009) state that,

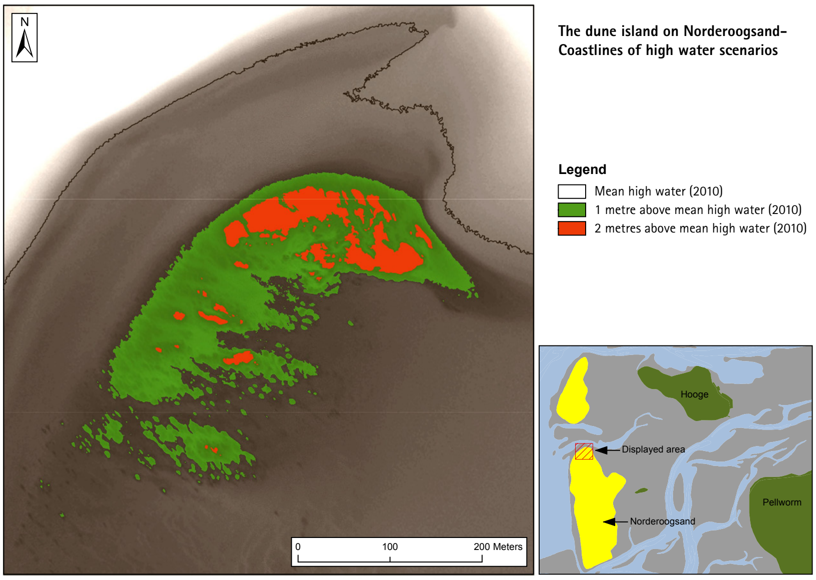


Fig. 17:
High water scenarios on the dune island.

depending on the availability of sediments, embryonic dunes, as well as dune ridges can start to form. They also state that this zone is exposed most of all to the highly dynamical coastal processes. On the dune island of Norderoogsand the tidal inlet Hoogeloch is the main influencing tidal stream. It caused erosion of sediments in the very north-west of the island, while deposition took place on the sheltered lee side in the north-east (Fig.13, 14). Due to the rather small zone between island head and dune system, only in the very south-west of the dune island, small embryonic dunes were found in 2013.

Number two in figure 18 has been defined as the dune bow complex. Lammerts *et al.* (2009) state that this part of the island is formed by huge amounts of sand, which have been eroded on the windward side of the island. They are forming a coherent system of dunes in a parabolic shape. Nutrients are only accumulated over time, due to the sandy sediments. However, this feature appears to be the most stable element in the system. Vegetation facilitates this development significantly. Even on the fairly young dune island on Norderoogsand, the parabolic dune complex was already in evidence in 2010. These dunes were densely covered with characteristic dune vegetation and also formed a distinct area with saltmarsh vegetation. The development of vegetation cover may have been influenced by the large amount of breeding seabirds with their dispersal of plant seeds and their nutrient input into the sediment through droppings. Vidal *et al.* (1998) found that larger seabird colonies over time lead to a shift towards ruderal vegetation on smaller islands. He also stated that the constant physical disturbance (treading and pulling out) favours ruderal plant communities over time. However Stock (2013) identified the critically endangered frosted orache *Atriplex laciniata* and 69 other plant species. This suggests that the remote and undisturbed conditions on the dune island were rather favouring plant diversity.

Number three on the model island is being described as the washover complex (Lammerts *et al.*, 2009). The washovers are a formation of depressions in north/south orientation. They are bordered by sandy ridges and all kinds of subelements such as embryonic dunes. Within this active washover structure seawater washes over the island during high tides. In the sense that washovers are characterized in the island model,

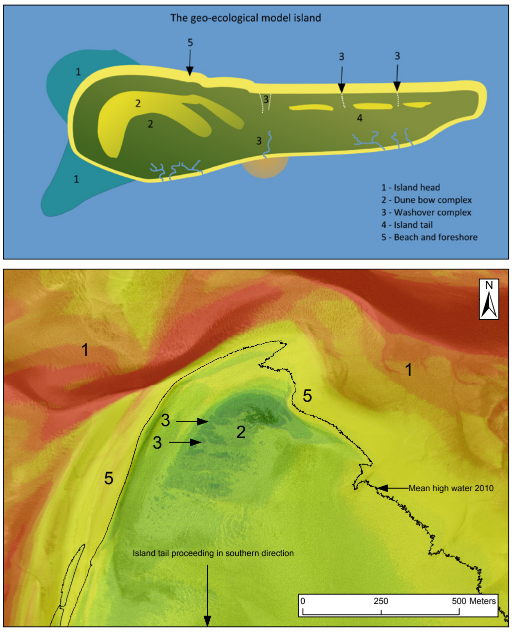


Fig. 18:
The geo-ecological model island and its components on Norderoogsand.

they were not part of the northern dune island. The washovers on the dune island of Norderoogsand resulted in storm surges or events of exceptional high water levels. Moreover, they were lacking the distinct dune ridges alongside their orientation. The washover structures on the dune island were densely covered with shell debris of various sizes and species, most likely to have been transported there during storm surges. Figures 13 and 14 also show that there is no distinct depression or channel structure in front of the washover structures towards the sea. However, figure 16 shows that the whole western side of the dune island had been affected by single or sporadic washover events.

Number four within the model barrier island has been described as the island tail. Lammerts *et al.* (2009) describe this structure as a very dynamic beach plain, where development is dependent on large scale geomorphological processes around the whole island system. They state that the island tail can be in different stages of development. The island tail might accumulate sediments and form parabolic complexes of dunes like the dune bow complex, but during erosion events developing dunes might also be levelled. The characteristic vegetation on the island tail is described as salt marsh vegetation. Like in the forementioned complex, washovers are being described as characteristic for the island tail. The dune island on Norderoogsand does not have island tail features in the way it has been suggested for the model island. Regarding the whole structure of the Norderoogsand, some features similar to the above mentioned could be identified.

