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Dune Landscape Rejuvenation by Intended Destabilisation in the Amsterdam Water Supply Dunes

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ABSTRACT

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In the Dutch coastal dunes, several projects have started in which aeolian activity is stimulated to enhance landscape rejuvenation by increasing aeolian erosion and deposition. The aim of these projects is to reverse vegetation succession and create opportunities for pioneer stages. In 1995, a drinking water extraction canal in the Amsterdam Water Supply Dunes was closed and the original landscape was restored. Since then, the development of the area was left to natural processes. This resulted in large-scale deflation structures and the development of sand drift areas. By means of air photographs, the changes in the landscape were studied. Initially, the sand drift area expanded, up to a maximum of 11 ha in 1999. In the following years, stabilisation of the surface by vegetation became more and more important. After 8 years of undisturbed development, half of the bare surface was still bare, and the active area was still 2.5 times larger than the stabilised area. But bare spots were scattered over the area, and the average size per spot decreased from 10 ha in 1995 to <1 ha in 2003. The percentage of surface covered by pioneer species was large (5 ha in 2003) and might result in increased stabilisation rates in future. Part of the stabilisation could be explained by meteorological conditions during the studied period. Part could be explained because the system is supply limited. Scale might be an important issue in the final success of remobilisation, as indicated by preliminary comparison to larger-scaled projects. Further comparisons are needed.

After eight years, it is still too early to say whether large-scale destabilisation measures in the case of artificially fixed coastal dunes result in durable aeolian activity and landscape rejuvenation. However, even if the area will be stabilised within the next years, the landscape has many impulses for new ecological development. For the next decade, we need to continue our monitoring programs; meanwhile, experimentation with methods of reactivation should be conducted.

ADDITIONAL INDEX WORDS: *Biodiversity, landscape restoration, dune mobility, management, aeolian processes, coastal dunes.*

INTRODUCTION

Coastal dunes in the Netherlands are subjected to several threats (Janssen and Salman, 1995). The ecosystem suffers from increased nitrogen input and acid rain. Groundwater extraction results in considerable lowering of the water table. Because of human efforts, most of the dunes were stabilised in the past (*e.g.,* Klijn, 1981, 1990). As a result, the younger and species-rich vegetation types in large parts of the dunes are threatened. After 1990, the policy for dune conservation changed considerably (*e.g.,* Arens, Jungerius, and van der Meulen, 2001). Many projects were executed in dune slacks where pioneer stages were restored by removal of vegetation and topsoil (with nutrients). The aim was to reverse vegetation succession and to restore these original nutrient-poor ecosystems. Awareness grew that restoration without attention to the geomorphological processes was of limited success (Arens and Geelen, 2001). Just by removal of vegetation in the dune slacks, the aeolian processes could not be reactivated because of the presence of the groundwater table and the usually moist conditions at the surface of dune slacks. Consequently, the method has to be reapplied after a number of years. However, repeatedly removal of the topsoil structurally lowers the surface, and finally, the height of the surface will be below the groundwater table. The manager ends up with a completely disturbed ecosystem of declined value. Currently, more sustainable methods are being developed that take into account the dynamic characteristics of a natural dune landscape. Introduction of dune dynamics leads to a rejuvenation of the landscape through the burying of vegetation by freshly deposited sand or by removal of vegetation after wind erosion. This will result in mosaics of established vegetation and bare spots with possibilities for pioneer vegetation types. Continuous erosion will eventually lead to the development of deflation zones, gradually developing into dune slacks. Ideally, reactivation results in enduring aeolian activity, ensuring permanent rejuvenation and possibilities for pi-

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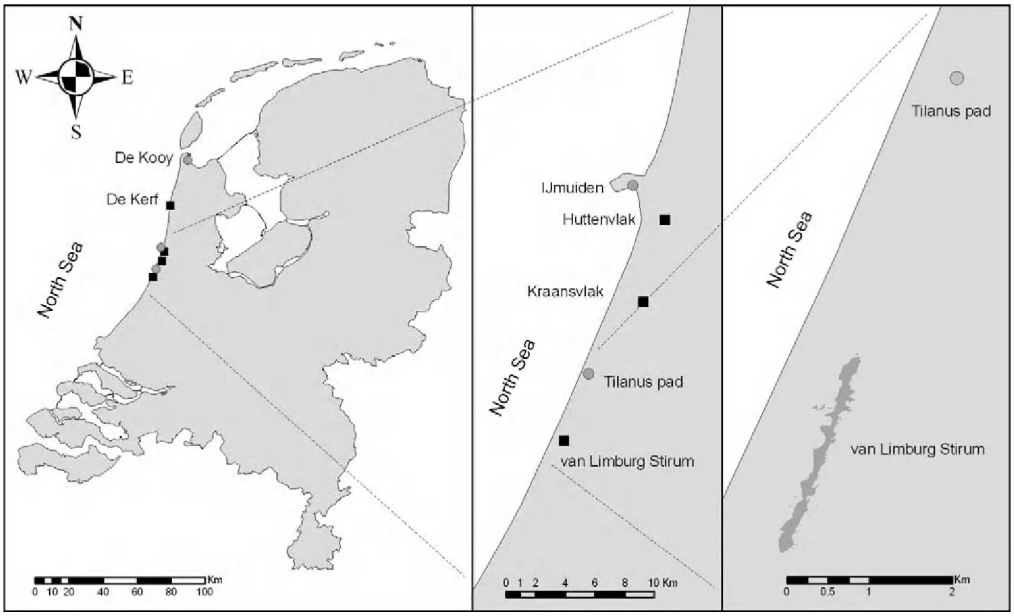

Figure 1. Study area.

oneer vegetation. If this succeeds, no further interference will be necessary.

Current Projects on Dune Reactivation

In several parts of the Dutch coastal dunes and the inland drift sand areas, managers applied the method of reactivation of blowing sand on several scales (KETNER-OOSTRA and SÝKORA, 2000; KOOIJMAN and VAN DER MEULEN, 1996; VEER 1998). Until now, most experience was gained from experiments with blowouts (VAN BOXEL *et al.,* 1997). Between 1995 and 2001, several larger scale projects have been started in the coastal dunes and the inland drift sands: Kerf Schoorl (1997, 9 ha; ARENS *et al.,* 2005), Kraansvlak (1998, 12 ha; ARENS, SLINGS, and DE VRIES, 2004), Huttenvlak (1999, 6 ha), Hoge Veluwe (2000, 40 ha), and Berkheijde (2001, 50 ha).

