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Possible impact of sea-level rise on some habitat types at the Baltic coast of Denmark

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Abstract. According to estimates from the Danish Meteorological Institute global warming until 2080 may cause a relative sea-level rise in Danish waters of 33 - 46 cm. In the present paper the possible impact of a sea-level rise of this magnitude on coastal habitat types is discussed for three case studies, based on previous investigations of vegetation, topography and soil of localities at the Baltic coast of Denmark.

The case studies include the following types of localities and habitats: (1) an off-shore barrier complex: sandy beach, sand dune, geolittoral, brackish, low-tidal meadow, reed bed; (2) a protected bay: geolittoral, brackish meadow, coastal grassland; (3) a dune area: mobile and fixed dune communities, and adjoining sea wall: coastal grassland.

In the geolittoral meadow and coastal grassland habitats the sea-level rise is expected to cause a horizontal displacement of vegetation zones and a reduction in area, depending on accretion rate (sedimentation, peat formation), local topography and inland land-use. In the beach and sand dune habitats the sea-level rise is expected to cause a change in groundwater level, influencing slack vegetation, and a change in the erosion/accretion pattern, resulting in landward rebuilding of the mobile dune as well as in a more or less diffuse inland sand drift, causing destabilization of fixed dune vegetation.

Keywords: Accretion; Barrier; Beach; Coastal meadow; Sand dune; Vegetation; Zonation.

Introduction

Sea-level rise due to global warming has been a matter of discussion and predictions during the last decade. In the reports of the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 1990, 1996), Warrick et al. predicted a global rise in sea-level until year 2080 of ca. + 50 cm and + 38 cm, respectively, mainly due to thermal expansion of sea-water and to melting of ice.

The genesis and species composition of coastal ecosystems are closely dependent on sea-level fluctuations, wave action and salinity. As a consequence, coastal habitats are expected to be strongly sensitive to a rise in sea-level. This matter has been the topic of national and international reviews and discussions during recent years, e.g. Stortenbeker & de Groot (1989), Boorman et al. (1989), Beukema et al. (1990), Boer & de Groot (1990), van der Meulen et al. (1991), Fenger & Torp (1992), Parkinson (1994).

In the present paper aspects of sea-level rise impact on coastal habitats along the western Baltic coast are discussed on the basis of previous investigations of vegetation, soil and morphology (Gravesen & Vestergaard 1969; Vestergaard 1991, 1994, in press). In accordance with the difference in genesis, geomorphology, species composition and ecology between coastal meadows (tidal marshes and low-tidal meadows) and sand dunes in relation to sea-level, these habitat types will differ in their responses to sea-level rise.

Processes in the response of coastal meadows to sea-level rise

Coastal meadows are developed on the geolittoral (i.e. the vertical interval between the mean water level and the highest level of inundation, disregarding extreme storm floods). The composition of the vegetation is determined by the distribution of the species in relation to the elevation according to their specific adaptations to factors regulated by frequency and duration of inundation at highwater, e.g. soil salinity, soil aeration, physical submergence (Tyler 1971; Ranwell 1972; Long & Mason 1983; Adam 1990; Huiskes 1990; Dijkema et al. 1990). Accordingly, a change in sea-level will theoretically cause a change in vegetation composition. By rise in sea-level the point of a given frequency and duration of inundation will gradually be displaced in the inland direction. This may suppress and gradually eliminate species from the lower part of their present, local range, but create the possibility to reestablish the species at higher levels, resulting in an inland displacement of vegetation zones and loss of meadow vegetation along the seaward edge of the meadow (see e.g. Dijkema et al. 1990).

This simple model of parallel displacement may be modified by changes in elevation caused by vertical accretion, i.e. sedimentation and peat formation, related to inundation (e.g. Huiskes 1990; Dijkema et al. 1990; Parkinson 1994). Accretion by sedimentation of material suspended in inundating sea-water at high tide has been studied in tidal areas by e.g. Richards (1934) and Randersson (1979) and summarized by Ranwell (1972) and Adam (1990). According to Adam the sedimentation rate (mm/yr) may be expected to be inversely proportional to elevation, and hence proportional to frequency/duration of inundation. Richards (1934) and Randersson (1979) found sedimentation rate also to be influenced by the character of the plant cover. So, a dense carpet of plants has an important role in trapping suspended material. Even more important, according to Randersson, is the role of root biomass in stabilizing sedimented material. Due to the role of plants the highest sedimentation rates are not nessesarily found at the lowest level of the marsh, but at the lowest level of continuous vegetation (Adam 1990). In a sparse *Puccinellia maritima* vegetation at the lowest part of a tidal marsh, Richards (1934) found sedimentation rates of 4 - 8 mm/yr, whereas at the transition to closed vegetation at a somewhat higher level – where the *Armerietum* community is found – rates of 7 - 15 mm/yr were measured. See also Dijkema et al. (1990).

