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Climate change and the ecology of the Weser estuary region: assessing the impact of an abrupt change in climate

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ABSTRACT: The objective of the present study is to assess the direct impact of a rapid change in climate on the amphibious and terrestrial ecosystems of the Weser Estuary, northern Germany, for the year 2050, discounting morphological adaptation. The status quo was documented on the basis of land cover classifications called 'biotope types'. Elevation, soil type, vegetation and land use data were digitised and assembled in a GIS database (ArcInfo/ArcView): 80% of the marsh (400 km^2), the forelands (55 km^2) and the tidal marshlands (45 km^2) are used as farmlands, of which 90% are grasslands and pasture. Only 2% of the area is habitat for reeds and associated species. Estimations of future climate changes are made on the basis of a downscaled regional climate scenario. Primary effects of climate change due to sea level rise and altered hydrology of the area are as follows: the forelands and the Weser Estuary will become more 'natural', because reed areas and shallow waters will increase, whereas grasslands will decrease. In the long term this development will have positive effects for birds and fishes. However, in the marshes and plains protected by dikes, hydrological changes will have minor effects on vegetation and species, because future land use and the management of the drainage and irrigation system determines the biocoenoses here.

KEY WORDS: Climate change · Estuary · Geographical information system · Grassland · Marsh · Water level

1. INTRODUCTION

Estuaries and coastal zones may be strongly affected by future climate changes and the rise of mean sea level (Warrick et al. 1993). The objective of the present study is to investigate the ecological effects of climate changes on the Weser estuary region in northern Germany. The study is part of the interdisciplinary project 'Climate change and the Weser estuary region' (see Schirmer & Schuchardt 2001, in this issue). In order to predict quantitative and qualitative ecological changes we employed the 'scenario technique' based on a regionalised climate scenario (von Storch et al. 1998) and used actual and simulated spatial and hydrographic data from our engineering projects: 'groundwater', 'water management' and 'hydrographic modelling' (see Section 4.2). A Geographical Information System (ARCInfo/ArcView GIS) was used as a database to assemble, combine and analyse the different data sets and sources (see Section 4.1). The paper focuses on the primary effects of hydrological climate change for the marshlands and forelands of the study area. To characterise the habitats, we used land cover classifications called 'biotope types' (von Drachenfels 1994, see Section 4.2). The following questions will be addressed: (1) Which habitats are especially sensitive to hydrological changes? (2) What quantitative changes and shifts in vegetation and land use can be expected and what early indicators of ecological consequences can be assessed?

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2. STUDY AREA

The Weser estuary is a coastal plain estuary. It is located in northern Germany and drains into the North Sea, creating a large estuary with a length of 120 km within the north German lowlands and the Wadden Sea. The study focuses on the inner estuary and the marshes between the city of Bremen and the harbour of Bremerhaven (Kraft et al. 1999, Fig. 1). The study area covers ~500 km^2 and includes the Weser Estuary (55 km^2), the marshlands protected by dikes (400 km^2) and the forelands (45 km^2).

The Weser Estuary has been systematically regulated and channellized during past decades to fit the needs of the shipping industry; 60% of the shorelines are reinforced and protected. Tides consequently reach the city of Bremen, 65 km from the coast, with a rise of ~4.2 m above mean sea level. The main habitats of the estuary are the deep shipping channel (35 km^2), shallow waters (5 km^2) and the eulittoral (15 km^2).

Along the Wadden Sea and the estuary, a continuous line of dikes protects the marshlands from tidal and stormsurge flooding.

The coastal and estuarine lowlands and marshes have elevations of no more than 0.5 m below and up to 2.5 m above mean sea level. 80% of the marshes are farmlands, 97% of which are used as pasture and meadows to produce cattle and milk. Half of the grasslands are managed intensively and the other half managed extensively (see Section 4.1). Agriculture has been made possible by the development of a complex drainage and irrigation system. During winter this water management system is used to drain the marshes in order to allow land use in the early spring. During dry summers with low precipitation the system is used to irrigate the ditches and plains.

Only 47% (21 km^2) of the forelands are periodically influenced by the tides, and 51% (23 km^2) of the former tidal marshes are today protected by low summer dikes. The width of the tidal marshes reaches from O(1 m) in urban areas up to 1000 m in rural areas. About 60% of the forelands are meadows and pasture. Only 20% of the tidal marshes are still natural wetlands dominated by typical reed species such as *Phragmites australis*.