In 1995, the Amsterdam Water Supply (WLB Amsterdam) started a project of landscape restoration (GEELEN, COUSIN, and SCHOON, 1995). In the southern part of the area, an extraction canal was closed. Sand derived from the digging of the canal still was present in the area. With the use of old maps, the original topography was restored. To enhance aeolian activity in the area and to stimulate the desired rejuvenation of the completely stabilised surrounding dunes, no stabilisation activities were performed, apart from the planting of two tracks crossing the area for the benefit of recreational users of the area. Consequently, a large 3-km-long and some hundreds of metres wide bare sand area was created. The direction of the area is SSW–NNE, which is not the direction of the most active wind (which is WSW–ENE). Although the total size of the bare area was 35 ha at the start, the project could be regarded as a chain of smaller scaled experiments of several hectares, which are developing more or less independently. Since 1995, the development of the area has been monitored. The main research question for the geomorphologic part of the monitoring is to investigate whether the large-scale reactivation has resulted in the persistence of aeolian activity and structural rejuvenation of the landscape. In this paper, we present the results of the monitoring of the geomorphic development since 1995. These results are compared with sand transport potential by combining wind conditions and rainfall data.

STUDY AREA

The study area is situated in the southern part of the Amsterdam Water Supply Dunes, which are located in the central area of the mainland coastal dunes (Figure 1). The area consists of mostly stabilised complex dunes with several small-scale blowouts imposed on a larger scale landscape of parabolic dunes alternated with deflation valleys (KLIJN, 1981). The study area is located at a distance of 700 m from the beach. The devegetated area is about 3 km long and 100–300 m wide. The longest part is oriented SSW–NNE. The resultant wind direction in the Netherlands is WSW. Most of the surface of the dunes in the northern part of the area is covered with a *Hippophao-Ligustretum typicum* vegetation, with a dominance of shrubs like sea buckthorn (*Hippophae rhamnoides*) and wild privet (*Ligustrum vulgare*). In the southern part, grass and moss vegetation (*Phleo-Tortuletum cladonietosum* and *Taraxaco Galietum cladonietosum*) with species like wood small-reed (*Calamagrostis epigejos*), little mouse-ear (*Cerastium semidecandrum*), common ragwort (*Senecio jacobea*), sand cat's tail (*Phleum arenarium*), and *Hypnum cuppressiforme Tortula ruralis* dominate. The sand in the dunes has a grain size of approximately 200 μm and is rich in carbonates and shell fragments.

Table 1. *Date and type of aerial photographs.*

Date	Scale	Recording	Geometric Correction	Type
29 June 1995	1 : 5000	Analogue	Not corrected	False colour
7 August 1997	1 : 5000	Analogue	Not corrected	False colour
28 April 1999	1 : 5000	Analogue	Not corrected	False colour
4 July 2001	1 : 10,000	Analogue	Corrected	False colour
13 June 2003	Digital	Digital	Corrected	Multispectral

Climate in the Netherlands is temperate humid, with most of the storm activity between October and March. Yearly rainfall on average is about 800 mm, although the last years have experienced considerably more rainfall than average (van Boxel and Cammeraat, 1999), with amounts up to 1000 mm. Because of variations in rainfall, the groundwater table fluctuates as well. In the study area, this results in the presence of small ponds in wet years and scattered moist patches in dry years.

METHODS

The development of the area was mapped from aerial photographs. Information on wind and rainfall is needed to investigate the differences in geomorphologic activity in time. To relate changes in the area to meteorological conditions, wind speed and direction and rainfall recordings were used from nearby stations. Wind speed and rainfall were combined to get some indication of the aeolian transport potential over longer time periods.