No data seem to be available on accretion processes in low-tidal meadows like those found along the Baltic coast. According to the similarity in the pattern of inundation at high tide with that found in tidal areas (see case study A), somewhat similar accretion processes are supposed to occur in low-tidal areas as well. So, in a study of coastal meadows along the Danish coasts of the Baltic, Vestergaard (in press) found a decreasing sediment:peat ratio with increasing elevation within the geolittoral.

In summary, in tidal as well as in low-tidal meadows the effect of a rise in sea-level is supposed to be determined by the combined effect of (1) increase in frequency and duration of inundation at a given point in the marsh, causing landward parallel displacement of vegetation zones, and (2) increase in vertical accretion, causing a delay in, or even a neutralization of the displacement of, the vegetation zones. Loss of meadow area will depend on the relation between rate of sea-level rise and rate of accretion. If accretion keeps pace with sea-level rise no loss of area will occur; if accretion is lower than sea-level rise, loss will occur from the seaward edge of the meadow. The topic was thoroughly discussed for the Dutch Wadden Sea by Dijkema et al. (1990) and for the East coast of the USA by Kearney et al. (1994). As pointed out by Kearney et al. accretion processes in coastal meadows are complex and not yet fully understood. Kearney et al. found a significant spatial and temporal variation in vertical accretion rates as a result of variation in micro-topography and vegetation, and stress that the variation complicates the assessment of the ability of the meadows to keep pace with sea-level rise.

A third important consequence of sea-level rise may be increased wave erosion along the seaward edge of the meadow, which tend to narrow the lower meadow zone (Burd 1989; Downs et al. 1994). According to Dijkema et al. (1990) the wave erosion will depend on the character of the accretion processes in the zone in front of the meadow.

Processes in the response of coastal sand dunes to sea-level rise

Sand dunes are developed beyond the direct influence of sea-water, and the dune vegetation is therefore more indirectly related to sea-level changes than is the coastal meadow vegetation. The sand dunes may be influenced by a rising sea-level by changes in erosion/accretion patterns, and by changes in groundwater level, as reviewed by Carter (1991) and Noest (1991).

A rise in sea-level will influence coastal erosion/accretion processes by raising the plane of activity from which the waves operate. Carter (1991) discusses alternative models of cross-shore response. In vegetated dunes, the most probable response seems to involve a two-way redistribution of the sand, composed partly by a seaward movement and deposition of eroded material below the new sea-level, partly by a landward sand drift resulting in new foredune growth behind the eroded dune as well as in sand deposition on older dune land further inland. This pattern may, however, be strongly modified by redistribution of eroded material along the shore, which may cause accumulation in some areas, with a rapid foredune propagation, and sediment starvation in other areas (Carter 1991).

Sand drift strongly influences the dune habitat. The most dramatic response is the rebuilding of the foredune, in which cooperation of dune-forming grasses, i.e. *Ammophila arenaria*, *Ammocalagrostis* x *baltica*, *Leymus arenarius*, *Elytrigia junceiformis*, is crucial. Especially *A. arenaria* will probably be favoured by the increase in sand movement (van der Putten 1989; van der Putten & Peters 1995). Ecologically, however, the character of the foredune habitat will hardly change, as this habitat generally is strongly dynamic and the species are adapted to redistribution of sand.

A stronger ecological impact may be the result of sand deposition in the fixed dune habitat behind the foredunes. Most plant species, composing this vegetation, are little tolerant of cover by sand. Depending on the amount of sand deposited, the habitat may destabilize, causing sand drift to continue.

Groundwater level is a major plant distributing factor in coastal dunes (Ranwell 1972). At a given sea-

