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Landscape ecology of the Dutch coast

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Abstract. This paper is a summary and elaboration of an earlier publication in Dutch on the compilation of a landscape-ecological map, scale 1 : 50 000, of the Dutch coast. It is argued that such an integrated map is the best basis for the conservation and management of the coastal dunes and salt marshes. It may be combined with local more detailed vegetation maps, some examples of which are mentioned in the context of management.

The Dutch North Sea coast is a ca. 350 km long chain of sandy beaches and sand dunes, from only 100 m to more than 10 km wide. On sheltered stretches of dune coasts along estuaries in the Southwest and on the Wadden Sea islands, salt marshes have developed. The small-scale gradient structure of the beach-dune-salt marsh complex is emphasized.

Since 1955, a classification of landscape types has been developed for this area, which is mainly based on vegetation, geomorphology, soil types and history of human use of the area. Local maps were prepared in the field, based on topographical maps, scale 1 : 25000, most of which were updated with the help of recent and more detailed maps, based on aerial photographs, scale 1 : 2500 - 1 : 10 000, combined with new field work. In the general report (Doing 1988), the main results are presented, including a map redrawn on the scale 1 : 50000.

The main principles of the landscape typology and mapping were:

1. A 'landscape' is defined as an area of land (and water), which can be recognized as an integrated structure, and distinguished from neighbouring units, both in the field and on aerial photographs. It can be described in terms of vegetation, geomorphology, soil and land use, where the relative importance of these aspects for landscape classification may be different in different regions and zones.
2. In sand dunes and salt marshes, there is usually a fine-grained, complicated pattern of ecosystems (units of vegetation which are functionally related to their environment). Such patterns can only be mapped on large scales (1 : 2500). Therefore, a landscape unit must be conceived as a complex of ecosystems. Consequently, various stages of succession may be included in one and the same mapping unit, especially in old dunes.
3. The repetition of certain patterns of ecosystems, showing functional and historical coherence, provides the geographical basis for the mapping units. Boundaries are usually determined by geomorphological aspects, which are related to geological, climatological, vegetation and land use history.
4. The units are identified with the help of a flexible system of letter and number symbols. There are 15 'main landscape types' (nine for sand dunes, six for salt marshes) and 16 'auxiliary types', some of which occurring in both dunes and salt marshes. Most units are combinations of these types; they are indicated by at least two letters, in a sequence adapted to the local situation. In this way, a 'landscape language' was developed, which needs some effort to understand, but proves to be an effective tool to describe a very complex situation.

Finally, some examples are given of the use of this landscape-ecological approach to problems and perspectives of the conservation and management of coastal landscapes.

Keywords: Coastal dune; Coastal salt marsh; Conservation; Land use history; Landscape type; Management; Mapping.

Nomenclature: van der Meijden et al. (1983) for most of the vascular plant species; Margadant & During (1982) for mosses and liverworts.

Introduction

This study is an English summary and extension of the monograph 'Landschapsoecologie van de Nederlandse kust' (Doing 1988). In this study a coloured landscape map in three sheets on a vegetation-ecological basis was presented in the scale 1 : 50 000. In addition a sheet with a landscape map of the Wadden Islands of Texel and Schiermonnikoog, scale 1 : 25 000 was published. This map was originally prepared for the Wadden Sea Working Group (Doing & de Graaf 1983). This study is still available via the Office of EUCC, the European Union for Coastal Conservation in Leiden, but is difficult to understand without an intimate knowledge of the Dutch language.

The contents of the Dutch study are as follows:

1. Introduction.
2. Legend to the maps.
3. Description of the main landscape types.
4. Description of the subordinate landscape types.
5. Description of the major mapping units.
6. Species lists.
7. History of vegetation and landscape.
8. Geological history.
9. List of local studies used for the compilation of the map.

In the present study the emphasis will be on the characterization of the landscape units and the composition of the map legend. In addition, some notes on the applications of the study will be presented.

Earlier general studies of flora and vegetation

Flora and vegetation of the Dutch dunes and salt marshes have been studied intensively (e.g. Westhoff 1947; Boerboom 1957, 1960; van der Maarel & Westhoff 1964; Doing 1966, 1974; Adriani & van der Maarel 1968; Sloet van Oldruitenborgh 1976; Dijkema & Wolff 1983; Westhoff & van Oosten 1991). A comprehensive account on the ecosystems of the Dutch dunes was presented by Dijkema et al. (1993) for the northern and van der Meulen & van der Maarel (1993) for the southern dunes.

Many local studies were published in Dutch and local vegetation maps are often included in student reports which were reproduced in small numbers and are not easily available, nor comparable with each other. On the other hand, the following maps are more generally available:

- Vegetation map of the Meijendel dunes near The Hague, scale 1:10 000 (Boerboom 1958). Broad vegetation complexes are the main units on this map. It served as a basis for an integrated plan for dune afforestation and recreation development while taking the natural values of the area into account.
- Vegetation map of the dunes of the province of Noord-Holland north of IJmuiden (Doing 1964). The context of this study was identical to the former one.
- Vegetation map of the nature reserve in the dunes near Oostvoorne, near Rotterdam and its harbour, scale 1: 2500 (van der Maarel & Westhoff 1964). The main map units on this map are formations, i.e. broad structural types; each of them was subdivided into plant community types. This map served as a basis for an overall management plan of the nature reserve owned by the foundation Het Zuid-Hollands Landschap.

20 years later, this map was repeated with the same approach for the same conservancy organisation (van der Maarel et al. 1985). By comparing the two maps and a separate study of five air photographs (van Dorp et al. 1985) the natural development of the dunes could be characterized and the management plan revised in order to develop a combined approach of allowing the natural developments to proceed and rejuvenating special parts of the landscape. One further outcome of this study is the increase in nitrophilous plant species, which is almost certainly due to the deposition of air pollutants, which is particularly heavy in the area.

- Landscape ecological map of the Meijendel dunes by van der Meulen et al. (1985). This map (1: 5000) was based on the 'landscape-guided method of vegetation survey' developed at ITC (Zonneveld 1972, 1995). Map units show the relationships between geomorphology, vegetation structure and floristic composition of the vegetation. These land attributes feature also as diagnostic criteria in the arrangement of the map legend. The map is used for management purposes by the Dune Water Works of Zuid-Holland

The need for a landscape map

The general need for an integrated description of the coastal area as a whole, mainly as a basis for conservation and management, cannot be satisfied by means of classical vegetation maps, which are the usual tool in the management and planning of local coastal areas. Technically, this would have been an impossible task, in view of the size and variation of the area. Moreover, the vegetation alone would not be an complete indicator of the ecological conditions; more information is needed on soils, geomorphology and the history of coastal zone management. Therefore, a classification of landscape units was developed, which enabled the mapping of the coastal area on the scale 1 : 25 000 - which scale had to be reduced to 1 : 50 000 in the final publication.

Inventories of coastal lands for planning and management need to include surveys in which all landscape-ecological aspects are considered which are important for these purposes. Geomorphological and ecosystem complexes have proved to provide a basis for mapping large areas on a convenient scale. Such 'landscape maps' should be supplemented by relatively detailed descriptions, based on field work.

Once established, the legend units of the landscape map should be recognized as integrated, holistic entities, in the field as well as on aerial photographs. Their contents are based on vegetation as much as possible, while their cartographic limits are often determined by geomorphology.

Although landscape units are basically descriptive, they are closely connected with geological and land use history and in this way dynamic units at the same time. In coastal sand dunes and salt marshes, they correspond to definite periods and rates of accretion and erosion of the coast, and to periods of mobility or stability of the substrate. Thus, hypotheses on the interrelation of vegetation, soil processes and geomorphology can be derived from the results of landscape mapping.

Since 1957, mapping projects have been carried out along the Dutch coast and after 30 yr the survey was completed (Doing 1988). Excluding the intensively cultivated areas at the inner side of the dunes, more than 600 km^2 of dunes, beach plains and salt marshes were included in the maps.

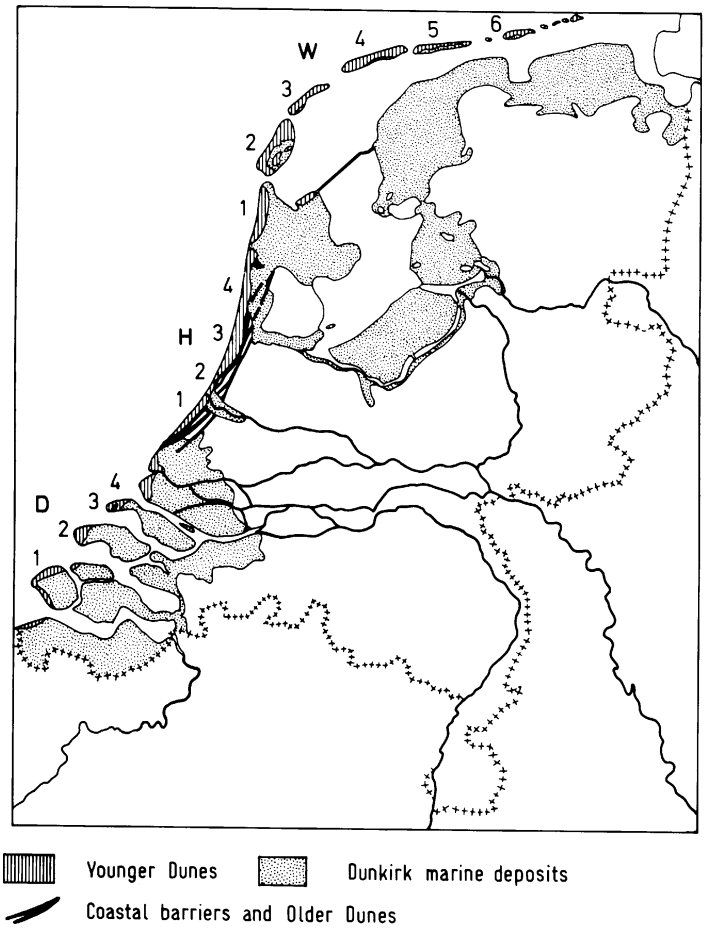

Fig. 1. Coastal regions of the Netherlands (after van der Maarel 1979).
D = Delta coast
D1 = Walcheren
D2 = Schouwen
D3 = Goeree
D4 = Voorne

H = Holland coast
H1 = Hook of Holland - The Hague
H2 = The Hague - Katwijk
H3 = Katwijk - IJmuiden
H4 = IJmuiden - Schoorl

W = Wadden Sea coast
W1 = Schoorl - Den Helder
W2 = Texel
W3 = Vlieland
W4 = Terschelling
W5 = Ameland
W6 = Schiermonnikoog and islets to the east

Outline of the coastal area of the Netherlands

Sand dunes are present almost along the complete length of the North Sea coast line of the Netherlands: 356 km, as measured along the foot of the foredunes; the remaining 36 km of coastline are dikes.

As to their width, the coastal dunes vary from a narrow strip of young foredunes to complexes of young and old dunes and beach plains up to 11 km wide, measured perpendicular to the present strand line.

