Landscape Ecology vol. *6* no. 1/2 pp 89-97 (1991)
SPB Academic Publishing bv, The Hague

Simulated impact of sea level rise on phreatic level and vegetation of dune slacks in the Voorne dune area (The Netherlands)

V. Noest
Institute of Ecological Botany, Uppsala University, ***Box 559,*** *751 22 Uppsala, Sweden*

Keywords: sea level rise, phreatic level, dune slack vegetation, interaction model, the Netherlands

Abstract

Effects of sea level rise and different coastline management options on the phreatic level in a coastal dune area are calculated, using a scenario with 60 cm sea level rise in the course of the next century, resulting from global climatic changes. Changes in the phreatic level – both lowering and rising – are evaluated for their effects on the dune slack vegetation, using a newly developed interaction model 'hydrology-vegetation'. Some indications of changes in nature conservation values are presented.

Introduction

During the last decade, much attention has been paid to the effects of increasing levels of atmospheric CO, and other greenhouse gases (NO,, CH,, O_3, etc.) on the global climate.

Although there is no general agreement between the different climate models as to detailed predictions, some effects seem likely to happen:

- a doubling of the atmospheric CO, content within the next century (Palutikof *et al.* 1984), resulting in a trapping of heat near the earth's surface and a rise in global mean surface air temperature;
- this temperature rise may lead to a rise in sea level, mainly caused by thermal expansion of ocean water (Huis **1989).**

For a low-lying country such as the Netherlands, a major rise in sea level can have formidable consequences, both economical and ecological.

The first landscape to be endangered within the Netherlands would be the coastal dune area, a large part of which is managed as a nature reserve (Meulen and Maarel 1989). **A** prime function of the coastal dunes is to protect the low-lying, highly populated hinterland against the sea. The Ministry of Roads and Public Works, responsible for coastal defence, has recently carried out an extensive policy analysis study of the possible effects of sea level rise on the development of the Dutch coastline, using different morphological and sea level rise scenarios (Min. of Roads and Public Works **1989).**

A retreat of the coastline, as predicted for the main part of the Dutch coast, is often believed to result in a fall of the water table in the remaining dune area, as a result of the narrowing of the dune body (a.o. Meulen **1990;** but see also Vestergaard **1989;** Doody **1989).**

In the present paper, the effects of coastline retreat on the water table are calculated, using a method developed by Bakker **(1981).** This method shows a general fall of the phreatic level as a result of coastline retreat. However, if the rise in sea level is also taken into account, the final results depend on the width of the dune body, the amount of erosion and the coastline management. In many cases, a rise of the phreatic level can be the overall result.

A second major function of the Dutch coastal dunes is public drinking water supply. Since the demand for drinking water exceeds the precipitation surplus, artificial infiltration of pre-purified river water is used. This type of land use disturbs the natural ground water regime in the dune area and leads to the disappearance of the dune slack environment, through changes in the phreatic level and eutrophication. Many dune slack species are sensible to even small changes in the phreatic level (Laan 1979). To optimize the compatibility of the functions of drinking water production and nature conservation, an interaction model 'hydrology-vegetation' has recently been developed (Noest in prep.). This model, HYVEG, predicts species performance for 100 dune slack species, given a set of values of environmental variables, most of which describe some part of the hydrological conditions.

Study area

The study area is the coastal dune area of Voorne, situated in the northern part of the estuaries of the rivers Rhine and Meuse (Fig. 1). The width of the dune belt ranges from 550 m in the south to 1600 m in the north. The northern part of the dune area comprises a series of parallel former foredune ridges, with primary dune slacks in between. In the southern part, some secondary dune slacks can be found. The hydrological regime is nearly natural; no drinking water has been extracted for 40 years.

Coastline predictions

Recently, the Ministery of Roads and Public Works carried out an extensive policy analysis study of the impacts of sea level rise on the development of the coastline (Min. of Roads and Public Works, Tech. Rep. 5 & 6, 1989). The timespan under study was the next century: 1990–2090. Changes in the position of the coastline were calculated, using a conceptual model of the coast. This model is based on the monitoring of coastline changes since 1843. The following processes are taken into account:

- adjustment of the vertical coast profile to sea level changes;
- onshore transport: net sediment transport from the shoreface onto the beach, mainly determined by the offshore wave climate;
- alongshore transport: mainly determined by the wave climate and the tide;
- dune formation: net loss of sand over the top of the first dune ridge.