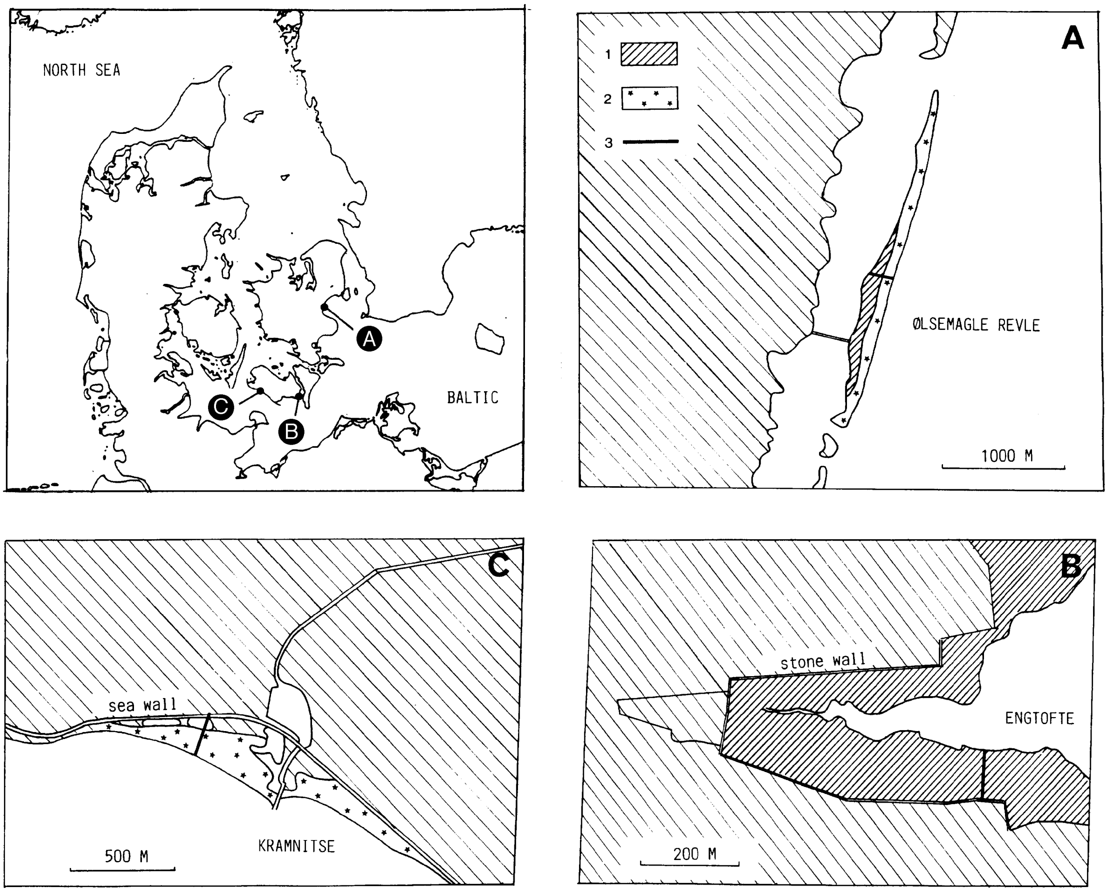

Fig. 1. Location of the case studies A - C (upper left) and details of the areas Ølsemagle Revle (**A**), Engtofte (**B**) and Kramnitse (**C**). 1 = Brackish meadow; 2 = Beach and sand dune; 3 = Transects studied.

level, the groundwater level in a dune is determined by the width of the dune body and by the net precipitation (i.e. precipitation minus evapotranspiration) (Noest 1991; Bakker 1990; van der Meulen 1990; Carter 1991). According to van der Meulen (1990) a rise in sea-level is initially supposed to cause a decline in groundwater level due to narrowing of the dune body by erosion. In a situation of continuing sea-level rise, however, the decline is going to be stopped, and the groundwater level will begin to increase (Noest 1991; Carter 1991). A possible increase in net precipitation due to climate change may further increase the groundwater level.

This sequence of groundwater level movements may have a strong influence on dune slack vegetation. The initial fall as well as the later rise in groundwater level will cause changes in competitive relations between the slack species and subsequently change in species composition, depending on the ecological amplitudes of the species (Ranwell 1959). The sequence of soil moisture changes in dune slacks may, however, be modified by sand movement, changing the shape of the dune system and hence the influence of groundwater.

Case studies

In this section the possible response of some coastal habitat types at the Danish coast of the Baltic Sea is discussed by means of three case studies (Fig. 1). In each case study site vegetation, soil and topography were studied along a representative transect.

The salinity of the coastal water in the area is low; the highest monthly average of salinity at the water surface is ca. 9 - 15 ‰ (Dietrich 1950), and the tidal influence is negligible (range < 25 cm) and moreover masked by non-tidal water level fluctuations, caused by meteorological conditions.

During the latest 100 yr southeastern Denmark has been subjected to a relative sea-level rise of a – regionally somewhat varying – magnitude. Based on monthly water level data since 1889 from a number of Danish tide gauge stations, Thomsen & Hansen (1970) developed an equation which expresses the relative sea-level rise of each station between 1890 and 1968 by linear graphs. Based on a linear extrapolation of such graphs relative sea-level rises between 1890 and 1990 of ca. 2.5 cm and 10 cm (0.3

and 1.0 mm/yr) have been estimated for the stations Copenhagen (referring to case study A) and Gedser (referring to case studies B and C), respectively (Fig. 2).

According to Duun-Christensen (1992) the relative sea-level rise in Danish waters has especially accellerated during the latest decades. Based on extrapolation of this tendency Duun-Christensen has predicted a rise in relative sea-level in Danish waters between 1990 and 2080 of +33-46 cm (3.7-5.1 mm/yr). The deviation from the predicted global figure (Warrick & Oerlemans 1990; Warrick et al. 1996) as well as the regional variation are due to spatial variation in isostatic land movements.

