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The Dutch Foredunes: Inventory and Classification[1]

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ABSTRACT

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Aeolian transport of sand onto the foredunes is of importance with respect to the sediment budget of the coastal system. A classification of foredune types has been made, based on development, management and aeolian activity, using aerial photographs and a morphometric database. This classification provides insight into the occurrence and extent of natural processes in the foredunes, and will serve as a tool for calculation of a sediment budget. In only a few places along the Dutch coast, the foredunes are formed completely by natural processes: the majority are to some extent influenced by man. Although in many places aeolian processes are suppressed by man, their role in foredune development is important either in supply or in redistribution of sand. Geographical variation in aeolian processes results from a variation in management, vegetation, topography and effective wind climate.

ADDITIONAL INDEX WORDS: *Foredunes, classification, the Netherlands, coastal processes, aeolian sediment budget, foredune management, aerial photographs.*

INTRODUCTION

The coastal dunes in the Netherlands have been subjected to a wide variety of investigations over decades (VAN DIEREN, 1934; VAN STRAATEN, 1961; JELGERSMA *et al.*, 1970; JUNGERIUS *et al.*, 1981; KLIJN, 1981). The foredunes are often excluded from these investigations because of the large anthropogenic influence on both form and development. Figure 1 illustrates the contrast between the largely influenced foredunes and the natural dune landscape. The Dutch foredunes are of vital importance for sea defence, as a large part of the hinterland is situated below sea level. Neglect of foredunes will inevitably lead to large-scale inundations; so from this point of view, it is understandable that the Dutch keep foredune development under permanent control.

Foredunes form an important link in the coastal sediment budget (PSUTY, 1986, 1988). Nevertheless, little is known of the aeolian processes acting there. Measurements of aeolian sand transport are restricted to the beach area (SVASEK and TERWINDT, 1974; SARRE, 1988) yielding information on quantities, but disregarding origin (erosion) or destination (sedimentation). The need for knowledge on this matter is increasing; in order to optimize foredune management, information on the transport of sand into and within the foredunes, as well as insight into both erosional and depositional processes, is essential. The amount of sand transported from the nearshore into the dunes should be quantified in order to calculate a coastal sediment budget. This is an important goal of the Dutch "Coastal Genesis" project (*e.g.* DE RUIG and LOUISSE, 1991).

In the Netherlands, interest in the natural processes of the dune ecosystem is increasing. A consciousness is growing that dunes have an enormous potential for nature conservation and rehabilitation, as well as their function for sea defence, drinking water supply and outdoor recreation. At carefully selected locations, the dynamic natural processes should be restored. In order to make the best selection, knowledge of these processes must improve.

In this article, an inventory and first quantification of natural processes in the Dutch foredunes is presented based on aerial photographs and a morphometric database. After a historical introduction on their development, a method is discussed for the classification of foredunes based on

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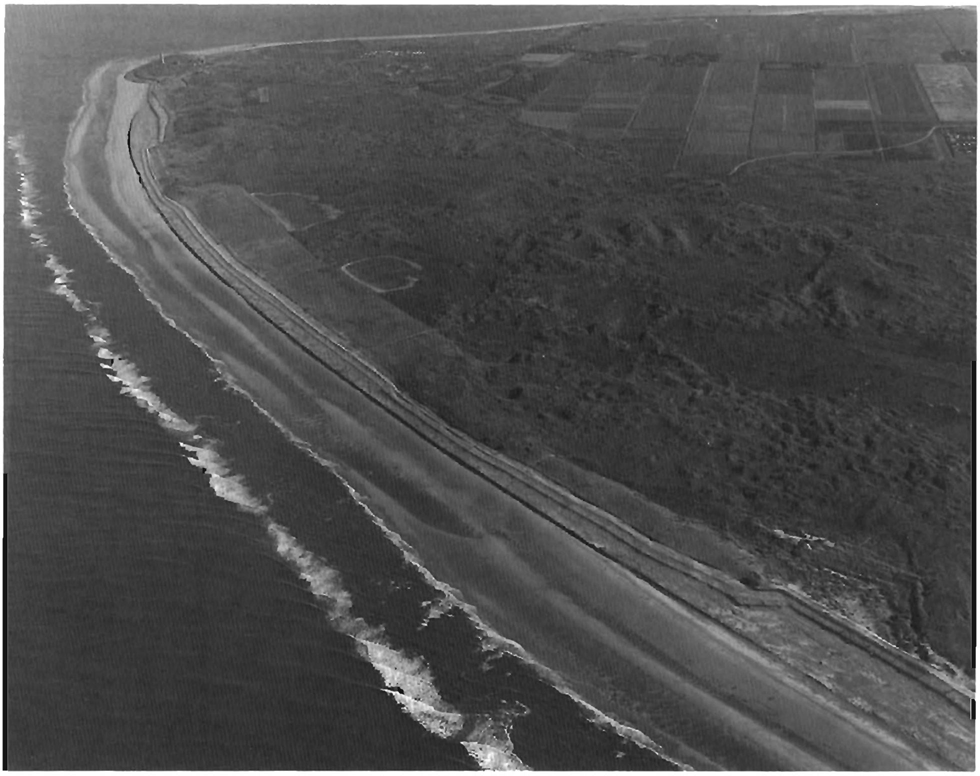

Figure 1. Oblique air photograph of the Wadden island of Texel showing a natural dune landscape cut off by an artificial foredune. (Source: KLM Aerocarto, vogelvlucht fotografie, KO 18187.)

developmental processes and management. The classification provides a tool for future calculation and explanation of the sediment budget of the Dutch foredunes. With this classification and a derived map, the Dutch foredunes are presented in detail. In order to give a general picture of the Dutch situation, a current division of the Dutch coast in three main regions is used. In the north a chain of barrier islands, the Wadden Islands (WI), are separated from the mainland. In the west an uninterrupted coastline of 118 km forms the Mainland Coast (MC). The southern part consists of several peninsulae, intersected by estuaries, referred to as the Zeeland Estuaries (ZE).