In the southwestern estuarine part of the Netherlands, and particularly on the Wadden Sea islands, salt marshes are bordering on, or alternating with sand dunes.

Fig. 1 presents the three main physiographic coastal regions in the Netherlands, the 'Delta coast', the 'Holland coast' and the 'Wadden Sea coast'. 14 main coastal regions are distinguished, each with its own features (van der Maarel 1979). Note that region W1 forms part of the Holland mainland, but both historically and phytogeographically it belongs to the Wadden coast. Fig. 1 also shows the position of old beach ridges and old dunes.

The major part of the Dutch dunes and salt marshes are still in a natural or semi-natural state, although large parts of the old barrier dune and beach plain systems from The Hague to Alkmaar (regions H2 and H3 in Fig. 1) no longer bear natural vegetation, but have been built-up or levelled for intensive horticulture, particularly for growing flower bulbs.

The coastal area of the Netherlands is, like most coastal regions, very dynamic and varied. It includes gradients from salt to fresh water situations, from waterlogged to arid ecosystems, from basic to acid soils and from pioneer to climax vegetation. These gradients are mostly found in small-scale patterns. In addition, there is considerable climatic variation from north to south and from the beach to sheltered situations in the inner dunes.

Concepts and Methods

Landscape-ecological principles (Naveh & Lieberman 1984) were used as a guideline. The concept of 'landscape' was defined as 'a geographically, functionally and historically interconnected complex of ecosystems'. The ecosystem, as a basic landscape element, can be recognized in the field by the homogeneous structure and composition of its vegetation and homogeneous morphometric features of the soil profile. More fundamentally, it is also characterized by its microclimate and by processes which can be described as input, movement, transformation and output of matter and energy. An important practical difficulty is, that these latter aspects can only be described with the help of time-consuming research, not compatible with extensive mapping projects. For the latter, the vegetation-soil complex ('geosystem') must be used as the visible expression of the underlying functional systems (Doing 1979). In summary, there is a clear distinction between ecosystem and landscape, the first indicating a homogeneous, the second a heterogeneous structure.

The way in which landscapes are built up of separate ecosystems or communities, is similar to the way in which the latter are characterized by their species (cf. Westhoff & den Held 1975; Schaminée et al. 1995). The complexes can be distinguished from each other on the basis of dominant, characteristic, differential, accompanying, obligatory and facultative ecosystems (Doing 1963, 1979). In the same way as the species within a certain community belong to very different taxonomic groups, there is no *a priori* requirement to assume a syntaxonomic, synecologic or even syndynamic relationship between the communities within a landscape; instead purely geographical affinity is the clue to their grouping together. In vegetation mapping, the choice between the representation of single communities and that of complexes is primarily a matter of scale. In fine-scale patterned landscapes, such as dunes and salt marshes, separate communities can usually not be represented on maps 1:10 000 or smaller.

Apart from recurrent community patterns, geomorphology and hydrology are fundamental and universal aspects of landscapes. They play an important role in the delimitation of mapping units. Landscape types, i.e. legend units of a landscape map, should always be described in terms of ecosystems as well as their geomorphology.

Thus, vegetation zones and mosaics, in connection with geomorphological and hydrological patterns, are the primary basis for mapping because of their overall visibility. The most prominent feature of vegetation on aerial photographs is structure. During the field survey, floristic composition has played a major role. Apart from this, there is no fundamental difference between our approach and the integrated surveys according to the 'ITC-method' (Zonneveld 1972, 1995).

The major differences between 'classical' vegetation maps and the landscape map presented here are:

1. In natural or semi-natural areas, vegetation is the most efficient starting point for mapping, but the other components of the ecosystem, as far as discernable in the field, should be weighed against it. Hence a purely vegetational classification is not sufficient. Each vegetation analysis should at least be complemented by a field description of the corresponding soil profile.

2. In intensively cultivated areas, with disturbed species-poor vegetation, soil and hydrology are the best primary features for a landscape classification. Here, vegetation is to be included in a description of land use systems.

3. Depending on the amount of detail in the local environmental pattern, all maps on a scale smaller than that on which separate homogeneous patches can be represented, should be conceived as landscape maps, i.e. maps of ecosystem complexes (zones, mosaics or other spatial arrangements). The smaller the scale, i.e. the more simplified the map, the more complicated the description of the legend should be, to avoid an unacceptable loss of information.

4. Geomorphology and hydrology are characteristics of landscapes, to be included explicitly in the description of the units.

Classification of coastal landscapes and composition of the landscape map

For the landscape map presented here, a hierarchical classification of landscape types has been adopted. The units are indicated by the following codes: capitals for the main types, supplemented by one or more lower case letters and/or numbers, for the subtypes. For the sake of easiness, the number of main types has been kept limited; subtypes are distinguished as much as desirable for the necessary detail. In this way, the same code system can be used for mapping projects on various scales.

The letters are derived from the names of important plants, vegetation units or geological or pedological features (see below). The vegetation units are phytosociological types, most of them being so-called alliances in the plant community system according to Braun-Blanquet. Most of these units are described in Westhoff & den Held (1975); additional information can be found in Doing (1963, 1974).

The distinction of the landscape types is easily made on the basis of geological substrate, geomorphology, hydrology and soils. Differences in vegetation vary

from region to region, but are usually clear-cut. The groups might be used for very small-scale maps, e.g. as a first approach to an inventory of European coasts, necessitating only a limited amount of field reconnaissance.

Legend of the map

The map legend is constructed by combining the symbols for the landscape types and elements in a flexible way, using at least two letters or numbers, and adding as many others as desirable in view of the scale of the map and the required amount of detail, and in an order of relative importance, based on cover percentages of vegetation types or abundance of species.

The legend, as presented in the original publication (Doing 1988) as a separate sheet to the map, consists of the following components.

1. The legend as such, a list of landscape types and subtypes with a letter combination and colour indication; the units are indicated, as far as possible, by common, characteristic names.
2. A list of individual letter symbols with their formal significance.
3. A list of phytosociological types.
4. A survey in the form of a diagonally structured table of the characterization of the landscape units by the phytosociological units.

The main landscape types and the elements for the subtypes will be briefly described in the text. Complete list of types and elements will be added to this paper as Apps. 1 and 2, while the information mentioned under points 3 and 4 will be added as Apps. 3 and 4.

Description of the main landscape types

For the main types, the following 10 letters are used:

A,**H**,**K**,**R**	Types of dry, basic, young dunes
C,**P**	Types of dry, acid, young dunes
E,**V**	Types of moist or wet, young dunes
W	Type of ancient dunes = old barriers and plains (dry, moist or wet)
M + number	Types of marine landscapes (recent or former salt marsh)

A *Ammophila (Marram) landscape*

This is the landscape of the 'yellow dunes', with much blowing sand, very poor in humus, very permeable for water (loose packing of the sand), without or with open, herbaceous, species-poor vegetation (e.g. *Ammophila*, *Leymus arenarius*, *Elymus farctus*, *Cakile*). It consists largely of foredunes, dry beaches and beach plains with heavy salt spray, partly with temporary inundations, but also mobile dunes further inland, where previous vegetation has been destroyed. This landscape is widely distributed throughout Europe and North Africa (van der Maarel 1993), and easily located on aerial photographs. Some dune areas consist only of this landscape type.

H *Hippophae (Sea buckthorn) landscape*

This is a shrub-dominated landscape on dry, basic dunes, rich in pioneer scrub (mainly *Hippophae rhamnoides*), but in some areas also with higher and denser scrub (mostly *Berberidion*) or woodland (with *Betula*, *Populus tremula*, belonging to the alliance *Alno-Ulmion*). Soils have only a very superficial humus layer, but decalcification is well under way.

In landscape succession, it is preceded by **A**-landscapes, i.e. depositional dunes, mainly built up by the sand accumulating behaviour of *Ammophila*. Therefore, it consists of former foredune ridges, or of parabolic or rejuvenated dunes in the process of re-establishment of vegetation. In the latter case, the dunes are mostly older and more distant from the beach than those of the **R**-landscapes, and the morphology of the ridges is intermediate between parabolic 'comb dunes' (Klijn 1981) and 'Wanderdünen' (transverse migratory dune ridges, cf. Cooper 1958). See Olson & van der Maarel (1989) for a typology and comparison of dune systems.

Like in many pioneer dune scrubs in other parts of the world, poverty of the soil in plant nutrients is partly compensated by symbiosis with nitrogen-fixing microorganisms. After further humus-enrichment of the soil, which involves leaching from the surface downwards, *Hippophae* scrub loses vitality (also in connection with microbiological changes in the root environment) and succession leads to a more open vegetation, mostly *Koelerion* (Doing 1983b), except in localities with relatively favourable moisture conditions. The geographic distribution is mainly from Normandy to the East Frisian islands and the English North Sea coast, with an optimum in the Netherlands.

K *Koelerion (Hair grass) landscape*

This landscape is characterized by the predominance of low vegetation, rich in mosses, lichens, small annuals, low graminoids and chamaephytes, sometimes with patchy scrubs or woodlands. It occurs on dry, moderately calcareous dunes ($CaCO_3$ - content mostly ca. 1 - 3 %). The humus layer is, especially on north slopes, well-developed and more or less acid, but not deep (generally 2 - 10 cm, except under woody vegetation). This landscape is found in various situations and zones, intermediate between **H** or **R** on the one hand, **C** on the other hand.

The common feature is the origin of its pioneer

vegetation on bare sand, carrying no, or scarce vegetation (e.g. scattered *Ammophila*-tufts) with its pre-existent root systems, or taking the place of dying vegetation (see under **H**). It is found on former basic mobile dune ridges, fixed by human interference, as well as in dry valleys in the **R** or **H**-zone, on abandoned cultivated land, or replacing the **R**-landscape near old sea-villages because of former human influence.

Its optimal floristic development is found in south-western France, e.g. in the Vendée (Géhu 1993), and its total area covers all moist-temperate European coasts, except where only acid dunes are present.

R *Rubus caesius (Dewberry) landscape*

This is a landscape with predominantly herbaceous vegetation, rich in mosses, locally with low scrubs or woodland fragments, found on dry, strongly basic dunes. In its optimal form this landscape type consists of systems of young, prominent, steep parabolic dunes 'comb dunes', not levelled by water erosion and mostly originating from the parabolization of former retreating, highly calcareous foredunes. The characteristic vegetation (*i.a*. abundance of *Rubus caesius*) indicates an accelerated speed of mineralization of organic matter, which in its turn results from its mixing with overblowing calcareous sand. The dune morphology points to an equilibrium between wind, blowing sand and vegetation, with maximal vitality of *Ammophila* in the early stages of succession - which are now rare in the Netherlands because of the protective management. This landscape type occurs from northern France and southern Britain to the east Frisian islands, and it is optimally developed in the Netherlands, especially between The Hague and Bergen. The sand is rich in coarse shell fragments, has a 'dirty' colour down to several dm and under a closed moss cover acidification of the soil surface proceeds with surprising speed.

