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Dune development and management, geomorphological and soil processes, responses to sea level rise and climate change

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Abstract Theories on the formation of coasts and dunes found in textbooks are not always based on up-to-date geomorphological research. They may lead to wrong decisions in coastal management. This paper exposes and corrects a number of these theories. It also identifies some enigmas in geomorphological dune research which have never been adequately solved. They include structural, process/response and scale problems. A conventional classification of dune landscapes which is relevant for dune management is used to describe the characteristics of dune landscapes. Some dune landscapes do not fit in with this classification because they depend on special factors: topography, past climate or former land use. Finally, the threats formed by sea level rise and climate change are discussed, ending with some geomorphology-oriented mitigation measures.

Keywords *Dune functions, embryodunes, algae, grey dunes, parabolic dune, water repellence, slope wash, sand nourishment.*

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INTRODUCTION

This paper is an adaptation of the presentation given at the EU TAIEX Workshop on Sustainable Coastal Management, Sea–Level Rise & Climate Change in the Baltic States, Poland and Russia, held in Palanga, Lithuania, April 2008. It is the aim of a TAIEX workshop to exchange information between specialists of old and new EU countries. This means that emphasis in this paper is on the management of dunes along the North Sea coasts.

Dune management is a complicated task, because the coastal dunes have many functions in modern society:

- defence against the sea
- nature conservation
- public drinking water extraction
- recreation
- housing and industry
- agriculture
- grazing
- military defence

Each of these functions requires customized management. For most functions, it is of vital importance to know how the geomorphological processes work, because coastal dunes belong to the most dynamic landscapes in the world. There are many theories about the geomorphology of dune landscapes. These theories are found in general textbooks, but they are often outdated and not based on geomorphological research. They are the cause that those in charge of coastal management can easily take wrong decisions. This leads to management measures which are counter-productive. The geomorphological processes of dune formation are not easily understood because wind is unpredictable and its effects are complex. Moreover, the additional effects of geomorphological processes caused by rain make the matter more complicated. Research is the only way to find out how nature really works. Management measures issuing from this insight have a more sustainable effect.

GEOMORPHOLOGICAL PROCESSES IN DUNE FORMATION

Research of the last decades, specifically aimed at understanding the geomorphological processes involved in creating and changing dune forms (Jungerius & Van der Meulen 1988), have proved several commonly accepted theories to be wrong. Some of these misconceptions are related to wind processes, others to pluvial, i.e. rain–induced processes, again others to the combination of wind and rain, or to the role of animals.

One of the common beliefs is that during heavy storms, sand from the beach can be blown far inland, burying roads and villages. This is true only for dust particles (< 0.05 mμ) such as loess which are transported in suspension. Wind moves sand grains, which are larger than 0.05 mμ, in saltation, closely following the ground surface (Bagnold 1954). Arens *et al*. (1995) and Van Boxel *et al*. (1999) have shown that wind accelerates when climbing up the slope of the foredune transporting sand grains from the beach, but as soon as the crest is reached, wind velocity drops off. The sand particles are deposited on the crest of the foredune or on the lee slope. In the latter case they seldom reach further than 100 m from the crest. This is clear for those who have selected *Wind* as screensaver in Microsoft Windows. The screensaver also shows that a different situation exists when the whole dune starts wandering. This can happen on a retreating coast when the protective Marram grass vegetation is removed from the face of the foredune. The entire foredune may move land inward, but this movement is basically a gradual mass movement process not directly related to wind speed. If not checked, the front of the wandering dune can eventually cover all obstacles in its way, but with a speed of 5 to 15 metres per year this is a slow process.

A physical law which is often wrongly interpreted is: the stronger the wind, the more erosion. This may be true for a simple system where wind can act unimpeded, but in dune terrains where the topography controls the wind pattern, the effect of the wind is not a linear function of its speed. Research has shown that the aerodynamics of the forms already existing influence further wind action. The cases in point are blowouts. Years of monitoring their development in the coastal dunes in relationship to wind speeds and wind direction have shown that blowouts are adapted to a specific balance between wind frequency and capacity (Jungerius *et al*. 1981). The results of two years of weekly measuring show a number of blowouts in a dune terrain along the Dutch coast (Fig. 1). It turned out that blowout formation was tuned to a wind speed of 11.25 m/s measured at standard meteorological height (line c in Fig. 1). Wind speeds lower than 11.25 m/s were less effective, whereas higher wind speeds upset the whole system: the blowouts filled up with sand instead of being eroded. Apparently the higher speeds caused turbulences with reduced the erosive effect of the wind.