Figure 19 shows several developing sandy ridges in the central western part at the MHW line. They were aligned parallel to the coast and showed small depressions separating each ridge. In the northern part of figure 19 two funnel shaped structures showed the development of a washover complex. On the lee side of the sandy ridges, sediment could accumulate and form slight elevations on the sandy plain.

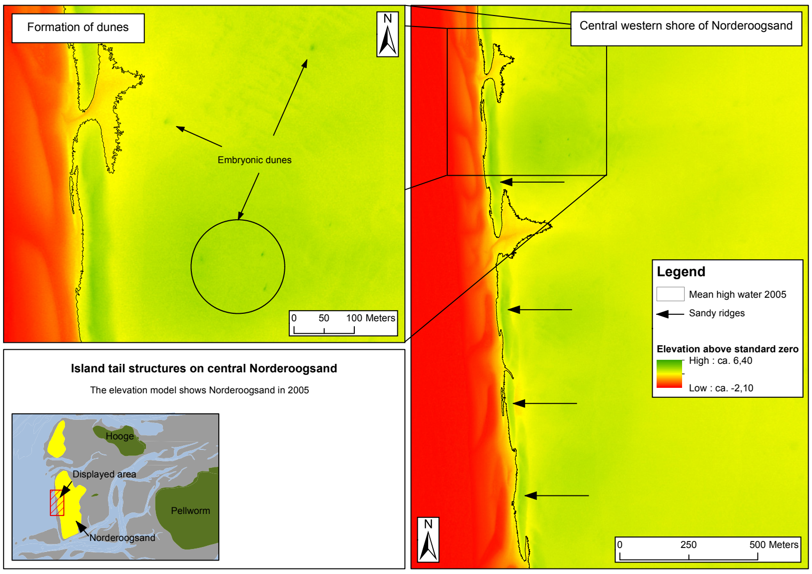
Figure 19 also depicts that on the lee side of the sandy ridges a small field of embryonic dunes had formed. As stated by Lammerts *et al.* (2009), these dunes are within a highly dynamic and exposed location and are very likely to be levelled by high water events. However, they seemed to be a quite stable component as they were recorded during the field campaign in 2013 as well.

The last element Lammerts *et al.* (2009) described on their model island is the beach and foreshore (Number 5). They describe it as an important cell for sediment transport and a pathway of eroded sediments. Sediments from the beach and foreshore can furthermore provide the base for embryonic dunes.

On Norderoogsand the beach and foreshore could be clearly identified throughout the dune island in the north and the whole sandbank. Norderoogsand showed a distinct beach and foreshore on the seaward, western shore, as well as in the very north and on the southern border of the sandbank. Figure 2 shows the main tidal inlets Rummelloch and Hoogeloch, which also carry sediments from and towards Norderoogsand.

In their synthesis report Lammerts *et al.* (2009) attribute a certain lifespan to each of the abovementioned components. The components of the island head (Fig. 18) are estimated to have a lifespan of 25-50 years. The findings of Hofstede

Fig. 19:
Structural features of the island tail.



(1997) and Wietz (2002) indicate that the tidal inlet Hoogeloch, on the northern border of Noreroogsand will narrow in the future and accumulate more sediments from the adjacent barriers Norderoogsand and Japsand. Therefore it is likely that the lifespan of all the island head's components will be prolonged, rather than shortened, due to reduced hydro-morphological pressures.

The sub-elements of the dune bow complex are estimated to have a lifespan of around 50 years, depending on environmental conditions. The washover complex has an estimated persistence of 25 to 100 years. This however, addresses an active washover complex and not the washovers on the dune island of Norderoogsand, which resulted from single extreme events. The persistence of the island tail is an estimated 25 to 50 years, but since the tail is only rudimentarily developed on Norderoogsand (Fig. 19) it is difficult to determine its life span. In the past, embryonic dunes which had developed on the island tail of Norderoogsand have been levelled during storm surges.

Many of the components Lammerts *et al.* (2009) identified for a model island could also be identified on the island on Norderoogsand. Their persistence and expansion over the last ca. 14 years sustain the presumption that the dune island is a new, persistent component within the central North Frisian Wadden Sea.

The formation of a new island is after all not an uncommon process in this dynamic environment. Around 1888 the sandbank Memmertsand, in the outer Eems-estuary near the Dutch-German Border, had developed successively into a dune island. Being a sandbank with sporadic formation of dunes and associated vegetation, storm surges had levelled the sandbank frequently, until the dune system had reached a persistent state (Schulz, 1947). Only some 2 km northwest of Memmert lies the Kachelotplate, another highly dynamic sandbank. Over the years it had developed certain barrier island structures, but was frequently exposed to strong storm surges. The Kachelotplate is presumably in a pre-barrier island state (Wehrmann and Tilch, 2008; Liebezeit *et al*, 2013). Memmert and the Kachelotplate are only two of several examples of the transformation of sandbanks in the Wadden Sea. The emergence of new small islands is a natural process in this ever changing environment.

Conclusions

The analysis of shorelines, aerial imagery, high resolution spatial data and field survey findings in the Norderoogsand area between 1947 and 2013 resulted in the following conclusions.

1. The Norderoogsand is a highly dynamic and highly mobile sandbank. Within the surveyed years, the sandbank had retreated in response to its exposure to wind, waves/currents, the tidal cycle and a sea level rise some 1050 m in a landward, eastern direction. Due to a slower landward retreat in the northern part and a faster retreat in the southern part, the sandbank had rotated around 18.5 degrees clockwise.
2. Despite its frequent movement, Norderoogsand has retained a quite stable area and volume above MHW. Volume and area of the sandbank developed proportionally. The sediments of the sandbank are redistributed internally.
3. In the north of Norderoogsand a dune island emerged in the early 2000s. The island has formed a coherent dune system with a dense cover of associated vegetation and a freshwater aquifer beneath the surface. Salt marshes are developing on the lee side of the main dune bow. During events of exceptional high water levels, seawater inundates the salt marshes and lower dune ridges.
4. The island has distinct features of a barrier island and seems to be a persistent structure on Norderoogsand.