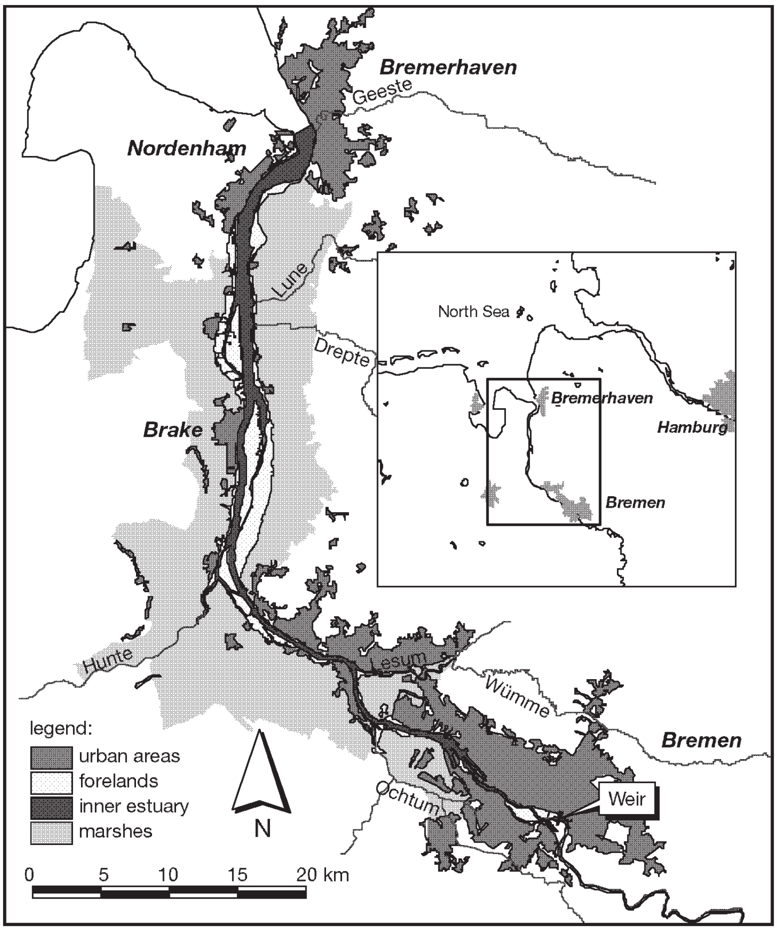

Fig. 1. Location and extent of the study area

3. CLIMATE SCENARIO

In order to assess the sensitivity of the region we formulated a climate scenario which is derived from model predictions and adapted to a time horizon of 5 decades, i.e. for the year 2050. Von Storch et al. (1998) derived a regionalised climate scheme using the climate model 'ECHAM4/OPYC3' with 'business as usual — best estimate' and 2 × CO_2 assumptions for monthly calculations of nearground air temperature and pressure, and Canonical Correlation Analysis for downscaling. The scenario comprises:

(1) A rise in mean sea-level of 55 cm by 2050, derived from IPCC (1996) and representing the 'business as usual — high estimate'. Expecting reduced energy dissipation, we added 30 cm to tidal amplitude.

(2) Influenced by (1), a rise in mean tidal high water by 70 cm in the inner Weser estuary, and in mean tidal low water of 30 cm. These data have already been used to model the hydrography of the estuary (Grabemann et al. 1999).

(3) A mean temperature rise of 2.7°C, especially in spring and winter. Temperature is used for modelling evapotran-

spiration in the groundwater project (Hoffmann & Meinken 1999).

(4) An increase in precipitation of 10%, with the strongest increase in spring (22%) and a reduction by 6% in summer. Precipitation is considered as a model parameter in the water management project (Maniak et al. 1999).

(5) A rise of the mean CO_2 concentration from today's 350 ppm up to 700 ppm.

To gain a more realistic basis for modelling the changing hydrographical parameters we added the predicted changes to the real weather and water level data for 2 reference years: 1991, a cold, dry year with low runoff, and 1994, a warm, humid year with high runoff.

4. METHODS

4.1. Methodological approach

A schematic representation of the methodological approach used for assessing the impact of climate change on the biotope types (see Section 4.2) of the forelands is given in Fig. 2. Using a GIS, the actual land cover classifications by biotope types were merged with data for elevation and local hydrology. Using knowledge of the vegetation characteristics of wetlands and tidal and fluvial marshes and their sensitivity to hydrology, temperature and land use, predictions of changes due to these factors can be made. Based upon this, we developed a simple 'if-then' model of interrelations between abiotic parameters and biotope types to estimate the impact of climate change on the development of vegetation and biotope types for the year 2050. The image processing, digitising and GIS work for the project was performed on an ArcInfo system, housed at the Leichtweiß Institute of Braunschweig, Germany. We used an ArcView GIS (version 3.1) to assemble and analyse the resulting data.

