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Influence of the blue mussel *Mytilus edulis* (Linnaeus) on the bottom roughness length (z_0) in the south-western Baltic Sea

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Abstract In the absence of hard substrata the blue mussel *Mytilus edulis* forms clumps up to several hundreds of mussels. These clusters are lying on the sediment surface, where they considerably increase the bottom roughness length z_0 of the sediment, as derived from median grain size. This value can be 10^3 to 10^4 fold higher (5 mm up to 40 mm) than the bottom roughness length (5-25 µm). A dataset of 2140 data points was used to map the distribution of the blue mussel with the use of a Geographic Information System. The z_0-values calculated from abundance distribution of the blue mussels were extrapolated to the field, to show the distribution of the species-specific roughness length in the southwestern Baltic Sea. The highest mussel z_0-values correlate with high energetic regions in the area of investigation. The mapping of biological affected z_0 demonstrate how important biological activities are, e.g. for the modelling of sediment transport.

Keywords *Mytilus edulis, GIS, sediment transport, benthic boundary layer, grain size distribution, Baltic Sea.*

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INTRODUCTION

Sediment transport driven by currents and waves is of major concern for coastal engineering and thus affects many applied problems along the southern coast of the Baltic Sea. So far, the models describing this process include 3-dimensional circulation patterns and waves (Gerritsen et al. 2001, Kuhrts et al. 2004) but they assume sediments to be smoothly distributed in the field. The hydrodynamic properties of the benthic boundary layer have a major influence on sediment transport. Because of the friction between water and bed, the current velocity decreases close-by the bed. With distance above the bottom, as flow velocities increase, inertial forces, and thus turbulence, emerge ($U_{(z)} = \frac{U_*}{\kappa} \cdot \ln \frac{z}{z_0}$, Gust 1989). In order to estimate resuspension, the shear stress and the bottom roughness length z_0 are needed; the latter being estimated from the median of the grain size (k_s) distribution ($z_0 = k_s/30$, Zanke 1982). Only few authors have tried to include the different scales of micro-bottom topography such as ripples and a variety of biogenic structures, both being much larger than grain sizes, in order to obtain a more realistic view of the near bottom processes. This paper is intended to make biological information on the seafloor available for modellers, i.e. to show how the scattered biological data can be converted into maps and to describe the effects of biological objects such as roughness elements.

Rich and diverse biota, ranging from microscopic algae and bacteria to bivalves and worms, inhabit the surface layers of most sediments Black and Paterson (1997). A minority of species inhabiting the sediment-water interface produce large quantities of biogenic structures (Wheatcroft 1994). These structures can either consist of the organism body by itself (bivalves), or they can be a variety of different traces such as mounds, pits or tracks. The blue mussel *Mytilus edulis* is one of the most frequent species in the Baltic Sea and causes the largest protruding structures alongside with the lugworm *Arenicola marina*. Because of a lack of hard substrate the blue mussels lie on the sediment in form of clumps where up to several hundreds of individuals stick together in one conglomerate, or sometimes even form mussel-beds. A Geographic Information System (GIS) was used to find out how these structures are distributed and to quantify their influence, and to visualize the appearance of biogenic structures generating macrozoobenthic species.

The term GIS (**G**eographic **I**nformation **S**ystem) appeared first in the 1960's (Cances et al. 2000), and became more and more used in aquatic science since then. Lehman (1998) has used GIS to model the distribution of macrophytes in Lake Geneva (Switzerland). Acosta and Perry (2002) used GIS to quantify vegetation community structures and to classify benthic habitats as sources or sinks for a crayfish population. In the combination with side scan sonar, Haltuch et al. (2000) analyse the invasion of *Dreissena polymorpha* in Lake Erie. Cropper et al. (2001) analysed the population dynamics of commercial sponge in Biscayne Bay, Florida with the use of GIS. Garrabou (1998) determined the growth rate of benthic clonally organisms with overlay procedures in GIS, and Hooge et al. 1997 developed an "Arc-View© GIS" extension to model animal movement in the marine environment. Because of the existence of large datasets on benthic organisms (HELCOM Baltic Monitoring Programme), it should be possible to create detailed maps of the macrofauna distributions at different locations in the Baltic Sea area. Furthermore it is possible to combine different parameters, like abundances and sediment grain size which allow ecological modelling and a more detailed view on habitat structuring. The aim of this study was to visualize the effect of the biogenic structures generated by clumps of the blue mussel on bottom roughness length (z_0). The results will be used for a 3-dimensional sediment transport model, which is developed within the framework of the interdisciplinary DYNAS-Project (dynamics of natural and anthropogenic sedimentation) were results of biologists, geologists and physical oceanographers are put together.