In total, 6 coastline predictions were made using **3** climate scenarios (assuming a sea level rise of 20, 60 and 85 cm, respectively, in the next century). Two process scenarios were used: an expected and an unfavourable one. The latter assumes a 20% more unfavourable sediment transport, implying a 20% decrease in onshore transport and a 20% increase in alongshore transport.

In this contribution, only the consequences of the intermediate climate scenario (60 cm sea level rise) and the expected process scenario will be evaluated.

The coastline of Voorne has a length of 9 km (cell nr. 82–91; see Fig. lb). Table 1 shows the prediction of the relative position of the coastline for different points of time within the next century. Only the predictions for the years 2050 and 2090 will be used in this paper. Sea level rise is assumed to take place in a more or less linear fashion, with a rise of 30 cm in 2050 and of 60 cm in 2090.

Table 1 shows that a coastal retreat up to 348 m can be expected in 2090 for the most protruding part of the area. It is however very unlikely that such a considerable retreat would be allowed to take place, because of the risk involved for the area behind the foredunes. This would necessitate re-enforcement of the foredune ridge.

To evaluate the combined effects of sea level rise and coastline management, 2 management options are used in the present paper: the first one allows a coastline retreat of 25 m at most for 2050 and 50 m for 2090, the second one 50 m and 100 m respectively.