Acknowledgements

I kindly thank Athanasios Vafeidis and Tobias Dolch for supervising my thesis, for their scientific advice and for their helpful and constructive criticism. Martin Stock and Karsten Reise are gratefully acknowledged for their counsel and support, furthermore Martin Stock is especially thanked for providing me laserscan data and literature. I would like to thank the AWI staff, especially Christian Buschbaum, Christian Hass, Joshua Kiesel, Elisabeth Herre and Kaibil E. Wolf. I am very grateful to the Jordsand Ornithological and Nature Conservation Society, in particular Christel Grave, who was of tremendous help organizing the trip and the transport to and from Norderoog. Furthermore I kindly like to thank Iko Schneider and Frank Paap, for hosting and supporting us during the field campaign.

From the University of Kiel I would kindly like to thank Hans Rudolf Bork for supporting and counselling me throughout my studies. Rolf Gabler-Mieck and Sophia Dazert are thanked for the provision of laserscan datasets and aerial imagery.

From Schleswig-Holstein's Government-Owned Company for Coastal Protection, National Parks and Ocean Protection (LKN-SH) I would like to thank Carl Carstensen for the permissions to work in the national park, Lutz Christiansen for technical support and advice, Arfst Hinrichsen for the provision of laserscan data, as well as elevation measurements and maps and Birgit Matelski for her support of my work.

From the Waterways and Shipping Board Tönning (WSA) I would kindly like to thank Veit-Hinnerk Bayer for information on water gauges and most helpful advice. Furthermore I thank Jan Christoph Thomsen and Traugott Hartkopf for gauge data.

From the Federal Maritime and Hydrographic Agency of Germany I am very grateful to Michael Hesse, who provided me with nautical charts, shapefiles and valuable counsel.

I thank the State Agency for Agriculture, Environment and Rural Areas (LLUR), especially Birgit Trölenberg and Petra Bracker who provided access to their archives and aerial imagery.

I would like to thank the State Agency for Geodetics and Geo-Information (LVermGeo SH), in particular Oliver Schneider for his help acquiring laserscan data and aerial imagery.

The State Archives Schleswig-Holstein and especially Jürgen Wieben are thanked for aerial imagery. I thank Germany's National Meteorological Service (DWD) for wind data of the survey area. Furthermore, I would like to thank Jacobus L.A. Hofstede for a very helpful telephone conversation, Wolfgang B. Hamer for his technical support and Marita S. Seidel and Sara S. Jones for their support during my work.

Literature

Ahrendt, K., 2005. Abschlussbericht Wattenmeersedimente: Sedimentinventar Nordfriesi-sches Wattenmeer.(http://www.iczm.de/kfi.pdf)

Anthony, E.J., 2013. Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. Geomorphology 199, 8–21. doi:10.1016/j.geomorph.2012.06.007

Anthony, E.J., Ruz, M.H., Vanhée, S., 2009. Aeolian sand transport over complex intertidal bar-trough beach topography. Geomorphology 105, 95–105. doi:10.1016/j.geomorph.2007.12.013

Brzank, A., Heipke, C., Goepfert, J., Soergel, U., 2008. Aspects of generating precise digital terrain models in the Wadden Sea from lidar–water classification and structure line extraction. ISPRS J. Photogramm. Remote Sens. 63, 510–528. doi:10.1016/j.isprsjprs.2008.02.002

Carter, R.W.., Forbes, D.., Jennings, S.., Orford, J.., Shaw, J., Taylor, R.., 1989. Barrier and la-goon coast evolution under differing relative sea-level regimes: examples from Ireland and Nova Scotia. Mar. Geol. 88, 221–242. doi:10.1016/0025-3227(89)90099-6

Christiansen, C., Aagaard, T., Bartholdy, J., Christiansen, M., Nielsen, J., Nielsen, N., Peder-sen, J.B.T., Vinther, N., 2004. Total sediment budget of a transgressive barrier-spit, Skallingen, SW Denmark: A review. Geogr. Tidsskr. J. Geogr. 104, 107–126.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merri-field, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergov-ernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Common Wadden Sea Secretariat (CWSS), 2008. Nomination of the Dutch-German Wadden Sea as World Heritage Site. Nomination dossier to the UNESCO for inscription into the World Heritage list. Wadden Sea Ecosystem No. 24. Wilhelmshaven, Germany.

De Groot, A.V., Veeneklaas, R.M., Bakker, J.P., 2011. Sand in the salt marsh: Contribution of high-energy conditions to salt-marsh accretion. Mar. Geol. 282, 240–254. doi:10.1016/j.margeo.2011.03.002

Ehlers, J., 1988. The morphodynamics of the Wadden Sea. Balkema, Rotterdam.

Eitner, V., 1996. Geomorphological response of the East Frisian barrier islands to sea-level rise: An investigation of past and future evolution. Geomorphology 15, 57–65. doi:10.1016/0169-555X(95)00116-M

Hayes, M.O., 1979. Barrier island morphology as a function of tidal and wave regime., in: Leatherman, S. (Ed.), Barrier Islands, from the Gulf of St. Lawrence to the Gulf of Mexi-co. New York, pp. 1–27.

Hofstede, J.L.A., 1997. Process-response analysis for the north Frisian supratidal sands (Ger-many). J. Coast. Res. 13, 1–7.

Hofstede, J.L.A., 1999. Regional differences in the morphologic behaviour of four German Wadden Sea barriers. Quat. Int. 56, 99–106. doi:10.1016/S1040-6182(98)00026-3

Jensen, J., Frank, T., Wahl, T., Dangendorf, S., 2011. KFKI-Projekt AMSeL „Analyse von hoch-aufgelösten Tidewasserständen und Ermittlung des MSL an der deutschen Nordseeküs-te". Siegen, Germany.

Lammerts, E.J., Petersen, J., Hochkirch, A., 2009. Beaches and Dunes. Thematic Report No. 15., in: Marencic, H., Vlas, J. de (Eds.), Quality Status Report 2009. WaddenSea Ecosys-tem No. 25. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group. Wilhelmshaven, Germany.