Marshlands. Soil moisture was calculated for the area on the basis of elevation, precipitation rates and simulated groundwater levels and water levels within the drainage system. We used 'derived soil moisture units' arranged on an ordinal scale. The sensitivity of biotope types to changes in temperature, evapotranspiration, soil moisture and increased CO_2 was estimated by analysing the sensitivity of mapped vegetation. The ArcView GIS was then used to detect future sensitive areas and biotope types due to changes of the soil moisture.

Forelands. In a first quantitative approach, the size of areas affected by a rise of 70 cm in mean tidal high water level was calculated. The sensitivity of the different biotope types to flooding was then estimated. Plausible assumptions on shifts and changes of vegetation and biotope types were made according to elevation, groundwater table, soil type, frequency and duration of inundation and land use. Changes and shifts of biotope types were then calculated quantitatively. As the last step, ecological effects of vegetational changes on land use possibilities and selected species were estimated. Estimations of the consequences of climate change are based upon the assumption that tidal marshes do not accrete parallel to the rise of the mean tidal high water. We assume no changes in the morphology of the Weser nor in the elevations of the forelands, in order to test the sensitivity of the area to extreme events. In fact, exact morphodynamics and future elevations cannot be simulated.

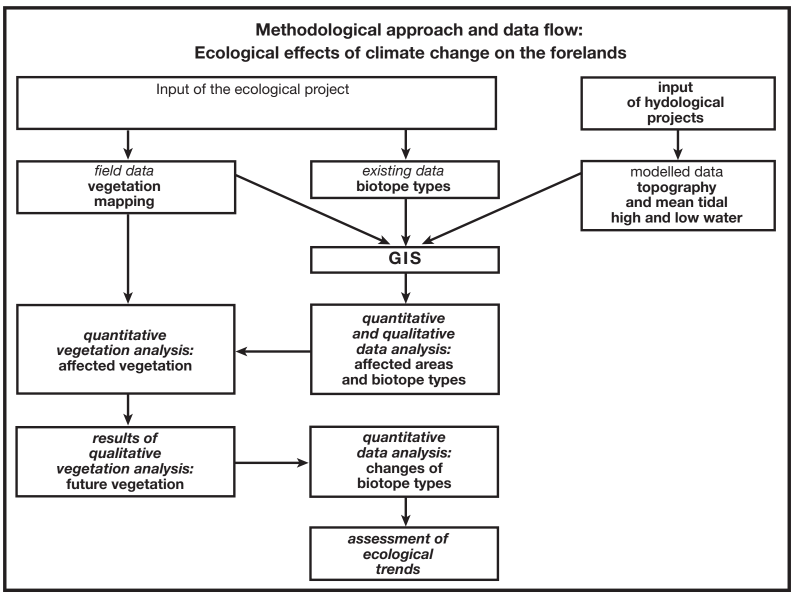

Fig. 2. Schematic representation of the methodological approach used

4.2. Data sources

The assessment of the impact of climate change is based on 3 different data sources:

(1) Regional data sources established by local authorities. The study is mainly based upon available regional data sources such as environmental impact studies. We compiled and digitised ecological information on landcover classifications called 'biotope types' (von Drachenfels 1994) using maps of scales 1:10 000 and 1:2500. Biotope types are land cover classifications used in landscape planning to characterise large

areas by different types of habitats, land use and composition of vegetation. Thus it is possible to map industrial areas, coastal protection constructions and parks, as well as natural habitats of estuaries, such as the eulittoral, and different types of meadows and pasture. For the present study we differentiate the following biotope types: intensively managed meadows and pasture poor in species are defined as 'intensive grasslands'; intensively managed meadows used as fields dominated by 2 or 3 plant species as 'grassfields'; and wet types of meadows and pasture rich in species are defined as 'extensive grasslands'. We later differentiate between eulittoral zones covered with reeds, tidal mud flats without vegetation, and scarcely flooded versus frequently flooded reeds.

(2) Field data. We obtained field data for representative areas. In order to gain more detailed ecological information on the level of species, we mapped vegetation according to the German 'Pflanzensoziologie' (Dierssen 1990, Dierschke 1994, Preising et al. 1997). These data were then used to calibrate biotope types.