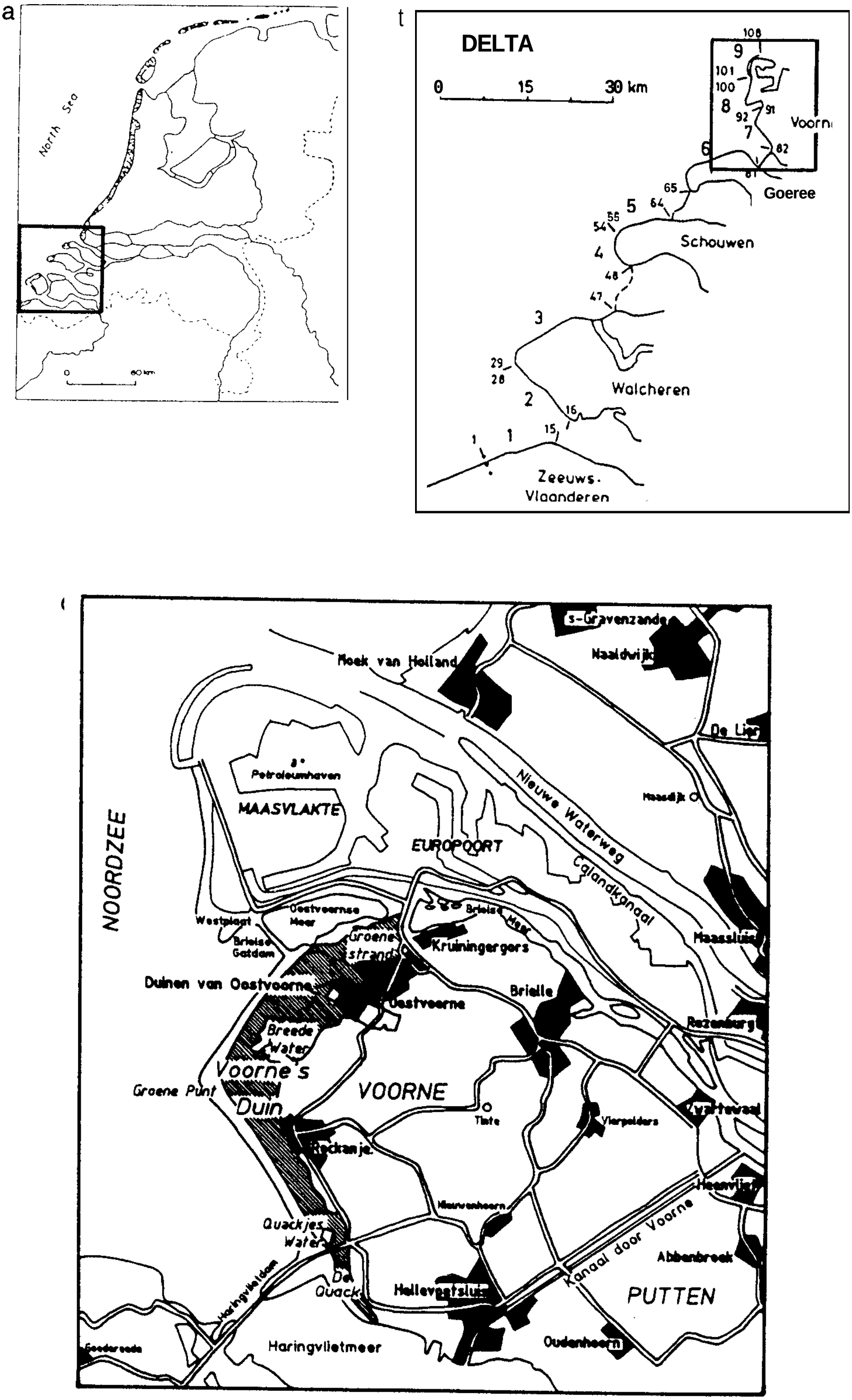

Fig. *1.* a. The estuaries of rivers Rhine and Meuse. b. Location of Voorne. Division of the coastline in 9 sectors and 108 cells. After: Ministry of Roads and Public **Works** (1989). c. The study area. Coastal cell nr. 82–91 (cf. Fig. lb).

Table 1. Changes in the position (m) of the coast of Voorne, relative to the position in 1990. After: Ministry of Roads **and** Public **Works** (Tech. Rep. nr. 5, 1989). *: cf. Fig. 1b.

coastal cell*	1995	2000	2010	2020	2050	2090
82	-1	-3	-6	-8	-17	-28
83	-1	-3	-6	-8	-17	-28
84	-4	-8	-12	-15	-27	-43
85	-6	-13	-23	-31	-58	-93
86	-21	-43	-76	-113	-177	-208
87	-41	-83	-151	-208	-307	-348
88	-6	-13	-26	-38	-77	-128
89	-1	-3	-6	-8	-17	-28
90	-1	-3	-6	-8	-17	-28
91	-1	-3	-6	-8	-17	-28

Interaction model 'hydrology-vegetation'

Based on vegetation analyses and environmental data from over 200 (2 x 2 m) permanent plots, recorded since the 1960-iesin wet dune slacks in the Voorne dune area, a vegetation model was developed (Noest in prep.). The environmental input variables of the model include a variety of site, hydrological and climatological parameters. Each of the 48 hydrological parameters (such as the mean high and mean low phreatic level, duration of inundation in summer and winter, duration of the 'dry period', i.e. phreatic level more than 30 cm below the surface, total fluctuation of the water table) describe part of the hydrological regime. They vary with location and time. The 18 climatological parameters comprise mainly the temperature in the different seasons and parameters derived from that (varying only with time, but not with location), while the 3 site parameters consist of the height above sea level, distance to the fore dune ridge and age of the slack.

Given a set of input variables, the model predicts the probability of occurrence of dune slack species, based on a logistic regression analysis. About a hundred species were sufficiently common to give significant results.

Effects on the phreatic level

To study the effects of sea level rise on the phreatic level and the consequences for the vegetation, *23* of the 56 available permanent plots in the study area were selected, to represent the existing variation in distance to the fore dune ridge, dune width, slack age and height above sea level, covered by the plots. For all plots, the phreatic level after sea level rise was calculated, using a method developed by Bakker (1981).

The basis of this method is the formula by Ghijben-Dupuit and Dupuit (Strack 1971):

$$(h^*)^2 = \frac{N}{k}\left(\frac{B^2}{4} - x^2\right) + \frac{41}{40}H_O^2 \qquad (1)$$

with:

h^* = water table relative to impermeable layer (m)
N = effective precipitation (m/d)
k = coefficient of permeability (m/d)
B = width of the dune body (m)
x = distance to the centre of the dune body (m)
H_O = depth of impermeable layer below sea level (m)

Bakker developed a formula to calculate the change in water table, as a result of narrowing of the dune body (see Fig. 2):

$$\left(\frac{B + \Delta B}{B}\right)^{1.73} < \frac{h_m + \Delta h_m}{h_m} <= \left(\frac{B + \Delta B}{B}\right)^{1} \qquad (2)$$

with:

ΔB = change in width of dune body (m)
h_m = water table at centre of dune body (m)
Δh_m = change in h_m (m)