Landesbetrieb für Küstenschutz Nationalpark und Meeresschutz Schleswig-Holstein (LKN), 2014. Fachpläne Küstenschutz - Digitales Geländemodell 1 (DGM 1) [WWW Document]. URL http://www.schleswig-holstein.de/Kuesten-Schutz/DE/C_Datengrundlagen/DGM1/DGM1_node.html (accessed 3.11.14).

Leica Geosystems Inc., 2005. GPS1200 RTK Quick Guide Version 2.0.

Liebezeit, G., Wehrmann, A., Hecker, N., Czeck, R., 2013. Die Kachelotplate - Einblicke in die Entstehung von Barriereinseln. Natur- und Umweltschutz (Zeitschrift Mellumrat) 12, 7–17.

Oost, A.P., De Boer, P.L., 1994. Sedimentology and Development of Barrier Islands , Ebb-tidal Deltas, Inlets and Backbarrier Areas of the Dutch Wadden Sea. Senckenbergiana maritima 24, 65–115.

Oost, A.P., Hoekstra, P., Wiersma, A., Flemming, B., Lammerts, E.J., Pejrup, M., Hofstede, J., van der Valk, B., Kiden, P., Bartholdy, J., van der Berg, M.W., Vos, P.C., de Vries, S., Wang, Z.B., 2012. Barrier island management: Lessons from the past and directions for the future. Ocean Coast. Manag. doi:10.1016/j.ocecoaman.2012.07.010

Reise, K., Baptist, M., Burbridge, P., Dankers, N., Fischer, L., Flemming, B., Oost, A.P., Smit, C., 2010. The Wadden Sea – A Universally Outstanding Tidal Wetland., in: Wadden Sea Ecosystem No. 29. Common Wadden Sea Secretariat, Wilhelmshaven, Germany, pp. 7–24.

Rosenhagen, G., Schatzmann, M., 2011. Das Klima der Metropolregion auf Grundlage meteorologischer Messungen und Beobachtungen. Springer, Heidelberg.

Schulz, H., 1947. Memmert, in: Die Welt Der Seevögel. Ein Führer Durch Die Vogelbrutstät-ten Der Deutschen Küsten. Anton Lettenbauer, Hamburg, pp. 30–35.

Stock, M., 2013. Seltener Pflanzenfund auf dem Norderoogsand. Seevögel 34, 169.

Stock, M., Braun, M., Fleet, D.M., Hellfritz, K.-P., Hälterlein, B., Knopp, L., Levsen, E.-J., 2013. Norderoogsand - vom Sand zur Insel? Falke 60, 321–324.

Tillmann, T., Ziehe, D., Wunderlich, J., 2013. Holozäne Landschaftsentwicklung an der West-küste der Nordseeinsel Amrum. Quat. Sci. J. 62, 98–119.

Trimble Navigation Ltd., 2012. GeoExplorer 3000 Series GeoXT Handheld Support [WWW Document]. URL http://ww2.trimble.com/geoxt3000_ts.asp?Nav=Collection-76246

Verein Jordsand zum Schutze der Seevögel und der Natur e.V., n.d. Norderoog-Sand (NP SH) [WWW Document]. URL http://www.jordsand.eu/index.php?id=45 (accessed 4.28.14).

Vidal, E., Médail, F., Tatoni, T., Roche, P., Vidal, P., 1998. Impact of gull colonies on the flora of the riou archipelago (Mediterranean islands of south-east France). Biol. Conserv. 84, 235–243. doi:10.1016/S0006-3207(97)00130-4

Wehrmann, A., Tilch, E., 2008. Sedimentary dynamics of an ephemeral sand bank island (Kachelotplate, German Wadden Sea): An atlas of sedimentary structures. Sencken-bergiana maritima 38, 185–198.

Wietz, P., 2002. GIS-gestützte Analysen und dynamische 3D- Visualisierungen der morpholo-gischen Entwicklung schleswig-holsteinischer Tidebecken. Kiel. (http://www.sterr.geographie.uni-kiel.de/downloads/Diss_Petra_Witez.pdf)

Author

Moritz Padlat
Hasseldieksdammer Weg 27
D-24114 Kiel

moritz.padlat@gmx.de

Jordsand – A Danish Wadden Sea island that has disappeared

John Frederiksen

Jordsand – A Danish Wadden Sea island that has disappeared

Introduction

Just before the turn of the millennium, the small Danish Wadden Sea hallig, Jordsand, ceased to exist. In the autumn of 1999, the nature observation hut on Jordsand was set on fire; a ritualistic act symbolising the end of Jordsand as an island in the Wadden Sea. The only Danish hallig had finally vanished, after centuries of erosion by the sea. The remainder became part of the high sandbank between the Danish mainland and the German island of Sylt (Fig. 1).

In 1974, Jordsand was still a small hallig surrounded by mud flats and high sandbanks, as shown in the aerial photograph (Fig. 2).

Jordsand in a historical light

Today, when looking at the Wadden Sea from the geest cliff on the mainland, it is hard to imagine that in the Middle Ages the present coastal zone of 6-7 km width was covered by an almost uninterrupted marsh surface, and, according to contemporary sources, only separated from the mainland by a tidal gully (Jacobsen 1941). What we do know, however, is that Jordsand for centuries was a hallig similar to the present Halligen in the North Frisian Wadden Sea, and that these are remnants of a former large salt marsh area eroded by the sea.

From several historic maps and nautical charts we do know that Jordsand must have had a significant size in 1600s and 1700s. The first charts of the Danish Wadden Sea date back from the late 1500s (Jepsen 1976). At first sight they seem inaccurate and simple, but the main purpose of nautical charts is coastal recognition and navigation at sea, not the representation of landforms and their dimensions. So these old charts cannot tell us the precise size of Jordsand at the time of their publication, nor can they indicate changes in the islands' land areas (Jensen 1997).

The first time Jordsand appears on a nautical chart is in 1585, when the Dutch cartographer Lucas Janzoons Waghenaer's (1534-1606) "Spieghel der Zeevaerdt" was published. This included a section of the North Sea and the Wadden Sea between the River Elbe and Blåvandshuk. In 1608, his successor Willem Blaeu (1571-1638) published his nautical chart "*Het Licht der Zeevaert*", which was based mainly upon information from Waghenaer's chart (Jepsen 1976).