(3) Simulated data. Model-derived data from our associated projects, which are based upon available data, our own measurements and the regional climate scenario data (see Section 3), were used to generate spatial information for hydrological properties of the area. Therefore the topography, distribution of precipitation, water levels of irrigation systems, river discharge, mean tidal high and low water levels and groundwater levels were considered. Grabemann et al. (2001) use a 1-dimensional hydrodynamic model to investigate changes in water levels and the water quality of the inner Weser Estuary. The water management system in the marshes has been simulated by the Leichtweiß Institute of the Technical University of Braunschweig (Maniak et al. 1999). The group of the University of Hannover is modelling the reaction of the groundwater system (Hofmann & Meinken 1999). The hydrological data generated were merged with data for the topography and soil types of the area (topography from maps at 1:5000 and, for the morphology of the Weser, from data prepared by the Water & Shipping Authority, Bremerhaven; soil data from the Lower Saxon Institute of Soil Science at 1:50000).

5. PRIMARY EFFECTS OF CLIMATE CHANGE

The objective of the study is to estimate the primary ecological effects of climate change on marshlands and forelands. Primary climate effects are defined as 'direct effects': the vegetation of the forelands is directly affected by a rise in mean tidal high water level and an increase in the frequency and duration of inundation. Flooding is therefore the main factor here, determining the kind of land use, vegetation and fauna. However, the vegetation and fauna of marshlands are determined by the hydrological situation of the area, which in turn is controlled by the capability and effectiveness of water management and irrigation systems in dealing with higher rates of precipitation in the winter and lower rates in the summer (see Section 3).

5.1. Primary effects on the marshlands

An important result is that the drainage and irrigation system will be able to compensate for the higher amount of precipitation during winter (see Section 3). Therefore, the marshlands will not be inundated over long periods. However, secondary economic effects might include higher costs of drainage and additional expense for agriculture.

Ecological effects of climate change on the marshes are determined by 2 factors, namely the kind of land use and the amount of soil moisture due to precipitation, groundwater levels and evapotranspiration rates. Dry summer periods with low precipitation and high temperatures (see Section 3) will lead to lower soil moisture. This has consequences especially for intensively managed grasslands on brackish marshes and for sites with high elevations (>1.5 m above normal chart datum). In Fig. 3 the typical biotope types of a brackish marsh are shown for a focus area, 5 km west of Brake (see Fig. 1 for location).

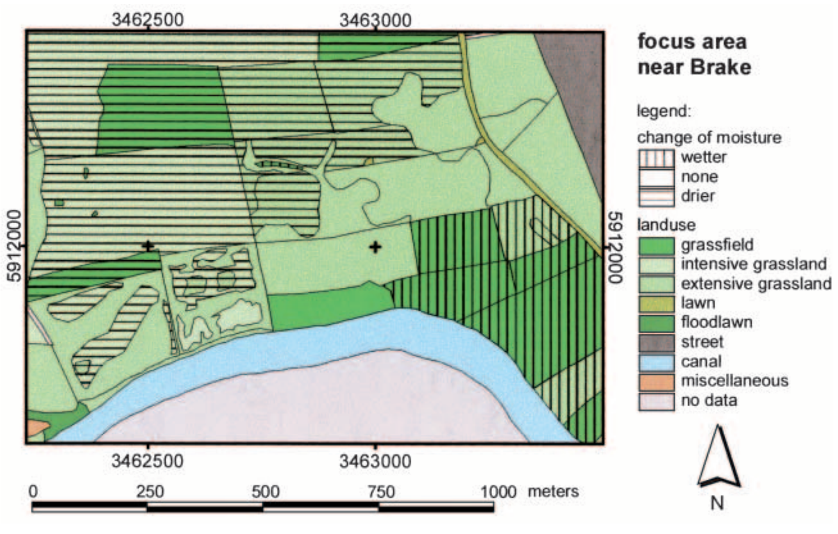

Fig. 3. Superposition of the actual landuse-biotope types of a focus area 5 km west of Brake and the expected changes of soil moisture