With known values for B, ΔB and h_m this formula gives the maximum and minimum amount of change in h_m. Furthermore, Bakker provides tables with values for the ratio $\Delta h/\Delta h_m$, enabling cal-

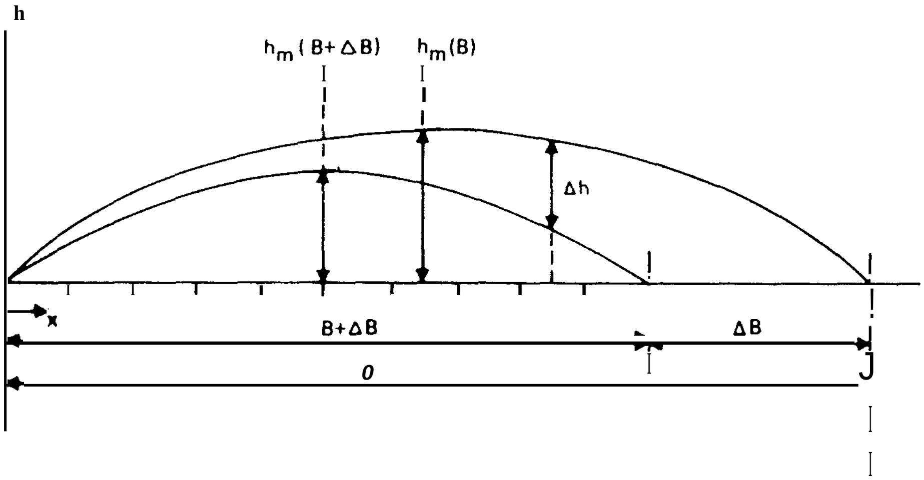

Fig. *2.* Changes in the phreatic level with narrowing of the dune belt (AB < 0). After: Bakker (1981).
B: width of dune body
h; phreatic level at centre of dune body
Ah: change in phreatic level, by narrowing of dune body.

culating of the change in phreatic level (Ah) at any point along a cross-section of the dune body.

When these formulae were applied to the selected plots, the results showed a fall in the phreatic level on all plots, as could be expected. However, the formulae do not take a sea level rise into account, but merely a decrease in width of the dune body. **A** rise in sea level of Δh_{sea} cm will lead to a rise of the phreatic level of Δh_{sea} cm at the fore dune ridge, decreasing to 0 cm near the inner dune ridge. In the absence of impermeable layers in the uppermost 10 m of the subsoil, this decrease will be linear with distance to the sea. In the presence of an impermeable layer, as in some parts of the Voorne dune area, this relation will deviate slightly from a linear one. However, this deviation will be small in comparison with Δh_{sea} (Bakker, pers. comm.). In this contribution, a linear relation between distance to the sea and rise of the phreatic level by sea level rise has been assumed.

When a sea level rise of 30 and 60 cm (for 2050 and 2090 respectively) was superimposed on the new phreatic levels (as derived by equation 2), most plots appeared to undergo a rise of the phreatic level. This rise was most pronounced for plots situated near the fore dune ridge, especially if the coastline retreat was small, either by re-enforcement of the fore dune ridge or as directly predicted from the coastline model. Table 2 shows the main parameters involved in calculating the changes in phreatic level for 2050, allowing a maximum coastline retreat of *25* m (management option 1). Table 3 shows the net changes of the phreatic level for 2050 and 2090, for both management options.

Predicting changes in vegetation

For each permanent plot, a data set with the current (1989) values for the hydrological, climatological and site variables was composed. From these data sets, 4 new sets were composed for each plot. These 4 sets consisted of the 4 possible combinations of the 2 coastline management options and the 2 years under study (2050 and 2090). The mean of the net changes in phreatic level from Table **3** were used to calculate new values for all hydrological variables. The temperature was assumed to rise 1°C by 2050 and a further 1°C by 2090. The site variable 'distance to the fore dune ridge' was adapted according to the values of Table 1. With each of these data sets *(5* for each site), a prediction of the vegetation was made, using the HYVEG model.

