13 The Impact of Wind Engine Constructions on Benthic Growth Patterns in the Western Baltic

Michael L Zettler and Falk Pollehne

13.1 Introduction

Global-scale environmental degradation and its association with non-renewable fossil fuels have led to an increasing interest in generation of electricity by renewable energy resources (Gill 2005). Since the planning of large offshore wind energy facilities in the German Bight and the Baltic Sea was initiated, concerns about the ecological compatibility of these structures have been expressed. Apart from direct impacts of disturbance during construction, operational sounds and rotating parts, which might primarily affect birds, bats, marine mammals and fish, the potential long term effects on the benthic environment have been discussed. These concerns are mainly focused on the questions, whether and how the natural benthic habitat in the vicinity of the constructions is modified by changes in bottom currents and turbulence, and whether the effects of the installations as artificial settling substrates are properly assessed. The ecologically relevant effects of offshore wind parks include e.g., increased habitat heterogeneity, and changes in hydrodynamic conditions and in sediment transport patterns. The potential ecological response of the macro-zoobenthos could involve long-term changes in diversity, abundance, biomass, community structure and such functional properties as nutrient regeneration or bio-turbation.

These problems have been in the focus of a project in the western Baltic which that was part of a national combination of projects called BeoFINO.[1] This effort has addressed the overall ecological risks of off-shore wind-power facilities in the North and Baltic Seas.

Such questions are most often viewed in the primary context of the effects on the biodiversity of the benthic community. In the Baltic Sea however, the specific hydrographical conditions emphasizes a problem which also involves the absolute biomass accumulation rates of epifauna

---

[1] Ecological research on offshore use of wind energy on research platforms in the North and the Baltic Seas (BeoFINO), established by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

on substrates that protrude into the surface mixed layer. Particularly in the inflow areas of denser, more saline North Sea water adjacent to the Belt Sea and the Danish Sound, severe vertical stratification between the surface mixed layer and the bottom water overlying the sediments is the rule rather than the exception. The stratification is much more stable than in the North Sea, as tidal mixing is not an effective source of vertical exchange in the Baltic. Surface productivity is high in these areas, at least partly due to anthropogenic eutrophication, and as the density gradient does not constrain organic particles from sinking into deeper water, but prevents dissolved oxygen from mixing downwards, these benthic areas are extremely susceptible to oxygen deficiency. The increase of benthic biomass due to enhanced nutrition over the past 50 years (Karlson et al. 2002) has already aggravated the problem of unbalanced oxygen supply and consumption. In Baltic estuaries with a similarly strong stratification regime, bottom anoxia events have been documented (e.g. Powilleit and Kube, 1997), with destructive wide-ranging effects on benthic ecosystems and such associated economies as fishing, tourism and recreation. Additional point sources of organic matter to the sedimentary systems in such areas may initiate local cores of anoxia, which then start to spread over larger areas in an exponential fashion, when the suffocated benthic biomass is itself subject to microbial decomposition and oxygen demand.

This scenario is particularly alarming, as most projected wind parks in the western Baltic are planned to be positioned exactly in the areas of most intense vertical stratification, either in the Pomeranian Bight at the estuarine stratification of the Oder plume, or at Kriegers Flak at the outlet and subduction area of dense saline water from the Danish Sound. As these environments are extremely sensitive to the input of additional organic matter, the export of benthic biomass from the higher parts of structures to the surrounding sediments became a relevant aspect in the study.

Recent studies on ecological impacts of offshore wind farms on the benthic ecosystems are rare and mainly published as reports (e.g. Birklund and Petersen 2004, Leonard and Pedersen 2004 et al. cited in Gill 2005). Within the present study, both qualitative and quantitative aspects of benthic growth dynamics in the western Baltic at an artificial pile model were investigated. A delay in the construction of a full size research platform in the key area of Kriegers Flak led to the installation of a reduced size model pile in the region of Darss Sill, which is an area restricted to research. Over a period of two years, larval settling dynamics, biomass development and a succession of benthic organisms was observed at and around this pile, as well as on additional artificial settling substrates throughout the water column. The presence of an adjacent autonomous monitoring station that registers and logs such basic environmental data as salinity, temperature and currents supported the interpretation of the results.