The intensively managed meadows and pasture are dominated by grass species such as *Lolium multiflorum*, *Lolium perenne*, *Poa trivialis* and *Phleum pratense*; the abundance of herbs is usually low. The vegetation can be classified as 'Poo-Rumicetum obtusifolii' (Preising et al. 1997). Higher temperatures and less precipitation in the summer will lead to altered evapotranspiration and lower soil moisture, especially within the intensively used, monotonous and poorly structured 'grassfields' (see Section 4.2). As a consequence, these grassland types will suffer from drought. The species *Poa trivialis*, which covers 25% of the grasslands, is particularly sensitive in this respect. Once dried out, arid marsh soils cannot be restored by irrigation because of their specific soil texture and the structure of marshes. Even though higher concentrations of CO_2 and higher temperatures undoubtedly have positive effects for biomass production (Mandscheid et al. 1997), the limiting factor will be the lack of precipitation and availability of water (see Hertstein et al. 1994). Subsequently biomass production will be lower and yields will be reduced: 5% of the study area will probably be affected by future summer dryness. Precautions to prevent loss of yields because of drought should include alterations in the use of fertiliser and higher water levels in the ditches during the summer. Another strategy could be to redevelop traditional extensive grasslands, rich in species (see Section 4.2). These are dominated by grass species such as *Lolium perenne* and *Cynosurus cristatus*, and important herbs such as *Caerastium fontanum*, *Cardamine pratensis* and *Bellis perennis*. These grasslands can be classified as 'Lolium-Cynosuretum' (Preising et al. 1997) and are mainly used today as temporary pasture for young cattle. These well structured meadows and pasture have a relatively low evapotranspiration rate and therefore a high capacity to adapt to different climate situations and changing local factors, such as drought. Poor harvests can also occur on intensively managed grasslands with low elevations (0.5 m below normal chart datum) and organic or bog soils, because higher groundwater levels will lead to increased wetness there. The consequences of this may include restricted options for land use because of increased soil moisture. Future land use (e.g. as extensive grassland and pasture) as well as higher soil moisture will promote the establishment of rush and sedges and the development of further species of type 'Calthion' (Preising et al. 1997). 2% of the area will probably be affected by a rise of the groundwater table and increased soil moisture.

Roughly 7% (28 km^2) of the study area may be directly affected by hydrological changes. Ecological consequences on vegetation and land use will be relatively low overall because primary effects such as drought or increased soil moisture can probably be compensated by land use and the water management system. The relative and the absolute increase of future extensively managed grasslands is predicted to be small in relation to the extent of the study area. Under the condition of conservative land use the ecological situation of the marshes in the year 2050 will not therefore be different from today (Fig. 4).

5.2. Primary effects on the forelands

The unprotected tidal marshes (21 km^2), which are open to periodical flooding, will be directly affected by a rise in mean tidal high water level of 70 cm. About 27% (12 km^2) of these tidal marshes are dominated by extensively managed meadows (biotope type: extensive grasslands). During short periods in the summer, parts of the grasslands are also used as pasture for young cows or sheep. The elevation of these grasslands ranges between 20 and 70 cm above mean tidal high water level. Agriculture is possible here because