PRESENT FOREDUNE DEVELOPMENT IN HISTORICAL PERSPECTIVE

Most of the coastal dunes in the Netherlands belong to the so-called Younger Dunes, formed between 800 and 1650 AD (KLIJN, 1981, 1990b). The total volume of sand present in the Younger Dunes along the Dutch coast is estimated at 2.7 $\times$ 10^9 m^3 (POOL and VAN DER VALK, 1988). The current theory is that they have evolved from the Older Dunes during a period of coastal regression (KLIJN, 1990b). Fast coastal regression would result in a breakdown of vegetation, causing uptake of sand from the foredunes and landward replacement in the form of transgressive dunesheets (PSUTY, 1989). If the theory of a retrograding coastline is accepted as the main cause of the Younger Dune formation, the coastline at the beginning of the formation must have been situated between 1 and 2.5 km seaward from the present coastline (POOL, cited in WIERSMA, 1991). To achieve an accumulation of such volumes, the *average* transport rate between 800 and 1650 AD along the Mainland Coast (117 km) is estimated at 27 $m^3m^{-1}year^{-1}$, during eight centuries, which is large compared to the amounts transported today. In a study for coastal defence in the Netherlands (RIJKSWATERSTAAT, 1989), transport rates from shoreface into the dunes were estimated at no more than 1 to 2 $m^3m^{-1}year^{-1}$ (STIVE and EYSINK, 1989). DE RUIG (1989) proved that this amount was too low. De Ruig computed an average transport rate of 3–3.5 $m^3m^{-1}year^{-1}$, comparable to the amount transported onshore from the −10 m depth line. For a severely eroding coast (1 km) on the Wadden Island of Texel, ARENS (*in preparation*), calculated *maximum* aeolian transport rates of 50 $m^3m^{-1}year^{-1}$. In this case large amounts of sand are removed from the dune system (negative sediment budget) during storm surges, part of which is re-entered into the foredunes afterwards. Dunes formed in this way are actually reworked older dunes (secondary dune formation), which possibly is comparable to the situation during the formation of the Younger Dunes.

In case of an accretional system, small scale dunes such as embryonic dunes and low foredunes are formed (PYE, 1984). The amount transported by the wind is much smaller, compared to the eroding system, but the sediment budget of the dune system is positive. This is supported by calculations by ARENS (*in preparation*) for accretional areas along the Dutch coast: in small areas (± 1 km) with very strong accretion, aeolian transport rates of 25 $m^3m^{-1}year^{-1}$ during some years were computed. KROON and HOEKSTRA (1990) calculated for Goeree maximum amounts of 75 $m^3m^{-1}year^{-1}$. However, this refers to a very local situation of only several tens of metres which is presumably influenced by the building of the Brouwersdam across the Grevelingen inlet.

Since 1850, human influence in the dune landscape has been increasing, leading to large scale fixations of the foredunes (KLIJN, 1990b). The role of aeolian transport in dune development, therefore, has diminished. Only on some locations is strong coastal erosion accompanied by high aeolian transport rates. Aeolian processes are mainly limited to the input of sand in accretional systems. Although these processes are relatively unimportant when compared to the scale of aeolian transport during formation of the Younger Dunes, the present input of sand onto the foredunes still is a substantial factor in the coastal sediment budget which should be taken into account.

CLASSIFICATION OF FOREDUNES

Preliminary to a calculation of the sediment budget of the foredunes, an inventory study was made of the extent of aeolian processes and the morphology of foredunes. Results of the inventory will be used to divide the Dutch coast into sections which are comparable in development and sediment budget. In order to come to a proper division, several classifications of coastal dunes and foredunes were considered (*i.e.* GOLDSMITH, 1978; KLIJN, 1981; PYE, 1983, 1990; HESP, 1984; PSUTY, 1988, 1989; and BIRD, 1990). Some of these classifications are reviewed below.

Existing Classifications

KLIJN (1981) has proposed a morphogenetic classification of the dunes of the Netherlands. Klijn does not distinguish between natural foredunes and foredunes influenced by man. His first two types, foredunes in development (accretion) and stable foredunes or foredunes with cliff (erosion), enclose almost all the foredunes found along the Dutch coast and can be used as a major division of foredune types. The other types, rolling foredunes (induced by man) and carved foredunes (by aeolian erosion) are very characteristic sub-types with restricted occurrence.

HESP and SHORT (1980) and HESP (1984) proposed a classification for natural foredunes. They distinguish two major units, based on geomorphological and ecological characteristics. Incipient foredunes formed by the catching of sand in pioneer vegetation belong to the first unit. If the incipient foredune is colonised by other vegetation types, it develops into an established foredune. A subdivision of incipient foredunes is based on ecological characteristics, whereas established foredunes are subdivided on the basis of geomorphological development. In situations in which the role of vegetation is less dominant (as is the case for example in South Africa), foredunes hardly develop (SHORT, 1987).

PSUTY (1989) recognised several varieties of dune forms which are the products of different combinations of natural and cultural practices in differing stages of growth and decay. He introduced a dune model that is the product of the interaction between the beach and dune sediment budget. Psuty proposed a division of foredunes into primary dunes and secondary dunes and sand sheets. Primary dunes (according to Psuty the only real coastal dunes because of their dependence on the coast and coastal processes) are characterised by an active exchange of sand between the foredunes and the beach. Fast progradation of foredunes results in a topography of low parallel ridges. In the case of secondary dunes such as sand sheets, there is a sink in the sediment budget as during landward movement sand is removed from the active zone. Fast regression results in washover topography without foredune development.

According to PYE (1983), the morphology of coastal dunes is influenced by wind regime, sand supply, vegetation and physiographic setting. He distinguishes impeded dunes, which are more or less fixed in position by vegetation, and transgressive dunes. True foredunes which form a part of the impeded dunes are characterised as continuous or semi-continuous ridges of sand, normally well vegetated, which lie parallel to, and to the rear of the beaches exposed to onshore wind energy.