13.2 Material and Methods

13.2.1 Investigation Area

As the ecological and faunistic background of the Baltic is totally different from that of the North Sea, a simple translation of results between the two research areas would not be plausible, so that basic investigations were carried out in both areas. While the North Sea group (Alfred Wegener Institute, Bremerhaven) was able to observe the process of primary colonisation at the full size research platform FINO 1 off Borkum Riff in the eastern German Bight, construction of the Baltic platform was delayed and a model steel substrate was submersed at the Darss Sill station at 54° 41.764’ N; 12° 42.085’ E, at a water depth of 20 m (Fig. 1).

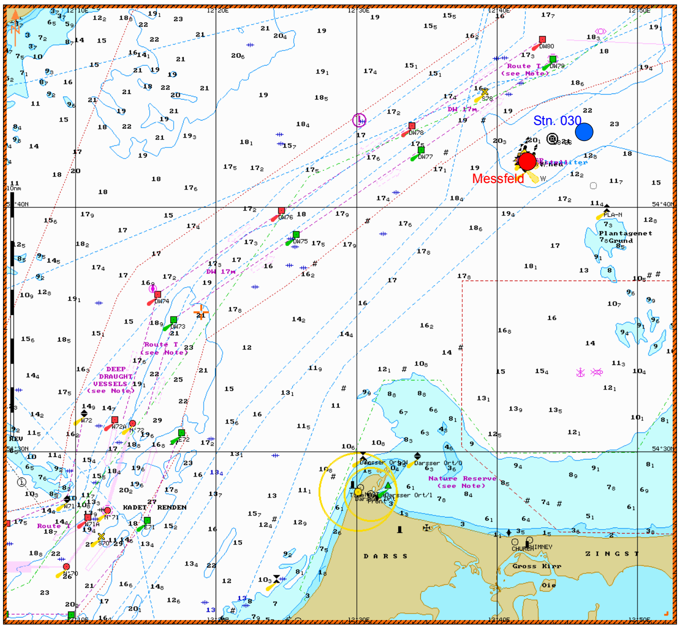

Fig. 1. Position of the experimental field at IOW-Messfeld (red). Stn. 030 (blue) marks a position, where a long term series of zoobenthos data from the HELCOM program is available

13.2.2 Design of the Sampling

Due to continuous high bottom currents driven by North Sea water inflow, the sediment is well sorted fine sand (median grain size ~200 µm) and the water column displays a haline stratification throughout most of the year. As a model for the base piles of offshore wind turbines, an uncoated steel cylinder of 2.2 m in diameter and 2 m in height (Fig. 2) was installed at a water depth of 20 m. The material was selected following the guidelines of the planning authorities for the construction of offshore turbine basements. The changes in hydrodynamic conditions close to the cylinder were recorded by an uw-video system, visual inspections and sampling by divers.

Fig. 2. Steel segment, which was deployed in April 2003 at 20 m depth to simulate the foot area of an offshore wind engine pile

Three additional moorings with square steel tiles of 20 x 20 cm at five different water levels throughout the water column (3, 6, 9, 12 and 15 m above bottom, Fig. 3) were deployed at the start of the experiment in April 2003, and were recovered consecutively after 143, 246 and 470 days. Each recovery of the substrates was accompanied by scratch sampling of an area of 20 x 20 cm at the main steel cylinder 1 m above ground by scuba divers. In July 2004, three new sets of steel tiles were moored, and the first one retrieved in January 2005 after 177 days, in order to study the dependence of the colonisation dynamics on the seasonal phase of deployment.