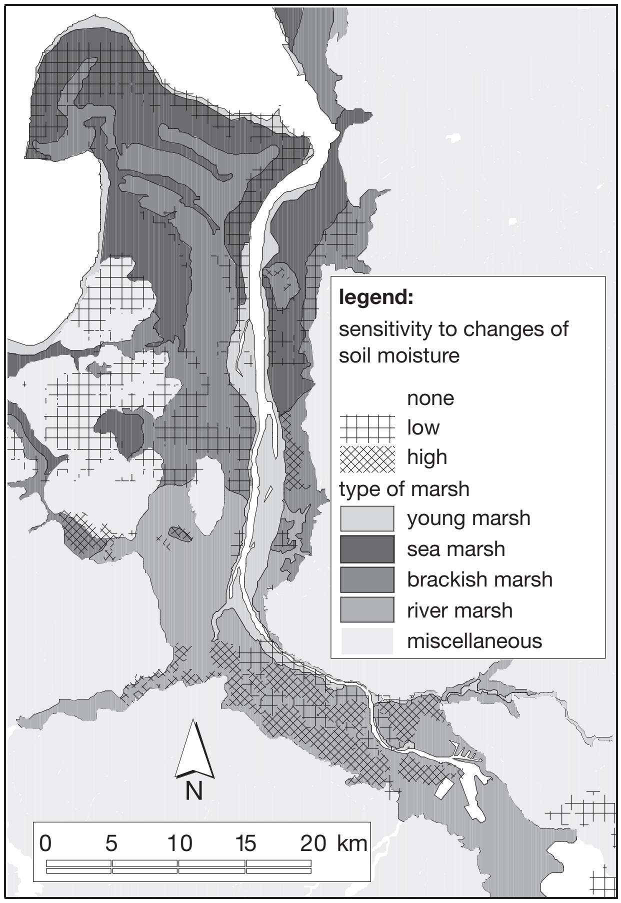

Fig. 4. Extent of marshland areas affected by changes in hydrodynamics

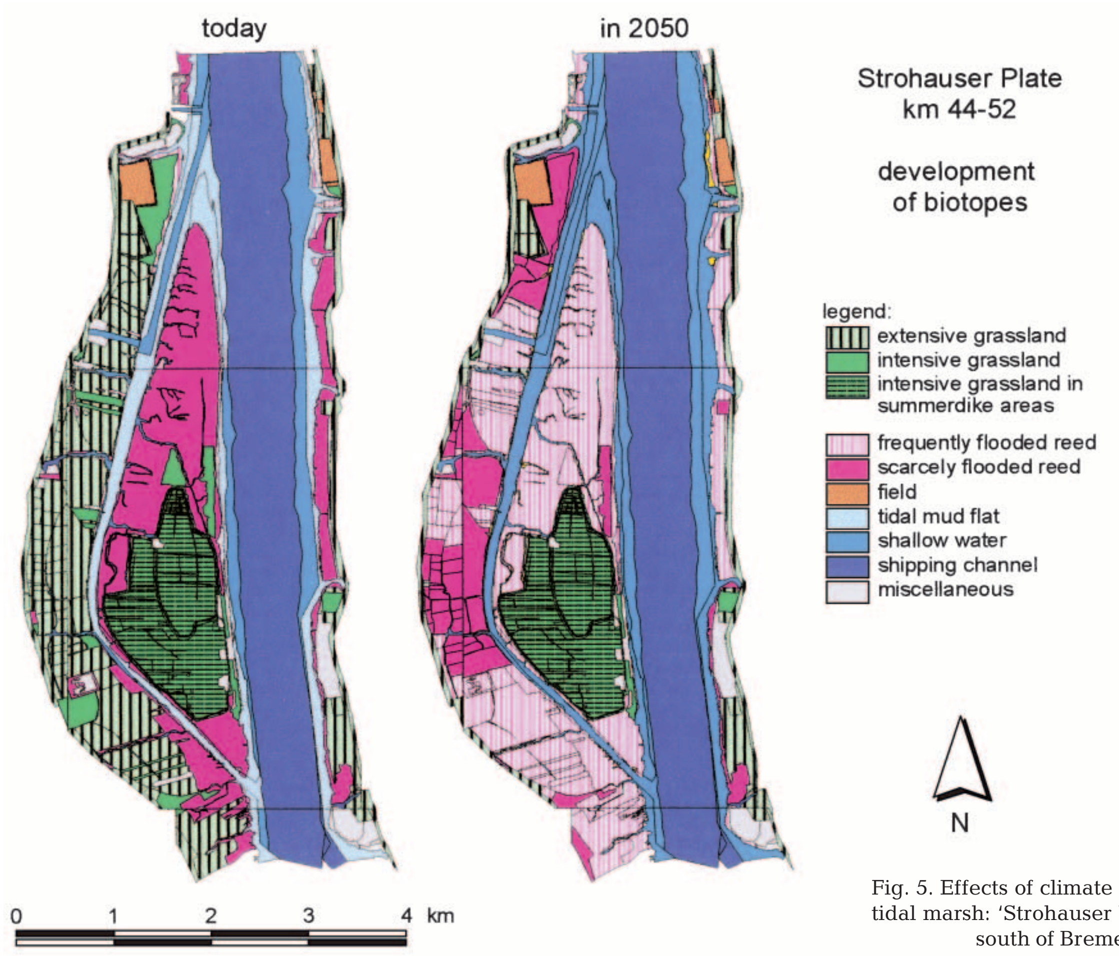

Fig. 5. Effects of climate change on a large tidal marsh: 'Strohauser Vorländer', 20 km south of Bremerhaven

the meadows are rarely inundated during the vegetation period and are provided with small but well maintained ditches to drain the areas. The vegetation is dominated by species such as *Alopecurus pratensis*, *Festuca pratensis*, *Agrostis stolonifera* and *Lolium perenne*. Important herbs are *Ranunculus acris*, *Taraxacum officinale* and *Cardamine pratensis*. These grasslands are classified as 'Ranunculus repens-Alopecurus pratensis' (Dierschke 1994, Preising et al. 1997). Up to 3 cuts are possible between May and the beginning of October. Applications of fertiliser range between 0.15 and 0.30 t N km^{-2} yr^{-1}. Natural reed stands cover 20% (9 km^2) of the tidal marshes. Along the main channel only comparatively small reed stands are found. Large reed stands are mainly located in the side arms of the Weser Estuary, where there is low hydrodynamic energy. The reeds are dominated by species such as *Phragmites australis* and *Scirpus maritimus*. The elevations of these wet and frequently flooded areas range between 1.5 m below and 20 cm above mean high water level.