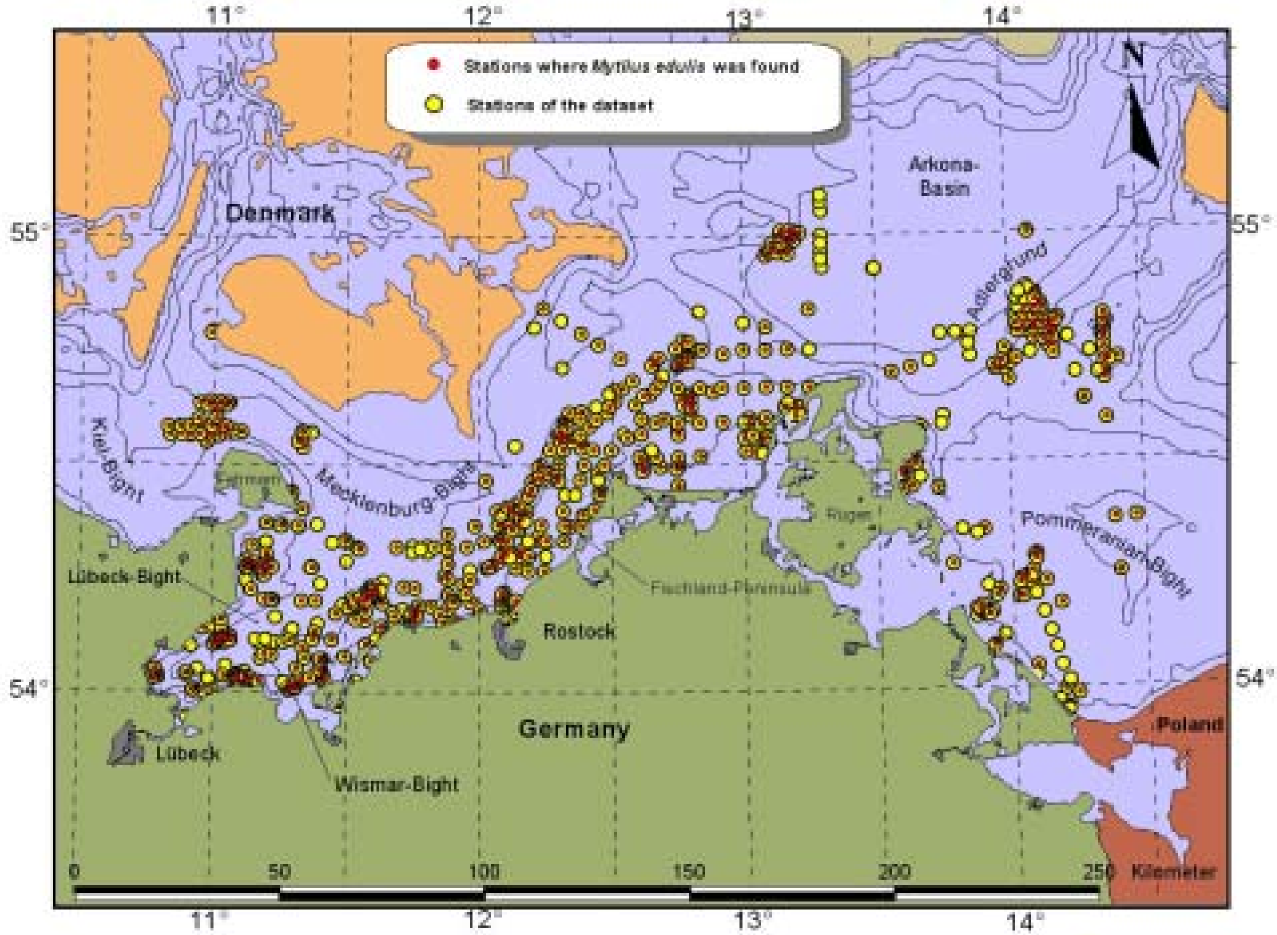

Fig. 1. Overview of the sampled stations in the area of investigation and the stations where *Mytlus edulis* appeared. One dot matches sometimes more than one sample, up to 20. The data are received from Institute of Applied Ecology Ltd Neu-Broderstorf, Baltic Sea Research Institute Warnemuende (IOW) and the National Office for Nature and Enviroment Schleswig-Holstein (LANU).

DATA AND METHODS

The area of investigation is the coastal region of Mecklenburg-Western Pomeranian, Germany, covering 10°46,999 E to 14°14,468 E in west-easterly direction and 53°56,85 N to 54°49,00 N from south to north. The main area of interest is the Mecklenburg Bight. The data used in this study were provided by the Institute of Applied Ecology Ltd Neu Broderstorf, the Baltic Sea Research Institute (Zettler pers. comm., Zettler et al. 2000), and the LANU-Schleswig-Holstein (National Office for Nature and Environment). The data were produced during national monitoring programs. Within the framework of the DYNAS-Project, a subproject (WISTMAK) was conducted by Powilleit (2003, 2004) who monitored 5 stations in the area of investigation to enhance the stations net. The used bathymetry data were provided by the Baltic Sea Research Institute, Warnemünde (Seifert et al. 2001)(Seifert et al., 2001).

These datasets contain a total of 1900 stations and more than 10000 sample points (i.e. van Veen grab, Fig. 1). Unfortunately, the first samples were taken some 15-20 years ago, therefore the red dots in Fig. 1 depict the long-term mean distribution of *Mytilus edulis* (2140 data points) rather than the actual situation.

With the use of the Arc-View Spatial Analyst extension software for Arc-View GIS 3.2a (ESRI, 1999) the point values (Figure 1) were converted into a grid covering the study area. The “Neighbourhood Statistics” operation in the Arc-View Spatial Analyst (ESRI 1999) will compute a result grid that carries out a mean value on a specified “neighbourhood” around each cell (Fig. 2, Wackernagel, H., 1995). In this study three different circle neighbourhoods, of 1 **n**autical **m**ile (nm), 3 nm and 5 nm diameter, were chosen. The statistics supported in this version of Arc-View Spatial Analyst include some dominance rules (maximum, minimum, etc.) and some contributory rules (mean (average), variety (diversity), sum, etc.). The neighbourhood can be defined as a rectangle or a circle, and dimensions of the neighbourhoods can be given in cells or distance units. The values in the result grid are set to the centre cell of each neighbourhood, and reflect the function (statistics) applied to the neighbourhood. With this function the data were gridded to three different cell sizes of 1 nm, 3 nm and 5 nm leg length to get a better area distribution. The abundance data were categorized into 9 groups of natural interceptions (given in the Arc-View legend editor) and ordered by the frequency of appearance of the groups (Fig. 5).

The *Mytilus*-z_0-value was calculated with a formula given in Dade et al. (2001,). The hydrodynamic bottom roughness length is proportional to the object height k_r, Y (psi) is the surface coverage rate and C_r is a constant varying between 0,5-1 if Y<<1. In our study the object height (k_r) and the surface coverage rate (Y) was idealised and approximated for the mussel clumps (Figure 3a).