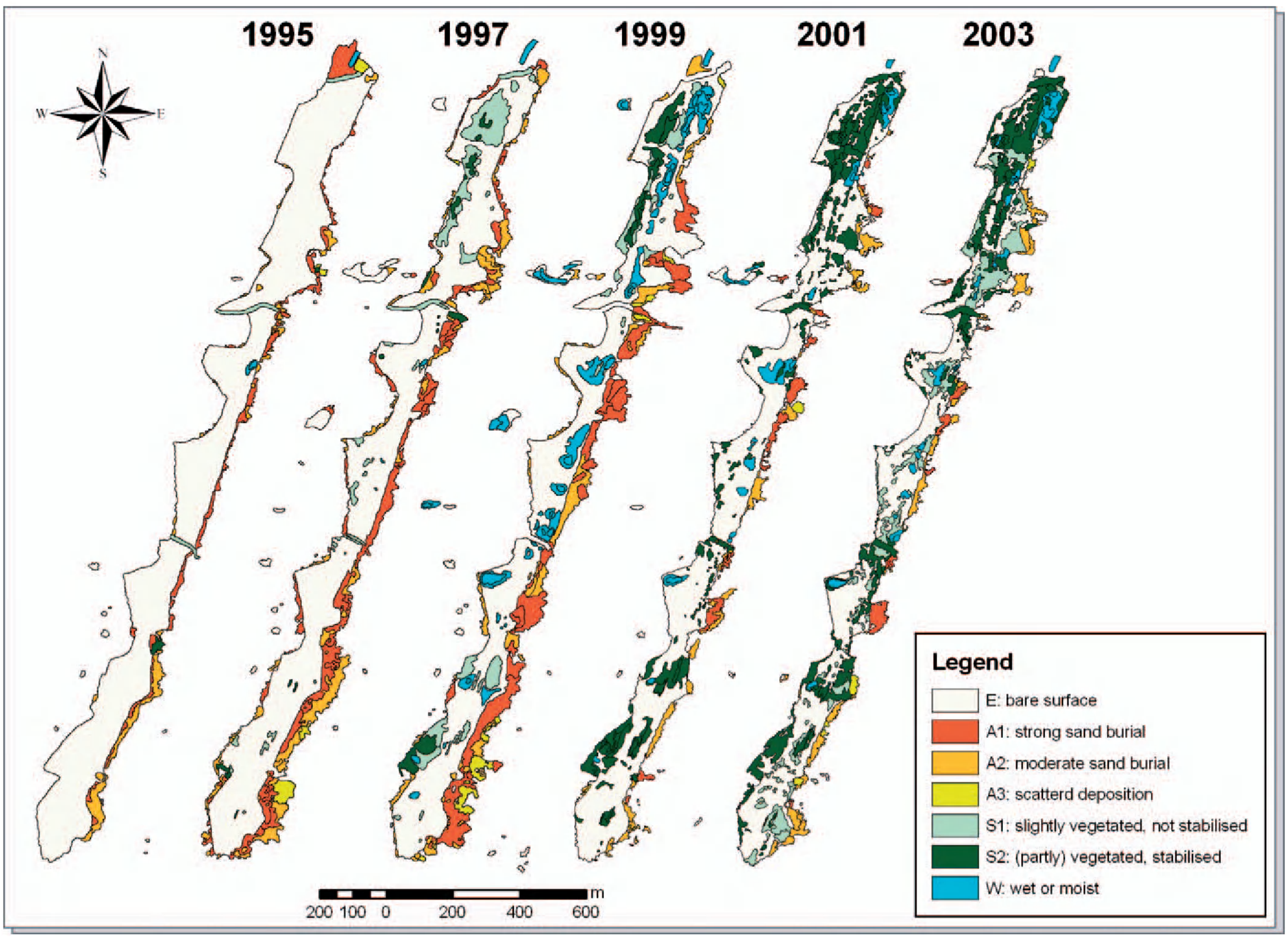

Figure 2. Maps showing the changing dynamics in the area since 1995.

Figure 3. Coppice dunes formed by burial of shrubs (April 2000). **For color version of this figure, see page 1167.**

Data and type of photographs are presented in Table 1. False colour analogue aerial photographs of 1995, 1997, and 1999, scale 1 : 5000 were used to make tracings of landscape units. The resulting maps were georeferenced and converted to a geographic information system afterwards. Aerial photographs of 2001 and 2003 were available in digital versions as orthophotos. For these years, the maps were made directly on the computer screen in ArcView. The maps of 2001 and 2003 are geometrically correct.

A detailed legend was used, from which a simplified version, used in this paper, was derived: E, bare surface, mostly erosive or transport surface; A1, strong burial by sand accumulation (plants completely buried); A2, moderate burial by sand accumulation (plants can be recognised); A3, scattered deposition of sand (no burial, but ecologically important); S1, slightly vegetated with pioneer plants, but not stabilised; S2, (partly) vegetated, stabilised; W, moist or wet surface.

To get some idea of the changes per year and those resulting from summer-winter variation, photographs from fixed spots were taken in the field at half-year intervals.

Hourly wind data of the nearby station of IJmuiden (16.5 km NNE) were used. At this station, wind speeds are recorded on a large breakwater. Daily rainfall amounts are measured locally at station Tilanuspad, which is located 3.5 km to the northeast. The locations of the measuring stations are indicated in Figure 1.

Wind speeds are used to calculate potential sand transport, with several types of transport equations. However, the actual sand transport is usually much lower than the predicted transport for several reasons. One of the most important reasons is the occurrence of rain during periods of strong winds (ARENS, 1996, 1997). In another study on long-term dune development, ARENS, SLINGS, and DE VRIES (2004) proposed the use of a rainfall index P_i, on the basis of the assumptions that (1) a daily average wind speed (U_{day}) of 4 m/s (measured at De Kooy in northwest Netherlands) might exceed the threshold for sediment transport; (2) a daily total precipitation of <5 mm does not impede sediment transport; and (3) during days with >5 mm of rainfall, transport is likely to be hindered. Daily wind speeds measured in IJmuiden are slightly higher than in De Kooy because the station is more exposed. Measurements of 1997 and 2002 showed that U_{day} (De Kooy) = $0.89 \cdot U_{day}$ (IJmuiden; $R^2 = 0.88$ for 1997, $R^2 = 0.90$ for 2002. Therefore in this study, we use 4.5 m/s as the critical daily wind speed for IJmuiden. ARENS, SLINGS, and DE VRIES (2004) recorded changes in height of a reactivated parabolic dune every 3–5 weeks. They concluded that in dry periods, actual transport was more in accordance to predicted

Figure 4. Photograph of the central part of the area, facing north (April 2000). **For color version of this figure, see page 1168.**

values than during wet periods. The division between dry and wet was based on a value of the rainfall index of 20%. The index for our study area is calculated by Equation (1).

$$P_i = \frac{\sum U_{day} > 4.5 \text{ m/s} \wedge P_{day} > 5 \text{ mm}}{\sum U_{day} > 4.5 \text{ m/s}} \times 100\% \qquad (1)$$

For an estimation of the potential for aeolian transport, we used the KAWAMURA (1951) equation and hourly average wind speeds of IJmuiden. Hourly friction velocities were calculated from the wind speed with the Law of the Wall. This will only give a rough estimate of transport; however, our intention is not to compare measured to predicted transport but to compare transport potential for different periods and relate that to long-term changes. Combination of wind power and rainfall gives us more insight into the possibility for sand transport for different periods over ranges of years. There is no good quantitative method to predict aeolian transport under rainy conditions. We made some rough estimate of the effect of rainfall on transport by assuming that the daily transport Q_{day} equals the potential transport Q_{pot} during days with daily rainfall $P_{day} < 5$ mm and $Q_{day} = 0$ during days with $P_{day} \geq 5$ mm.

Finally, we compare the transport potential with the observed changes in geomorphologic activity in the area.

RESULTS

Figure 2 shows the maps indicating the aeolian activity in the area. Initially, the amount of freshly blown sand increased considerably, mostly at the eastern side of the area. Sand was blown from the bare area and deposited over the vegetated edges. As a result, distinct long dune ridges and coppice dunes developed, the morphology of which depended on the type of vegetation that trapped the sand (Figure 3). In the bare area, lag deposits developed locally, occasionally with remnants of debris, roots, *etc.* Several major processes occurred in the landscape after 1995.