Case Study A. Ølsemagle Revle - an off-shore barrier island

Ølsemagle Revle is a sandy off-shore barrier island, situated at the bay of Køge Bugt, Sealand, delimiting a shallow lagoon, surrounded by brackish meadows and reed beds. The locality was investigated in 1968 (Gravesen & Vestergaard 1969) and the meadow in 1979-1990 (Vestergaard 1994, in press). The barrier is relatively young. It arose from submarine sandy bars in the beginning of the 20th century and has gradually developed into the present stage, which, in cross-section, includes the elements shown in Fig. 3. The vertical extension of the geolittoral is ca. 70 cm. By combining levelling data and tide gauge data from the nearby harbour of Køge Havn, the frequency and duration of inundation at high tide in 1985 was found to be exponentially declining with elevation (Fig. 4). This pattern is very similar to that found in tidal areas (e.g. Ranwell 1972; Huiskes 1990).

The soil is composed of an upper organic horizon, thickness 6 - 13 cm, on marine sand (Fig. 3). The organic horizon is peat in the upper and middle geolittoral meadow and peat mixed with sediment in the lower geolittoral reed bed. The organic soil horizon has developed during a period of ca. 75 yr, giving an accretion rate of 0.8 - 1.7 mm/yr, highest in the lower geolittoral.

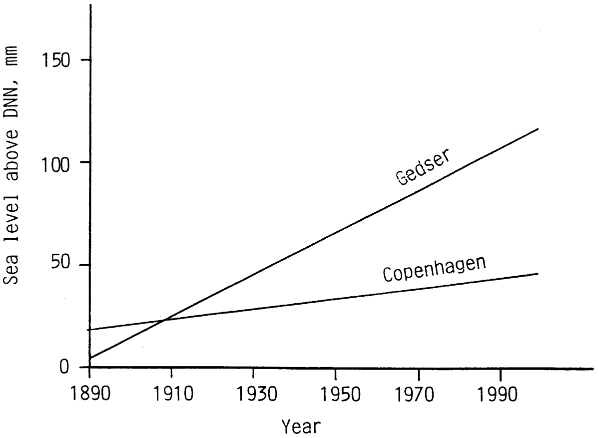

Fig. 2. Relative sea-level rise from year 1890 to year 1990 at two stations. Equations:
Gedser: $H_A = 47.1 + 1.012$ (yr A – year 1930);
Copenhagen: $H_A = 29.3 + 0.247$ (yr A – year 1930),
where H_A denotes height of sea-level above DNN (Danish Ordnance Datum) in year A. After Thomsen & Hansen (1970).

Possible impact of sea-level rise

The relative sea-level rise expected until year 2080 amounts to ca. 40 cm (4.4 mm/yr). In the beach and dune this is expected, following the model B of Carter (1991), to cause erosion, followed by rebuilding of the dune in an landward direction and by deposition of sand in the upper part of the geolittoral meadow. The amount of sand available for these processes may increase due to accretion of sand by long-shore transportation along the coast, which has been an important process in the formation of the barrier up to now. The prediction of landward displacement of the dune row and hence of the barrier in total at rising sea-level agrees with e.g. Nielsen & Nielsen (1978).

In the meadow, the isolated effect of the sea-level rise is expected to be a duneward displacement of the plant communities. When calculated on a purely geometrical basis in relation to the present topography, the present ca. 120 m of geolittoral meadow and reed bed will be narrowed into a ca. 30 m belt within the present upper geolittoral + lower part of fixed dune, and hence the meadow area will be reduced by ca. 70 % (Fig. 5A). This response may be modified by accretion and sand drift. The rate of peat formation and sedimentation will probably increase due to increased inundation and may reduce the duneward displacement of the meadow communities and hence diminish the reduction of the meadow area. Because of the sheltered position of the meadow increased erosion by wave action is not expected to be a significant consequence of the sea-level rise.

Case Study B. Engtofte - a brackish meadow

Engtofte is a brackish meadow situated along a small shallow bay at Guldborgsund, the island of Lolland. The meadow is at least 150 yr old; in a map from 1837 the shape of the meadow was not very different from now - and the meadow has probably been continuously grazed by cattle for a long time. Landwards the brackish meadow is separated from arable land by a low stone fence. The meadow, which was described in

1982-1986 as part of a study of coastal meadows in southeastern Denmark (Vestergaard in press), includes the elements shown in Fig. 6. The vertical extension of the geolittoral amounts to ca. 60 - 70 cm.

The soil is composed of an upper organic horizon, thickness 30 - > 40 cm, on clay (Fig. 6). The organic horizon is peat in the *Festuca rubra* meadow, and peat mixed with sediment in the *Puccinellia maritima* meadow. The rate of build-up of the organic horizon up to now has amounted to maximum 2.3 mm/yr in the middle geolittoral, somewhat less in the upper geolittoral and somewhat higher in the lower geolittoral, calculated from a minimum age of the locality of 150 yr.