It is usually believed that blowouts expand downwind. Whereas it is true that particles taken up by the wind move in the same direction as the wind, the

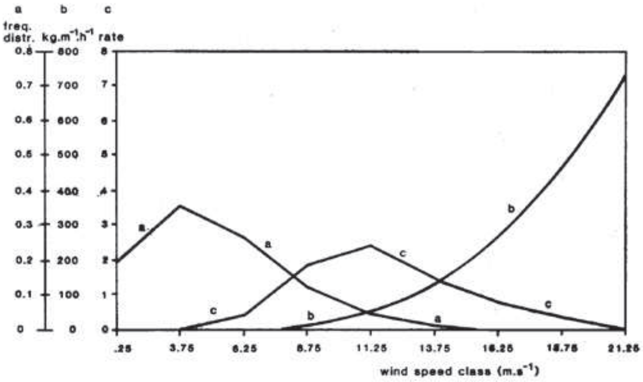

Fig. 1. The relationship between wind speed and frequency. In this case, 11.25 m/s is the most effective wind speed (Jungerius *et al*. 1991).

form resulting from the erosion process expands in the opposite direction, against the wind. The reason is that wind has its full erosive power when reaching the blowouts (Fig. 2), but looses energy as soon as it has

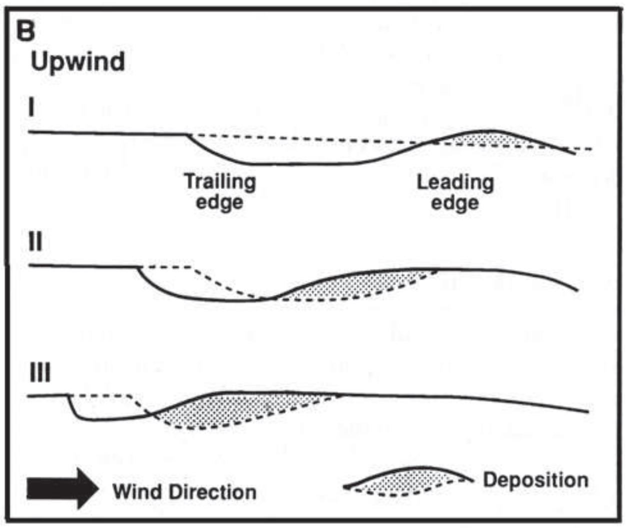

Fig. 2. Erosion at the windward side of a blowout or secondary dune valley. Fig. 2a shows the upwind migration of blowouts as drawn by Charter *et al*. (1990).

to transport the sand grains it has taken up. At a certain distance from the beginning of the blowout, erosion stops altogether because the wind needs all its energy for sand transport. When there is not even enough energy to keep the sand grains in the air, the wind drops its load and a dune is formed (Charter *et al*. 1990). This is the reason why wind erosion forms generally terminate in a dune. A similar phenomenon in fluvial geomorphology is known as retrograding erosion: the water of a river flows downstream, but undermines a waterfall, which moves upstream.

Fig. 2b is an actual example from the Dutch coast. The prevailing wind comes from the left.

Fig. 3. Reactivated parabolic dunes looking leeward (Råbjerg Mile, Denmark).

A related theory which has no more than limited truth content maintains that parabolic dunes are moving downwind. Air photo analysis and monitoring show that the leeward expansion of parabolic dunes in humid climates is often restricted because the crest is soon stabilized by vegetation. For the same reason as is the case for the terminal dune of blowouts, the parabolic dune is formed where the wind has no more energy for transport and drops his load in the vegetation. The higher the parabolic dune, the more sand has to be shifted and the slower the downwind movement. Finally the dune becomes stationary. This changes when the vegetation is removed from the crest. Then the parabolic dune is reactivated and moves downwind, often not over its full width, but by scattered outbreaks. Famous example is the Råbjerg Mile in the north of Jutland (Fig. 3).