Changes in Bare Surface

On the bare, devegetated surface, most changes are caused by either erosion (lowering of the surface) or vegetation establishment (stabilisation of the surface or dune development by trapping of sand). The surface is mostly a deflation and transport surface (Figure 4), although temporarily accumulative bedforms develop. In some spots, moist patches developed after deflation down to groundwater. Moist or wet spots vary in size from 0.2 to 4.3 ha, depending on the height of the water table. It was exceptionally wet in 1999, and a large amount of small lakes and wet surfaces were present. In

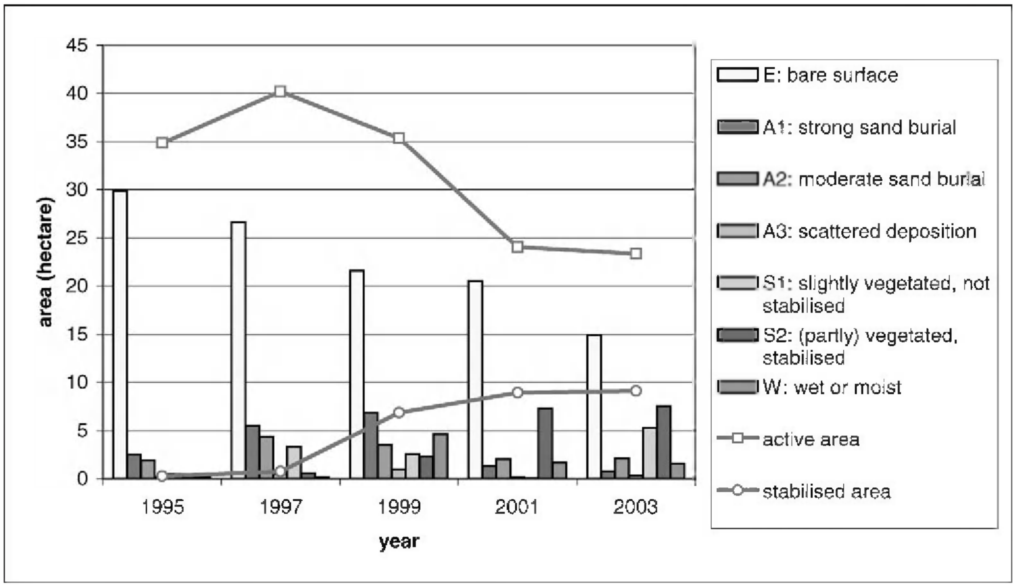

Figure 5. Changing of surface areas of mapping units in time.

Figure 6. Sand sheet rolling over a stable, vegetated surface (December 1995).

Figure 7. Shadow dunes formed after the establishment of saltwort (*Salsola kali*; July 1999). **For color version of this figure, see page 1169.**

some of the wet spots, the linear characteristics of the former channel can be recognised. In other places, lag deposits developed because of the presence of debris. Over the whole area, the amount of sand available for transport decreased. Slight erosion of the surface, or even the passing of sand during transport events, prevents the establishment of seedlings of pioneer species. There are some examples of expansion of the bare surface because of aeolian erosion, mostly in the form of blowout-like features. The total bare surface area has gradually decreased from 29.9 ha in 1995 to 14.9 ha in 2003 (Figure 5).

Sand Burial

Every winter, a large, previously vegetated surface is covered with drift sand. Mainly sand sheets formed (Figure 6), but locally, also small coppice and shadow dunes (Figure 7). The burying occurs mostly with southwesterly to northerly winds. Occasionally during cold winter conditions (1996), northeasterly winds deposit sand on the western side of the area. The most important increase in buried surface was in 1997 (10.3 ha) and 1999 (11.3 ha). In 2001 and 2003, burial decreased, with a total surface of approximately 3 ha. After burial, plants tend to grow through the covering layer of sand. The result is restabilisation if burial does not continue. When plants grow through the sand sheet, in fact, the sand present in the deposit is withdrawn from the transport system. As a result, the sand available for transport gradually decreases with time. Occasionally, plants disappear because of strong burial and are replaced by marram grass (*Ammophila arenaria*). There were no observations of complete remobilisation of dunes because of sand burial; *i.e.,* no parabolic or any kind of transverse, barchanoid, or other type of mobile dune developed. This is one of the important conclusions of this study: the large-scale destabilisation has resulted in several major changes in landscape activity, but mostly in the form of small-scale features like local sand burial or erosion and occasionally in the form of thick sand sheets.

Establishment of Pioneer Species on Bare Surfaces

Initially in the southern part, the pioneer saltwort (*Salsola kali*) invaded a large part of the area. Gradually, this species also spread to the northern part. In the south, most of the saltwort had disappeared by 2002, and the surface was mostly stabilised because of subsequent vegetation succession. There are some rare spots, however, where the surface was remobilised again after disappearance of saltwort. In 2003,