In 1990, Pye presented a general model of dune morphological development based on the concept of PYE (1983). His genetic model which relates form of the foredunes to their development is believed to be most useful in order to divide a coastal area into parts with comparable sediment budgets.

From the models discussed above, it is clear that a division of foredunes based on development (which reflects the sediment budget) is considered essential. However, almost everywhere along the Dutch coast management exerts a certain influence on development, varying from a slight adaptation of natural processes, to a complete control of foredune shape and development. Because of this, a classification was proposed (ARENS and WIERSMA, 1990) which distinguishes foredunes on the basis of development, processes and management.

A Method for Classification of Foredunes

The purpose of the classification is to gain insight into the geographical distribution of different types, the degree of naturalness and the importance of aeolian transport in the Dutch foredunes. A classification of foredunes suitable for this purpose should be based on:

—development: prograding, retrograding or stable foredunes, change in volume;
—management: which measures are taken today, is there a long term influence;
—aeolian processes: are there signs of active aeolian erosion and/or deposition.

Attention will be paid to the relationships between environmental parameters and aeolian transport of sand. In the future, the classification

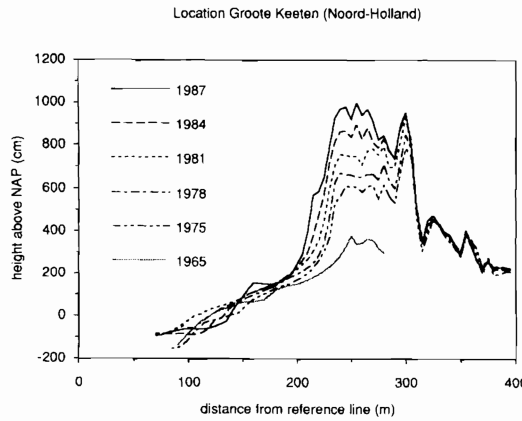

Figure 2. Example of profile development recorded with the JARKUS-database (location cross-section 9.28, Groote Keeten, Noord-Holland).

will be used for the calculation of a sand budget of the foredunes.

Sources and Methods

Long-term development of the foredunes is analysed using the JARKUS-morphometric database of Rijkswaterstaat (Figure 2) with yearly profile measurements of coastal cross-sections since 1963. In the JARKUS-database, cross-sections are defined along the Dutch coast with a spacing of 200–250 m covering both foreshore and foredunes. Only the "dry" part, which concerns the foredunes, was studied (for more information on this database reference is made to DE RUIG and LOUISSE, 1991). Of 1,432 cross-sections, dunefoot migration and volumetric changes are recorded qualitatively.

The present (1988) state of the foredunes has been catalogued using full-colour aerial photographs, scale 1:4,000 of the Survey Department of Rijkswaterstaat. In these photographs, the altitude of the cross-sections of the JARKUS-database are recorded photogrammetrically. For some areas, comparisons are made with black and white aerial photographs from 1977 of the Survey Department, and to black and white aerial photographs, scale 1:8,000, made by the British Royal Air Force in 1944.

In order to make a semi-quantitative inventory, cross-sections are divided into beach, dunefoot, seaward slope, summit and landward slope. For all these segments, parameters are recorded de-

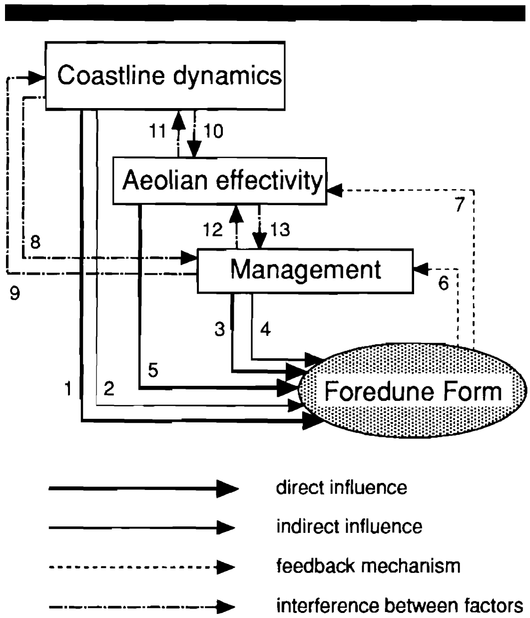

Figure 3. Relationships between coastline dynamics, management, aeolian activity and form of the foredune (after ARENS and WIERSMA, 1990). Explanation in text. Legend: 1. direct influence: coastal erosion; 2. indirect influence: supply of sand; 3. direct influence: *e.g.* mechanical (re)modelling of the foredune; 4. indirect influence: *e.g.* affecting wind speed by planting of marram grass; 5. direct influence: formation of foredunes; 6. feedback: *e.g.* intervention because of safety requirements; 7. feedback: *e.g.* wind speed as influenced by foredune height and slope; 8. *e.g.* the control of management by coastal erosion or accretion; 9. *e.g.* effects on the large-scale sediment transport by fixation of foredunes; 10. *e.g.* availability of sand for aeolian transport; 11. *e.g.* effects on the large-scale sediment transport by withdrawal of sand due to fast landward transport; 12. *e.g.* the control of aeolian processes by sand fences; 13. *e.g.* intervention after blowout development.

scribing management, morphology, processes and vegetation. Of the 1,432 cross-sections included in this study, 120 were omitted because of the presence of dykes instead of dunes. Percentages and numbers presented below, therefore, refer to 1,312 cross-sections.

Basic Concepts

Fundamental to the classification is the concept presented in Figure 3. A foredune is considered to be the result of the interaction of coastline dynamics, management, aeolian processes and the foredune itself.