It is often believed that straight lines in nature are artificial, because only man is supposed to work straight. What is not realized is that marine processes

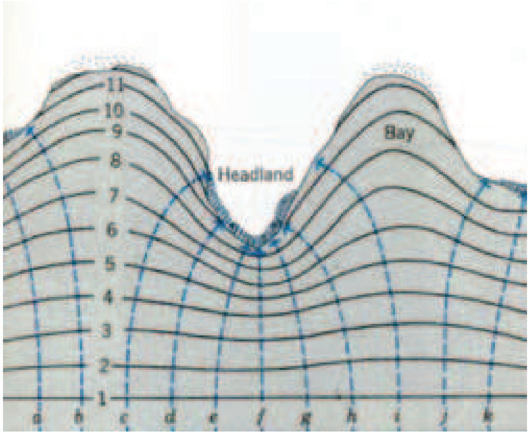

Fig. 4. Wave refraction on an embayed coast. The headlands are eroded, the bays filled in (Strahler & Strahler, 1992).

Fig. 5. The gaps in the original parallel foredune ridges in Tasmania are caused by European settlers in the 19th century (Davies, 1972).

tend to make straight coastlines: wave refraction concentrates wave energy and erosion upon promontories, and alongshore drift fills up the bays with the eroded material. The mechanism is explained by Strahler & Strahler (1992; Fig. 4). Foredunes along a straight coast are also straight, because they are formed parallel to the edge of the beach. Gaps in such systems are generally caused by man (Fig. 5) although the sea can form over washes when overtopping the dune ridge during an exceptionally high tide.

It is widely held that dune sands are extremely permeable. This is largely true for moist sand, but when the sand is dry it is often impermeable and water repellent after a dry period. Especially in the grey dunes behind the foredunes this causes slope wash when it starts raining (Fig. 6). Water entering the soil moves along preferential flow paths (Dekker & Jungerius 1990).

A related theory which is equally misleading is that only wind is a prominent geomorphic factor in coastal dunes. This is true only as long as the sand contains no organic matter, for instance in the foredunes. It is

Fig.6. A combination of wind ripples (wind came from the left) and slope wash (rill and colluvial fan).

difficult for wind to move the humic sand of the grey dunes further inland. This sand is water repellent when dry and is subject to water erosion and slope wash.

Many people believe that wet sand will not be taken up by wind. In actual fact, *splash drift* is a very effective process in coastal dunes (Rutin 1983). During rain storms, aggregates of sand are dislodged by raindrop impact and blown downwind and stick to objects they find on their way (Fig. 7). This process is the reason that excluding rainy days will often not improve the correlation between sand drift and wind in daily records (Rutin 1983).

Grazing animals such as rabbits are often blamed for starting wind erosion in the dunes, but the alleged cause-effect has never satisfactorily been established. Rabbits are commonly restricted to the grey dunes

Fig. 7. Splash drift, caused by rain during a storm.

because the white sand of the foredunes is too loose for digging their holes. The many small burrows they dig in the grey dunes *i.a.* to find food, seldom reach the loose erodible sand below the A horizon of the dune soil (Rutin 1983). The rabbits dig their much larger holes in north-exposed slopes where the risk of collapse is low, because the sand there has relatively high soil moisture content and is fairly coherent. This sand is not erodible by wind either. Rutin carried out his measurements before the major outbreaks of Myxomatosis and RHD, when rabbits were still abundant in the coastal dunes. Compared to processes caused by wind and rain, rabbit activity turned out to be insignificant. In fact, a statistical correlation between sand drift and the burrowing activity of rabbits is difficult to find (see Hole 1981, and Boorman 1977 in Rutin 1983).

DUNE LANDSCHAPES ARE AMBIGUOUS

After many decades of geomorphological research in dune landscapes, there are many questions which remain unsolved. Three of the puzzling questions are mentioned here.

The architectural enigma. The building stones of most dunes are simple and amount to no more than three types. What dune formation needs is **a)** wind of more than 6 km/hour (Bagnold 1954), **b)** sand between 100 and 600 mμ, or even between 200 and 400 mμ in size, and **c)** a sand binder, commonly Marram grass (*Ammophila arenaria*) which can outgrow burial of more than 1 metre of sand. How then can we explain the baffling variety of dune forms? Dunes are often described as chaotic, but measurements show that they are formed according to definite geometric relationships (Van der Wal *et al.* 1993).