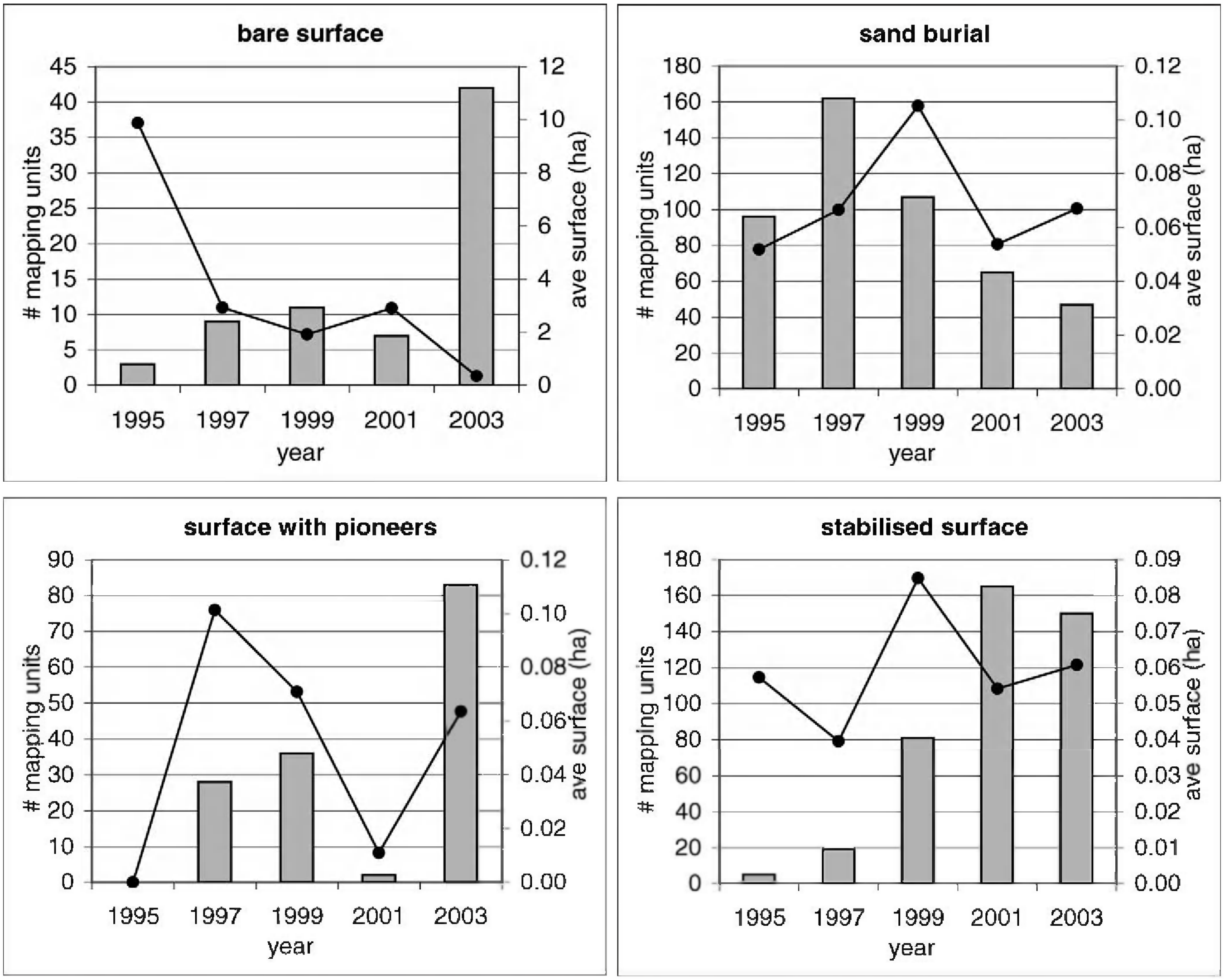

Figure 8. Number of mapping units (bars, left axis) and mean surface area of mapping units (lines, right axis) for main surface types.

after a calm but dry winter, a huge part of the bare surface (5.3 out of 20.5 ha of bare sand in 2001) was covered by pioneer species. The surface still is active, but if vegetation succession proceeds in the next growing seasons, the size of the stabilised area will exceed the size of the active area.

Establishment of Vegetation by Regrowth from Root Remnants

After the reactivation measures in 1995, roots were left under the surface in some parts of the area. Especially in the northern part, plants recovered (mainly sea buckthorn) and started to stabilise the surface. After invasion of marram grass, most of the surface in this part was stabilised by 2001. In other parts, roots of common reed (*Phragmites australis*) started to regrow along the former banks of the channel and started to trap sand. This resulted in some strange, linear dunes, indicating the former channel banks. These dunes are still trapping sand and growing in height, but locally, they are stabilised. Since 1995, the stabilised surface has increased in area to 8.3 ha in 2003.

Fragmentation of Landscape Units

Figure 8 illustrates the tendency of fragmentation in landscape units in the study area. The number of mapping units is increasing in time, whereas their average size is decreasing. There is some influence of mapping accuracy because the digital air photographs of 2001 and 2003 show much more detail and therefore provide better opportunities for detailed mapping. The most drastic change is in the bare surfaces. Initially, two very large bare areas resulted in large-scale sand transport. In 2003, there were >40 bare spots, and their scale was limited. Some spots are isolated. As a result, the transport capacity and the possibilities for sand burial at the edges decreased.

Table 2. *Wind power index per month for IJmuiden, with rainfall data from Tilanuspad.*

Period	Potential Transport (m³/m)	Transport Estimate (m³/m)	Total Rainfall (mm)	No. of Days with Average Wind Speed >4.5 m/s	No. of Days with Average Wind Speed >4.5 m/s and Rainfall >5 mm	Rainfall Index (%)
July 95–June 96	126	113	468	270	21	7.8
July 96–June 97	139	109	733	244	42	17.2
July 97–June 98	130	82	806	278	48	17.3
July 98–June 99	180	132	1008	273	56	20.5
July 99–June 00	168	107	874	278	53	19.1
July 00–June 01	126	89	1038	279	63	22.6
July 01–June 02	186	139	950	276	52	18.8
July 02–June 03	80	50	841	224	40	17.9
Period 1						
July 95–June 97	265	222	1201	514	63	12.3
Period 2						
July 97–June 99	309	214	1814	551	104	18.9
Period 3						
July 99–June 01	295	197	1912	557	116	20.8
Period 4						
July 01–June 03	266	189	1790	500	92	18.4

The number of units with sand burial decreases slowly; their average size is more or less constant. A slight decrease in the number of units with stabilisation occurred in 2003. Meanwhile, the mean surface area of those units increased slightly, which suggests that stabilised spots are being connected.