Coastline Dynamics

The large-scale coastal processes of supply and withdrawal of sand by the sea determine the sediment budget of the interface between land and sea. Landward losses are negligible due to the present management. In natural systems, landward migration of sand also influences the sediment budget. The large-scale coastal processes are considered to be the driving force behind the present development of the Dutch foredunes. In the case of a net supply of sediment, the marine influence on foredune development is indirect, as the sand supplied to the beach will only contribute to the dunes if it is transported by the wind. In contrast, coastal processes exert a direct influence on the foredune in the case of marine erosion. In places which suffer continuous erosion, a negative sediment budget and a typical steep-sloped foredune (often with a bare dune-cliff) will result. Two other main factors of concern, foredune management and aeolian activity, are controlled by the supply or withdrawal of sediment.

Based on the JARKUS-database, foredune cross-sections are divided into groups which differ in their development (between 1964 and 1988). The distinction between "development types" is based on dunefoot migration and on changes in volume (Table 1). For each "development type" an indicative sediment budget is estimated. Differences in development are due to differences in coastline dynamics, but also to differences in management, aeolian activity and the local situation. Three major groups are distinguished: regressive (R), stable (S) and progressive (P) foredunes. Intermediate groups (not shown in Table 1) are: foredunes with moderate regression (SR) and foredunes with moderate progression (SP). Major groups are divided into five subtypes depending on the kind of (significant) aeolian deposition: (1) deposition on top (increase in height), (2) deposition in front of the foredunes (often temporarily and due to sand fences), (3) deposition both on top and in front of the foredunes, (4) deposition at the lee side, and (0) no deposition.

Aeolian Effectivity

Wind is an essential factor in foredune development; without wind, no (fore)dunes would exist. Depending on the rate of wind activity and the predominance of either deposition or erosion, or a combination of both, the shape and the volume of the foredunes change. The influence of the wind on foredune morphology is direct.

The differences in wind climate along the Dutch coast are slight. Of more importance, with respect to foredune development, is the effective wind

Table 1. *Division of cross-sections based on long term development.*

PROGRESSIVE FOREDUNES			
type	in	out	net
P1	++	0	++
P2	++	0	++
P3	++	0	++
STABLE FOREDUNES			
type	in	out	net
S1	+	0	+
S2	±	0	±
S3	+	0	+
S4	+	0	+
S0	0	0	0
REGRESSIVE FOREDUNES			
type	in	out	net
R1	+	--	-/--
R4	+	--	-/--
R0	0	--	--

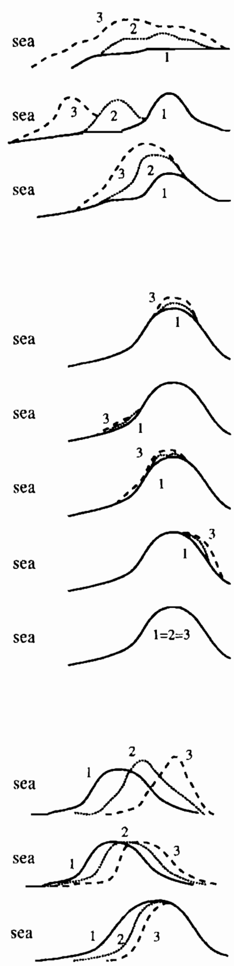

Table 2. *Division of cross-sections based on present aeolian effectivity.*

Type	Wind effects
none	no effects of wind activity visible
d	weak to moderate deposition visible
D	strong to very strong deposition visible
e	weak to moderate erosion visible
E	strong to very strong erosion visible
de	combination d + e
dE	combination d + E
De	combination D + e
DE	combination D + E
	Special characteristics
0	active development of embryo dunes on the beach
*	carved foredunes

climate, *i.e.* the distribution of on- and off-shore winds (ARENS, 1992). Landward winds are capable of moving sand onto the dunes. The most severe erosion (usually from bare seaward slopes) is also related to landward winds. Field measurements showed that during the gale force winds, no sand movement took place due to very humid conditions (high precipitation rate and air humidity and low evaporation, ARENS, 1992). This implies that the resultant wind vector of winds carrying sand (actual transport) may differ very much from the overall wind vector (potential transport). If the effective wind climate is defined as the wind climate in which only landward winds capable of transporting sand are taken into account, it is clear that for several regions of the Dutch coast, the effective wind climate will differ very much depending on coastal orientation. As a result, there is a large variation in the geographical distribution of features of aeolian activity.

Other factors which influence aeolian processes are vegetation density (reduction of wind speed near the surface), beach width (increasing fetch resulting in a larger sand carrying capacity up to a certain maximum), foredune height, slope and topography (change of wind speed) (KLIJN, 1990a; ARENS, 1992). The way in which dune erosion occurs is also important: blowouts develop if dune erosion is very local; whereas during large scale dune erosion, wind erosion will be more gradual (SHORT and HESP, 1982).

Finally, aeolian processes are strongly influenced by man. Deposition and erosion is controlled through the erection of sand fences and planting of marram grass. After smoothing or remodelling the foredunes, usually by heavy machinery, traces of aeolian processes are erased. In such cases, aeolian effectivity is seemingly very low. Recently, aeolian processes are influenced during beach nourishments when strange (coarse or very fine) sediments are introduced in the system.

Table 2 gives a simple division of aeolian effectivity based on a qualitative interpretation of aerial photographs of 1988. Features of aeolian activity are recorded for each cross-section. Two remarkable features are indicated separately: presence of embryo dunes and presence of carves (blowouts).

Foredune Management

Strong feedback relationships exist between foredune management on the one side and coastal and aeolian processes on the other. The type of management in general depends on coastal and aeolian processes; in areas which suffer erosion, different measures will be taken than compared to stable areas. However, management measures by themselves will also influence coastal and aeolian processes. The influence of management activities on coastal processes is particularly clear in the following cases:

The construction of harbour moles at IJmuiden (Mainland Coast) has changed the pattern of coastal erosion and sedimentation in the adjacent areas. In the immediate vicinity of the harbour moles, significant accretion was induced due to the interference of the longshore current; some kilometres to the south, a former stable area is currently subjected to moderate erosion.