Possible impact of sea-level rise

The relative sea-level rise expected until year 2080 amounts to ca. 45 cm (5.0 mm/yr). The isolated effect of the sea-level rise will be a landward displacement of the plant communities, which, according to the local topography, will result in a reduction of the area of the geolittoral part of the meadow by ca. 45 % (Fig. 5B). If the present stone fence is replaced by a regular sea wall to prevent inundation of the arable land, the area of the coastal grassland will be strongly reduced as well, as is also indicated in Fig. 5B.

This response to sea-level rise may be modified by erosion and accretion. The lower part of the present

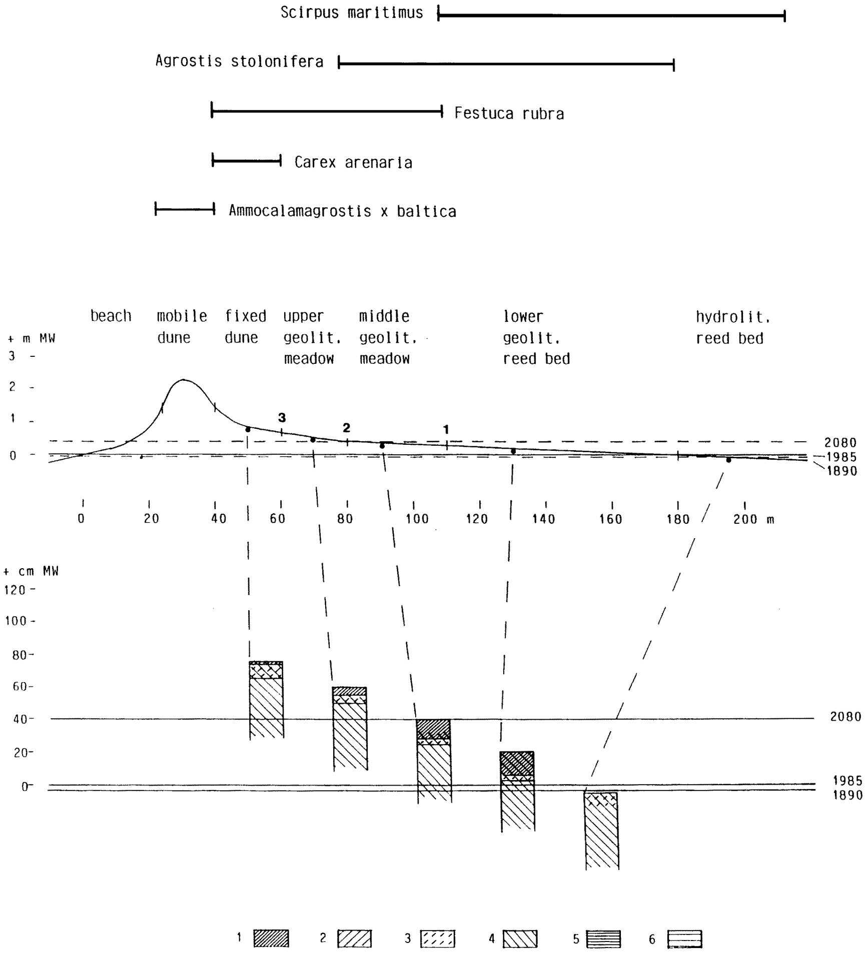

Fig. 3. Case study A: Ølsemagle Revle. Transect showing vegetational zonation and soil profiles, in relation to sea-level, years 1890, 1985 and 2080. MW: Mean sea-water level. Soil legend: 1 = high content of organic matter, 2 = medium content of organic matter, 3 = low content of organic matter, 4 = sand, 5 = high content of clay, 6 = low content of clay. The boundaries between the elevation zones are numbered 1 - 3.