Relation of Landscape Change to Meteorological Conditions

The results of the meteorological measurements and calculations are presented in Table 2 and Figures 9 and 10. Figure 9 illustrates that many of the months with high wind power (large transport estimates) coincided with large amounts of rain (although overall correlation is poor: $R^2 = 0.14$). As a result, aeolian activity will be much less than predicted. Table 2 shows the potential and estimated transport, rainfall, and rainfall indices for the four mapping periods. In sheer wind power, period 2 is the most important, which coincides with the largest extension of sand burial in the period. For period 1, wind power is much less, but because the rainfall index is also much lower, it is possible that the actual transport is the same order of magnitude as in period 2. In period 3, the rainfall index is higher; in period 4, the wind power is less and the rainfall index is comparable to that of period 2. Therefore, it is likely that aeolian transport in periods 3 and 4 is less than in periods 1 and 2. This could explain (part of) the decrease in activity in the area from 1999 to 2003. Ideally, yearly air photographs would be studied, but these are not available. This might have an effect on the interpretation of landscape changes. For example, if a year with many storms is followed by a year with few, we can expect that at least some of the changes because of stormy winter will fade in the next year. Examining the yearly data reveals that most “lows” in estimated transport are in the winter preceding the recording of the air photographs. The year 1999 is the exception, with a high transport estimate just before the air photograph was taken. This might well have an effect on the interpretation of landscape chang-

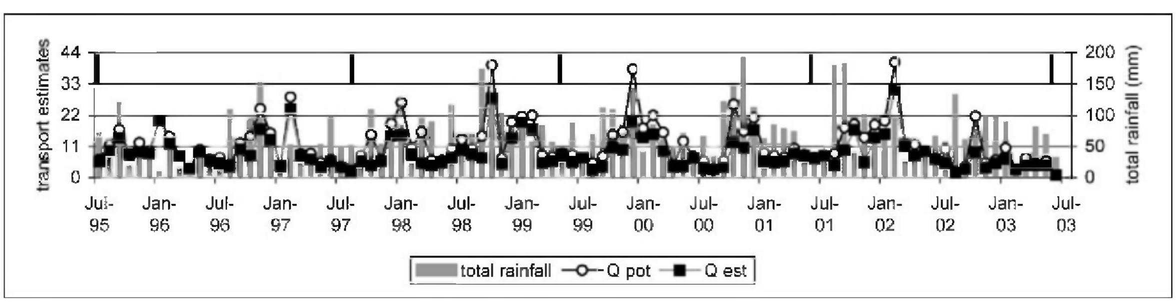

Figure 9. Monthly potential Q_{pot} and estimated transport Q_{est} and rainfall from July 1995 to June 2003. The vertical, black bars indicate the dates of air photograph recordings.

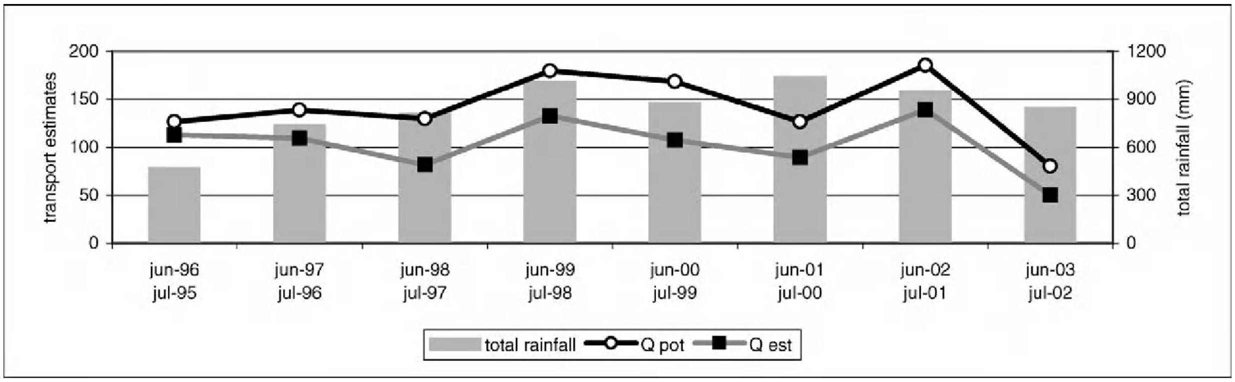

Figure 10. Potential and estimated transport and rainfall per year.

es. If a stormy winter is followed by a calm winter, traces of the stormy winter will be less visible. Figure 11 illustrates the seasonal and year-to-year variation of sand burial. The photographs are taken from the same spot in the north of the study area. In the winters of 2001 and 2002, the amount of sand burial is comparable; in 2003, it is much less. The figure also clearly demonstrates the seasonal variation in sand burial. The photographs of summer 1999 and 2000 show much less bare sand than the winter photographs. In the central part of the area, marram grass gradually covers the surface.

DISCUSSION AND CONCLUSIONS

The results show that after large-scale destabilisation, aeolian processes in the area increased considerably in the first years. Initial changes in the landscape were mainly in the development of large areas in which plants were buried under fresh aeolian deposits, with a maximum extension of 11.3 ha in 1999. In the following years, stabilisation of the surface became more and more important, either because of the establishment of pioneer species on the bare surface and subsequent vegetation succession or because of growth of new plants from old, remnant roots. After eight years of undisturbed development, half of the bare surface was still bare, and the active area was still 2.5 times larger than the stabilised area. But bare spots were scattered over the area, and the average size per spot had decreased from 10 ha in 1995 to <1 ha in 2003. The percentage of surface covered by pioneer species was large (5 ha in 2003) and might result in increased stabilisation rates in the future.

Part of the stabilisation is explained by meteorological conditions during the period studied. The period of expansion of sand burial in the area coincided with higher potential aeolian transport, whereas stabilisation in later years coincided with larger rainfall amounts. In terms of "expected activity," the last two periods (1999–2003) had lower sand transport expectations than the previous periods (1995–1999). This was even truer if only the conditions of the year previous to the air photograph recordings were considered. However, meteorological conditions probably only explain part of the landscape dynamics. Invasion of the bare surface by pioneer plants is probably as important, but its relation to meteorological conditions are not yet well understood. Regardless, the system is supply-limited (KOCUREK and LANCASTER, 1999). In a supply-limited system, the correlation between wind and transport is vague. For example, if the groundwater table lowers, the supply of sand increases because larger surfaces with bare sand become dry and sand can be taken up there. After an increase in water table height, the supply decreases, and higher wind speeds are needed to transport the same amounts of sand.