The process/response enigma. The three main dune–forming processes are equally simple: **a)** erosion (deflation), **b)** transport (ripples), and **c)** accumulation (dune formation). For the development of a dune this means that there are, in the direction of the wind, areas of loss (erosion), no change (transport), and gain (accumulation). Why is there such a staggering diversity of forms?

The scale enigma. The variation in space and time needed for dune formation can be caught in a simple matrix (Table 1), but the thresholds between the scales remain unexplained.

Table 1. Scales of space and time in dune formation.

Space	Time	Form
centimetres	seconds	wind ripples
decimetres	hours	initial dunes
metres	days	blowouts
decametres	months	initial foredunes
hectometres	years	parabolic dunes

CLASSIFICATION OF DUNE LANDSCAPES

The well–known classification of dune landscapes (Fig. 8) recognizes different geomorphic and ecological zones and is management–oriented, with:

Zone 1	Beach with embryodunes: dominance of eolian processes (erosion and transport).
Zone 2	White (or yellow) dunes including foredunes: dominance of eolian processes (dune formation) decreasing with distance from the sea.
Zone 3	Grey dunes: dominance of soil-forming (water repellence) and pluvial processes (slope wash, colluviation), minor eolian processes (blowouts).
Zone 4	Brown (mature) dunes: dominance of soil-forming processes (forest soils), minor pluvial processes.

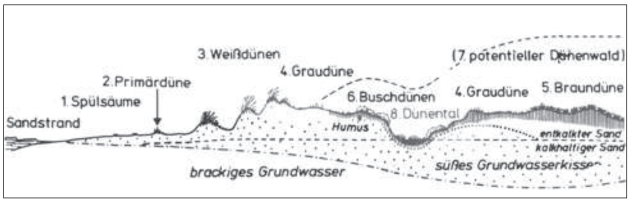

Fig. 8. Classification of the dune landscape (Ellenberg, 1978).

Ad Zone 1: Beach

On the upper part of the beach in the transition zone to the foredune, there is a variety of sand-catching vegetation forming initial dunes. The architecture of the plant determines the shape of the initial dune (Fig. 9).

Ad Zone 2: White (or yellow) dunes including foredunes

The foredune is a shore–parallel sand ridge, formed at a certain distance from the sea. This critical distance is determined by i.a. wind characteristics, availability and quality of the sand and slope of the beach. The wind on a *prograding* coast forms a new foredune in front of the old one when the width of the beach exceeds the critical distance.

The foredune is an accumulation form resulting from the combined action of sea and wind. Erosion of the foredune by sea or wind means destroying their own creation, which is intrinsically not plausible, in contrast to erosion by man. The seemingly defenceless foredune is therefore more resistant to natural erosion processes than non-specialists realize. But the foredune on a *retreating* coast is forced to shift inland with the coast line. It is remodelled by the wind through formation of blowouts and other incisions, so-called *secondary*

Fig. 9. Initial dunes. From left to right shadow dune, embryodune and obstacle dune.

dune valleys. Obstacles in front of the foredune such as wartime bunkers on the French beach, cause wind turbulence and promote the erosion of the foredune. Research has shown that these incisions seldom reach the lower area behind the foredune; sand accumulation and dune formation blocks the path of the wind at the end of the incision (Fig. 10) or the wind changes direction before reaching the crest of the foredune (Fig. 11). If the incision would break through, it might form a parabolic dune. This happens when the incision suffers from frequent passage by the public in beach resorts like near Merlimont, France.

The white dunes include the zone behind the foredune, where the time for soil formation has been too short to leave its mark in the sand. The sand is colonized by plants, and wind plays hardly a role anymore. The natural stabilization of the white dunes often begins with algae (Fig. 12) (Graebner 1910; Van den Ancker *et al*. 1985). When mosses and lichens appear, there is no more wind erosion. At this stage the white dunes turn into grey dunes.

Ad Zone 3: Grey dunes

The grey dunes where lichens or mosses dominate, owe their name to the colour of the humic surface soil (Graebner 1910; Jungerius 1990). This material is not sensitive to wind erosion. It is water repellent when dry, so rainwater will flow over the surface when a rain falls after a dry period (Jungerius & Ten Harkel 1994). Pluvial processes such as rain splash and slope wash are therefore the dominant geomorphic processes in this zone (see Fig. 9). In terms of Davis' cycle theory which he developed between 1884 and 1899 (Davis 1909/1954), the grey dunes are subject to the *normal cycle of erosion* of humid temperate regions. It implies an orderly evolution of landscape features with the passage of time: a dune once formed will be worn down by the erosional processes of a humid climate, just like any landscape in the humid climatic zones of the Earth.