Table 2. Calculation of the changes of the phreatic level in 2050, with a sea level rise of 30 cm and a maximum coastline retreat of 25 m.

plot	B (m)	h_m (cm)	x (m)	AB	Δh_m (cm)		Δh_B (cm)		Δh_{sea} (cm)	Δh_{net} (cm)	
					max	min	max	min		min	max
1 – 3	1500	365	650	– 17	– 7	– 4	– 14	– 8	28	14	20
4	1250	300	375	– 17	– 7	– 4	– 12	– 7	24	12	17
5 – 7	1250	300	325	– 17	– 7	– 4	– 11	– 6	23	12	17
8 – 9	1600	375	650	– 25	– 10	– 6	– 19	– 12	28	9	16
10 – 12	1600	375	250	– 25	– 10	– 6	– 13	– 8	20	7	12
13 – 16	1500	365	500	– 25	– 10	– 6	– 18	– 11	25	7	14
17	1500	365	350	– 25	– 10	– 6	– 15	– 9	22	7	13
18 – 19	1500	365	50	– 25	– 10	– 6	– 10	– 6	16	6	10
20	1500	365	– 50	– 25	– 10	– 6	– 9	– 6	14	3	8
21 – 22	750	275	125	– 17	– 11	– 6	– 15	– 8	20	5	12
23	550	260	– 100	– 17	– 14	– 8	– 9	– 5	10	1	5

B = width of the dune body
h_m = phreatic level at centre of dune body
x = distance to the centre of the dune body. **A** negative distance means that the plot is situated inland from the centre of the dune body.
Δh_B = change in phreatic level at plot, caused by narrowing of dune body
Ah,„ = change in phreatic level at plot, caused by sea level rise
Ah,„ = total change **(Ah,** + Ah,„).

Table 3. Mean net changes in phreatic level for 2050 and 2090, under 2 coastline management options. *: cf. Fig. 1b.

plot	coastal cell nr.*	mean net Ah (cm)			
		coastal man. 1		coastal man. 2	
		2050	2090	2050	2090
1 – 3	89	17.0	36.5	17.0	36.5
4	89	14.5	32.5	14.5	32.5
5 – 7	89	14.5	32.0	14.5	32.0
8 – 9	88	12.5	24.0	– 4.0	– 21.0
10 – 12	88	9.5	19.5	– 1.5	– 1.5
13 – 16	88	10.5	22.0	– 4.0	– 6.5
17	87	10.0	20.0	– 3.0	– 5.5
18 – 19	87	8.0	15.5	– 1.5	1.5
20	86	5.5	13.5	– 1.5	– 1.0
21 – 22	83	8.5	20.5	8.5	20.5
23	83	3.0	8.0	3.0	8.0

The model-output consists of the probabilities of occurrence for 100 species in the years 2050 and 2090. Changes in species composition of the plots have been evaluated by Canonical Correspondence Analysis (Braak 1986), by using the computer program CANOCO (Braak 1988). Figures **3** and 4 show the species and samples biplots produced by CANOCO from the 5 data sets of 9 representative plots.

Results

The main variation in vegetation, reflected by axis 1 and 2 of the ordination (Fig. **3)**, is related to the variation in moisture as expressed by the parameters ‘duration of the inundation’ (‘INUN’) and the ‘dry period’ (‘DRY’). A second gradient represented is based on distance to the foredunes (‘DIST’). **As** the arrows in the figure show, these gradients run slightly obliquely.

Names of 32 characteristic species are added. To the left are species characteristic of young, wet slacks near the foredunes, partly indicators of brackish conditions. The middle, lower part of the figure contains species of open, calcareous slacks, while the upper part consists of species of older slacks with a thick moss and humus layer. To the right are species of relatively dry slacks with a mown vegetation.

Figure 4 shows the position of 9 of the plots in the starting situation 1989 and with the simulated vegetation composition in the years 2050 and 2090, under the 2 management options. By connecting the positions of one plot, one can obtain an idea of the direction of change. Two main types of changes can