C *Corynephorus (Grey hairgrass) landscape*

This is a landscape with mostly low, open vegetation, rich in graminoids and lichens on dry, acid dunes. In some zones, not too close to the sea, oak woodlands and pine plantations may occur. Vegetation structure, dune morphology and variation in origin are similar to those in the **K**-landscape. Because of the absence of free lime, there is no intensive mineralization of organic matter and therefore a depressed vitality of sand-binding species.

Because of this, the dunes are not very resistant to wind erosion, which is reflected in their morphology. Moreover, the dune surface tends to be hydrophobic, a property which is increasing after a change in fixation and mobility. This intensifies the aridity of the ecosystems and causes water erosion because of increased run-off, also influencing the dune morphology (Jungerius & van der Meulen 1988). Where there are parabolic dunes, the ridges tend to be lower and less steep than in the **R**- of **H**-landscapes, not arranged into comb dunes and with rather large slacks, sometimes several km long. In other areas, 'conic dunes' are found, also called basin dunes (Doing 1983a), 'kopjes-dunes' (Klijn 1981) or rolling dunes (Olson & van der Maarel 1989).

P *Empetrum (Crowberry) landscape*

This landscape features continuous heath vegetation on dry or somewhat moist, very acid dunes with, locally and rather recently, acid woodland (with mostly *Betula* and *Populus tremula*, belonging to the alliance *Quercion robori-petraeae*, which also occurs in **C**-landscapes). Soils have a 'mor' humus layer, a leached A_2-horizon but no compact C-horizon. The *Empetrum* type occurs in the more or less flat, older parts of the north-atlantic, acid dunes, in dry valleys and along the inner border of higher dune complexes. It extends from Bergen (Noord-Holland) to northern Jutland, and is optimally developed along the Danish North Sea coast (Jensen 1993).

E *Hydrocotyle (moist dune slack) landscape*

This is a landscape of moist or temporarily wet or inundated, young slacks in basic as well as in acid dunes. The variation ranges from pioneer situations, almost bare of vegetation, to continuous herbaceous vegetation and to low scrub or woodland on mineral soil. It occurs in primary and secondary valleys in all European dune regions with sufficient width and history and sufficient rainfall for the maintenance of freshwater conditions. In the Netherlands, the lower limit is determined by a groundwater level of maximally ca. 110 cm below the surface in summer. Local species dominance by strong competitors, e.g. *Calamagrostis epigejos*, may prevent the establishment of phreatophytes, in which case the mapping unit should be determined on the basis of the hydrological conditions.

Because of the very large variation within moist slacks, a more detailed classification than that occurring on the maps (Doing 1988) is proposed. The main criteria for the subdivision are the age of the slack and the pH in the soil.

E_0 *Moist, bare sand*, sometimes inundated in winter. Vegetation e.g. *Littorellion uniflorae*.
E_1 *Moist slacks*, with open vegetation (e.g. *Nanocyperion flavescentis*) or continuous vegetation containing pioneer species (e.g. *Centaurium* spp.).
E_2 *Basic, moist slacks*, with continuous vegetation (e.g. *Caricion davallianae*).
E_3 *Neutral, moist slacks*, with continuous vegetation without an important share of indicators of basic or acid

conditions (e.g. *Caricion curto-nigrae, Phragmition*).
E_4 *Acid dune slacks*, with continuous vegetation (e.g. *Pyrolo-Salicetum, Junco-Molinion*).
E_5 *Very acid, moist dune slacks*, with continuous vegetation with *Sphagnum* spp., or dwarf shrubs (e.g. *Ericion tetralicis*).

V *Peat landscape*

The Peat landscape (indicated with the letter **V** from the Dutch veen = peat), is characteristic of permanently wet or inundated, young dune slacks. It includes aquatic, shore or fen vegetation, including high willow scrub and alder woodland. The soil environment is characterized by the process of peat formation (lack of aeration), but in relatively recent situations, time may have been insufficient for building up a well-developed peat layer. In former periods of dune formation this landscape type was distributed more widely than at present, as peat layers in the subsoil witness. These peat or humus layers indicate periods of stability in the history of dune formation. At present the **V**-landscape is mainly restricted to scattered, relatively wide dune areas along the NW-European and Baltic coasts (e.g. Boorman 1993, Wojterski 1993). Within the Netherlands, its major occurrences are found on the islands of Voorne and Texel.

W *Landscape of old barrier dune ridges and former beach plains*

This type includes a system of barrier dunes behind, and partly underneath, the younger dunes, which are rarely older than ca. 1000 A.D. and are primarily the product of erosion. This barrier system was formed from subboreal times to the early Middle Ages during periods of accretion of the coast. The landscape was originally covered with forest, later partly with heath (in connection with sheep grazing, if this continued long enough to produce podzol profiles). Still later it was cultivated, reclaimed, excavated or occupied by housing or industrial developments. The woodlands which are now found on the remnants of this landscape are all planted, but nevertheless may carry interesting semi-natural vegetation. They are mainly developed in the provinces of Zuid-Holland and Noord-Holland, from Hoek van Holland to northeast of Alkmaar (H1-H4 in Fig. 1). Other small areas are found in French and Belgian Flanders and in Schleswig-Holstein; these are geologically younger.

M *Marine landscapes (salt marshes and mudflats)*

These can be arranged into six zones from low to high, with decreasing height, length and frequency of inundation by salt water.

M0 *Mud flats, creeks and other tidal areas*, inundated by the sea (North Sea or Wadden Sea), all, or most of the time. This main type is always found at the lower limit of the series **M 1** - **M5**. In its highest parts, vegetation of algae, sea grasses or some scattered *Salicornia*, *Spartina* or *Suaeda* may be present.

M1 *Low salt marsh*, inundated during all high tides except neap tides, occurring on relatively flat, muddy or sandy areas with open vegetation of predominantly *Salicornia*, *Spartina* or *Suaeda*.

M2 *Medium salt marsh*, inundated at least during spring tides. Active sedimentation of silt, often on a sandy subsoil. Consists of a pattern of reeks, levees and basins. Mostly a continuous vegetation of *i.a. Halimione*, *Puccinellia* and *Limonium.*

M3 *High salt marsh*, inundated only during storm surge tides, on relatively flat, mostly sandy areas with some wide and deep creeks, bordered by high levee banks. Vegetation with *i.a. Festuca rubra, Juncus gerardii, Armeria maritima, Artemisia maritima*.

M4 *Transitional marsh*, between high salt marsh (**M3**) and moist dune valley (**E** or **V**), inundated only during exceptionally high tides, or brackish because of former inundation or recent salt spray. Vegetation with *i.a. Agrostis stolonifera* and *Potentilla anserina*.

M5 *Transitional marsh*, between high salt marsh (**M3**) and low, dry dunes (mostly **K** or **H**). Vegetation with *Elymus athericus* or *Sagina maritima*.

Description of the subtypes

Subtypes of the main types are formed by adding a specific characteristic to the main description. First of all, this can either be a characteristic referring to the type itself, when this occurs in a species-poor, 'pure' form, or to another main landscape type, when this occurs in a mosaic with the main type. The subtypes are indicated with a lower case referring to the main type.

a *With Ammophila (blow-out) elements*

In **Aa**: pure *Ammophila*-landscape, without important other components, species-poor. In **Ca**: very dry and acid dunes with open vegetation, rich in lichens and small, non-flowering tufts of *Ammophila*. This subtype is predominating within type **C**. In other main types, e.g. **Pa**: presence of blow-outs, including an accumulation zone with *Ammophila* at the leeward side.

b *With scrub elements*

Scrub belonging to the order *Prunetalia spinosae* can occur in type **K**: **Kb**, or **C**: **Cb**, in this case often large colonies of *Rosa pimpinellifolia* (Burnet-rose) occur.

c *With indicators of dry, acid soils*

These are indicators such as *Corynephorus* and lichens. A 'pure' **Cc**-landscape exists, but is only found on inland dunes.

e *With moisture-indicating vegetation patches*

Patches with phreatophytes (ground-water bound plants) or patches on soils with a large water-holding capacity of soils rich in humus and nitrogen. A typical combination is **Ve**, with dominance of *Phragmites australis* (reed).

h *With Hippophae scrub*

The subtype **Hh**, which can occupy extensive areas, is characterized by the dominance of Sea buckthorn scrub, with *Calamagrostis epigejos* as the most important herbaceous species. In **Rh**, Dewberry and Sea buckthorn occur in combination.

k *With indicators of dry, calcareous soils*

This is an element of *Phleo-Koelerion* low pioneer vegetation, established on bare sand, which can be found as undergrowth of open scrub: type **Hk**.

m *With patches of salt marsh*

Such patches can be differentiated from very low open salt marsh to very high, sandy salt marsh (*Elymus athericus* or *Saginion maritimae*), while using the indications **m0** to **m5** (see type **M**).

r *Rubus caesius element*

With indicators of calcareous sand blowing over vegetation on a stable surface. Occurs particularly in the combination **Hr**; the difference between **Rh** and **Hr** is floristically subtle and is determined mainly by geomorphology.

In addition, lower case letters are used to indicate variants which do not refer to a main type. Examples here are:

d for grassy and/or mossy aspects related to former grazing or mowing, e.g. **Kd**, **Md**;

f for nitrogen indicators on places where large amounts of nitrogen are released through the decomposition of organic material, e.g. **Cf**;

g for tall grasses, indicating disturbance such as the death of woodlands or the lowering of the phreatic water level; for instance *Calamagrostis epigejos* (Wood small-reed grass) in **Hg**, *Molinia caerulea* (Purple moor-grass) in **Eg**;

i for local *Salix* (Willow) dominance, notably in **Vi**;

l for patches of heath in **Cl** (*Calluna*) or **E1** (*Erica*) or with dominant or codominant *Calluna* in **P1**;

w for woodland elements, e.g. oak (*Quercus robur*), birch (*Betula*) and aspen (*Populus tremula*) and planted trees, notably pine, for instance in **Hw**.With the exception of type **W**, where the natural vegetation is practically always a forest, forests are not mapped as separate landscape types, according to the principle that all succession stages may be present within one main type.

Illustrations of the landscape map and some landscape types

Map of Schiermonnikoog

Fig. 2 presents a fragment of the landscape map including the island of Schiermonnikoog. It is a type II island in the typology of Doing (1983b; see Dijkema et al. 1993), a medium-size west-east directed Wadden island which moves in a northwest-southeast direction. The island moves in the sense that there are interrupted periods of heavy erosion at the western tip and accretion at the eastern side. In the Middle Ages the nucleus of the island was situated 3 - 5 km to the west of the present western edge of the island and several villages were found there.

The western part of the island is the oldest one, at least 400 yr old, and characterized by various **C**-types. The seaward dunes are younger and consist of **A** and **R** landscapes. To the west and northwest an extensive beach is found with an $\mathbf{A_o}$ landscape.

The eastern part of the island is a vast beach plain carrying **M** landscapes with small dune complexes with a variety of **A** landscapes. The oldest part, bordering the **H** landscapes is ca. 200 yr old, the easternmost part is completely bare and starting a vegetation development. The salt marshes develop at the protected south side of the island where silt accumulates.

Photographs of landscape types

In photos (Fig. 3 by S.M. Arens; all others by H. Doing) various landscape types will be illustrated on the next pages.