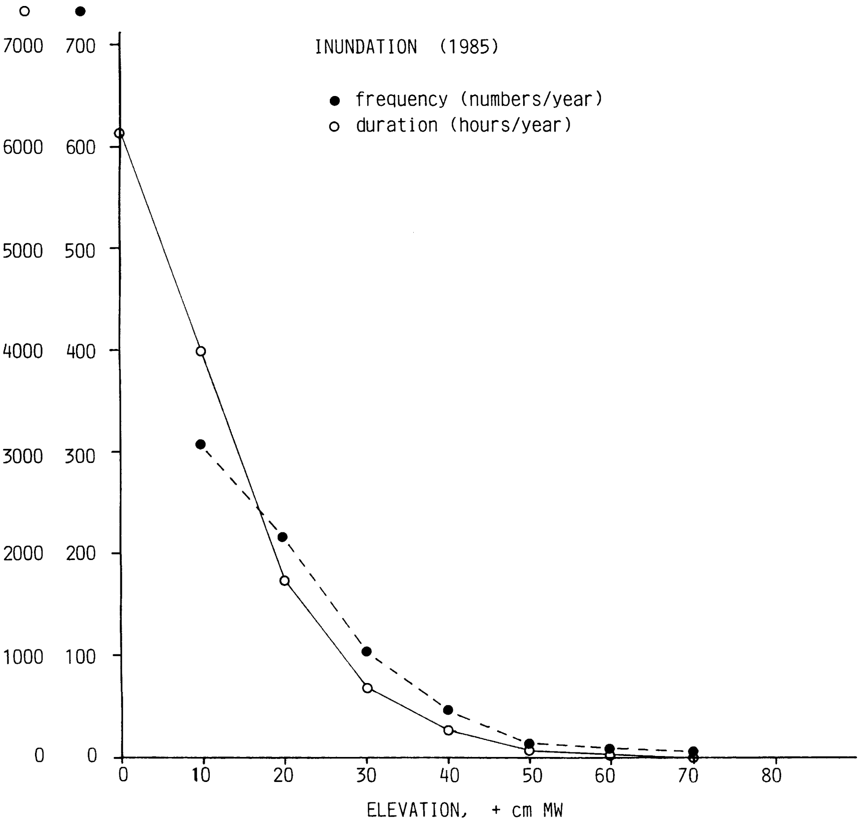

Fig. 4. Relationship between inundation and elevation above mean sea-water level (MW) at Ølsemagle Revle (year 1985).
log frequence = – 0.033 × elevation + 2.921, $r = 0.995^{***}$;
log duration = – 0.044 × elevation + 4.026, $r = 0.989^{***}$;
$^{***} = p < 0.001$.

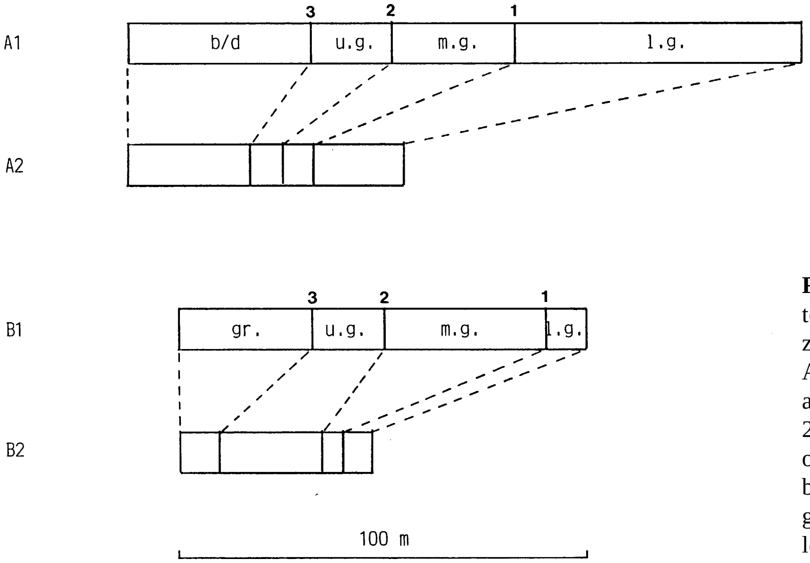

Fig. 5. Reduction in coastal meadow area due to sea-level rise. A1 and B1 denote the present zonation of case study A and B, respectively. A2 and B2 denote the zonation of case study A and B after a predicted sea-level rise until year 2080 of 40 and 45 cm, respectively, calculated on the basis of the present topography. b/d = beach and dune; gr. = grassland; u.g. = upper geolittoral; m.g. = middle geolittoral; l.g. = lower geolittoral. The boundaries between the elevation zones are numbered, corresponding to Figs. 3 and 6.