Large-scale destabilisation has resulted in several major changes in landscape activity, but mostly in the form of small-scale features like local sand burial (small-scale transgressive dune fields, shadow dunes, and coppice dunes; see HESP and THOM, 1990) or blowout development. This is remarkable because most of the underlying landscape consists of large-scale aeolian features. It might indicate that the underlying large-scale bedforms are fossilised and not related to present day processes (which could mean that the large-scale activity of the past was related to climatic change; see, *e.g.*, LANCASTER, 1997). LANCASTER (1988) developed Equation (2) to quantitatively index the mobility and stability of sand dunes. This M-index is widely used by geologists and geomorphologists to determine whether sand dunes would be active or fixed, as well as the expected effect of climate change on dune fields. The M-index equation is based on the ratio of W (the percentage of time during the year with sand-moving winds, which represents the factor of mobility of sand dunes) to P/PET (the quotient of mean annual precipitation to the mean annual potential evapotranspiration, which represents the factor of soil moisture available for vegetation).

$$M = \frac{W}{P/\mathrm{PET}} \qquad (2)$$

The M-index was calibrated by LANCASTER (1988), who found the critical values of M for southern Africa to be >200 for fully active dunes with no vegetation and <50 for inactive vegetated dunes. The M-index for IJmuiden, Holland, is 42, which defines a climate that causes fully stabilised dunes (LANCASTER, 1988). So, the present Dutch climate might not be suitable for large-scale dune mobility.

There are examples of dune landscapes changing from sta-

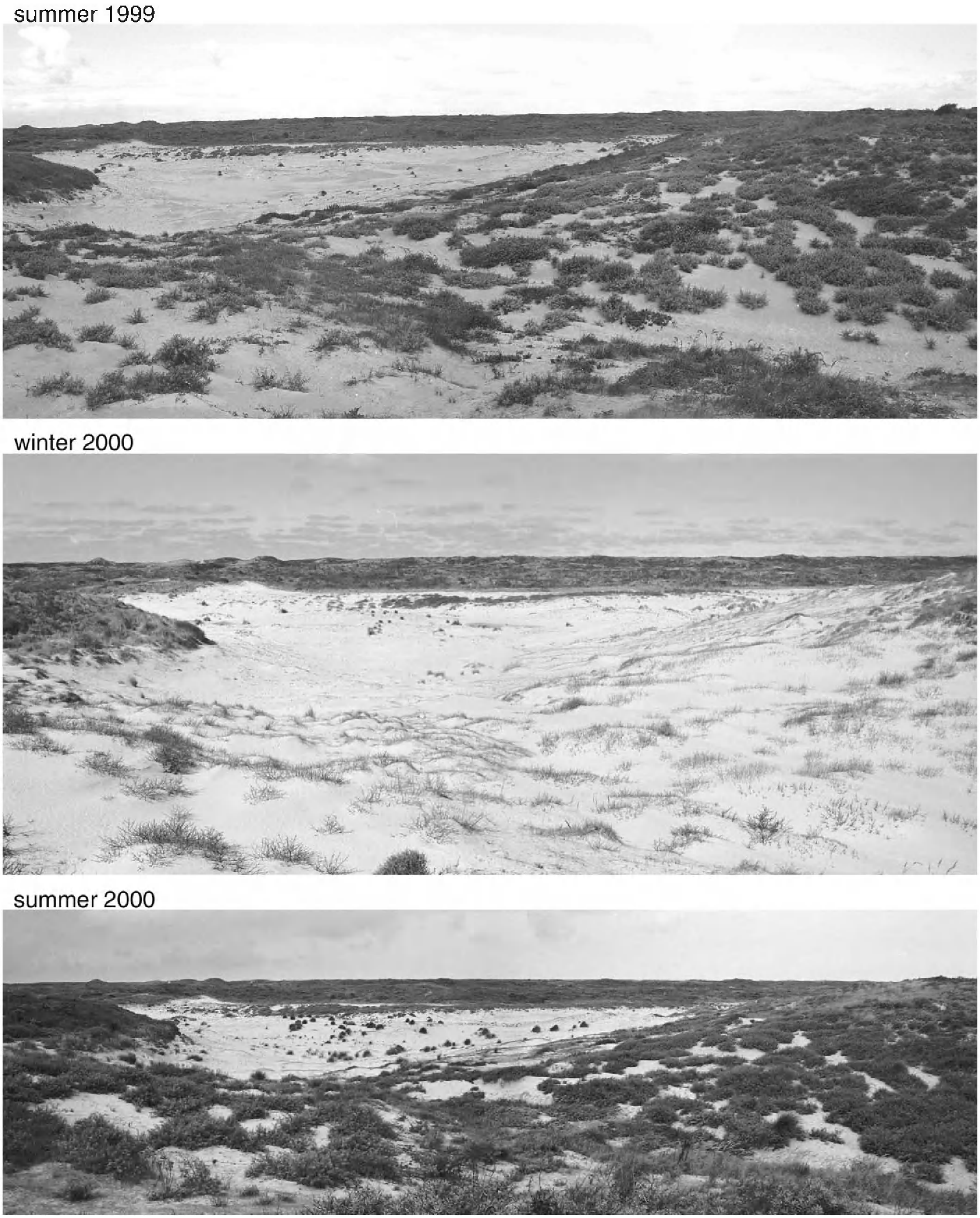

Figure 11. Year-to-year variation in sand burial; from top to bottom: summer 1999; winter and summer 2000; and winters 2001, 2002, and 2003. **For color version of this figure, see page 1170.**