Consequences of climate change on vegetation and land use are shown in Fig. 5 for a representative area with large tidal marshes. The 'Strohauser Vorländer' is located in the inner Weser estuary, 20 km south of the harbour of Bremerhaven, and has an area of 9.5 km^2. In the year 2050 a rise of the mean tidal high water due to climate change will lead to an expansion of reeds and associated flora as well as to an extension of shallow water zones, whereas the amount of tidal mud flats and meadows will decrease.

An example of the consequences of a rise of the mean tidal high water level is given in Fig. 6 for a region with narrow tidal marshes and grasslands protected by summer dikes. These areas are intensively managed as pasture for milk production. The poorly structured grasslands are dominated by species such as *Agropyron repens*, *Lolium perenne*, *Lolium multiflorum* and *Phleum pratense*. Among herbs, *Rumex obtusifolius*, *Stellaria media* and *Cirsium arvense* are widespread. The vegetation can be classified as 'Poo-Rumicetum obtusifolii' (Preising et al. 1997). Applications of fertiliser reach up to 0.4 t N km^{-2} yr^{-1}. The meadows are harvested 3 to 5 times between May and October. The polder is equipped with a complex drainage and irrigation system comparable to those of

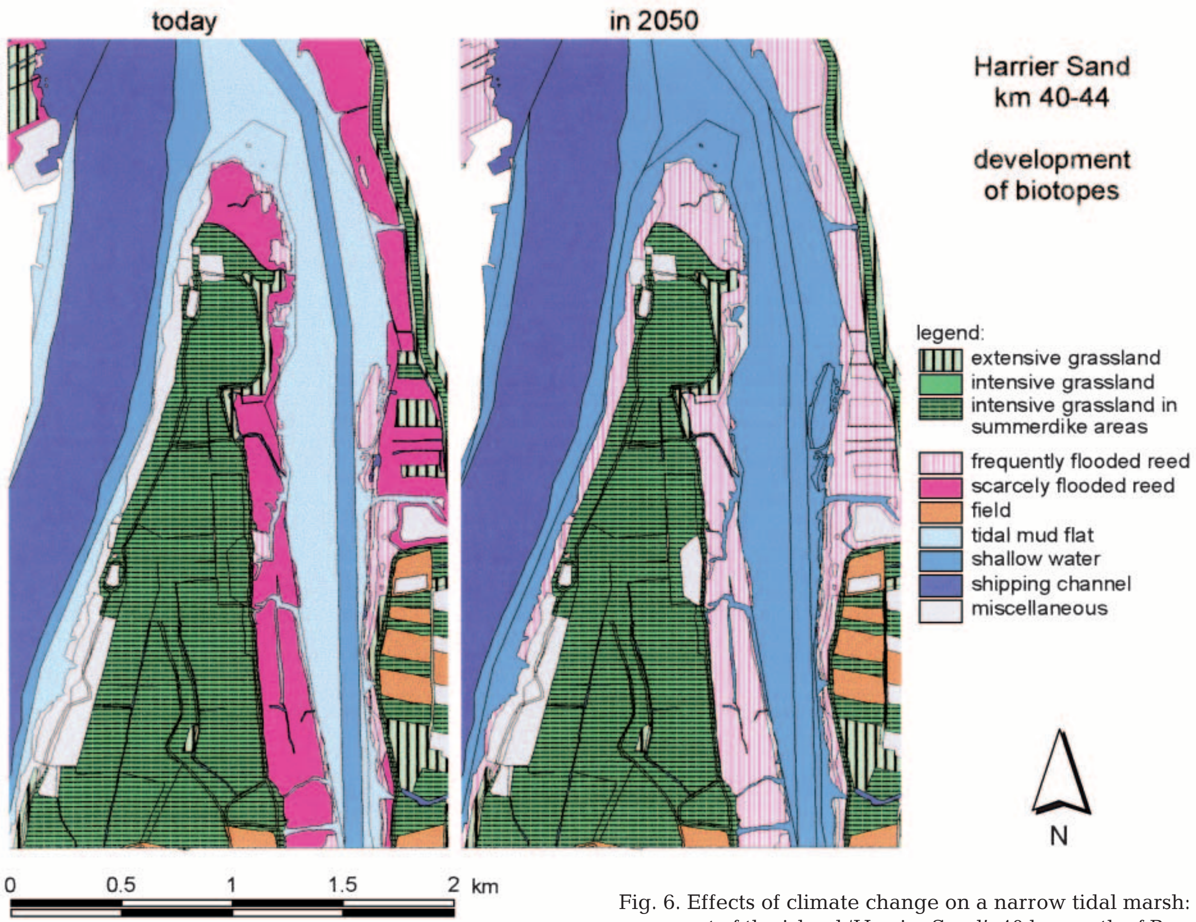

Fig. 6. Effects of climate change on a narrow tidal marsh: northern part of the island 'Harrier Sand', 40 km north of Bremen

the plains. However, the hydrology of the area is managed and controlled mechanically. Drainage is only possible during times of tidal low water. The summerdikes with an average height of 3.5 m come close to the Weser and leave little space for reeds, tidal mud flats and shallow waters. The following changes in vegetation and land use due to climate change can be expected in the year 2050. The character of the reeds changes from scarcely flooded reed stands to frequently