Fig. 2. Landscape map of the Wadden island of Schiermonnikoog. See text and Apps. 1 and 2.

Fig. 3. Accretional coast with **Aa$_0$**-landscape.

Fig. 4. Erosional coast, foredune ridge with strong human influence (**Aar**-landscape); behind this micro-parabolic dunes with human influence (**Aar**-landscape); behind this micro-parabolic dunes (**Rh**-landscape) with *Hippophae rhamnoides* (Sea buckthorn) in former blow-outs. Calcareous dune area.

Fig. 5. Scrub of *Crataegus monogyna* (Hawthorn) and tall *Hippophae rhamnoides* (Sea buckthorn) in a dry calcareous valley: **Hb**-landscape.

Fig. 6. Formerly mobile dune ridges in a very acid dune area. Foreground: **Ca**-landscape. Very high ridge at the horizon: **Ca**-landscape, planted with *Pinus nigra*.

Fig. 7. Young, wet, primary slack in a calcareous dune area. **Hb**-landscape (ridge), **E_3**-landscape (slack).

Fig. 8. Young, wet secondary slack in a calcareous dune area. **Aah**-landscape (with much blowing sand), **E_2**-landscape (slack).

Fig. 9. Old, primary slack with peat formation in a calcareous dune area. **V_0-** (open water), **Vey**- (shores), **Vi** (*Salix* scrub) and **Vv**- (*Alnus* wood) landscape.

Fig. 10. Old beach barrier with woodland and village: **Ww**- and **We**-landscape; old beach plain with dairy farming: **Wvd**-landscape.

Zonation of landscape types

As a result of differences in geological history, landscape succession, management and climate, various types of zonation occur along the coast. This is one of the most conspicuous aspects of the coastal dune system and hence it will be discussed in the following paragraphs.

Calcareous mainland dunes between Hoek van Holland and Schoorl (Fig. 1: H1-H4)

Zonation **A_0mo - Aar - Rr - Hh - Hb - Kb - Kc - W**. In this stretch of coast, there is a virtually uninterrupted sandy beach without vegetation (**A_0m0**), bordered by a high foredune ridge, which is stable or retreating slowly after cliffing during storm tides (**Aar**). The front of this ridge has taken an unnatural straight form as a result of management for coastal defence by public authorities, and carries normally a species-poor *Ammophiletum*. At the lee side, vegetation is more varied and consists of i.a. *Festuca rubra, Rubus caesius, Hippophae rhamnoides* and *Sambucus nigra,* and at the inner border a *Tortulo-Phleetum.*

In former times, mainly in the 18th and 19th century, many blow-outs occurred, starting from erosion of the foredunes, which resulted in repeated periods of parabolization. In most of these areas, there is now a zone of fixed comb dunes, mapped as **R**-landscape, up to 4 km wide (but mostly 1 - 2 km). The youngest parts, exposed to strong winds and the influences of salt spray, are poor in scrubs, except those of *Ligustrum vulgare* (**Rr**-landscape). Further inland, mineralization of organic material as well as decalcification have progressed to a stage involving the development of *Hippophae* shrubland, mainly in the hollows. In the slacks there are locally small woodlands of *Betula* or *Populus tremula* (**Rh**-landscape). The sand in the **R**-zone is characterized by the abundant presence of coarse shell fragments, and originates from the recent hollowing out of the North Sea bottom combined with the retreat of the coast. This resulted in the mixing of large amounts of semi-fossil shells with the dune sand.

Mainly around old sea-villages (Scheveningen, Katwijk, Noordwijk, Zandvoort, IJmuiden, Wijk aan Zee, Egmond), this zone is interrupted by **Ks**-landscapes, with a confused 'blow-out morphology' (Doing 1986), and species-rich vegetation, connected with former trampling nutrient enrichment.

In the next main zone, parabolic dune ridges generally are less steep, more distant from each other and tend to be joined in a direction parallel to the coastline, leaving secondary valleys of relatively great width (**H**-landscapes). This points to a longer history of mobility. The ridges and slopes are dominated by *Hippophae* scrub, with much *Calamagrostis epigejos* (**Hh**), the slacks, hollows and feet of slopes are rich in denser and higher scrubs with deeper soils and *i.a. Crataegus monogyna, Euonymus europaeus* and *Rosa canina*, locally also with *Rhamnus catharticus, Berberis vulgaris* and *Cornus sanguinea*. In the moist slacks, *Betula* woodlands are found (**Hb**-landscape). Geomorphologically, these **H**-landscapes represent an older stage of parabolization than the **R**-landscape. They are mainly found in the centre of more than 3 km wide dune areas, which is a hydrologically favoured position. The sand is calcareous, but shell fragments are much finer than those in **R**-landscapes. They correspond with an older phase of major instability, which occurred mainly in the 15th-16th centuries in most areas.

Not only is the distance from the present coastline relatively great, but also was this line situated further west at that time. Therefore, the sand of the **H**-landscape has undergone a much longer history of decalcification and loss of organic material. This is reflected in the dune morphology being intermediate between parabolic and transverse migratory dunes. From historical data it is known that these central parts of the dunes were fixed at a relatively late stage, and much bare sand was present until the 19th or even the beginning of the 20th century.

The innermost major zone of the widest areas of the younger dunes (mainly near Wassenaar and Bloemendaal) consists of series of large valleys and high, broad ridges with gentle windward and steep leeward slopes, originating from the middle ages (Jelgersma et al. 1970). The calcium content of the sand is relatively low, and the vegetation is a varied mosaic of low, partly open vegetation with many patches of scrubs and woodlands, the latter often dominant in the slacks (**K**-landscape).

The sand of these large, up to 55 m high, formerly mobile dunes is derived from parts of the old barrier dune ridges, which were destroyed during a catastrophic phase of wind erosion around the 10th - 12th centuries, the cause of which has not been completely clarified. The ridges were threatening settlements and agricultural land during this period. Vegetation succession started from bare sand after fixation by human efforts, which was successful in most places around the end of the 12th century, simultaneously with the protection of large areas against the sea by dike construction. In the relatively lime-rich and stable areas, vegetation on the slopes is characterized by large populations of *Rosa pimpinellifolia* (**Kb**-landscape), on other parts of the ridges, with more acid and hydrophobic sand, *Corynephorus* is common (**Kc**-landscape). The difference is probably determined by the share of leached old dune sand at the present surface, which had not been in contact with the sea for a very long time.

The age, origin and vegetation of the system of old

barrier dune ridges and beach plains is briefly described in the section on the main landscape types (**W**-landscape). South of The Hague and north of Alkmaar most of it has been eroded by the sea, and other large parts are covered by, or mixed with, the younger dunes. On what is left, only for a minor part semi-natural vegetation is present, mainly planted deciduous woodlands. On the maps, a division is made into dry, sandy, leached ridges **Ww**-landscape, often with *Pteridium aquilinum* and *Quercus robur*, moist, low, sandy ridges and plains (**We**-landscape, with *Anthriscus sylvestris* and *Ulmus minor*) and wet, peaty plains (**Wv**-landscape, with *Filipendula ulmaria* and *Alnus glutinosa*).

The slacks in the **R**, **H** and **K**-landscape zones are all secondary dune valleys, blown out by wind and originally moist to very wet (**E** and **V**-landscapes). Mainly through extraction of drinking water and afforestation, they dried out in the first half of this century, and must now be mapped as belonging to the main types mentioned above. However, most of the larger valleys were temporarily used for agricultural purposes (grazed or ploughed), mainly in the 18th and 19th centuries.

This did not only result in a loss of natural vegetation in large areas, but also in enrichment with organic material. The latter effect, combined with the following lowering of the phreatic water level, resulted in an intensive leaching process. Moreover, succession after abandonment of the cultivated land often started on bare soil. Because of this, species-poor mossy or grassy types (**Kk**, **Kd**) are now found in such places, even in the **R** and **H**-zones.

Another local change in the natural landscapes has been caused by the planting of coniferous forests (mostly *Pinus nigra*). These areas have been mapped as much as possible on the basis of geomorphology, substrate and surrounding vegetation. In some cases, there have been irreversible changes in the original landscape. New plantations are now restricted to very small areas.

Still more recently, pre-purified water has been infiltrated in most areas for the purpose of maintaining the supply of drinking water, creating artificial ponds and seepage situations in adjacent slacks. These have only been mapped in detailed studies in partial areas (photo-interpretations on scales 1 : 2500 to 1 : 5000).

The position of the area between IJmuiden and Bergen is different from that further south, because originally it was more accessible to the sea, and therefore was intermediate between the closed coast of the mainland and the island coast of the Wadden Sea. The zonation of the younger dunes is geomorphologically similar, but the sand is all '**R**-sand', very rich in coarse shell fragments. The **H**-zone is lacking, and is replaced by a **Rhb**-zone, instead of a **Kb**-zone (see above) there is a zone mapped as **Rkb** (without *Rosa pimpinellifolia*).

The estuarine islands (Fig. 1: D1-D4)

In this region, the old barrier dune system was situated much further west than the present coastline, and has been virtually completely eroded. The calcium content of the present dunes varies strongly. There are old dune areas, cliffed coasts as well as accretional, very young dune systems, which are not present on the mainland, and therefore must be described here.

Zonation of dry dunes in accretional areas, rich in lime: ***A - H - K***

Where various rows of former foredunes are present because of coastal accretion and absence of large-scale parabolization, dune ridges remain low and *Ammophila*-vegetation is replaced by *Hippophae*-scrub as soon as the fresh supply of sand, being blown from the beach, is cut off. Very soon, other shrubs, notably *Crataegus monogyna* and *Rhamnus catharticus*, establish (**Hb**-landscape). Where minor blow-outs occurred in the relatively fertile sand - a situation which is common on these islands - *Ligustrum vulgare*, favoured by the mild 'southern' climate, and *Rubus caesius* are also abundant (**Hrb**-landscape). On the tops and higher ridges, leaching is unavoidable because of the permeability of the sand and its poverty of minerals, the scrubs die off in the long run, and are replaced by lower vegetation, rich in *Rosa pimpinellifolia* (**Kb**-landscape). On the Voorne dunes, this type of succession has been taking place from the 17th century to the present time.

Zonation in wet primary slacks: ***E - V***

When a beach plain is cut off from inundations from the sea, conditions are brackish at first (**M4e**-landscape), but fresh-water conditions soon prevail, in contrast to e.g. the slacks in dry mediterranean climates (**E**-landscape). In the moist primary slacks, succession leads to high, dense scrubs (**Eb**); in the flat, sandy polders behind the dunes, planted woodlands are found, similar to those described under **We** (**Ew**-landscape). In some of the wet slacks (exclusively on Voorne) natural lakes and marshes are present (**V**-landscape).