The accurate surface cover rate (RD) determination of the blue mussels from field samples is difficult. The mussels either form beds or clumps, the latter being the common structure in the area studied. Because of the stratification of different sized individuals (bigger at the basis and smaller at top of the clumps), we therefore suppose in this study, that the surface area covered by a *Mytilus*-clump is influenced by only 1/3 of the mussels involved in a clump, i.e. of the mussels

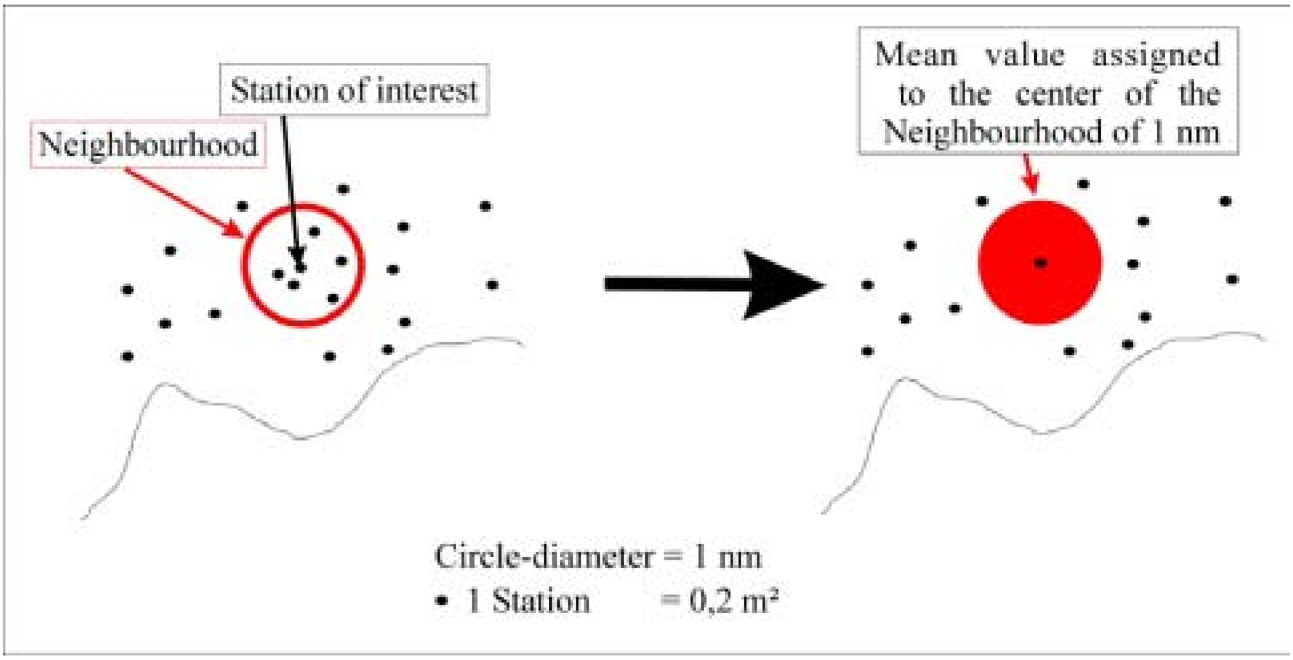

Fig. 2. Schematic description of the neighbourhood statistics technique. The initial situation is shown on the left side. By calculating a mean value of the six data points within the red circle, we got it assigned to the center of the Neighbourhood of 1 nm on the right side.

situated at the ground of the clump. Assuming that this situation apply to the whole area of investigation we calculated the surface cover rate (Y) of 1/3 of the abundance (Ind. m^{-2}). The percentage surface coverage rate is derived from an assumed medium ground area of a mean sized individual mussel by calculating an elliptic area (Fig. 3b), whereas 1 m^2 according to 100% . The mean height of a *Mytilus*-clump was examined by *in situ* video observations and box-corer samples and was found at 8-10 cm (Peine, pers. observations).

RESULTS

The distribution of sampling stations across the area is unsteady, with a high density of stations in the western part of Mecklenburg Bight and fewer stations in the area north and east of the island of Rügen (Fig. 1). Fig. 1 also shows the abundance-distribution of *Mytilus edulis* stations (red dots). Fig. 4 (a,b,c) depicts the extrapolated neighbourhood on 1 nm, 3 nm and 5 nm leg length. There are some hotspots with high abundances in the western part of Lübeck-Bight, north of Wismar-Bight, northwestern off Rostock-Warnmuende, northern of the Fischland-Peninsula and on Adlergrund, northeast of the island of Rügen. Furthermore, there is a small hotspot in the Pomeranian-Bight. All these hotspots are close to the coast in shallow waters less than 20 m, except the Adlergrund. Fig. 5 shows the frequency of the different groups of abundances, of which the 0-177 Ind. m^{-2} was the most frequent one, which is also visible in Fig. 4c (5 nm extrapolation). The preferred sediment types of *Mytilus edulis* are sandy sediments. Fig. 6 shows the grain-size spectrum of the study area (Bobertz 2000) and the stations with the blue mussel data. The reduced availability of hard substrates triggers the blue mussels to form aggregates or mussel-clumps (Fig. 3). These conglomerates are not attached to the sediment and they are swept away by current speeds exceeding 15 cm s^{-1}. The roughness length values for the sediment surface were calculated from the median grain sizes ($z_0=k_s/30$, Zanke 1982) and consequently show an identical spatial distribution as the grain sizes. Consequently z_0 follows the grain size distribution (Fig. 7). In the deeper basins (Central Mecklenburg Bight and Arkona Basin) the z_0-values are very low, approximately 1-4 µm. At regions with higher dynamical environment (coast west of Rostock) it increases up to 24 µm.

The calculated z_0-values of *Mytilus edulis* are showing a distribution that closely resembles the abundance distribution. There are 4 hotspots with values from 20 mm up to 45 mm, in the Lübeck bight and westerly of the Fischland-Peninsula. The predominant areas are covered with z_0-values of 5 mm, sometimes 10-15 mm (the light pink areas in Fig. 7).