For the same reason, construction of groynes has reduced coastal erosion in certain areas, but adjacent areas usually suffer from erosion after installation of the groynes, which make Dutch coastal engineers speak of the "Law of Conservation of Misery".

Fixation of the foredunes in some parts of the Netherlands has led to a change in the coastal cross profile. Locally, the beach width has decreased resulting in a change in wave energy and possibly a higher erosion risk.

Management activities can be divided into two groups.

(1) The first group of practices merely interferes with the natural processes. Influence on the form of the foredune, therefore, is **indirect.** Measures are taken to control or stimulate natural processes and are usually applied in areas with stable or prograding foredunes. Two of these measures stimulate deposition of blown sand and thus prevent erosion: planting of marram grass and erection of sand fences. GOLDSMITH (1978) classifies foredunes affected by these measures as "artificially inseminated dunes". An extreme example along the Dutch coast is the so-called "stuifdyke", a formation completely due to the use of sand fences placed in a row. Other measures are directed at preventing or diminishing damage or loss of sand by marine erosion. During beach nourishments, a large amount of sand is (artificially) added to the system which will then be gradually removed by the sea. In the future, suppletion of sand on the shoreface is also considered. Groynes and rows of piles are constructed to diminish coastal erosion. An important management technique is the "rolling foredune": vegetation of the foredune is removed (mechanically) and a landward replacement of the foredunes by aeolian processes is induced. This technique is applied in order to prevent the loss of sand to the sea, the advantage being that the foredune slope becomes very gradual and the beach width will not diminish.

(2) The second group of practices exerts a **direct** influence on the foredune form: sand is artificially supplied to the foredunes, or the foredune slopes are remodelled. With increasing effort, foredune form becomes less natural. Usually these measures are taken in areas where severe marine erosion has compromised safety requirements or where foredune regression is undesirable because of interests in the hinterland. Examples are: dune suppletion, *i.e.* artificial supply of sand at the front or the back side of the foredune; smoothing of blowouts; remodelling of foredunes that have become too steep; remodelling of the seaward slope.

This definition of indirect and direct measures differs from the definition used by PYE (1990) who defines as direct effects all measures within the dune system itself, and indirect effects as all measures which affect the wave climate, nature of tidal currents and the sand supply.

On a particular location, several measures can be taken, but only that which exerts the largest influence on the form of the foredune is recorded according to Table 3. Measures which indirectly influence coastline migration like groynes and pile rows are excluded.

When recent and still visible management activities have been taken for a succession of years, they can reflect the long term effect of management. A special shape to the foredune may be the result. It is also possible that no sign of activity exists, but the foredune has an unnatural form. For example, a stabilised foredune which seems to lack both active processes and management may have lost its natural character because of aeolian inertia. For each cross section, a qualitative division of the foredune form from natural to artificial is recorded (Table 4).

Table 3. *Division of cross-sections based on present management measures (1988).*

Type	Activity
none	no recent activities visible
	Indirect effects
i1	planting of marram grass
i2	sand fences
i3	beach nourishment
i4	recent "stuif-dyke"
i5	rolling foredune
	Direct effects
d0	small-scale effects due to recreational use
d1	small-scale smoothing
d2	remodelling of seaward slope
d3	large-scale smoothing or remodelling
d4	artificial foredunes; remodelled or suppletion

Table 4. *Division of cross-sections based on degree of naturalness (general impression).*

Type	Degree of naturalness
N	natural foredunes with undisturbed development
S	semi-natural foredunes with mainly indirect effects of management
U	unnatural foredunes with mainly direct effects of management
A	artificial foredunes

In contrast to the stabilised foredunes, dynamic foredunes have an insignificant, and often invisible, management history. The earlier dune history of an area is usually not recognised, as coastal dunes may look completely natural in a few tens of years (GOLDSMITH, 1989). This illustrates the small time scale of the geomorphological processes acting on the foredunes.

APPLICATION OF THE CLASSIFICATION TO THE DUTCH SITUATION

As mentioned before, a total of 1,312 cross-sections along the Dutch coast with a spacing of 200–250 m are classified using the classification discussed above. In this section, the results will be presented using frequency diagrams, cross tables and a map. First, the frequency distributions of the four main themes will be discussed for the Wadden Islands, Mainland Coast, Zeeland Estuaries and the Dutch coast as a whole. It should be remembered that the results refer to the situation in 1988.

Frequency Diagrams of the Four Main Themes

Figures 4–7 give the frequency distribution of the "foredune types" according to Tables 1–4, for the three regions and for the Dutch coast as a whole. On the left axis, the number of cross sections is given; on the right axis, the percentage with respect to the total number of 1,312 cross sections is shown.

Development Types

For the Dutch coast as a whole, a high percentage (39%) of the foredunes are stable or stabilised (Table 5.1). Of the unstable areas, the percentage of regressive foredunes (38%) is larger than the percentage of progressive foredunes (23%). Between the three main regions there are distinct differences. Both strongest regression and progression occur on the Wadden Islands. There, stable foredunes are in the minority (25%). On

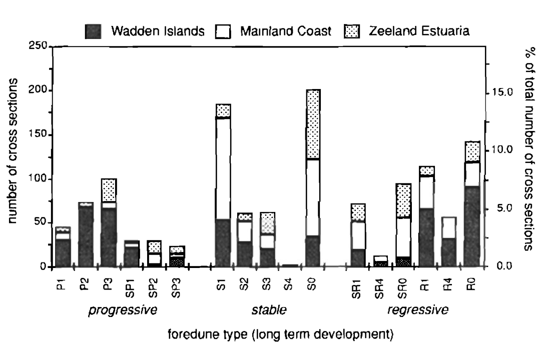

Figure 4. Frequency distribution of development types.