An early phase of young dune formation, probably around the 7th century, had led to the formation of complexes of low and irregular 'kopjes' (rolling) dunes, now leached and strongly influenced by grazing (**Cd**-landscape, after afforestation **Cf**- or **Cw**-landscape, after partial excavation **Cz**-landscape). Their geographical situation and morphology point to an origin in a sheltered situation, probably behind the remnants of an eroding barrier coast. Since that time, there has been accretion of the young dunes in the northern, and erosion

in the southern part of the region. On each separate island, the same tendency can be observed on a smaller scale. Where the older dunes have come into contact with the younger dunes as a result of mobility of the latter, transitional landscape types are found (e.g. **Ca**, **Ck**, **Ci** or **Kk**). In some places, recent erosion is so intensive that foredunes (**Aa**-landscapes) are missing.

Where areas, sheltered by dune ridges, are, or have recently been accessible to the tides, Salt marsh landscapes (**M1**-**M5**) are well-developed. Those on Voorne and Goeree are relatively recent developments, resulting from coastal accretion; those in Zeeuws Vlaanderen are remnants of formerly more extensive areas, especially the 'Zwin' on both sides of the Belgian border.

The area between Bergen and Camperduin

Before the younger dunes were formed, a large inlet ('Zijpe') existed between the calcareous 'blond' dunes, containing iron oxide and some heavy minerals (Eisma 1968) in the south, and the acid, white dunes in the north. After the closing of this gap, the general direction of the coast of Noord-Holland changed from SSW-NNE to a more S-N direction (compare the direction of the old barrier ridges with the present coast-line). The southern end of the northern, acid dune system, curving inwards along the former inlet, is still present at Bergen (**Wez**-landscape); NW of the present coastline it was eroded by the sea. Between Bergen and Camperduin, an up to 4.5 km wide and 56 m high dune lobe has been blown over sea clay, peat, older dunes and (in the south) calcareous younger dune areas. The sand is the poorest in mineral content of all Dutch dune areas, and pronouncedly mobile dune forms prevail (**Ca**-landscape). The eastern part is planted with pines.

The formerly wet slacks are extensive, have dried out and carry since ca. 1900 a heath vegetation, with mainly *Empetrum* and *Calluna* (**P1**-landscape). At the inner border oak forest is conspicuous (**Pw** or **Cw**-landscape, dry *Quercion robori-petraeae*). The ecotone between acid and calcareous dunes is rich and interesting, with i.a. **Cr** (*Corynephorus* and *Rubus caesius*), **Clb** and **Cb** (*Corynephorus*, *Calluna* and *Rosa pimpinellifolia*) and **Kc**- (*Koeleria macrantha* and *Corynephorus*) landscapes.

The Wadden region (Fig. 1: W1-W6)

In general, the dunes in this region are acid, but in some parts $CaCO_3$-contents up to 2% occur, which is an important variation for vegetation composition and dune morphology. As in all regions, a fundamental difference exists between landscape succession in accretional and in erosional areas.

Zonation of accretional coasts with calcareous sand: ***Aj*** *-* ***Aa*** *-* ***Hr*** *-* ***Cb*** *(Rosa pimpinellifolia) -* ***Cld*** *(Corynephorus, Calluna, Festuca ovina).*

On wide beaches, low, ephemerous crescentic dunes without vegetation are found (**Aj**), in somewhat more stable situations there are embryonic dunes with *Elymus farctus* (**Aj_0** or **Aj**). In **Hr**, there are high and dense scrubs of *Hippophae* and *Sambucus nigra*, which die after one or two generations.

In southern Texel (Doing 1989), the age of the dune complexes is about the same as on Voorne. The difference in age between **Aa** (now present since ca. 25 yr) and **Hr** is 40 - 80 yr, between **Hr** and **Cb** 50-90 yr and between **Cb** and **Cld** 100 - 150 yr. South of Den Helder we find a more exposed coast and there is a **Cak**-zone between **Aa** and **Cb**.

Where calcium content is lower, the **Cb**-landscape is absent, and from **Hr** the zonation is from **Hc** (open *Hippophae* scrub with *Corynephorus*) to **Cah** (*Corynephorus*, *Ammophila* and some *Hippophae*). On low ridges, *Empetrum* may be abundant in both series (**Hp** or **Cp**).

Zonation of erosional coasts with calcareous sand: ***Aa*** *-* ***R*** *(various subtypes) -* ***K*** *(mostly* ***Kc****) -* ***Ci*** *-* ***Cd****.*

The process of parabolization first leads to an **R**-landscape (*Rubus caesius*), but because of loss of lime and organic material (a reciprocal reaction) this is followed up (here after ca. 100 yr) by a more open vegetation (**K**) on older ridges.

Further penetration of the dunes, away from the beach, mostly takes place across wet slacks, where *Salix arenaria* is almost always present, and grows up with the overblowing sand. Together with further leaching and humus-mineralization this leads to a **Ci**-landscape, with hydrophobic sand. Loss of cohesion of sand and vegetation finally leads to lower, irregular dunes, suitable for grazing: **Cd**-landscapes, up to 400 yr old. Trampling by cattle causes mixing of organic material with the subsoil and water erosion.

Zonation of erosional coasts with acid sand: ***Aa*** *-* ***Cah*** *-* ***Cap*** *-* ***Ca***

The pH of the sand in the foredunes is still high because of the supply of sand from the beach and of salt spray. Behind these, it quickly decreases, even after 5-10 yr, and a **C**-landscape is found, at first with scattered *Hippophae* (**Cah**), at a slightly later stage replaced by *Empetrum* (**Cap**) and still later lacking both (**Ca**).

Because of the insufficient waterholding capacity of the soil, *Empetrum* dies in dry years. The danger of

losing vegetation, and formation of high (up to 45 m), mobile dune ridges is increasing with age. Such ridges are now mostly planted with *Pinus nigra*. In a few cases, an individual mobile dune became detached from the main complex, wandered eastward with increased speed (van Dieren 1934), and is now found as a **Cap** or **Aa_0**-landscape far away from any foredunes (more than 5 km in the direction of the prevailing winds).

Zonation in dune slacks

Corresponding with the ridges, a difference must be made between primary slacks on relatively undisturbed, accretional coasts, and secondary ones, caused by blow-outs at disturbed or erosional coasts.

In the former case, part of a beach plain has become isolated from tidal influences. Before this isolation was completed, this part was in a sheltered position, and some silt was deposited (**M4a**). Thereafter, fresh-water conditions soon prevail, and succession leads from **E_0m_4** via **E_1** etc. to **E_5** in moist slacks (see description of the subtypes). The lower the lime content of the sand, the quicker the succession, but, in contrast to the North Frisian and Danish coasts, stages with basic conditions are present. However, with time and widening of the dunes, there is a tendency for the phreatic level to rise, and succession of slacks leads from **E** to **V**-landscapes, with permanently high watertable and peat formation. An example of this type of zonation is: **E_2** (*Schoenus nigricans*, *Parnassia palustris* etc.) - **E_3e** (*Phragmites*, *Hydrocotyle*) - **Ve** (tall *Phragmites*, *Rumex hydrolapathum*) + **V_0** (open water) - **V_0** + **Vi** (*Salix cinerea*). In the last stage, there is a dune lake, surrounded by tall reeds and willow scrub. The latter is only found on mineral subsoil, mainly along the borders of the slack. In secondary slacks, there is no silt layer and, in the case of coastal erosion, a lowering of the water table occurs. Added to this, there is also a danger of overblowing with sand from various directions, and therefore of raising of the soil surface. For these reasons, there is no marine stage, no tide mark of shells and organic material, and no succession towards **V**-landscapes. The most common succession (= zonation of slacks of increasing age and distance from the origin of initial disturbance) is **E_0** - **E_3i** (*Mentha aquatica*, *Salix arenaria*) - **E_4xp** (*Oxycoccus macrocarpos*, *Myrica gale*, *Empetrum nigrum*) - **E_4w** (acid birch woodland with *Empetrum nigrum*). This series lacks the full development of **E_2** and shows a tendency towards heath vegetations. Along the borders of primary valleys, or where these have become drier, e.g. by overblowing, similar landscape types are often found. In the driest situations, **Cp**-landscapes (*Corynephorus* and *Empetrum*) are common.

Zonation in dune areas with low relief

Behind high, one-time mobile dune ridges, mainly at the inner dune border, there are areas which cannot be classified as ridges, nor as slacks. Because of their sheltered position, good vegetation cover and geographical situation, they have always been suitable for grazing or even cultivation (both terminated since about 1900). They are now covered with heath (**P**, **Cp** or **Ci**-landscapes), grassy or mossy vegetation of acid soils (**Cd**, **Ci** or **Ce**-landscapes), or pine plantations (here **Cf**, **Cfw** or **Cfe**-landscapes).

Zonations of accretional coasts, with primary ridges and slacks, only locally disturbed by blow-outs, are found around the Zwanenwater (Petten-Callantsoog, now part of the mainland), on Texel (except the northern part which is the former island of Eyerland), the western ends of Vlieland, Terschelling and Ameland and (fragmentarily) the whole of Rottumerplaat. Smaller primary systems also occur on the younger parts of Schiermonnikoog and Ameland. Special cases are the artificial sand dikes of eastern Terschelling, Ameland and Schiermonnikoog, discussed in the following paragraph. All other dune areas are dominated by processes of secondary dune formation.

Zonations of salt marshes and isolated dunes

These must be discussed in close connection with human interventions in landscape building processes. Although human habitation was much older, most of the present villages on the Dutch Wadden Sea Islands date from around the 13th century. This was also the time of the construction of a coherent system of dikes to protect major areas of agricultural land. This also included sand dikes and the planting of marram grass, where the natural dunes did not give sufficient security. The present island polders consist partly of reclaimed salt marsh (**M**-landscapes), partly of low lying sandy areas (**Ce**, **E** and **V**-landscapes, locally with sea clay in the subsoil (van Oosten 1986). Ecologically, they are now potential woodlands (**w**-landscapes) on soils, enriched by manuring (**t**), artificially levelled (**z**) and carrying a short and dense grass turf (**d**). For these reasons, they are indicated on the maps as **Cwedtz**, **Ewdt**, **M4ewdtz**, etc.

Because of the rising sea level and the sinking land, the natural foredunes were not rectilinear, and they were interrupted by inlets and overwash areas in many places.

The present closed, straight and high foredunes as well as former foredune ridges have grown with the help of man, even where this is not evident at first sight. Therefore, there is no clear distinction between sand dikes and natural primary dune complexes on accretional coasts. The inner dune ridges near the Zwanenwater and

between Texel and Eyerland originated as sand dikes at ca. 1630. On high sand flats, situated in the shelter of stable dune complexes, mainly at the eastern end of some of the islands, series of circular or crescentic foredune complexes of various sizes and ages occur (Doing 1983a). They originated as primary dunes, developing under the influence of sand, blowing from all directions, but often have been remodelled by subsequent erosion.

After the construction of the long sand dikes, mentioned before, which mostly took place in the first half of this century, large parts of the sand flats became protected against floods from the North Sea. This initiated the development of large areas of salt marsh vegetation (Westhoff 1947). Sand movement by wind was stopped, causing fixation and leaching of the isolated circular dunes, and the deposition of silt was started after the establishment of salt marsh vegetation, mainly *Salicornia* (**M1**), and became most intensive in the medium salt marsh (**M2**). In accretional areas, the complete zonation from **M0** via **M1** etc. to **M4** or **M5** (see description of the main types) is found. In erosional areas, one or more of the zones (in the first place **M1**) may be missing. Stable, isolated dune complexes are mostly mapped as **Ck** or **K** (**Kc**, **Kk**, **Ka**), mobile parts as **Aa** or **Ca**.