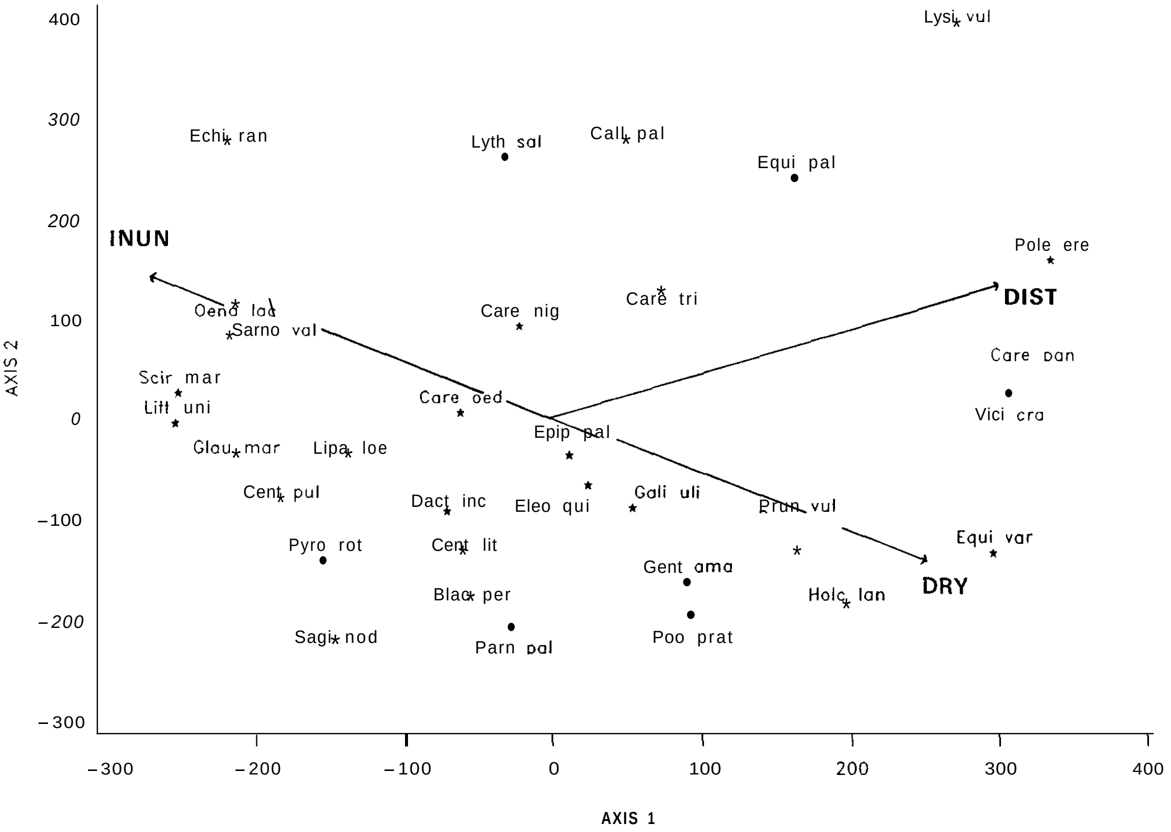

Fig. 3. The position of the species centroids and the main environmental variables, represented by arrows, from the CCA. The projection of a specific point onto the arrow of an environmental variable indicates the position of the species curve along the environmental variable. See Appendix for abbreviations of species names.

be observed. The first type is represented by plot 3: because of the relatively small coastline retreat (17 and 28 m respectively for 2050 and 2090), the two management options give the same result. In both cases, the rise in phreatic level caused by the rise in sea level dominates over the fall of the phreatic level caused by the coastline retreat. This leads to much wetter conditions and a corresponding change in species composition. Plot 22 represents a special case of the same type. For this plot only the species composition for 2050 could be calculated. In 2090, the water table never falls below the surface, turning the plot into a permanent dune lake. This situation lies beyond the scope of the vegetation model.

Plot 23 shows the same type of change: wetter conditions regardless of the management option. However, changes in phreatic level and species composition are very small, since the plot is situated inland of the centre of the dune body.

The second type of change occurs on plot 9. Management option 1 leads to much wetter conditions (sea level rise dominates over coastline retreat), but with management option 2 the situation becomes reversed. Plots 13, 17, 12, 10 and 18 show the same type of reaction, but the change to drier conditions as a result of management option 2 becomes less and less pronounced, because of the increasingly inland position of the plots.