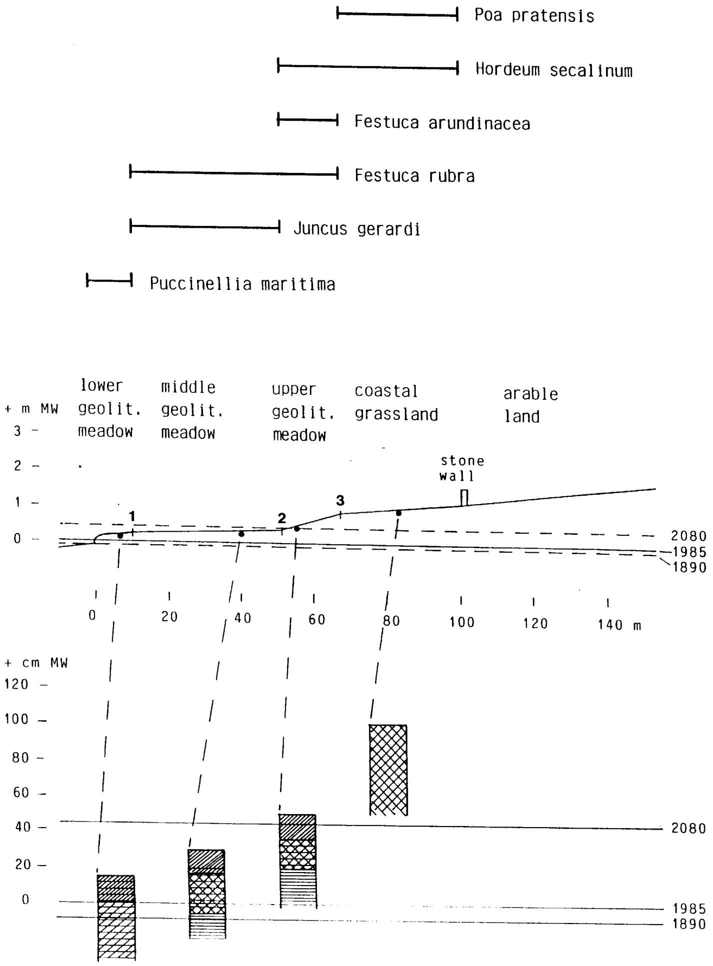

Fig. 6. Case study B: Engtofte. Transect showing vegetational zonation and soil profiles in relation to sea-level, years 1890, 1985 and 2080. MW: Mean sea-water level. Soil legend: see Fig. 3. The boundaries between elevation zones are numbered 1 - 3.

meadow will probably be eroded by increased wave action. Part of the erosion material will, however, be sedimentated at higher levels. In combination with increased peat formation this will increase the elevation and thereby probably reduce the landward displacement of the plant communities and diminish the reduction of the meadow area.

Case Study C. Kramnitse - sand dune and sea wall

The Kramnitse area is situated at the south coast of the island of Lolland and includes a sand dune system seawards of a brackish lake (former lagoon) and a sea wall, protecting reclaimed land (Fig. 7). The sand dune system was described by Vestergaard (1991). It is composed of six dune rows separated by dry slacks. The dune system is supposed to contain a fresh groundwater body with a convex surface (cf. Bakker 1990; Noest 1991). In the slacks there is no botanical indication of even temporal groundwater influence. So, regarding the actual elevation of the bottom of the slacks in relation to mean sea-level (ca. 70 - 80 cm), the maximum height of the groundwater level above sea-level seems to be no more than ca. 10 - 20 cm (cf. Ranwell 1972).

From the content of organic matter in the soil as well as from old maps, the age of the inner parts of the dune system (ridge 3 - 6) can be estimated to be more than 150 yr – ridge 6 up to 450 yr old. The seaward ridges, 1 and 2, are less than 150 yr old and were probably formed after the construction of a nearby harbour pier in the 1870s, which caused a seaward accretion of sand at the locality, which is still proceeding (Anon. 1991).

Dune ridge 1 is a mobile marram dune with *Ammophila arenaria* and *Ammocalamagrostis* x *baltica* . The other ridges are fixed dune, representing different stages of dune succession, with increasing influence of shrubs, mainly *Rosa rugosa,* on the oldest ridges. In front of the mobile dune a belt of embryonic dune with *Elytrigia junceiformis* has developed.

The 3.5 m high sea wall was constructed in the 1870s after a storm surge catastrophe in 1872 (Vestergaard 1983). The sea wall protects reclaimed, now arable land