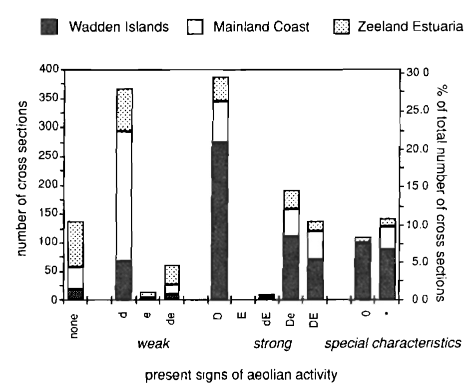

Figure 5. Frequency distribution of (present) features of aeolian effectivity.

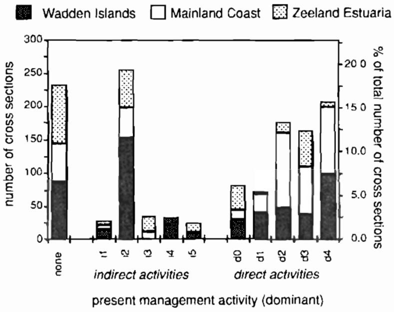

Figure 6. Frequency distribution of present (dominant) management activities.

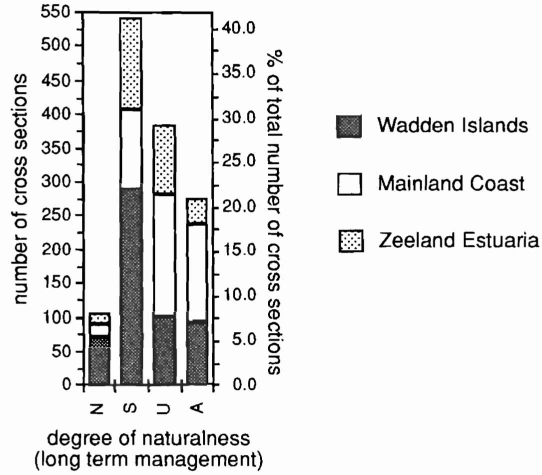

Figure 7. Frequency distribution of degree of naturalness.

the Mainland Coast, progressive foredunes are rare (8%). More than half of the foredunes (53%) are stable or stabilised. In the Zeeland Estuaries, almost half of the foredunes (44%) are stable or stabilised. Regressive foredunes are somewhat more common than progressive foredunes.

With respect to progressive foredunes, most common are those which increase both in height and in width (P3 + SP3: 41%). Of the stable foredunes too, a very large number (S1 + S3: 48%) increase in height. Another important group (S0: 38%) shows no change at all. In many locations, regressive foredunes show a decrease in width without other changes (SR0 + R0: 48%). However, more than half of the regressive foredunes also experience an aeolian redistribution of sand within the system.

In Table 5.2 totals of "form of deposition" are given. With respect to "Σ 0", differences between the three regions are remarkable. The number of occurrences is comparable, which means that on the Wadden Islands 1/4, on the Mainland Coast 1/3, on the Zeeland Estuaries 1/2 and along the Dutch coast on average 1/3 of the foredunes are static. For the Dutch coast, 2/3 of the foredunes are influenced by aeolian processes, either by deposition of sand transported from the beach giving rise to an increase in height or width, or by redistribution of sand within the foredune itself.

A qualitative sand budget is presented in Table 5.3. According to Table 1, for each development type a net sand budget is estimated. Adding up of the cross-sections with a specific sand budget gives some insight into the total sand budget for the Dutch foredunes. Without any further indication of quantities, for 555 cross-sections (approximately 120 km) the sand budget of the foredunes is positive, while for 493 cross-sections (approximately 110 km) the sand budget is negative. Cross-sections with a strongly negative budget dominate over cross-sections with a strongly positive budget, while cross-sections with a moderately positive budget dominate over cross-sections with a moderately negative budget. The qualitative sand budget will be improved when average volumetric changes for all development types are known, which is the subject of future papers.

Aeolian Activity—Effectivity

In approximately 10% of all cross sections, no features of aeolian processes are visible. The largest part (58%) shows signs of deposition, either weak (Mainland Coast), or strong (Wadden Islands). Strong features of aeolian erosion are mainly found on the Wadden Islands, obviously related to the less intensive management, but probably also due to a different type of sediment. It is remarkable that strong aeolian erosion without deposition (E in Table 2) never occurs.

Of the special characteristics, the high percentages present on the Wadden Islands are noteworthy. Embryonic dunes are almost exclusive to the Wadden Islands. Carved foredunes occur on the Wadden Islands and to a lesser extent on the Mainland Coast.

Table 5. *Totals of major groups and qualitative sand budget. (WI = Wadden Islands, MC = Mainland Coast, ZE = Zeeland Estuaries, NL = WI + MC + ZE.)*

	WI	MC	ZE	NL	% (NL)	
			5.1. Totals "Dunefoot migration"			
Σ P	164	17	39	220	17	(P1, P2, P3)
Σ SP	36	22	26	84	6	(SP1, SP2, SP3)
Σ S	138	245	132	515	39	(S1, S2, S3, S4, S0)
Σ SR	35	85	60	180	14	(SR1, SR4, SR0)
Σ R	187	91	35	313	24	(R1, R4, R0)
Total	560	460	292	1,312	100	total number of cross sections
			5.2. Totals "Form of deposition"			
Σ 1	190	201	56	447	34	(P1, SP1, S1, SR1, R1)
Σ 2	99	36	31	166	13	(P2, SP2, S2)
Σ 3	96	30	62	188	14	(P3, SP3, S3)
Σ 4	41	31	0	72	5	(S4, SR4, R4)
Σ 0	134	162	143	439	33	(S0, SR0, R0)
Total	560	460	292	1,312	100	total number of cross sections
			5.3. Totals "Qualitative sand budget"			
Σ ++	164	17	39	220	17	(P1, P2, P3)
Σ +	112	155	68	335	26	(SP1, SP2, SP3, S1, S3, S4)
Σ 0	62	112	90	264	20	(S2, S0)
Σ −	35	85	60	180	14	(SR1, SR4, SR0)
Σ − −	187	91	35	313	24	(R1, R4, R0)
Total	560	460	292	1,312	100	total number of cross sections
A	−23	−74	4	−93	−7	A = Σ(++) − Σ(−−)
B	77	70	8	155	12	B = Σ(+) − Σ(−)

Present Management Measures

On 18% of the foredunes, no recent management measures are visible (which does not mean that these foredunes are naturally developing). A large proportion of the foredunes on the Wadden Islands is influenced by sand fences (12%). Complete or partial remodelling is applied to more than 41% of the Dutch foredunes.