DISCUSSION

The results of the mapping demonstrate the usefulness of GIS-Systems for a better understanding of macrobenthic ecology. With GIS it is possible to obtain a combined visualisation of different "geoinformations". We have used this data to generate distribution maps of the macrofauna that generates biogenous structures. It subsequently is possible to show probable habitats for specific organisms, in this case the blue mussel. By extrapolating sampling results to regional maps (Fig. 4 a,b,c) it becomes obvious how widespread the distribution of *Mytilus edulis* is. We used the Neighbourhood Statistics in order to reveal the spatial variation of the abundance values. Investigating the spatial autocorrelation, the resulting semivariograms reveal no spatial correlation for any scale. Hence, interpolation methods, assuming a spatial correlation between the values like Kriging cannot be applied. Sampling a small part of a square meter and extrapolating or interpolating the value to an area of some nautical square miles appears to be hazardous, especially for macrobenthos communities with a patchy

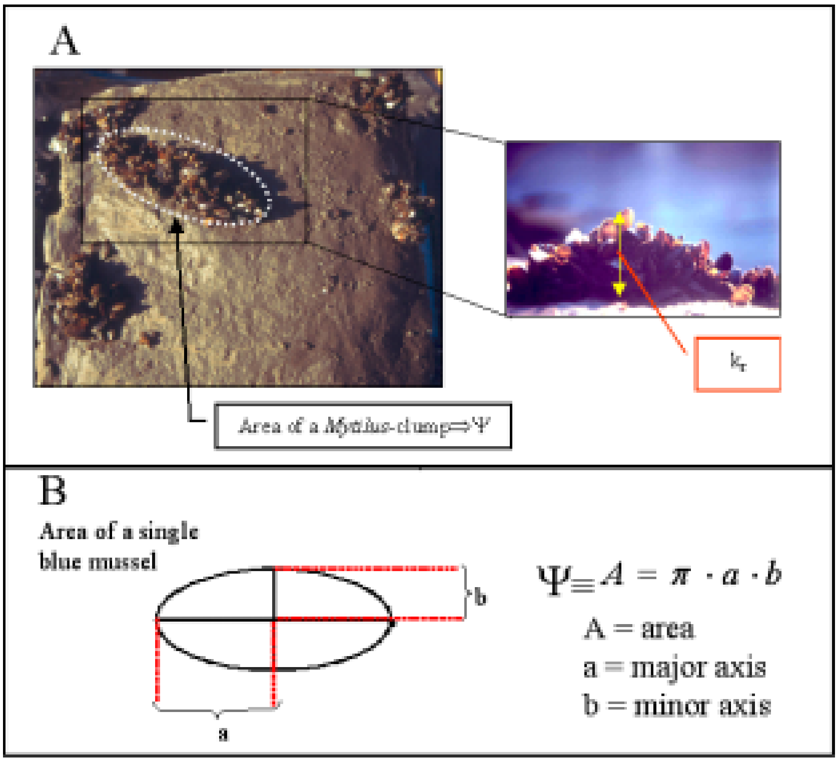

Fig. 3. (A) *Mytilus*-clumps lying on a sediment core and a description of parameter used in the z_0 calculation (Dade et al. 2001). (B) Schematic depiction of the elliptic area of a single blue mussel and the proper formula to it.

distribution that is poorly represented by the small sampling devices used. However, it is the only way to generate a regional-scale visualisation of habitat structures observed on a small sampling scale. In order to improve the significance of the results obtained, GIS incorporates proven statistical methods for testing hypothesis and for error handling as well as the illustration of the impact on the outcomes of models as used for environmental management (Burrough 2001).

Another advantage of GIS is the combination of different datasets, like abundances and grain size distribution parameters. Fig. 6 shows that the blue mussel predominantly occurs on sandy sediments in the coastal zones between the shoreline and 20 m depth line. It is not an unknown fact that the blue mussel is also living on sandy sediments, but we can produce the hypothetic distribution resulting from the sampled stations. Because the grain-size distribution also reflects the current and wave energy acting in the area, the combination of this factor with the mussel incidence suggests that the mussels prefer higher current velocities. In fact, being filter feeders, they need a good supply of particulate matter.

Fig. 6 also shows, that the fine sediments are in the deeper parts of Mecklenburg-Bight (dark colours), and the coarser sediments are next to or parallel to the coastline. These regions are dominated by currents of high velocity, predominantly flowing from west to east. Two-dimensional current measurements are not available but there are some results of numerical current modelling (Rietz et al. 2000). Some areas in the western part of Lübeck-Bight are in light white (Fig. 6). These areas were sampled selectively while probing for deposits for beach replenishments. Hence, only known regions with coarse sand were probed. This region usually is characterised by fine-grained mud (Anonymous 1987; Bresau 1957).

The most important result of this study is the strong increase of the roughness length by *Mytilus edulis* (Fig. 7). It is shown, that the mussels increase z_0 by a factor of 10^4. We calculated the surface cover rate of the mussels via a simple assumption of their size and of the mussel