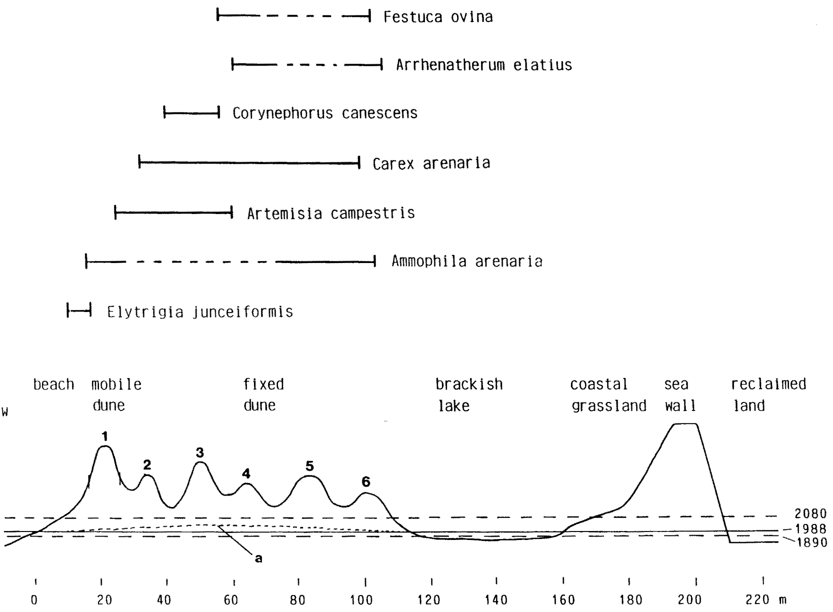

Fig. 7. Case study C: Kramnitse. Transect showing dune ridges 1 - 6 and dominating plant species, in relation to sea-level years 1890, 1988 and 2080. MW: mean sea-water level. a: estimated maximum groundwater level.

below sea-level. The vegetation of the sea wall is a dry coastal grassland, dominated by *Festuca ovina*, *Holcus lanatus* and *Anthoxanthum odoratum*. The lowermost part along the lake is a moist, slightly brackish meadow.

Possible impact of sea-level rise

The relative sea-level rise expected until year 2080 amounts to ca. 45 cm (5 mm/yr). In the beach and dune this is expected to cause erosion, followed by rebuilding of the mobile dune in a landward direction and a more or less diffuse deposition of sand in at least the outer parts of the fixed dune area. The deposition of sand is supposed to cause destabilization of the vegetation which may maintain, or even increase, the sand drift.

The water level of the lake is supposed to rise with sea-level. This will cause erosion risk along the landward edge of dune ridge 6, even if the wave energy in the protected lake is low. The seaward slope of the sea wall will be influenced as well, partly by change of the lowest part of the grassland vegetation into a more wet, perhaps also more saline, type of meadow, partly by erosion.

The groundwater level of the dune may change according to the sequence outlined by Carter (1991) and Noest (1991), resulting in an increase compared to the present situation. As a result, the dry slacks will gradually change into wet slacks with peat formation, which, by increasing the water-holding capacity of the soil, will tend to preserve the wet slack communities, once formed.

Discussion

In the case study areas, inland displacement and reduction in area of the geolittoral meadows caused by sea-level rise until 2080, were estimated on a purely geometrical basis (Fig. 5), and the values will probably be reduced by accretion. In general, zonal displacement and area reduction of geolittoral meadows will vary from locality to locality, depending on (1) local topography, (2) local accretion regime – which among others may be determined by local land use, e.g. grazing, which strongly influences surface micro-topography; (3) wave erosion regime, which depends on exposure.

Reduction in the area of coastal meadows will have many serious implications in countries such as Denmark, where coastal meadows are widespread and of significant importance for the protection of low-lying inland areas, in agriculture (grazing) and as nature resources (Würtz Jensen 1988; Vestergaard 1995).

As was pointed out earlier (e.g. Boorman 1989), the inland displacement of coastal meadows due to sea-level rise depends on the presence of a low and gently sloping hinterland in which the plant communities can regenerate. In many localities, however, the coastal meadow is (or will probably be in the future) landwards delimited by a sea wall, protecting low-lying arable land or urban areas. In such places natural regeneration of the meadow zones further inland after a sea-level rise is totally or partly prevented, and the meadow will accordingly be reduced in area.

Impact on the sand dune habitat after sea-level rise includes modifications of the ecosystem caused by sand drift and change in groundwater level. As sand dunes by their nature are very dynamic, such modifications are not nessesarily negative at least from a nature conservation point of view. Along many European coasts, however, the sand dunes are important for the protection of agricultural or urbanized hinterland, as well as for providing fresh water resources. At such coasts narrowing of the dune belt may have serious consequences (van der Meulen et al. 1991).

The possible impacts of sea-level rise on coastal habitats suggested in the present paper as well as in other contributions are speculative by their nature. Regarding the importance of these habitats for coastal protection, nature conservation and recreation, and considering the difficulties of obtaining empirical data from realistic experiments, such theoretical predictions seem however to be justified, as has recently been confirmed by the second assessment by the IPCC of global sea-level rise due to climate change (Houghton et al. 1996).

To specify such predictions detailed knowledge of key processes in species and habitat responses to sea-level changes are required. Such processes include adaptation and interspecific competition of species in relation to inundation, soil salinity, soil aeration and sand deposition as well as to sedimentation and soil development. A factor which has also to be considered in species responses to changes in sea-level is population differentiation in terms of polyploid series, which may allow species to adjust to e.g. higher inundation frequency, as pointed out by Huiskes (1990).

In addition to sea-level, climate factors such as temperature and rainfall are also predicted to change. Therefore the suggested response model of parallel inland displacement of the present meadow zones probably will be modified by vegetation processes, related to a change in climate, especially increasing temperature. Such processes may include immigration of new species, exclusion of present species and changes in the balance of the competition between species (Adam 1990).

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