Applications to conservation and management

Many vegetation and landscape maps of the Dutch coasts have been published over the past 40 yr, but apart from the much simpler map 1 : 100 000 by Bakker et al. (1981) the present landscape-ecological map is the only one covering the entire coastline of the Netherlands. This map is based on an holistic concept of the landscape. It includes the combination of broad landscape units and vegetation types, which renders it suitable for applications in coastal management, particularly in the dunes. Almost all open dune landscape is protected from major urban-industrial development and is managed for the catchment of drinking water, nature recreation, and/or the preservation or even development of the natural biodiversity.

First the map can serve as a basis for dune afforestation. This is hardly actual any longer in the Dutch situation. In retrospect, several less successful afforestations could have been avoided if a landscape-ecological map would have been available. Now it may be used to reconstruct plantations.

Second it can be used as a basis for the regulation of recreation, i.e. the planning of car parks, walking routes, meadows for sun bathing, natural history paths and the protection of local sites of ecological interest. This can be exemplified with the planning of the Meijendel dunes, which are managed by the Zuid-Holland Drinking Water Company (formerly the Water Works of the City of The Hague). This company gets advice from a scientific committee and produces elaborate management plans, in order to extract drinking water and at the same time optimize the recreation capacity of the area, situated at the outskirts of the city of The Hague. Finally ecosystem diversity is maintained and enhanced through selected grazing and the local rejuvenation of the dune landscape by stimulating the formation of parabolic dunes (Jungerius & van der Meulen 1989)

The third and most important field of application is nature conservation, which can be successfully based on a landscape-ecological map. The main types of natural and semi-natural vegetation types and their biotic communities can be understood in their landscape-ecological context and managed more optimally. The management may even include measures to restore the natural variation in vegetation types. The example of 'parabolization' of the dunes, mentioned above, is an outstanding one. Another example is the restoration or at least re-approximation of the original groundwater level. This can be done by changing the regional hydrology. In the Meijendel dunes this was realized by means of the infiltration of purified river water (e.g. van der Meulen 1982; van Dijk 1989).

In this way, wet dune slacks were formed in the older dunes in which part of the original dune slack plants reappeared. The re-creation of dune slacks and the prediction of subsequent vegetation development in this area were studied in a special project (Noest et al. 1989).

Another example of ecohydrological studies leading to the maintenance and extension of species-rich dune slack vegetation is found in the work by Grootjans (Grootjans et al. 1991, 1995) in the older, northwestern part of the dunes of the Wadden island Schiermonnikoog (Fig. 2). It concerns the local upwelling of base-rich groundwater resulting from the passage through calcareous subsoils.

The map of Schiermonnikoog (Fig. 2) also summarizes the development of salt marsh. The island is growing eastward and the youngest stages of salt marsh development are found at the eastern tip (type **A_om0**); from there we can follow a series of salt marsh stages along the southeast coast via low and medium to high salt marsh (**M1 - M3**).

Finally, an example of the use of the landscape-ecological map for management planning is given[1]. This concerns the dunes near Haarlem, where the Amsterdam Water Works extract drinking water. Here, a detailed landscape-ecological map, scale 1 : 5000 was

[1]with the help of A. Ehrenburg, Amsterdam

made of an area of 3500 ha; this map can be directly related to the general map discussed in the present paper, because both maps result from a holistic concept of the dune landscape. The local map was used to develop a management plan for the area. The various landscape zones were described with a particular interest in the natural processes underlying the dynamics of the vegetation types.

This means in fact a new type of management, 'process management', which allows the natural processes to take place as far as possible (cf. van der Meulen & Jungerius 1989 and particularly Wanders 1989).

The following aspects of the new management can be mentioned.

- The outer, mobile dunes are characterized by the **R**-landscape (*Rubus caesius*). This zone originated through the regular drifting of sand. Blow-outs with their associated pioneer plant communities are maintained or even stimulated in this zone.
- Grass encroachment occurs in the middle dune zone with the **H**-landscape (*Hippophae rhamnoides*). In several such areas the local management has included grazing by domestic cattle to counteract the advancement of grassland. However, in a more natural management approach grass encroachment in this particular landscape can be accepted and no measures are necessary.
- In the **Kb**-landscape pine plantations can be found, which are not important any longer from a protection of wood production viewpoint. They can be removed on the basis of the distribution of natural understorey, particularly with *Rosa pimpinellifolia*.
- In the **C**-landscape (*Corynephorus canescens*), developed on former agricultural fields created earlier, detailed sequential mapping of the vegetation has revealed that the dense, tall and ecologically less interesting grassland which had been formed there, was changed into a short more species-rich grassland with a moss layer (from type **Cdg** to **Cd**) through mowing. The change took place in only 8 yr.

Concluding remarks

The present study was summarized more than 10 yr ago (Doing 1988) and data for some regions and islands are already 20 yr old. Since then, many changes have occurred, as may be expected in the extremely dynamic dune and salt marsh landscape. Foredunes or parts of sand dikes have disappeared, others have grown. In some places they are artificially stabilized by deposition on the beach of sand gathered from the sea offshore. Succession has progressed in some places, perhaps accelerated by dry deposition. Where maintenance became less intensive, new blow-outs may have appeared. Slacks became wetter or drier because of activities of drinking water companies, climatic conditions or the blowing of sand. Dune heathland may have changed in **Pl**-landscapes through the replacement of *Calluna* by *Empetrum*.

All these changes are asking for an updating of the map. However, on the level of the broad landscape units as mapped at the scale 1 : 50000, these changes are of minor importance, except perhaps in the case of large-scale development of mobile, bare dunes on exposed beach plains, and large-scale building of houses and industries (mainly in the region IJmuiden - Wijk aan Zee). Thus, the landscape-ecological map as described here does not need a very regular updating, whilst more detailed maps will be necessary every 10 yr or so.

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App. 1. Landscape types and subtypes with a letter combination and colour indication. The units are indicated as much as possible by common, characteristic names. The formal significance of the code letters is listed separately (App. 2).

A_om Beach landscape
Aj Beach dune landscape
Aa Landscape of blowing dunes (mostly foredunes)
Aar Landscape of blowing dunes with *Alnus* scrub
Aas Landscape of blowing dunes, subtype near old sea-villages
Ac *Ammophila* landscape with *Corynephorus*
Ah *Ammophila* landscape with *Hippophae*
Ak *Ammophila* landscape with *Sedum acre*

Hh *Hippophae* landscape (pure form)
Hr *Hippophae* landscape with *Sambucus*
Hb Dry *Crataegus-Betula* landscape
Hk Open *Hippophae* landscape
Hc *Hippophae* landscape with *Corynephorus*
Hw Wooded *Hippophae* landscape
He Moist *Hippophae* landscape

Rr *Rubus caesius* landscape (pure form)
Rh *Rubus caesius* landscape with *Sambucus*
Rk Open *Rubus caesius* landscape
Rc *Rubus caesius* landscape with *Corynephorus*
Rs *Rubus caesius* landscape near old sea-villages
Rb *Rubus caesius* landscape with *Euonymus*
Rw Wooded *Rubus caesius* landscape
Re Moist *Rubus caesius* landscape

Kk *Koeleria* landscape with dominant moss vegetation
Ka *Koeleria* landscape with blow-outs
Kh *Koeleria* landscape with *Hippophae*
Kr *Koeleria* landscape with *Rubus caesius*
Ks *Koeleria* landscape near old sea-villages
Kc *Koeleria* landscape with *Corynephorus*
Kb Calcareous *Rosa pimpinellifolia* landscape (cf. **Cb**)
Kw Wooded *Koeleria* landscape

Ca Open *Corynephorus* landscape rich in lichens
Cd Grassy *Corynephorus* landscape (closed vegetation)
Ch *Corynephorus* landscape with *Hippophae*
Cr *Corynephorus* landscape with *Rubus caesius*
Ck *Corynephorus* landscape with *Koeleria* communities
Cb Acid *Rosa pimpinellifolia* landscape (cf. Kb)
Ci *Corynephorus* landscape with *Salix repens*
Cl-Cp *Corynephorus* landscape with heath
Ce Moist *Corynephorus* landscape
Cf *Corynephorus* landscape with *Chamerion angustifolium*
Cw Wooded *Corynephorus* landscape

Pp *Empetrum nigrum* landscape
Pl *Calluna* landscape
Pc-Pa Open heath landscape
Pe Moist heath landscape
Pw Wooded heath landscape

Ww Dry old barrier beach-ridge landscape
We Moist old barrier beach-ridge or beach-plain landscape
Wv Peaty old beach-plain landscape
Wf Old barrier beach-landscape with *Dryopteris dilatata* woodland

E_o Moist dune-slack landscape with scarce vegetation
Ee Moist dune-slack landscape with *Phragmites australis*
Ei Moist dune-slack landscape with *Salix repens*
Eb Moist dune-slack landscape with *Hippophae* and *Betula*
Ex Moist dune-slack landscape with *Vaccinium macrocarpon*
Ep Moist dune-slack landscape with *Empetrum*
El Moist dune-slack landscape with *Erica tetralix*
Ev-Ey Very moist dune-slack landscape
Ew Wooded dune-slack landscape
E- Moist dune-slack landscape, slightly brackish

V Dune-lake with permanent open water
Ve Wet dune-slack with *Phragmites australis*
Vy Dune-lake with colonizing communities
Vi Wet dune-slack with *Salix* scrub
Vv Wet dune-slack with *Alnus* woodland on peat
Vw Wet dune-slack with *Alnus* woodland on sandy peat

M0 Mud-or sandflat or tidal gully without vegetation
M0.1 Mud-or sandflat with scarce vegetation
M1.0 Low salt marsh with scarce vegetation
M1≥1 Sandy low salt marsh
M1t Muddy low salt marsh
M2.1 Basin of medium salt marsh
M2≥2 Levee of medium salt marsh
M2d Grazed medium salt marsh
M3<3 Basin of high salt marsh
M3.3 Levee of high salt marsh
M3d Grazed basin of high salt marsh
M3>3 High salt marsh with low dunes
M4<4 Brackish flat with salt marsh elements
M4e Brackish flat with dune slack elements
M4≥4 Brackish flat with low dunes
M5<5 Very high, sandy salt marsh
M5h Low dunes with *Hippophae* on very high salt marsh
M5a-k Low dunes with open vegetation on very high salt marsh

Main types of salt marsh landscape

M0 Mud or sandflat landscape
M1 *Salicornia* landscape
M2 *Puccinellia* landscape
M3 *Lolium perenne* landscape
M4 *Agrostis stolonifera* landscape
M5 *Elymus pycnanthus* landscape

Important sub-type in salt marshes:

t tide mark landscape

Special map signatures:

i Combination with *Salix* scrub or dwarf scrub
d Short and dense grassy vegetation
s Landscapes near old sea-villages
Border between main landscape types
Border between subtypes
Border between the old barrier beach-ridge and plain landscape

App. 2. Derivation and significance of the code letters and numbers.