Degree of Naturalness

Most of the Dutch foredunes are semi-natural (42%). For the Mainland Coast, unnatural and artificial foredunes dominate, which is presumably related to tradition and the multifunctional use of the inner dunes (built-up area, drinking water infrastructure). Only a small proportion of the foredunes are natural: 8% for the Dutch Coast, as a whole, most of which is situated on the Wadden Islands.

THE GEOGRAPHICAL DISTRIBUTION OF THE FOUR THEMES; MAP PRESENTATION

The geographical distribution of foredune types is best visualised using maps. For this paper, a map of scale 1:250,000 is constructed based on a simplification of the four themes. Two legends are presented, "Foredune Dynamics", derived from a combination of "development" and "aeolian features", and "Foredune Management", derived from a combination of "degree of naturalness" and "present management measures".

The derivation of "Foredune Dynamics" is visualised in Cross Table 1 (Appendix). Moderate and strong progression (P and SP) are put together, as are moderate and strong regression (R and SR). Features of aeolian activity are split into weak (0, d, e and de) and strong (D, De, dE and DE). A total of 21 mapping units is derived. Presence of features of aeolian erosion (e, de, De, dE and DE) or of carved foredunes and of embryo dunes are indicated with special signs. The colors of the mapping units are according to those of Cross Table 1.

"Foredune Management" is derived from Cross Table 2 (Appendix). The four classes of "degree of naturalness" are split into groups with comparable management measures, leading to a legend with 9 mapping units.

Relationships Between Classification Units

In general, the most intensive and sustained management efforts are applied to areas suffering from coastal erosion. However, there are exceptions. Due to tradition and lower safety standards on the Wadden Islands, management there is less intense than elsewhere.

Along the Mainland Coast (especially in section "Rijnland"), management efforts are often higher than expected. In large areas with stable foredunes, dynamic processes are suppressed and vegetation cover is kept as dense as possible.

In the Zeeland Estuaries, safety requirements dictate most of the management activities. In many places only a single foredune ridge protects the hinterland from the sea; most of these are stabilised. In other places (Schouwen, Goeree), slight regression was tolerated.

Erection of sand fences clearly influences the evolution of progressive foredunes (combination i2–P2, P3 occurs often). Sand fences stimulate deposition in front of the foredunes, progression is fast, but foredunes will not increase much in height. Without sand fences, foredunes would increase in height although progression would then be much slower. For example, on aerial photographs of 1944 of the island of Schiermonnikoog, a high and irregular foredune is visible which is not influenced by sand fences. This "fossil" foredune still exists, but in front of it several low foredunes have developed due to stimulation from sand fences.

It is clear that the type of management is also influenced by the functions of the inner dunes. Another important factor is the management tradition, which can differ a great deal in different coastal regions.

There is a distinct relationship between the type of management and the extent of aeolian features. Intense management erases all signs of aeolian activity. The form of deposition is also influenced. In places with blowouts or wind gulleys, wind erosion is apparently "allowed". In places without management (*e.g.* eastern Schiermonnikoog and eastern Ameland), foredunes develop freely and signs of strong aeolian erosion are visible.

Areas of accretion show many signs of strong or moderate deposition. In the progressive foredunes of Ameland, Schiermonnikoog and Terschelling, strong deposition occurs on the leeside; in Texel and Vlieland, deposition is very strong locally. This does not necessarily mean that there is an import of sand from the beach as (especially on the island of Texel), there is evidence of strong aeolian activity related to recent coastal erosion. In such a case where the sediment budget of the dune-system is negative, one should speak of dune deformation instead of dune formation.

Geographical Variation of Foredune Types

A first impression of the maps indicates strong regional contrasts in both dynamics and management. At the scale of some kilometres, a large variation is visible in many areas. On the Mainland Coast, the difference between the northern and southern part is remarkable. In the north, regressive and progressive as well as natural and artificial foredunes alternate within a range of several kilometres. In contrast in the southern part, variation is small and comparable types extend over most of the region. With respect to the Dutch coast as a whole, some important groups of foredune types are distinguished.

Dynamic Foredunes, Natural Development

Naturally developing foredunes are very rare along the Dutch coast and are almost exclusive for accretional areas on the Wadden Islands. Three important groups are discernible.

On the eastern parts of the Wadden Islands of Terschelling, Ameland and Schiermonnikoog and on the north-eastern part of Goeree, dynamic foredune systems have been developing. These systems are characterised by low and irregular foredunes, often with discontinuities through the sea has access to salt-marshes in the hinterland. Often features of severe aeolian erosion are present in the form of blowouts and extremely carved foredunes (especially on the island of Schiermonnikoog). These areas belong to the most natural coastal systems in the Netherlands.

In some locations, new foredunes have arisen (locally more than 10 metres high) without any interference from management. Remarkably, despite a free development, signs of aeolian erosion are only present in the front zone, possibly because the large supply of fresh sand benefits the vegetation which prevents further erosion. These areas vary between some hundreds of metres to less than 3 km wide. Examples can be found on the island of Vlieland, (Groote Keeten and the island of Vlieland are different locations) near Groote Keeten and IJmuiden in Noord-Holland and in front of some sea-dykes in the Zeeland Estuaries (Brouwersdam, Zeeuws-Vlaanderen).