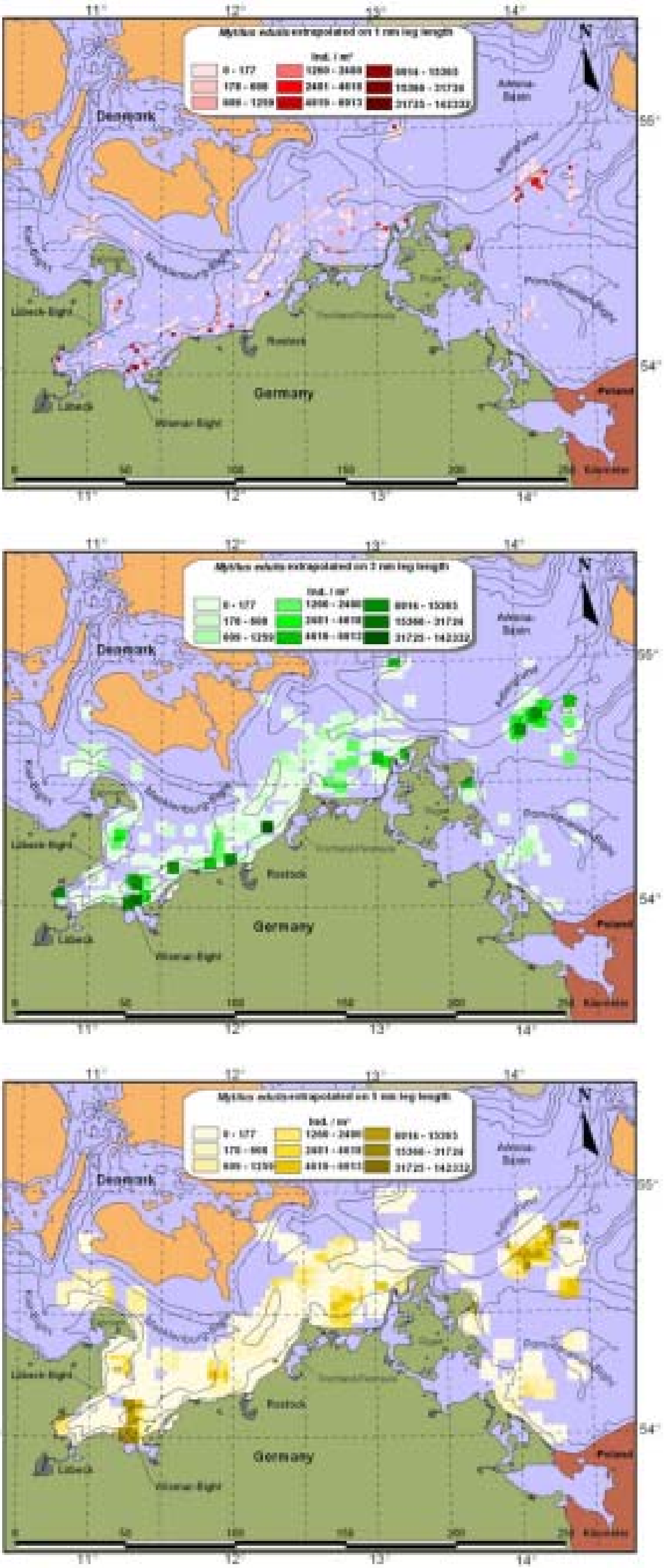

Fig. 4. Extrapolated abundances of *Mytilus edulis* on 1 nm leg length (a), 3 nm leg length (b), and 5 nm leg length (c).

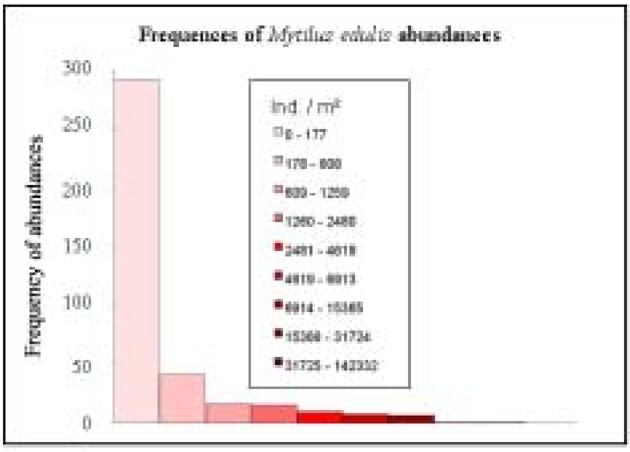

Fig. 5. Frequency of blue mussel abundances in the area of investigation.

surface area (Fig. 3) depending on abundance as well. If very high abundances are found in a sample it could be due to a high amount of juveniles (Powilleit 2004). Juvenile blue mussels need a hard substratum to settle, which is given, in absence of hard rocks or others, by adult mussels forming mussel-clumps. With our assumption, that only 1/3 of the examined abundance of *Mytilus edulis* is responsible for the surface coverage rate, we tried to diminish the mistake of a total abundance influence on Y . Because of the dependence of z_0 on Y, high abundances result in high z_0 values. So, the extreme high z_0 values >25 mm are possible overestimations depending on high abundances of juvenile mussels in the samples.

When extrapolating the results to the field (Fig. 8), it becomes distinct that the mussels have a major influence on the roughness length, even though it seems that the clumps are lying more or less isolated on the sediment (Fig. 3).

The role of increasing numbers of roughness elements on the sediment stability was controversially discussed in past publications. Rhoads et al. (1978) noticed a higher erosion threshold in the presence of worm tubes. However they assumed flow detachment at the tube tips to be a major factor. In return, Eckman et al. (1981) and Luckenbach (1986) found worm tubes to destabilise the sediment at low population densities. Nowell and Church (1979) provided a first systematic study of the flow effects of "Lego" bricks, 0.9 cm high and 2.6 cm² in area, with roughness densities ranging from about 0.8% to 13% surface cover. They measured vertical velocity profiles between the structures. The profiles were nearly undisturbed at low densities, termed as "isolated" or "independent" flow conditions. At intermediate densities around 2%, the