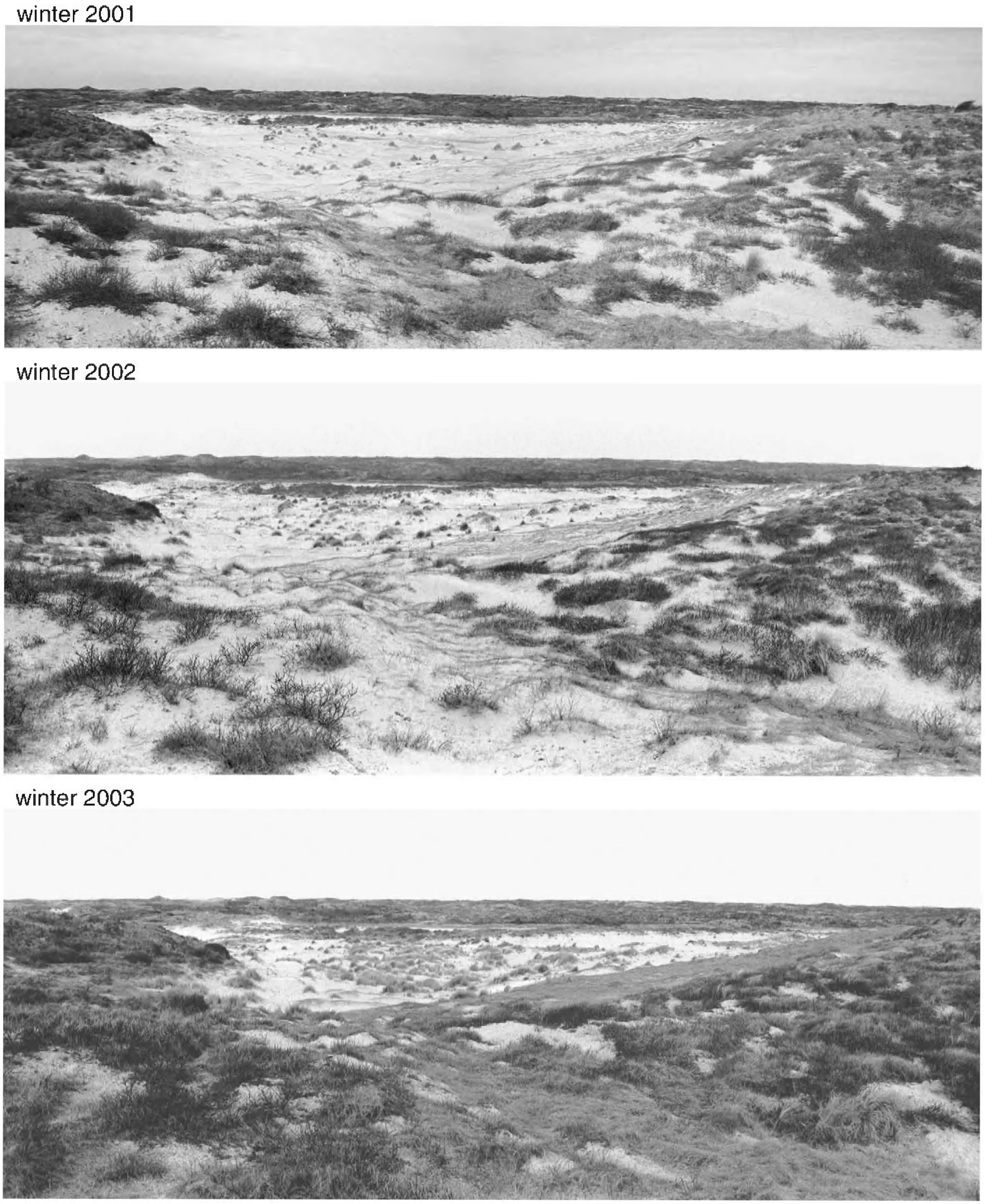

Figure 11. Continued. **For color version of this figure, see page 1171.**

ble to mobile because of human interference (HESP, 2001). Another reason for stabilisation could be that the scale of the reactivation is too small. The orientation of the area is not according to the resultant wind direction, so in the direction of the wind, the bare surface extends ≤600 m. Preliminary comparison of the results with other projects differing in scale (*e.g.,* ARENS, SLINGS, and DE VRIES, 2004; ARENS *et al.,* 2005) suggests that the scale of a reactivation might be decisive for final success. However, more research is needed, and the results of other, larger scaled projects need to be considered, too.

A third reason might be that stabilisation can occur relatively easily because many (living) roots still remain after devegetation and removal of the topsoil. However, this study clearly indicates that one event of destabilisation at this scale under the present climatic conditions does not lead to the large-scale sand movements that must have caused the development of the Younger Dunes (JELGERSMA *et al.,* 1970; KLIJN, 1990).

Other factors that enhance stabilisation (and obscure the relationship between aeolian dynamics and meteorological conditions) are the withdrawal of mobile sand from the system, variation in the water table, and trapping capacity of the plants (HESP and THOM, 1990). If sand is deposited over vegetation and the buried plants recover afterwards, sand previously available for transport then becomes immobilised. If this happens over large areas, the amount of sand that is available for transport becomes more and more limited. The burial rate of a vegetated surface determines whether the plants survive. If the plants survive, continuous burial is needed to avoid stabilisation. If they die, the surface will be completely mobilised. If the surface is bare, establishment of seedlings is prevented in case of slight erosion (some centimetres per year); once seedlings (pioneers) manage to colonise a surface, the surface tends to stabilise. The tendency of vegetation to get back into the area, colonise bare surfaces, or grow through sand burial might be of more importance in the development of landscape activity in the long term than the amount of wind and rainfall. Therefore, we need to investigate more of these restoration projects.

Good Management?

Finally, we want to address the question: are large-scale destabilisation measures in case of artificially fixed coastal dunes good management practices. The main aim of these measures is to restore landscape dynamics in such a way that periodic rejuvenation of the landscape is ensured and self-maintaining. Only then, rare and endangered ecosystems can be preserved in a durable way. On the basis of this study, we cannot give definitive answers to that question yet. At least on a time scale of 10–20 years, the measure had a massive effect on the ecosystem. Even if the area will be stabilised within the next years, the landscape has many impulses for new, ecological development. However, after another 10–20 years, new measures might then be necessary because vegetation succession will continue and the landscape probably will develop into the same state that existed before the destabilisation activities. For the next decade, we need to continue our monitoring programs and meanwhile extend the experimental program, *e.g.,* by conducting a remobilisation experiment by removing roots and re-establishing vegetation for a number of years.

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LITERATURE CITED

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