Fig. 10. The foredunes along the Danish North Sea coast are eroded in many places, but no parabolic dunes are formed in the adjacent lowlands.

Fig. 11. Often seen along the Danish and Dutch coasts: deviation of an incision preventing breaching of the foredune.

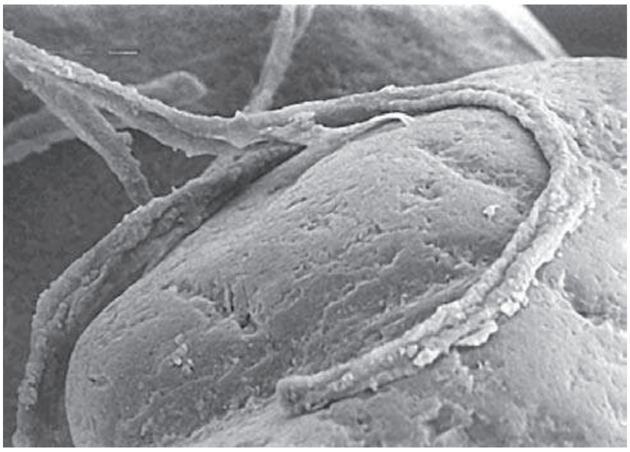

Fig. 12. Bonding of sand grains by algae (Van den Ancker *et al*., 1985).

An exception is formed by the blowouts found in this zone. The removal of the humic soil material from the upper slope by slope wash exposes the clean dune sand underneath which is subsequently affected by wind erosion (Fig. 13). This is the reason that most blowouts in the grey dunes occur in upper slope regions. Paradoxically, water erosion prepares the way for blowout formation by wind erosion.

Fig. 13. Erosion of the upper slope by slope wash has prepared the way for blowout formation by wind erosion.

Table 2 shows the production of one year of measuring the various processes on a grey dune along the Dutch coast, in an area that is closed to the public (calculated from Rutin 1983). The importance of slope wash is evident, especially on south-exposed slopes and in summer when the effects of water repellence are most noticeable.

Ad Zone 4: Brown or black dunes

This is the zone of dunes where heathland and/or woodland dominate and all geomorphic processes have stopped. The colours refer to the soil type which is formed under these types of vegetation (Van der Maarel 1993).

Table 2. Relative amount of sand passing 1 metre slope width along dune base, calculated from Rutin (1993). Winter period = 1.11.1979 – 1.5.1980; summer period = 1.5.1980 – 1.11.1980.

Process	Exposure	Season	Vegetation cover %	Production of sand, % of total
Wind	north		0	1,2
,,	south		0	7,5
Splash	north	winter	50	0,2
,,	,,	summer	76	0,1
,,	south	winter	12	1,4
,,	,,	summer	18	0,8
Slope wash	north	winter		0
,,	,,	summer		1,3
,,	south	winter		19,3
,,	,,	summer		67,8
Rabbits digging				0,1
,,				0,2

SPECIAL DUNE FORMS

There are a number of special dune forms which do not fit the classification given above. They are subject to specific geomorphological processes induced by the factors that formed the landscape. Some examples are given below.

Cliff dunes, the role of topography. Cliff dunes are often spectacular. They are formed where onshore winds climbing up a steep cliff accelerate and become more erosive (Arens *et. al*. 1995). Sand torn from the cliff moves up with the wind and drops down on top of the cliff where the wind velocity drastically decreases. Famous example is Råbjerg Knudde in Denmark where the new dune obscured the lighthouse from view (Fig. 14) and Dune du Pilat in southern France.

Comb dunes or rake dunes, the role of climate change in the past. Comb dunes or rake dunes are linked parabolic dunes. Those along the Dutch coast (Fig. 15) were formed between 1000 and 1600 ye. AD, at the same time as similar dunes in drift sand areas further inland. It was a period of enhanced storm frequency that has been associated with the Medieval

Fig. 14. The lighthouse of Råbjerg Knudde was overrun by a cliff dune, but has recently been exhumed.

climate optimum. Efforts to reactivate them have been ineffective.