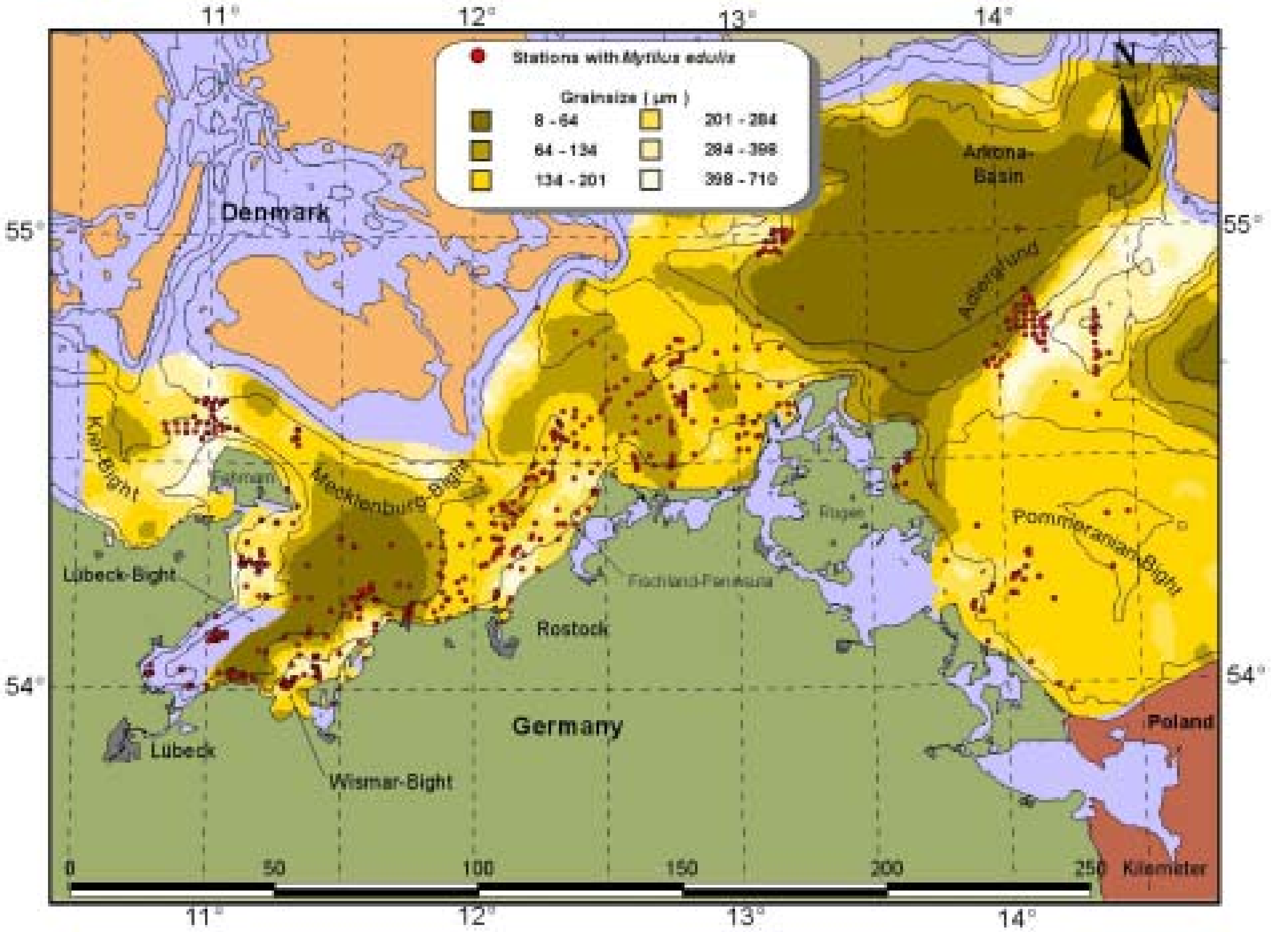

Fig. 6. Mean grain size distribution in the area of investigation (Bobertz, 2000) and stations where the blue mussels were found.

wakes of the individual structures started interacting, thus called “interacting flow”. The highest densities of 8-13% produced a strong flow reduction and the formation of a new boundary layer above the structures. This condition was called “skimming flow”. Flow resistance and turbulence were highest for interacting flow. The turbulence intensity profiles continuously decreased towards the bed in independent flow, but remained high throughout the wake region at interacting flow. Skimming flow showed turbulence maximum at the height of the structure tops for skimming flow.

Butman et al. (1994) reported a 3-10 fold increase of the turbulent stress over *Mytilus edulis* mussel beds (estimated RD around 80%), and Crimaldi et al. (2002) report decreasing Reynolds stresses below a stress maximum layer, for increasing clam densities. These findings were verified for artificial worm tube densities by Friedrichs et al. (2000). They reported a switch from destabilising to stabilising conditions at 2-4.5% surface cover rate, and purely skimming flow established at surface cover rate around 4.5-8.8% for large tubes (3 cm high and 0.5 cm diameter) and around 0.7-1.0% for small tubes (2 cm by 0.2 cm) (Friedrichs 1996). Friedrichs (2003) observed a raise of z_0 by a solitary mussel of up to 78% of the structure height. It becomes obvious, that mussels have a major influence on the bottom roughness length.

The blue mussels covering major surface areas up to 3%, but also some hotspots where they have a surface cover rate of up to 12% (Fig. 8). Here they are responsible for skimming flow conditions, hence they strongly influence the sediment transport, only due to their body structure.

CONCLUSIONS

The use of GIS allows showing distributions of different parameters, in this case of the bottom roughness length. *Mytilus edulis* is widespread in the southwestern Baltic Sea, and has a major influence on the bottom roughness length. The roughness length of the sediment (0-24 µm) is increased by a factor of 10^3 when the blue mussels are present. In some regions the roughness densities are increase up to 12%, so the influence of the blue mussels on the sediment transport is expected to be considerable. Since *Mytilus edulis* also has a strong filtration potential, the ecological impact of these animals becomes clear by displaying their distribution with GIS. To depict the deposition and resuspension potential of the blue mussels will be the next step in interdisciplinary work between geology and biology. Furthermore we used GIS for a better understanding of macrofauna distribution in the area of investigation and to integrate the distribution data into a 3-dimensional sediment transport model.