flooded reed stands. In these areas no expansion of the reeds can take place because of the lack of space. Shallow water zones will have extended; the area of tidal mud flats will have decreased. Grasslands within the summerdikes will not be severely affected by the initial change in mean tidal high water level, as the drainage and irrigation system will be able to compensate for the altered water levels of the estuary. Only in years with extreme flooding in both winter and spring will intensive land use be limited.

Expected quantitative and qualitative changes on the forelands are as follows (Fig. 7). Within the tidal marshes, meadows will be converted into reeds. There will be heavy losses of tidal mud flats due to the rise of mean high water and colonisation of these new tidal areas by reeds. Shallow water areas will increase significantly.

The character and appearance of the Weser estuary will change from an agricultural area dominated by grasslands towards a landscape characterised by more natural vegetation (grasslands will decrease by 50%) and habitats such as reeds, within a large eulittoral (Table 1). According to these quantitative changes a

Table 1. Quantitative and qualitative effects of climate change on the forelands of the Weser estuary

Affected biotope types	Quantitative effects	Qualitative trends
Grasslands	–	+
Scarcely flooded reeds	+/–	+/–
Frequently flooded reeds (eulittoral)	+	+
Tidal mud flats (eulittoral without vegetation)	–	–
Shallow waters	+	+

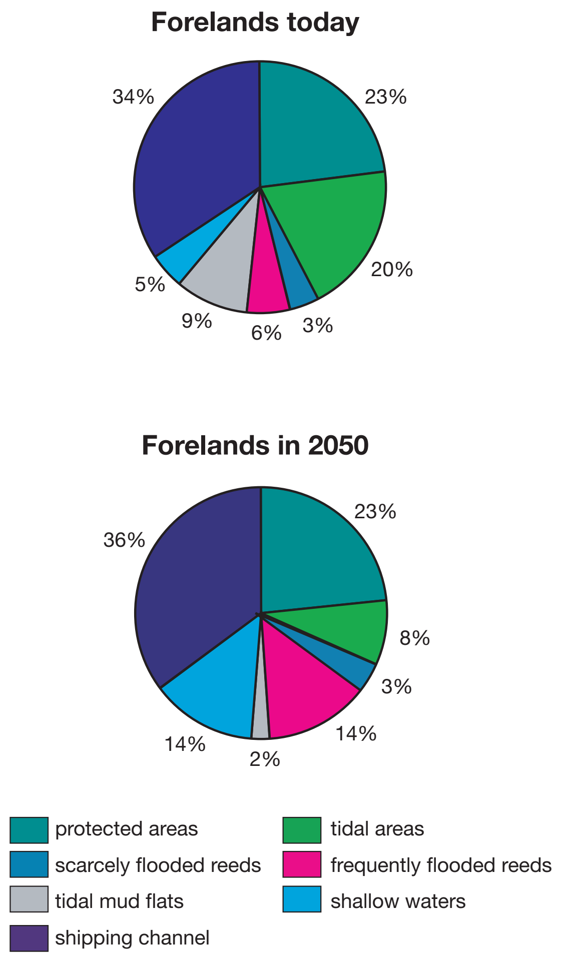

Fig. 7. Overview of distribution of biotope types in the forelands today and in the year 2050 due to a rise of 70 cm in mean high water level

rise in mean high water level will probably, in the long term, have positive ecological effects for breeding birds as well as for resting birds, fishes, young fish and fry, because shallow water zones increase.

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