There are few freely developing foredunes in regressive areas; one example is the south-western part of the Wadden Island of Texel. On a beach plain, a dune area developed in front of a former foredune. However, accretion ceased and for the last 10 years the area has been eroding. The dunes are very dynamic, small vegetated dunes alternating with aeolian gulleys and blowouts.

Dynamic Foredunes, Controlled Development

There are many examples of accretional areas which do not develop freely. In areas with a large supply of sand, sand fences are often erected in order to stimulate foredune development. Marram grass is planted to catch sand and to prevent erosion, often resulting in a very regular foredune ("stuif-dyke"). A large part of the foredunes on the Wadden Islands and along the coast of Noord-Holland were created in this way. Although natural development is suppressed, dynamic processes play a role in the form of often significant sand deposition; the central and western part of Schiermonnikoog and the western parts of Ameland and Terschelling are examples.

Other examples of dynamic foredunes of which the development is controlled by man are the "rolling foredunes". This technique was applied on the Wadden Islands (Terschelling, Texel) and along the coast of Noord-Holland.

Beach nourishment is another important measure which does not directly affect the form of the foredunes. A large amount of sand is added to the system which will then be gradually removed by the sea to be renewed some years later. In the future, suppletion of sand on the shoreface is to be considered. Many suppletions have been applied, among others on Goeree (central part). In this particular case, the take away of the erosional thread offered possibilities for the foredunes to develop more freely. An increase in beach width may lead to increasing landward transport of sand, which in turn exerts a positive influence on the marram grass.

Static Foredunes

In places with little or no dunes, it is of vital importance that foredunes be kept as stable as possible. If the supply of sand from the beach is limited and the position of the coastline is stable, these stabilised foredunes show no change in time and are called "static". On Walcheren, a single foredune ridge forms the sea defence. It is obvious that in this case, natural processes in the foredunes are not permitted. There are other locations along the Dutch coast where the reason for a completely stabilised foredune is less clear especially in the region of Rijnland (southern part of the Mainland Coast) where the foredunes are part of a very wide dune zone. It is difficult to tell whether the stability of the foredunes in this region is due to the management or despite of the management. However, the impression is that a limited increase of natural processes will not have any adverse effects on these foredunes.

Artificial Foredunes

In areas suffering from strong or continuous erosion, a decrease in the volume of the foredunes will inevitably lead to a situation in which the safety requirements are trangressed. Mechanical landward movement of the foredune remnants might be a solution if the dune zone in question is wide. Another alternative is to rebuild the foredune using offshore sand (dune suppletion). In both cases, the original foredunes are completely destroyed and the newly constructed foredunes lack any natural characteristics. Occasionally, foredunes are modelled in a form corresponding to the surrounding dune morphology. In current times, these measures are replaced increasingly by beach nourishments.

DISCUSSION AND CONCLUSIONS

Knowledge of natural processes is essential for an optimal management of foredunes. In the future, quantification of aeolian processes in foredunes will be an important issue in dune research. In studies for coastal defence policy, the importance of aeolian processes for the coastal sediment budget has been underestimated to date.

A classification of foredunes is proposed which provides a basis for quantification of the sand budget of foredunes. Fundamental to the concept is that foredunes are the result of interaction between coastline dynamics, management and aeolian processes. By means of this classification, the Dutch coast is divided into areas with different development and sediment budget characteristics.

Geographical variation in aeolian processes along the coast of the Netherlands results from a variation in the effective wind climate and local characteristics such as beach width, foredune morphology, vegetation and sediment. Aeolian processes play an important role in the development of the foredunes, either in supply of sand or in its redistribution. Presently 66% of the foredunes are influenced by aeolian processes, a large number of which are increasing in height due to a continuous supply of sand. However, in many places aeolian processes, especially erosion, are suppressed by management.

The main purpose of management is to conserve and, where possible, enlarge the volume of the foredunes. One consequence is that in accretion zones the continuous interference of management results in straight structures in the coastal landscape. Stabilisation and fixation of foredunes disturb the dynamic exchange of sand between shoreface, beach and dune. Erosion of the shoreface may continue, leading to a steepening of slope and a decrease in beach width; in the long run, this may become a serious threat to the foredunes. There are some interesting alternatives offering a more dynamic foredune management. By suppletion of sand on the shoreface, the underwater profile can be restored without affecting the foredunes themselves. With a decrease of the erosion threat, an increase in natural processes might even be permitted. Another alternative is to allow the wind to move the foredunes landward ("rolling foredune"), keeping the coastal profile intact.

Management depends on coastal development, but also on interests in the hinterland, geographical situation and tradition. For the three main regions along the Dutch coast (Wadden Islands, Mainland Coast and Zeeland Estuaries), differences in management strategies are observed. More than 40% of the foredunes are unnatural or artificial. Natural development is rare and almost exclusive for accretional areas. Only 10% of the Dutch foredunes are developing without any interference of man, mostly on the Wadden Islands. The strongest occurrence of aeolian processes is found in accretional areas. However in these areas, dynamic processes are often limited because of the prevention of aeolian erosion. Compared to forty years ago, dynamic processes along the Dutch coast have diminished which has led to a reduction in natural forms.

In a stabilised foredune, the influence of wind is restricted: if there is a supply of sand, the action of wind is limited to deposition. However without further management interference, the role of wind in foredune development will gradually increase. After some tens of years, the former stabilised foredune will be transformed to a highly dynamic and natural system (as is the case on the eastern part of Schiermonnikoog). This relatively short time scale offers possibilities for a natural rejuvenation of foredunes. Any foredune could be transformed from a shapeless sand-dyke into a natural transition between land and sea within some tens of years. With the necessity of a safe sea defence in mind, possibilities for natural restoration will be found in stable or accretion areas which have a wide dune zone and no other major interests.

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Editorial correction added in proof: On the first map of the series of three, change "Management and Dynamics" to read "Dynamics and Management" on the island of Vlieland. This change only applies to the color bars for stations 40–50 where "Dynamics" should apply to the outer color bar and "Management" to the inner color bar.