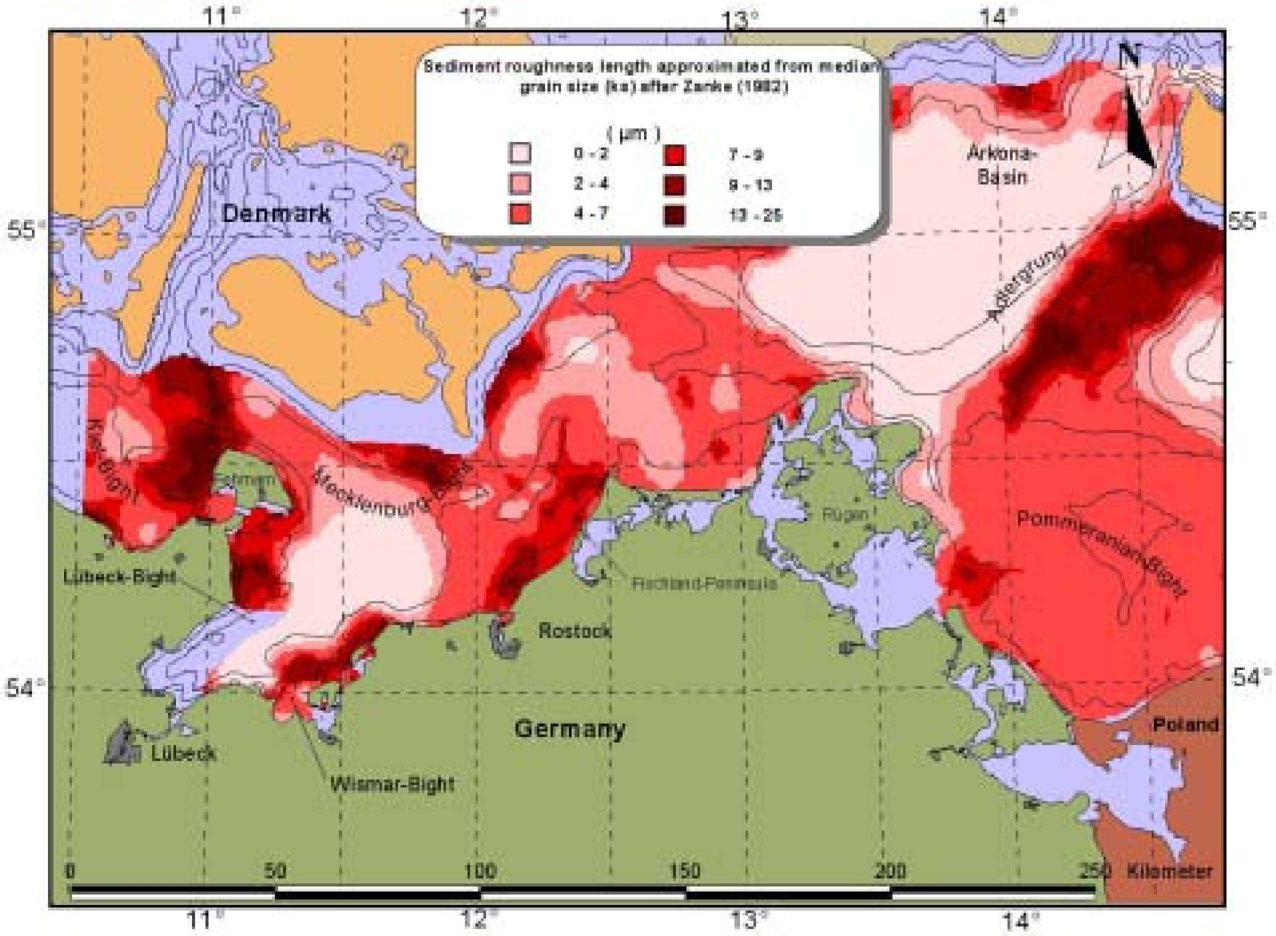

Fig. 7. Sediment roughness length transformed from mean grain size (after Zanke, 1981).

This is not the first attempt to use GIS in marine biology but it allows locating and to describe habitats. For a more detailed interpolation of the data to the field it would be helpful to have a station net with defined distances between the sampling stations, i.e. a defined raster. Furthermore it would be helpful to sample the stations always by the same way (every season, every year).

The use of GIS simplifies the search of organisms in the field and the work with habitats that are difficult of access.

Acknowledgements

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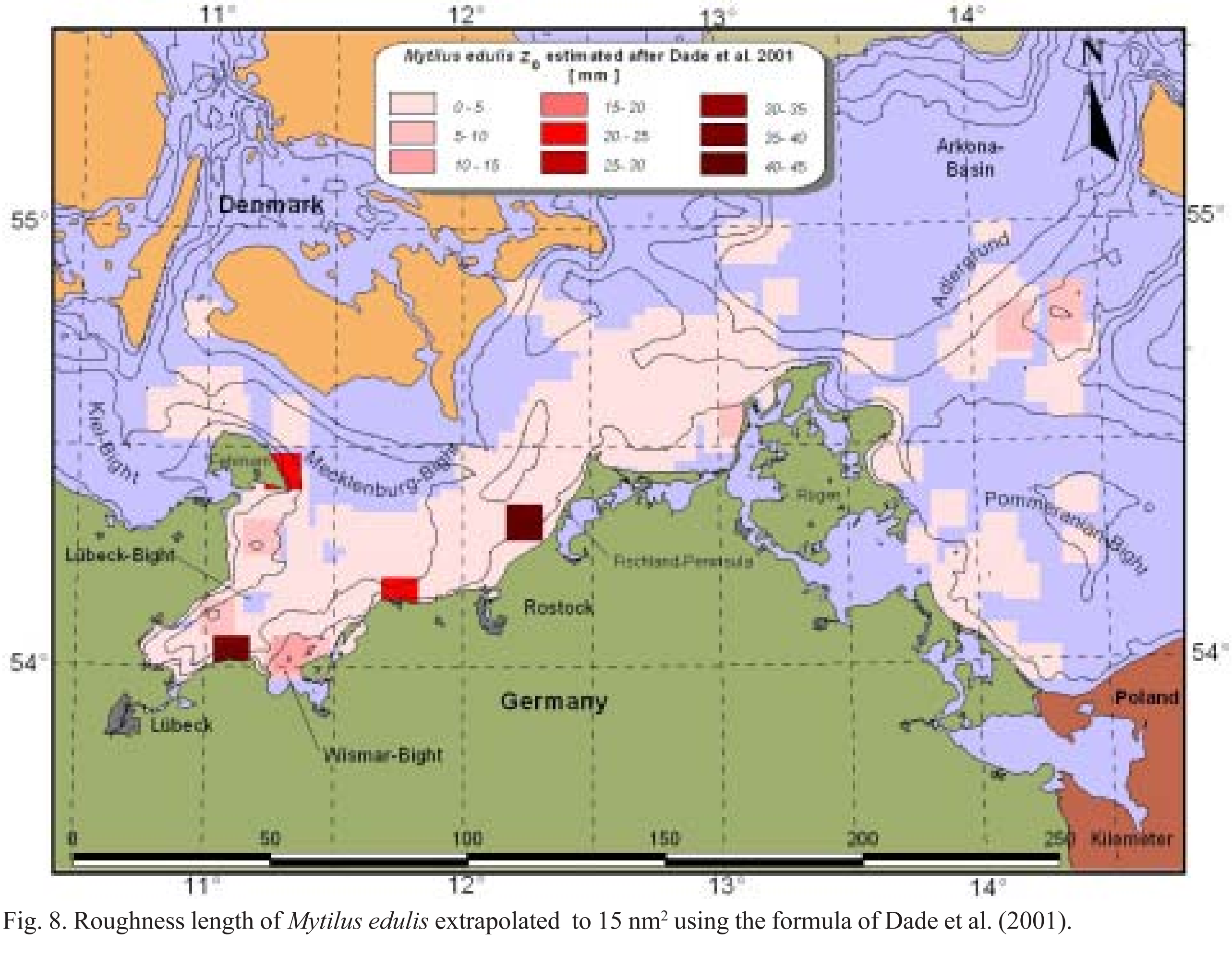