On Blaeu's chart the island of Rømø (Rÿm) features only a church tower and what is probably a mill on a silhouette of the dunes. It does not mean that there were no settlements on Rømø at the time, but the chart indicates only the visible elements that were important for navigation at sea. The two farmhouses on the flat marshland on Jordsand (Jurtmans huys), however, were visible from the sea and could therefore be used for navigation. The chart gives a heading to the northern house - ENE, a dash to the south - to secure entry through the Lister Deep (Diep van List).

Fig. 1:
Satellite photo of the island Sylt and the sand banks (white) on the location of the former isle of Jordsand, August 2006.
Source: Wikimedia Commons.

Fig. 2:
Jordsand in 1974, with the observation hut. In the background the mainland coast. Photo: Svend Tougaard.

In the mid-1600s, maps and charts of Schleswig-Holstein by the Danish cartographer Johannes Meier (1606-74) were collected in the work "Newe Landes-beschreibung there zwey Hertzogthümer Schleswich und Holstein" (Fig. 4). The size of Jordsand was then, roughly six km^2 (600 ha). Meier's charts and maps were

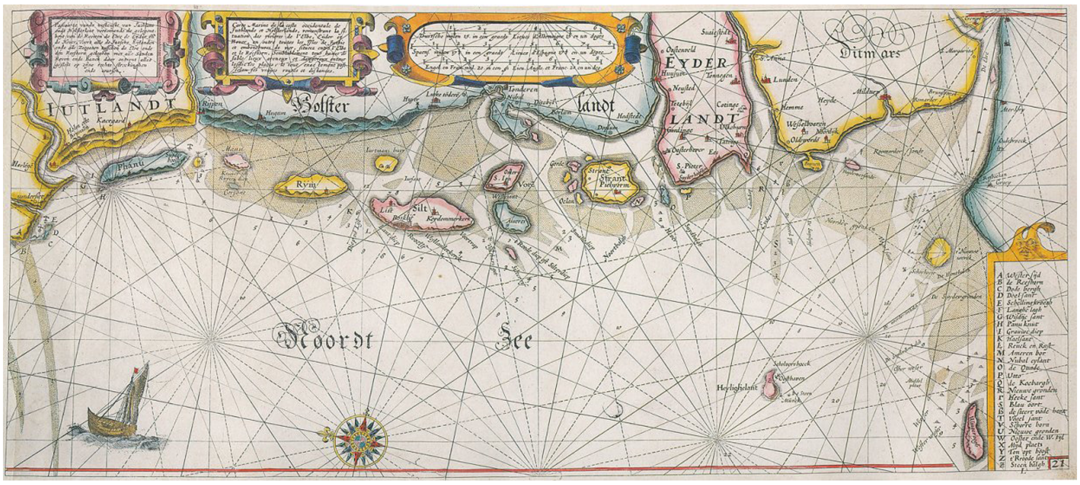


Fig. 3: Section of Willem Blaeu's chart from 1608 showing the North Sea and the Wadden Sea between the river Elbe and Blåvandshuk.

considered to be reasonably accurate by his contemporaries, although it is difficult to determine which information results from actual measurements and which originates from oral narrations (Fig. 4).

Fig. 4: Section of Johannes Meier's map from 1648 showing the Wadden Sea around Jordsand; with an indication of a sea battle in 1644 between the Danish fleet and a combined Swedish-Dutch fleet.

In 1805-07, the first thorough cartographic measurements of the Danish Wadden Sea were carried out (Fig. 5). A comparison with today's navigational charts indicates that Jordsand is accurately positioned. The size of the hallig by this time is approximately 40 ha. Thus it is not until the early 1800s that we have dependable land outlines and dimensions in the Danish Wadden Sea and hereby a more exact indication of the dynamics in the different parts of the Danish Wadden Sea.

Jordsand's degradation

From 1807 onwards, the degradation of Jordsand was rapid. In 1807 the hallig's 40 ha consisted exclusively of marsh land. By 1873 the surface area had decreased to 20 ha, of which 75 % was marsh. In 1936 there was no more than 8 ha left, and in 1973 only 2.3 ha, of which less than 10 % was marsh land. Only 0.2 ha was left in 1994. Finally, in 1999, the hallig of Jordsand no longer existed (Jespersen & Rasmussen 1995).

Apparent from the sketch in figure 6, the degradation of marsh land took place mainly

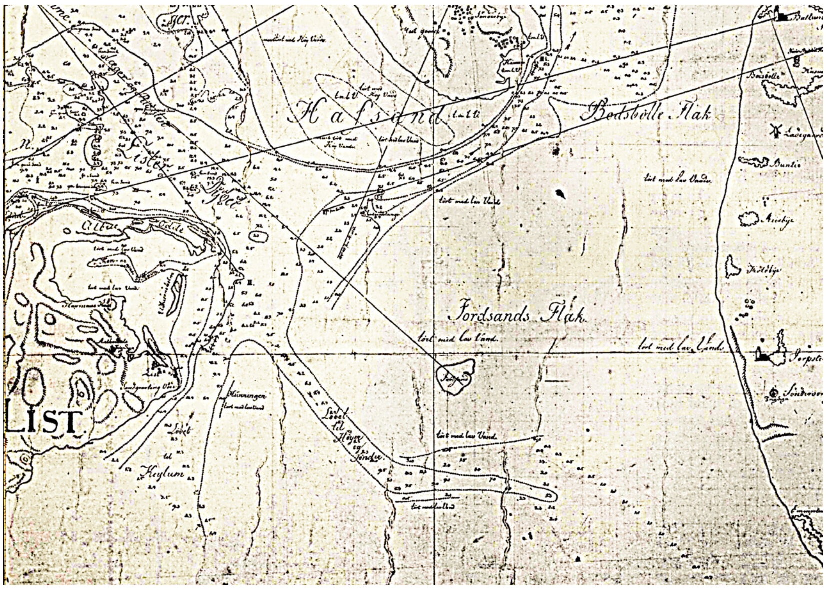


Fig. 5: Section of Holst and Tuxen's chart of the Danish Wadden Sea from 1807.