Wandering dunes, the role of past land use. The Słowiński National park in Poland is famous for its wandering dunes, moving eastwards in the prevailing direction of the wind. The cause of their development was the destruction of natural vegetation cover on the sand bars some centuries ago (Wojterski 1992). They shift between 6 and 15 m per year, covering forests in their path and leaving the characteristic 'dead forests' and fossil forest soils in their wake.

NATURAL THREATS

Dune landscapes are exposed to numerous threats. Many of these threats issue from their recreational function which is a continuous source of concern for dune managers. Especially in the Netherlands, the dune landscape is also endangered by so-called 'nature restoration' projects which implies expensive digging in dunes to increase biodiversity. It means destroying geomorphic systems which is often centuries old.

This paper is restricted to sea level rise and climate change as natural threats. The impacts of these threats are twofold: the landscape-forming processes are affected and the dunes may disappear altogether (Van der Meulen *et al*. 1991).

Sea level rise. There are many causes of sea level rise applying to the European low-lying coasts, many of which have no relationship with the present global warming. They include:

tectonic movements;

Quaternary isostatic compensation;

sedimentation in the sea basins;

compaction of sediments, mainly Tertiary and Pleistocene clays;

dehydration of Holocene peat;

groundwater withdrawal;

exploitation of gas, salt or peat;

global increase in the volume and mass of the ocean;

melting of ice caps.

The actual consequences for the dunes are unpredictable, because erosion of the coast at one place will be accompanied by coastal accretion somewhere else along the coast.

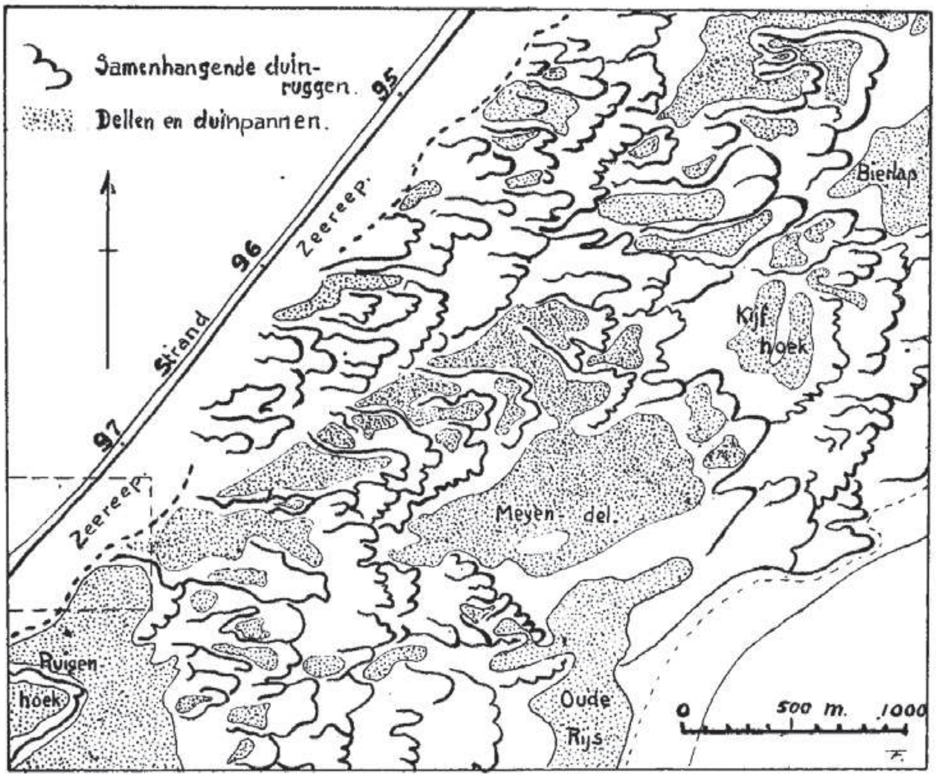

Fig. 15. The comb dunes along the Dutch coast (Faber 1947).

Climate change. Climate is the master factor of the natural processes of the dune landscape. Research of the consequences of climate change for coastal dunes started more than 20 years ago (Van der Meulen *et al.* 1991). Some of the conclusions were that an extended dry season in Mediterranean climates will lead to degraded and fragmentary plant cover and reduced sand fixation, thereby promoting eolian processes, whereas the more Atlantic climate in Baltic areas will encourage spreading of vegetation and slow down eolian processes in the white dunes (Jungerius *et al.* 1991) as well as slope wash processes in the grey dunes (Van Huis 1989).