It is difficult to evaluate the predicted changes in terms of nature conservation values. **As** an indication we may say that the rare dune slack species with a narrow ecological amplitude are found from the lower middle of the diagram towards the middle left, with mostly species of the brackish young and open calcareous slacks, such as Samolus valerandi, Littorella uniflora, Blackstonia perfoliata and Par-

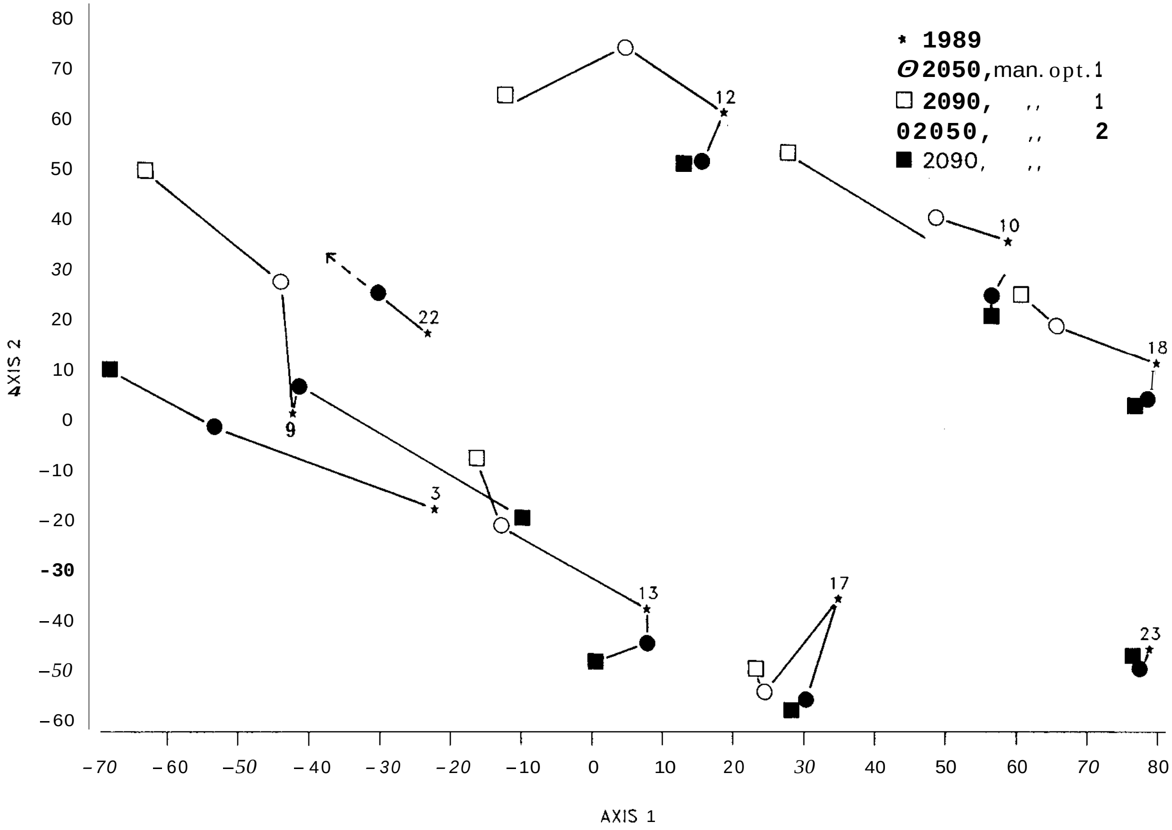

Fig. 4. Sample scores (weighted average species scores) from **CCA** for **9** plots. See main text for explanation.

nassia palustris. Some plots (notably nr. **9)** move in that direction under coastline management option 1.

Conclusions

The results of the present study are speculative by their nature. Many of the processes regarding climate changes and their effects are still incompletely understood. It is, however, important to try to predict the possible effects to the best of our present knowledge in order to be prepared for future developments.

The present study indicates that a sea level rise does not necessarily lead to a fall of the phreatic level in the dune area. The optimal coastline management depends on the width of the dune body, distance of the plot to the fore dune ridge and the initial vegetation and hydrology. A rise of the phreatic level can often be expected.

The results of the Canonical Correspondence Analysis indicate, that the corresponding changes in species composition can be quite large. Narrowing of the dune body can lead to the return of brackish species, under the influence of salt spray. However, the vegetation of an old slack with a well developed humus and moss layer will not be replaced by a vegetation, characteristic of a young, open dune slack by a mere rise of the preatic level.

Supplementary management activities, such as removal of the top soil, will be needed to reach such a result. A well-considered management, which takes both coastal defence and nature conservation into account, can result in a gain of nature conservation.

Acknowledgements

I wish to thank Theo Bakker, Martin Sykes, Eddy van der Maarel, Frank van der Meulen and an anonymous reviewer for their valuable comments on a previous version of the manuscript.