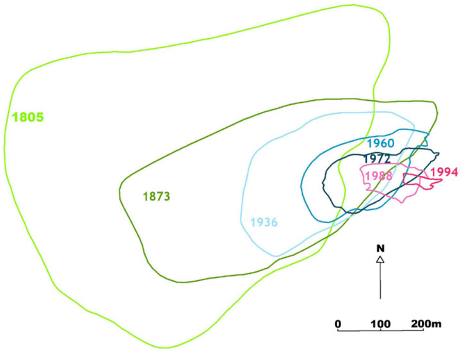


Fig. 6: Jordsand's degradation from 1807 to 1994. The delineation shows the areas with vegetation coverage. After Jespersen and Rasmussen, 1996; modified by Svend Tougaard, 2013.

on the northern and western sides of Jordsand. The last remnants of the marshes disappeared in 1983 but simultaneously with the erosion of the marshes, sand ridges were built up on the eastern side. In 1999 the last vegetation-covered sand ridges were also engulfed by the sea.

In the period 1976-78, attempts were made to stop the erosion by constructing brushwood groynes. These coastal protection measures failed though, and the maintenance of the groynes was abandoned in 1987.

The main reason for the degradation of Jordsand was that the hallig, like the existing Halligen in the North Frisian Wadden Sea, was never surrounded by a proper dyke to protect it against the destructive forces of the sea. Moreover, Jordsand was located within the only tidal basin in the entire Wadden Sea the hydrological conditions had undergone drastic changes in the last 50 years due to the construction of dams between the islands of Sylt and Rømø and the mainland in 1927 and 1948. Since then, tides and storm surges have been flowing in and out through the one and only tidal inlet (Lister Deep) between two barrier islands; water transport across tidal watersheds was no longer possible. Whether these changed conditions have contributed to the downfall of Jordsand has not been documented. However, measurements within the Lister Deep tidal basin in 1968 and 1994 demonstrated an erosion of 1.3 million m^3 of sediment for the entire intertidal area in these 25 years, which is equivalent to an average erosion of 1 mm per year (Anonymous 1999).

Jordsand – an inhabited Hallig

Since the early 1900s Jordsand and surroundings has been subject to regular surveys and monitoring to document its natural values and importance. Less is known of Jordsand's cultural (historical) conditions through time. Very few artefacts have been found to cast light on the puzzle of how human habitation has unfolded in this isolated and exposed edge of Denmark.

Details on the nautical charts from the late 1500s and 1600s indicate that there was human settlement (farms) on Jordsand in that period, but settlement has been reliably reported as early as the 1200s. In the Danish king's records from 1231, Jordsand is referred to as "Hjortsands House". This has been interpreted as the king's residence during his hunting trips on the hallig, for deer and other game. The name Jordsand is thought to be derived from the Danish word "hjort" for "deer" (Jacobsen 1941).

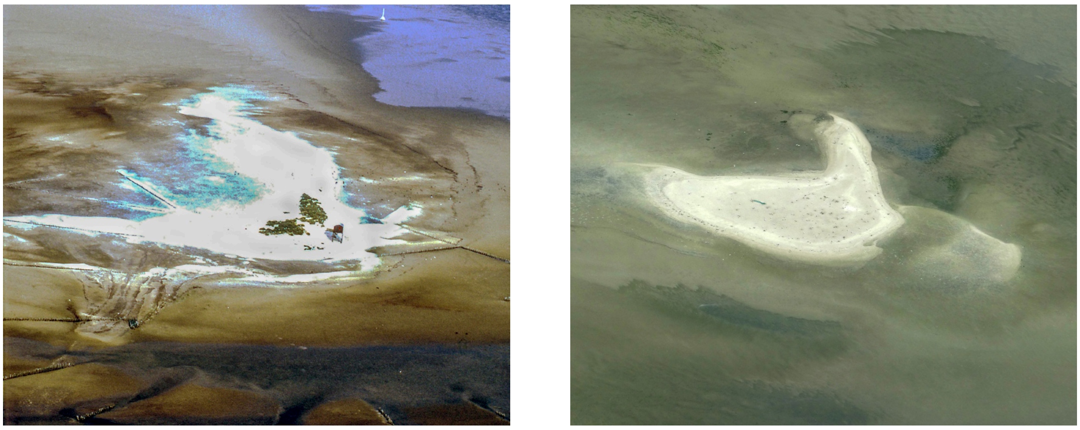


Fig. 7: Areal photographs of the Jordsand area in 1996 (left; Svend Tougaard) and 2014 (right; Karsten Reise).

At what time in its history the hallig was inhabited all year round, and when this was replaced by seasonal habitation cannot be determined with certainty. From local archives it can be proven that in 1543 there was one settlement on the hallig; in 1607 the archives referred to two settlements. From records in the late 1600s it can be seen that permanent habitation of Jordsand probably ceased around 1695, partly due to a violent storm surge that year. Since then, the hallig is thought to have been used only for grazing and hay making during the summer season. From 1700 onwards, archives deal almost exclusively with correspondence between land-owners and authorities about requests for tax reductions, probably in conjunction with the damage and loss of land on the hallig due to the continuous attack by the sea (Jepsen 1976).

In 1897, the owners requested the Prussian State to pay for the reconstruction of the shepherd's brick hut and the dwelling mound it was built on. These had been destroyed by a storm surge one and a half years earlier. The application, however, was refused and the dwelling mound was never reconstructed.

In August 1923, a storm surge that drowned sheep and horses brought a total halt to the agricultural use of the hallig of Jordsand.

Traces of past habitation

In 1969, the first archaeological evidence of Jordsand's habitation history was discovered, when the owner unearthed a drinking water well made of bricks. In 1975, another brick-lined well was found and in 1978 the last remnants of a clay-lined well appeared. The most recent find showed up in 1982, when a profile of cut clay-blocks was exposed. All four records are within a distance of approx. 100 meters (Fig. 8).