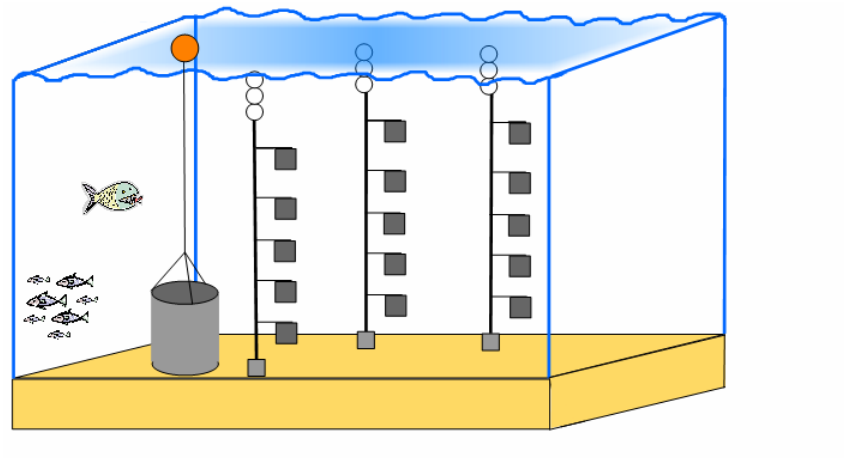

Fig. 3. Scheme of the experimental setup at the Darss-Sill station. On the left, note the permanently exposed steel cylinder, and on the right, the periodically exchanged steel settling substrates. Water depth is 20 m; the vertical distance between the artificial substrates is 3 m

Sampling of the ambient sediments was performed by means of by diver-operated acrylic cores of 10 cm diameter and 50 cm length. The penetration depths of these cores, and hence the mean sampling depth, was 15 cm. In May 2004 and March 2005, samples were taken at distances of 0.5; 1.0; 1.5; 2.0 and 2.5 m in all four directions from the cylinder, to estimate the range of impact (sampling scheme see Fig. 4).

The samples were sieved through 500 µm mesh and preserved in 4 % formaldehyde until analysis in the lab. For a comparison and classification of the results, the data from the nearby monitoring station were consulted. This station has been sampled annually for fifteen years, using a 0.1 m² van Veen grab. Samples are sieved through 1 mm mesh; preservation and laboratory analyses are identical to those in the present study.

Temperature, salinity, current speed and direction were recorded at the adjacent automatic observatory (Marnet-Station) of the Federal Maritime and Hydrographic Agency (BSH) which is operated by the Baltic Sea

Research Institute. Data were continuously recorded and kindly supplied by the instrumentation group of the institute.

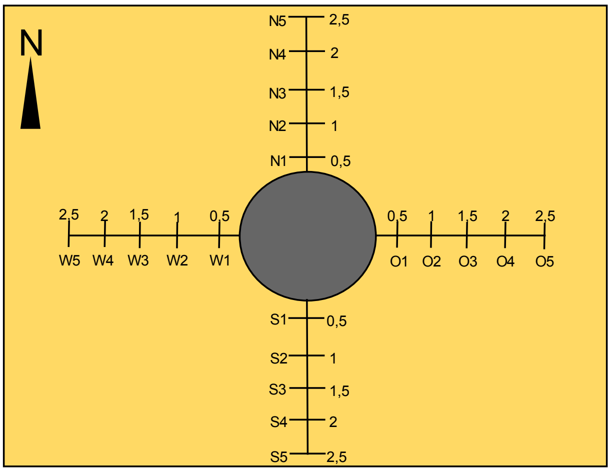

Fig. 4. The diver operated sediment sampling in May 2004 and March 2005 after 417 and 697 days of exposure followed the displayed scheme. The samples were taken at intervals of 0.5 m away from the central steel cylinder. Samples were labelled according to distance and direction

13.3 Results

13.3.1 Hydrographical Boundary Conditions

The time series of temperature and salinity (Fig. 5) show clear different hydrographical backgrounds in 2003 and 2004. Bottom salinity remained in the range of about 20 psu (practical salinity unit) over nearly the whole of 2003, whereas in 2004 larger periods of complete mixing with less saline water in the bottom water occurred. In 2003, one of the largest inflow events of North Sea water into the Baltic was recorded (Feistel et al. 2003), which led to a renewal of bottom water in all basins of the western and central Baltic Sea, and is visible in this dataset as well. As a result of a more intense stratification in 2003 and a generally warm summer, the surface layer could absorb more energy, so that the temperature conditions between these years also differed.

These generally differences in the physical background, with an almost continuous stratification in 2003, were also reflected in the settling and growth dynamics of benthic organisms.