References

Bakker, T.W.M. 1981. Nederlandse kustduinen; Geohydrologie. Doctoral thesis. Pudoc, Wageningen, the Netherlands, pp. 189.

Braak, C.J.F. ter. 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology 67: 1167–1179.

Braak, C.J.F. ter. 1988. CANOCO – an extension of DECORANA to analyze species-environment relationships. Vegetatio 75: 159–160.

Doody, J.P. 1989. Climate change and sea level rise – impacts on coastal sand dunes and dune vegetation in Great Britain. *In:* Landscape ecological impact of climatic change on coastal dunes in Europe. 19 pp. Edited by Van der Meulen et al. Working report for LICC conference. Lunteren, the Netherlands, pp. 171.

Huis, J. van. 1989. European dunes, climate and climate change, with case studies of the Coto Doñana (Spain) and the Slowiński (Poland) national Parks. *In:* Perspectives in coastal dune management. pp. 313–326. Edited by Van der Meulen et al. SPB Acad. Publ., The Hague.

Laan, D. van der. 1979. Spatial and temporal variation in the vegetation of dune slacks in relation to the ground water regime. Vegetatio 39: 43–51.

Meulen, F. van der. 1990. European dunes: consequences of climate change and sea level rise. *In:* Dunes of the European coasts. pp. 209–223. Edited by T.W. Bakker et al. Catena supplement 18. Catena Verlag, Cremlingen-Destedt, Germany.

Meulen, F. van der, and Maarel, E. van der. 1989. Coastal defence alternatives and nature development perspectives. *In*: Perspectives in coastal dune management. pp. 183–195. Edited by Van der Meulen et al. SPB Acad. Publ., The Hague.

Ministry of Roads and Public Works 1989. Ministerie van Verkeer en Waterstaat. Discussienota kustverdediging na 1990. The Hague, the Netherlands. 20 Technical Reports.

Noest, V. in prep. A hydrology-vegetation interaction model to predict dune slack species performance.

Palutikof, J.P., Wigley, T.M.L. and Lough, J.M. 1984. Seasonal climate scenarios for Europe and North America in a high-CO,, warmer world. U.S. Dept. Energy. Report DOE/EV/10098-5. pp. 70.

Strack, O.D.L. 1971. Stroming zout grondwater: Stationaire problemen. Stichting Postacademiale Vorming Gezondheidstechniek, Delft.

Vestergaard, P. 1989. Morphology and vegetation of a dune system in SE Denmark in relation to climate and sea level rise. *In:* Landscape ecological impact of climatic change on coastal dunes in Europe. 12 pp. Edited by Van der Meulen et al. Working report for LICC conference. Lunteren, the Netherlands. pp. 171.

Appendix: list of species abbreviations and names

Species of youg, wet slacks near the fore dunes (partly brackish):

Cent pul	*Centaurium pulchellum*
Echi ran	*Echinodorus ranunculoides*
Glau mar	*Glaux maritima*
Litt uni	*Littorella uniflora*
Oena lac	*Oenanthe lachenalii*
Samo val	*Samolus valerandi*
Scir mar	*Scirpus maritimus*

Species of open, calcareous slacks:

Blac per	*Blackstonia perfoliata*
Care oed	*Carex oederi*
Cent lit	*Centaurium littorale*
Dact inc	*Dactylorhiza incarnata*
Eleo qui	*Eleocharis quinqueflora*
Epip pal	*Epipactis palustris*
Gali uli	*Galium uliginosum*
Gent ama	*Gentianella amarella*
Lipa loe	*Liparis loeselii*
Parn pal	*Parnassia palustris*
Pyro rot	*Pyrola rotundifolia*
Sagi nod	*Sagina nodosa*

Species of older slacks with a well-developed moss and humus layer:

Calt pal	*Caltha palustris*
Care nig	*Carex nigra*
Care tri	*Carex trinervis*
Equi pal	*Equisetum palustre*
Lysi vul	*Lysimachia vulgaris*
Lyth sal	*Lythrum salicaria*

Species of relatively dry slacks, with a mown vegetation:

Care pan	*Carex panicea*
Equi var	*Equisetum variegatum*
Holc lan	*Holcus lanatus*
Poa prat	*Poa pratensis*
Pote ere	*Potentilla erecta*
Prun vul	*Prunella vulgaris*
Vici cra	*Vicia cracca*