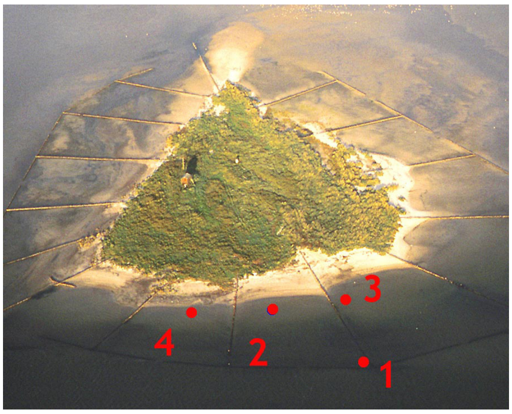


Fig. 8: Aerial photo of September 1979 with locations of the archaeological finds at Jordsand: 1 = brick-lined well (1969); 2 = brick-lined well (l975); 3 = clay-lined well (1978) and 4 = clay block profile (1982). Photo and graphics: Svend Tougaard.

The brick-lined well found in 1969 was about two metres deep and one meter in diameter. It was built of rhombic, hand-made bricks, piled without mortar in a spiral form with decreasing diameter from bottom to top (Fig. 9). The profile of the cut clay-blocks (30x30 cm) at location 4 is shown in figure 10.

Fig. 9: The brick-lined well found in 1969. Photo: Private.

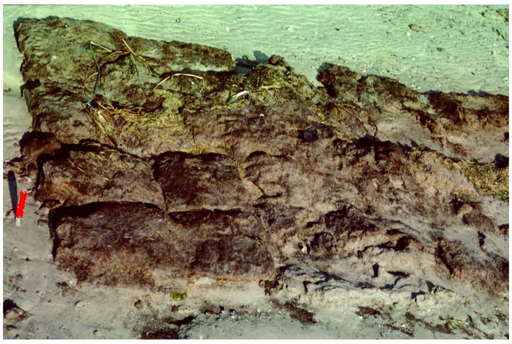


Fig. 10 (right): Profile of cut clay-blocks. Photo: John Frederiksen.

Several sources have claimed that the two brick-lined wells were cisterns and remains of the settlements in the 1500s and 1600s. Cisterns to collect fresh water from the roofs for the residents are characteristic past features of the freshwater supply in many parts of the Wadden Sea area in (Fig. 11).

It was, however, a great surprise that the excavation of the brick-lined well of 1969 revealed that this well, unlike the characteristic cisterns on the Halligen, rested on an open pinewood sill similar to wells on the geest (Fig. 12).

Fig. 11 (right): Excavated cistern from Hallig Hooge in the North Frisian Wadden Sea, 1965. Photo: Thorkild Funder.

The pinewood sill and its nail holes could indicate that this well originated from the late 1800s and perhaps had been in use until 1923, when agriculture on the hallig ceased. This hypothesis is supported by the shape and size of the bricks and by their probable origin. In the 1800s, in the village of Koldby on the mainland opposite Jordsand, two brick kilns producing bricks of the same shape and size as those found in the well on Jordsand were in operation.

Regardless of the age of the brick wells, one must pose the question: how can "open-bottom" wells serve as freshwater storage in the saline environment of the Wadden Sea? Were there any special conditions on and around Jordsand, like the presence of an aquifer in the subsoil, which made it possible to form and maintain a body of freshwater?

Comparable conditions are found in the North Frisian Wadden Sea. After the storm surge in 1962 comprehensive studies of fresh water supply in all halligen were carried out. These revealed a well in the salt marsh just east of Hamburger Hallig containing a salt concentration of only 160 mg NaCl/l (Wohlenberg 1962). The explanation of the low salt concentration was fresh water pressure from the geest, north of Bredsted – almost ten kilometres east of the well! So could this context have been encountered in the case of Jordsand, fed by fresh-water from Hjerpsted geest cliff on the mainland seven kilometres away? Or does the explanation lie in the circumstance that the fresh rainwater has simply superimposed itself on the much heavier salt water in the wells of Jordsand? And was it that this capacity was sufficient to meet - or supplement - the human need for fresh water in the summer stays on the hallig? We don't know. And there have never been studies of the geological stratification in this part of the Wadden Sea that could shed light on this phenomenon.

Jordsand – a fore post of Wadden Sea protection

In the period 1864-1920, Jordsand was part of the Kingdom of Prussia. On both sides of the border at that time, there was an interest in protecting nature. The Wadden Sea was already known for its rich bird life, and a summer visit by German birdwatchers to the hallig in 1907 was the beginning of the formation of bird conservation organization "Verein Jordsand". Unlike the hallig, the German society still exists and is very active in the protection of coastal birds in the German part of the Wadden Sea and along the German Baltic coast. This more than 100 year-old initiative will probably be the only thing that will continue to remind us of the name of the now-defunct Danish hallig in the Wadden Sea.

After the hallig again became Danish, the Danish Ornithological Association (DOF) continued the observations on Jordsand. In 1922, the same year as the hallig's bird life was preserved by a statutory order, DOF contributed to the continuation of the German pioneering work with the appointment of a warden. During the summer months he continuously studied the hallig's rich bird life. The result of this voluntary work at Denmark's first bird station was the creation of the first Danish game reserve in the Wadden Sea in 1939. From 1960, the bird life on and around Jordsand became the subject of more extensive scientific studies which were made from the observation hut that was burned down in 1999.

Fig. 12:
A 1979 photo of part of the wooden sill of the well found in 1969. During these ten years the well was almost entirely washed away.
Photo: John Frederiksen.

Fig. 13:
The logo of Verein Jordsand.
Source: Wikipedia Commons.

Fig. 14:
The ritualistic burning of the observation hut in September 1999 symbolised the demise of Jordsand as a hallig in the Wadden Sea.
Photo: Svend Tougaard.