Fig. 16. Artificially planted Marram grass often lacks vitality (Baltic Sea coast, Germany).

The expected effects on the geomorphology of the dunes depend on scale (Van der Meulen *et al.* 1991):

On the scale of centuries: increased storm surge frequency and associated inundations were the main stimulants of coastal development including dunes in the past and will presumably be so again in the near future.

On the scale of decades: the influence of long periods of desiccation or above-average precipitation on geomorphic and ecological processes is important.

On the scale of weeks: most important to predict what is going to happen with a dynamic system such as the dunes, is to know what the actual weather will be, but that information is not supplied by the climate change models.

It is generally assumed that the presence and duration of extreme climatic conditions are more important for dune systems than mean values. This hypothesis has been tested in the Dutch dunes where extreme events of various natures have been recorded. It was found that their effects were spurious and of minor importance compared to events with a lower magnitude but a higher frequency (Van der Meulen *et al*. 1991). The possible explanation is that the extreme events are too short-lived to have much effect on dune morphology and/or that they trigger other processes which reduce their effectiveness (negative feedbacks).

MITIGATION

Before we start to interfere with nature, we must realize that nature has her own defence mechanisms. Many processes provoke opposite feedbacks, mitigating their destructive effect. The beach-foredune system provides an example: the correlation between the steepness of the slope angle of the foreshore, which is a measure of the vulnerability of the coast, and the height of the foredune, which is a measure of its resistance. The foredune of a retreating coast with a steep foreshore is therefore higher and resists marine erosion. Another example: wind erosion of the beach is offset by sand deposition in the Marram grass *(Ammophila arenaria)* of the foredune. This keeps the Marram grass healthy, because vital Marram grass needs a continuous supply of fresh sand to outgrow the soil zone where nematodes and fungi infest its roots (De Rooij-van der Goes 1997). Modern experiments show that naturally growing, vital Marram grass is often sufficient to stabilise the foredune (Arens *et al.* 2001).

Due to ignorance of the processes involved, remedies are often counterproductive. Systematic planting Marram grass as is often done, stops the supply of the fresh sand to the foredune, decreases the vitality of the Marram grass and weakens the coastal defence. It is unnecessary and expensive (Fig. 16).

Sand nourishment. Our best help to protect the coast is sand nourishment to stimulate the formation of a foredune. Sand nourishment mimics the natural geomorphological process of sediment brought to the sea by the rivers and spread out along the coast by alongshore currents. It needs a source of sand, which is along the Baltic shores not everywhere available.

Several methods are used. The most simple method is beach nourishment, but it has several disadvantages. Ill-prepared beach nourishment may harm the beach system, spoil the natural quality of the coast and chase visitors away. Foreshore nourishment is more natural, because it is left to the surf to bring the sand to the beach where the wind can take it up for dune building (Fig. 17). It is also cheaper.

Fig. 17. Foreshore nourishment.

CONCLUSIONS

Wind is a very complex geomorphologic force. Unlike flowing water it comes from all sides with continuous fluctuations in strength, which makes the forms it creates difficult to explain. Unfortunately, standard theories about dune formation often take this fact insufficiently into account. The first part of this paper shows that popular theories can be misleading and may lead to wrong management decisions when applied to specific dune sites. On the other hand, the building materials are simple, and so are other aspects of the eolian geomorphology as is explained in the subsequent part. An example is the assemblage of dune forms which often appears to be chaotic, but reveals a clear geometric pattern when investigated.

Only research can provide the information needed for management decisions which aim at sustainable results. This applies especially to knowledge of dune forming processes which is often insufficiently used. For instance: in the grey dunes behind the foredune, slope wash is more important than wind erosion, also for vegetation and fauna. Moreover, the research should be adapted to the specific properties of the dune terrain under discussion, and to its intended functions. The practical classification of Ellenberg serves dune geomorphology as well as dune ecology. It has been shown to be useful also for dune managers.

Main natural threats to the dunes are sea level rise and climate change. They need mitigating measures, but before we start to interfere with nature, we must investigate nature's own defence mechanisms. Many damaging processes of nature provoke opposite feedbacks, mitigating their destructive effects: erosion at one site is always complemented by deposition elsewhere.

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