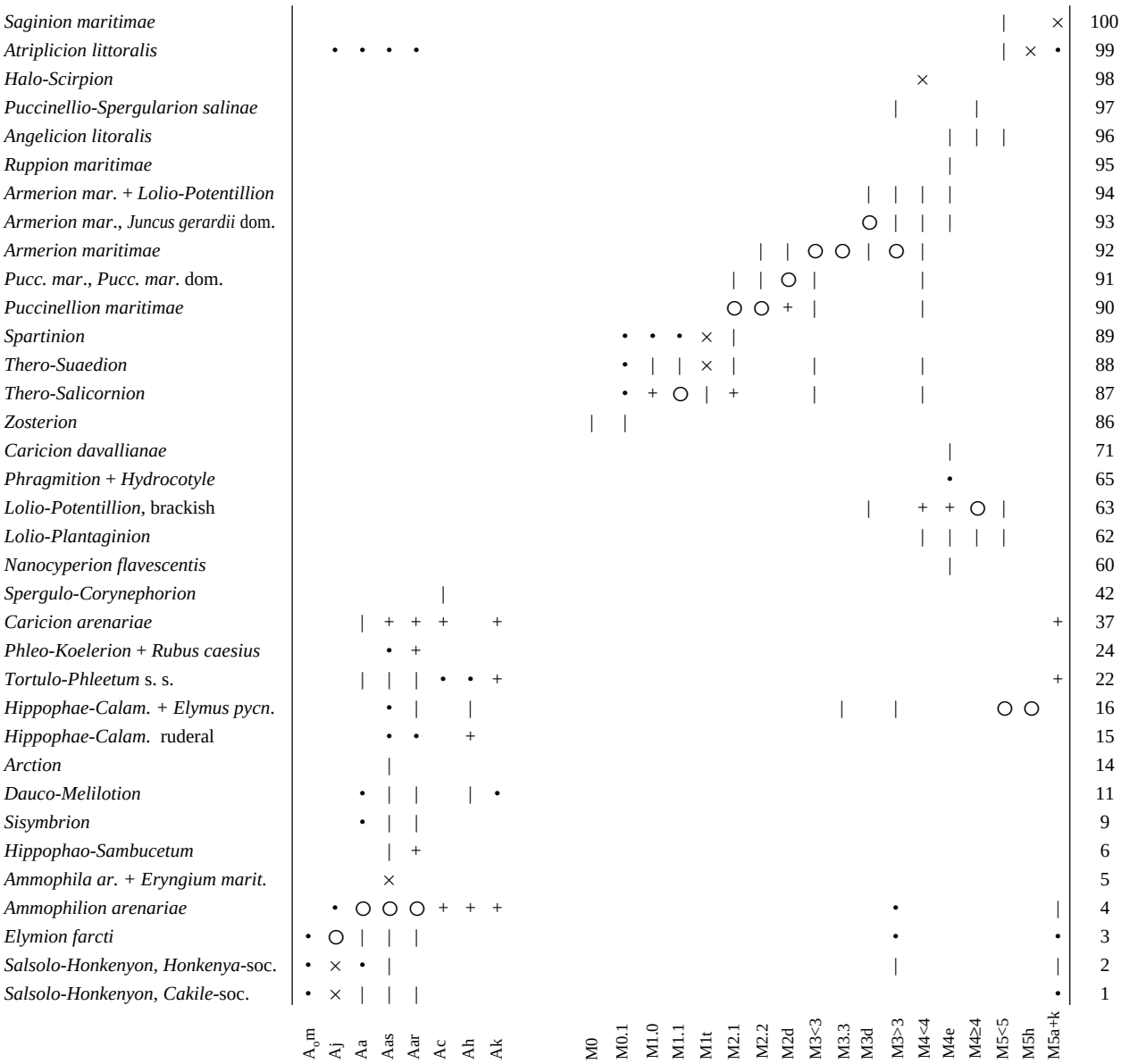
A	Landscapes with strongly blowing sand
b	Rich in scrubs (mainly *Crataegus*, *Euonymus*, *Rosa* spp.)
C	*Corynephorus* landscape (dry, acid, younger dunes)
d	Rich in dense short grass vegetation (sometimes dense mossy), mostly induced by (former) grazing or mowing
E	Moist dune slacks
f	With indicators of a 'nitrogen-shock' in an acid environment
g	Rich in dense long grass vegetation, mostly caused by a sudden change in environment (e.g. dying-off of woodland or scrub, lowering of water table)
H	*Hippophae* landscape (depositional, calcareous, humus-poor young dunes)
i	Rich in *Salix* scrub (in dry landscape types: formerly moist, overblown valleys with *Salix arenaria*)
j	Beach dunes, bare or with vegetation (mostly with *Elymus farctus*)
K	*Koeleria* landscape (dry, moderately calcareous younger dunes)
l	With heath vegetation (*Calluna*, *Erica tetralix*)
M	Marine landscapes (salt marshes and mud flats)
M0	Mud flats
M1	Low salt marsh
M2	Medium salt marsh
M3	High salt marsh.
M4	Brackish transition zone between high salt marsh and moist young dune slack
M5	Transition zone between high salt marsh and dry young dunes
n	Not mapped (e.g. parking areas)
0 (zero)	No or scarce vegetation
P	Heath landscape; dry or moist, acid, densely vegetated younger dunes in the 'Wadden District'
q	Marine communities on stone dikes and rocks
R	*Rubus caesius* landscape (overblown, calcareous, very young dunes)
s	Landscapes near old villages (dry, calcareous, humus-poor, very young dunes, floristically and chemically enriched by long-term outside influences, e.g. former human activities)
t	Nitrophilous communities, induced by short-term chemical enrichment by mark deposition or human disturbance
u	With 'southern' species, occurring in the 'Delta' area
V	Landscape of permanently wet dune slacks
W	Landscape of old barrier dunes and beach plains
Ww	dry old dune ridges
We	Moist old dune ridges or beach plains
Wv	Wet old beach plains
x	Vegetation rich in *Vaccinium*, *Myrica* etc. (dune slacks with superficial peat formation in an acid environment)
y	Presence of colonizing vegetation in chemically rich dune lakes (including those caused by artificial infiltration)
z	Excavated or levelled areas (incl. formerly cultivated parcels)
A, **C** etc.	Main types, also occurring as subtypes (**a**, **c** etc.)
b, **d** etc.	Only occurring as subtypes
$\mathbf{E_1}$	Moist dune slack with pioneer species
$\mathbf{E_2}$	Moist dune slack with basic soil
$\mathbf{E_3}$	Moist dune slack with neutral soil
$\mathbf{E_4}$	Moist dune slack with acid soil
$\mathbf{E_5}$	Moist dune slack with very acid soil

App. 3. Characteristic plant species of the landscape units and combinations thereof.

Aa	*Ammophila arenaria*
Aj	*Elymus farctus*
Ajs	*Honkenya peploides*
At	*Leymus arenarius, Sonchus arvensis* var. *maritimus*
A_0t	*Cakile maritima*
Aas	*Eryngium maritimum*
Asu	*Calystegia soldanella, Euphorbia paralias*
C	*Corynephorus canescens, Teesdalia nudicaulis, Cladonia portentosa, Cornicularia aculeata*
Cd	*Aira praecox*
Cb+Kb	*Rosa pimpinellifolia*
Cs	*Trifolium arvense, Scleranthus perennis*
C+K+ P+Ww	*Polypodium vulgare, P. interjectum, Veronica officinalis, Dicranum scoparium, Cladonia arbuscula*
C+P	*Hypnum jutlandicum, Pleurozium schreberi*
E	*Hydrocotyle vulgaris, Mentha aquatica, Lotus uliginosus, Juncus articulatus, Cirsium palustre, Carex trinervis*
E_0	*Littorella uniflora, Samolus valerandi, Gnaphalium luteo-album, Chara sp.*
E_1	*Juncus bufonius, J. bulbosus, Centaurium* spp., *Anagallis tenella, Sagina nodosa, Carex oederi* ssp. *pulchella*
E_2, Em4	*Schoenus nigricans, Parnassia palustris, Epipactis palustris, Juncus alpino-articulatus*
E_4	*Juncus conglomeratus, Carex nigra, Ranunculus flammula, Cirsium dissectum, Molinia caerulea, Sieglingia decumbens*
E_5	*Sphagnum* spp., *Polytrichum commune, Dryopteris carthusiana, D. cristata, Eriophorum angustifolium, Potentilla palustris*
Eb	*Ajuga reptans, Listera ovata*
Ee+Ve	*Phragmites australis, Typha angustifolia*
f	*Rubus fruticosus, Chamerion angustifolium, Prunus serotina, Dryopteris filix-mas*
fe	*Dryopteris dilatata*
fu	*Rubus ulmifolius*
H	*Hippophae rhamnoides, Asparagus officinalis, Cynoglossum officinale*
Hb+Kb +Rb	*Crataegus monogyna, Euonymus europaeus, Rosa canina, Rhamnus catharticus, Inula conyza, Lithospermum officinale*
He	*Eupatorium cannabinum*
Hh+g	*Calamagrostis epigejos*
i	*Salix arenaria*
K	*Koeleria macrantha, Phleum arenarium, Sedum acre, Erodium glutinosum, Myosotis ramosissima, Tortula ruralis, Cladonia foliacea, C. furcata, C. rangiformis*
K+R	*Hypnum cupressiforme* var. *lacunosum, Cerastium semidecandrum, Lotus corniculatus, Cardamine hirsuta*
K+C+R	*Carex arenaria, Festuca ovina, F. rubra* ssp. *arenaria, Galium verum, Erophila verna, Hieracium pilosella, Thymus pulegioides, Viola canina, V. curtisii, Luzula campestris*
Kc	*Populus canescens, Racomitrium canescens*
KS	*Silene conica, S. nutans, S. otites, Anacamptis pyramidalis, Rhinanthus* spp., *Sedum album*
KS+Aas	*Artemisia campestris* ssp. *maritima, Anthyllis vulneraria*
Ksu+Csu	*Eryngium campestre, Trifolium scabrum*
Ks+Rs	*Orobanche caryophyllacea, O. picridis, Gentiana cruciata*
Ku+Hu +Ru	*Senecio jacobaea* var. *jacobaea*
M0	*Zostera marina, Z. noltii*
M1	*Salicornia dolichostachya*
M1t	*Spartina anglica, Salicomia brachystachya, Suaeda maritima*
M2	*Puccinellia maritima, Halimione portulacoides, Limonium vulgare, Plantago maritima*
M2t	*Aster tripolium, Spergularia maritima, Cochlearia anglica*
M3	*Armeria maritima, Juncus gerardii, Festuca rubra* ssp. *litoralis, Artemisia maritima*
M3t	*Juncus maritimus, Triglochin maritima*
M4	*Scirpus maritimus, Trifolium fragiferum, Oenanthe lachenalii, Odontites verna*
M4+Ed	*Agrostis stolonifera, Potentilla anserina, Rumex crispus, Festuca arundinacea*
M4t	*Glaux maritima, Carex extensa, Puccinellia distans, Triglochin palustris*
M4d+ed +vd	*Lolium perenne, Prunella vulgaris, Trifolium repens*
M5k	*Sagina maritima, Plantago coronopus, Ononis spinosa, Lotus tenuis*
M5u	*Blackstonia perfoliata*
M5g +M3g+Rg	*Elymus athericus, E. obtusiusculus*
M5t	*Atriplex litoralis, A. patula, A. prostrata, Matricaria maritima*
P	*Empetrum nigrum*
Pl+Cl	*Calluna vulgaris, Genista anglica, G. tinctoria*
Ple+E_5	*Erica tetralix, Potentilla erecta*
Px+Ex	*Oxycoccus macrocarpos, Myrica gale, Nardus stricta*
R	*Rubus caesius, Ligustrum vulgare, Rosa rubiginosa, Galium mollugo, Picris hieracioides*
Rk	*Ononis repens* var. *mitis, Tortella flavovirens*
Rh+Hr	*Sambucus nigra, Bryonia cretica, Anthriscus caucalis*
V	*Alnus glutinosa, Iris pseudacorus, Rumex hydrolapathum, Galium palustre, Caltha palustris*
V+Ev+ Eb+Wv	*Filipendula ulmaria, Angelica sylvestris, Lycopus europaeus, Scutellaria galericulata, Lysimachia vulgaris, Lythrum salicaria, Calamagrostis canescens, Carex acuta*
Vi	*Salix cinerea, S. multinervis*
V+E	*Scirpus lacustris, Alisma plantago-aquatica, Hippuris vulgaris*
Vy+Ey	*Typha latifolia, Carex paniculata, C. pseudocyperus, Ranunculus lingua*
We	*Ulmus minor, Populus alba, Hedera helix, Anthriscus sylvestris, Aegopodium podagraria, Stachys sylvatica, Veronica hederifolia, Ornithogalum umbellatum, Corydalis solida, Viola odorata*
We+Ww	*Quercus robur, Fagus sylvatica, Ilex aquifolium, Poa nemoralis, Polygonatum multiflorum, Milium effusum, Scilla non-scripta*
We+Wv	*Fraxinus excelsior, Prunus padus, Ficaria verna, Festuca gigantea, Rumex sanguineus, Adoxa moschatellina, Allium ursinum*
Wv	*Carex remota, Cardamine flexuosa*
Ww	*Pteridium aquilinum, Holcus mollis, Aulacomnium androgynum, Polytrichum formosum*
Ww+Cw +Kc	*Lonicera periclymenum, Convallaria majalis, Teucrium scorodonia, Mnium hornum, Leucobryum glaucum*
Ww+C+E +H+K+R	*Betula pendula, B. pubescens, Populus tremula, Sorbus aucuparia*