Epilogue

"Nothing in this area can survive unchanged. Erosion and sedimentation processes bring about continual change which, at the same time, both aid and hinder documentation efforts. In general, experience gathered in recent decades has shown that the destruction of cultural signs or traces in the Wadden Sea Area continues to advance and that there is indeed reason to make immediate use of these cultural signs for research into the history of the land and its settlement before they disappear forever"...(Vollmer *et al.* 2001).

Acknowledgements

Svend Tougaard, Ribe, for the use of photos, graphics and other valuable contributions to the article. Hans Peter Krogh, Koldby, for oral information about the brick production in Koldby, 2013.

Literature

Jacobsen, N. H. (1941): Jordsand. Haderslev-Samfundets Aarsskrift. Haderslev.

Jepsen, P. U. (1976): Jordsand – Fuglenes ø i Vadehavet. Bygd, Esbjerg.

Jensen, T. (1997): Omkring et søkort. Sjæk'len, Esbjerg, 1998.

Jepsen, P. U. (1976): Jordsand – Fuglenes ø i Vadehavet. Bygd, Esbjerg.

Jespersen, M. & Rasmussen, E. (1995): En beskrivelse af de nationale geologiske interesseområder nr. 104 og 105. Skov- og Naturstyrelsen, Kbh., 1996.

Anonymous (1999): Lister Dybs Tidevandsområde og Vadehavsfronten. Kystinspektoratet, Lemvig.

Jacobsen, N.H. (1941): Jordsand. Haderslev-Samfundets Aarsskrift. Haderslev.

Wohlenberg, E. (1962): Die Trinkwasserversorgung der Halligen nach der Sturmflut im Februar 1962. Die Küste, Heft 2, Heide.

M. Vollmer, Guldberg, M., Maluck, M., Marrewijk, D, Schlicksbier, G. (2001): Landscape and Cultural Heritage in the Wadden Sea Region – Project Report, Wadden Sea Ecosystem No. 12, CWSS, Wilhelmshaven.

Author

John Frederiksen
Dronning Margrethes Vej 23,3
DK- 8200 Aarhus N
emiljeppe@yahoo.dk

Issues of the Publication Series „Wadden Sea Ecosystem“

No. 1: Breeding Birds in the Wadden Sea 1991. 1994.
No. 2: Migratory Waterbirds in the Wadden Sea1992/93. 1994.
No. 3: Guidelines for Monitoring of Breeding Birds in the Wadden Sea (in Dutch, German, Danish). 1995.
No. 4: Breeding Birds on Census Arteas 1990 until 1994. Status of Shorelark, Twite and Snow Bunting in the Wadden Sea. 1997.
No. 5: Migratory Waterbirds in the Wadden Sea 1993/94. 1996.
No. 6: Trilateral Monitoring and Assessment Program. TMAP Expert Workshops 1995/96. 1996.
No. 7: Assessment of the Wadden Sea Ecosystem. 1997.
No. 8: Monitoring Breeding Success of Coastal Birds. Monitoring Pollutants in Coastal Bird Eggs in the Wadden Sea. 1998.
No. 9: Wadden Sea Quality Status Report 1999. 1999.
No. 10: Breeding Birds in the Wadden Sea in 1996. 2000.
No. 11: Contaminants in Bird Eggs in the Wadden Sea. Spatial and Temporal Trends 1999 - 2000. 2001.
No. 12: Lancewad. Landscape and Cultural Heritage in the Wadden Sea Region. 2001.
No. 13: Final Report of the Trilateral Working Group on Coastal Protection and Sea Level Rise. 2001.
No. 14: Wadden Sea Specific Eutrophication Criteria. 2001.
No. 15: Common and Grey Seals in the Wadden Sea. TSEG-plus Report March/June 2001.2002.
No. 16: High Tide Roosts in the Wadden Sea. A Review of Bird Distribution, Protection Regimes and Potential Sources of Anthropogenic Discturbance. 2003.
No. 17: Management of North Sea Harbour and Grey Seal Populations. Proceedings of the International Symposium at EcoMare, Texel, The Netherlands November 29 - 30, 2002. 2003.
No. 18: Contaminants in Bird Eggs in the Wadden Sea. Recent Spatial and Temporal Trends. Seabirds at Risk? Effects of Environmental Chemicals on Reproductive Success and Mass Growth of Seabirds at the Wadden Sea in the Mid 1990s. 2004.
No. 19: Wadden Sea Quality Status Report 2004. 2005.
No. 20: Migratory Waterbirds in the Wadden Sea 1980 - 2000. 2005.
No. 21: Coastal Protection and Sea Level Rise - Solutions for Sustainable Coastal Protection. 2005
No. 22: Breeding Birds in the Wadden Sea in 2001. 2006.
No. 23: Seriously Declining Trends in Migratory Waterbirds: Causes-Concerns-Consequences. Proceedings of the International Workshop on 31 August 2005 in Wilhelmshaven, Germany. 2007.
No. 24: Nomination of the Dutch-German Wadden Sea as World Heritage Site. 2008.
No. 25: Wadden Sea Quality Status Report 2009. 2009.
No. 26: Science for Nature Conservation and Managment: The Wadden Sea Ecosystem and EU Directives. Proceedings of the 12th International Scientific Wadden Sea Symposium in Wilhelmshaven, Germany, 30 March - 3 April 2009. 2010.
No. 27: Exploring contrasting trends of migratory waterbirds in the international Wadden Sea. 2010.
No. 28: CPSL Third Report. The role of spatial planning and sediment in coastal risk management. 2010.
No. 29: The Wadden Sea - A Universally Outstanding Tidal Wetland. The Wadden Sea Quality Status Report. Synthesis Report 2010.
No. 30: Migratory Waterbirds in the Wadden Sea 1987-2008. 2010.
No. 31: Trends of Migratory and Wintering Waterbirds in the Wadden Sea 1987/1988-2010/2011. 2013.
No. 32: TMAP-Typology of Coastal Vegetation in the Wadden Sea Area. 2014.
No. 33: Dynamic Islands in the Wadden Sea. 2014.