Fig. 8. Roughness length of *Mytilus edulis* extrapolated to 15 nm^2 using the formula of Dade et al. (2001).

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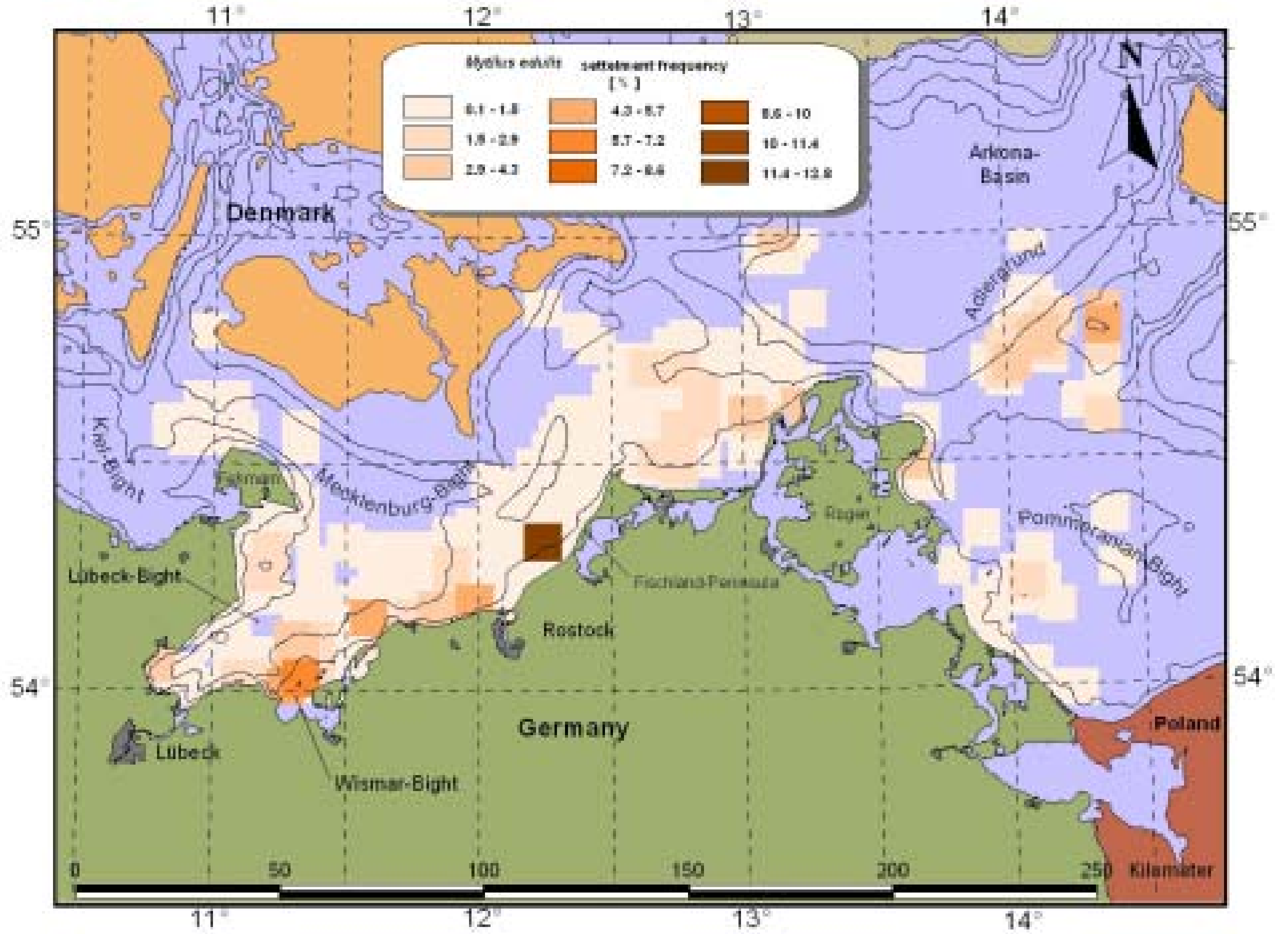

Fig. 9. Settlement frequency (%) of *Mytilus edulis* extrapolated to 15 nm^2.

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