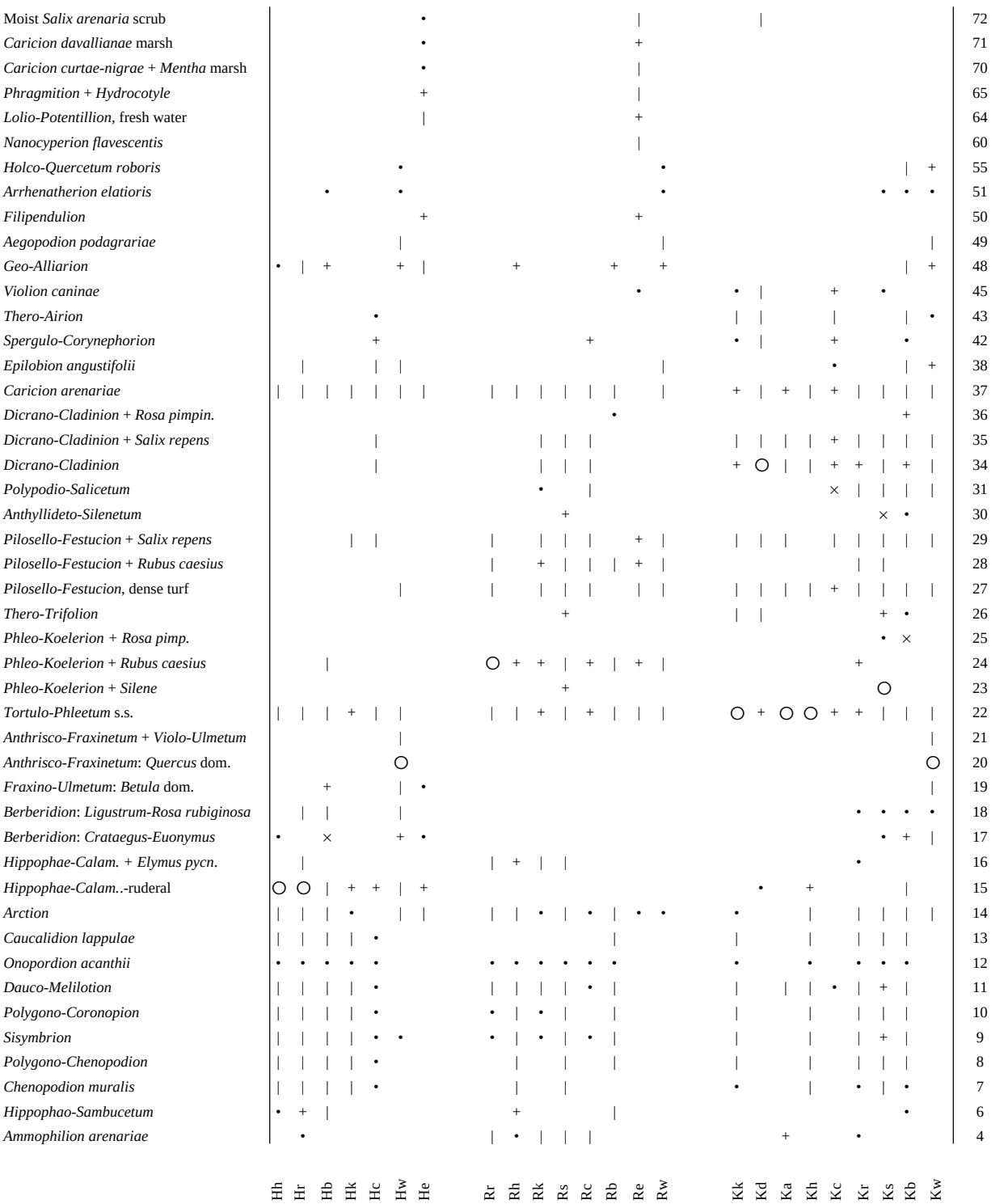
App. 4. Characterization of the landscape units by phytosociological units: **A** and **M**-landscapes. Units indicated by a running number and a name which is either an alliance from the Braun-Blanquet system of plant communities (Westhoff & den Held 1975), or/and dominant species.

o = dominant in the relevant landscape type
× = mostly not dominant, but characteristic or at least optimally developed here
\+ = present obligatory
| = present facultatively
• = present more or less frequently; but mostly fragmentarily



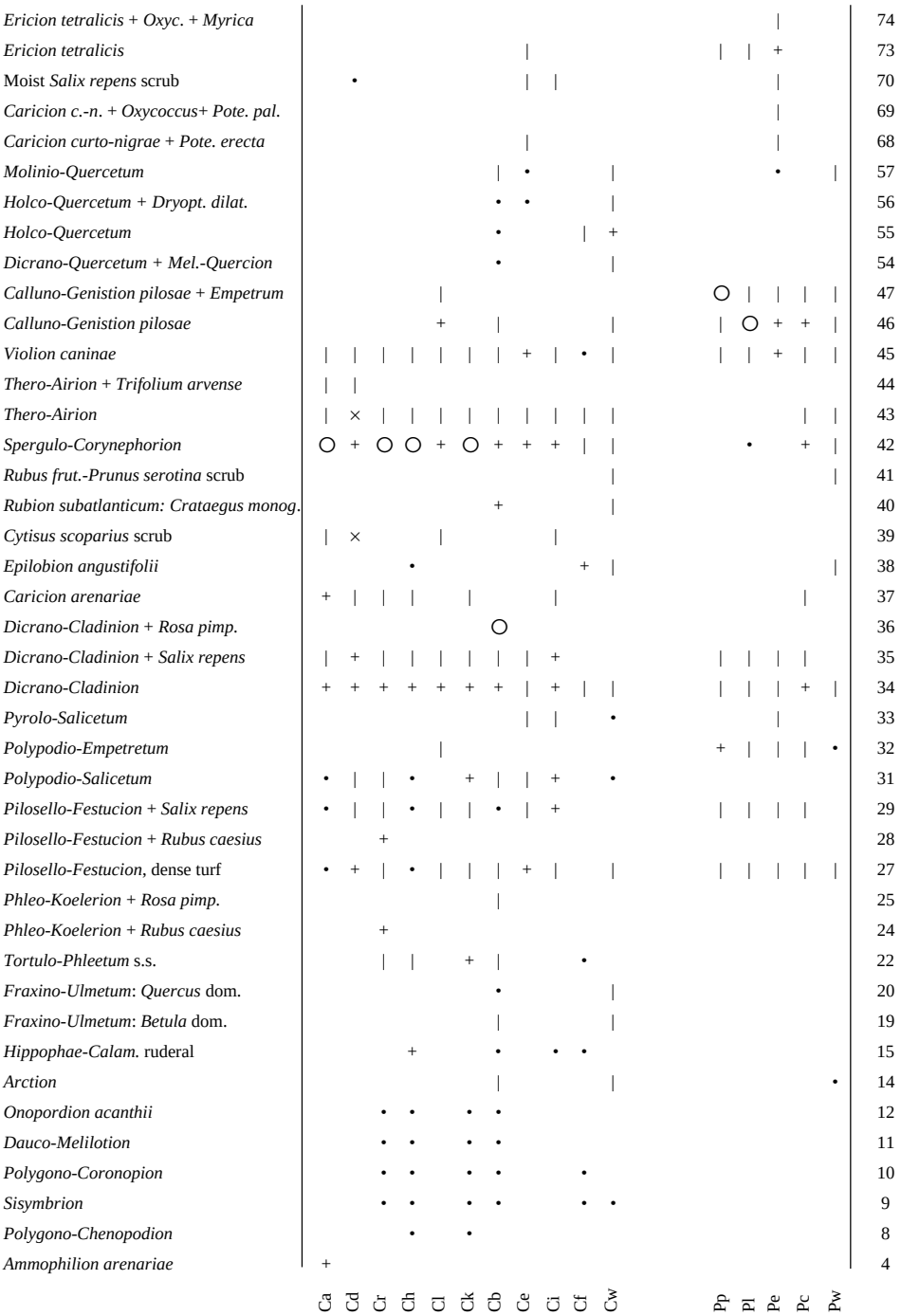
App. 4. (cont.) H, **R** and **K**-landscapes.

Symbols: see first page of App. 4



App. 4. (cont.) : C and **P-**landscapes.

Symbols: see first page of App. 4



App. 4. (cont.) : E, V and **W** landscapes.

Symbols: see first page of App. 4