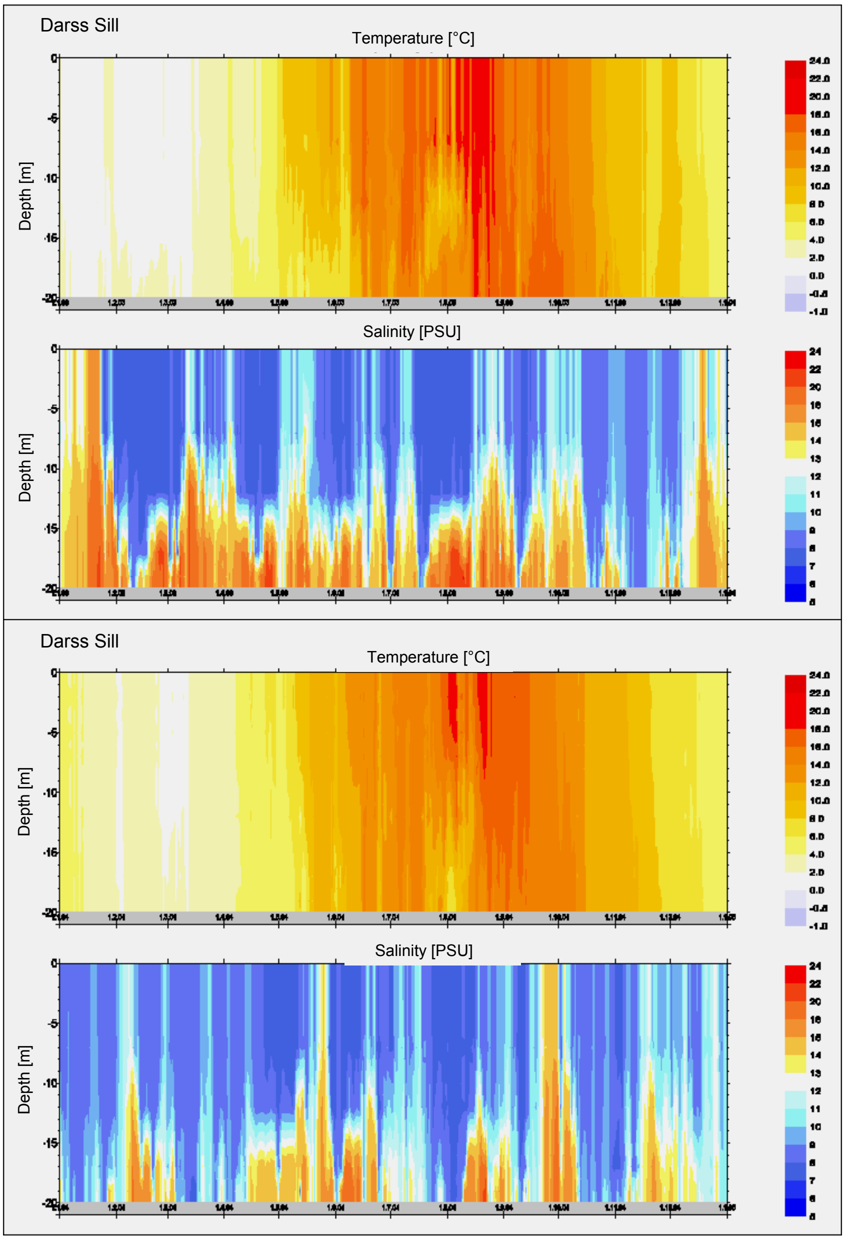

Fig. 5. Temperature and salinity at the Station Darss Sill in 2003 and 2004. Stratification of the water column and heating of the surface layer was much more pronounced in 2003 than in 2004 (data by courtesy of IOW-MARNET Group)

The measurements of the current direction showed a clear alignment in either the south-west or the north-east direction (Baltic outflow or inflow situations, respectively). Mean current speed was in the range of 20 cm sec^{-1} with maximal values reaching 60 cm sec^{-1}.

The recorded long term current conditions can directly be related to the sediment relocation processes at the foot of the cylinder (Fig. 6).

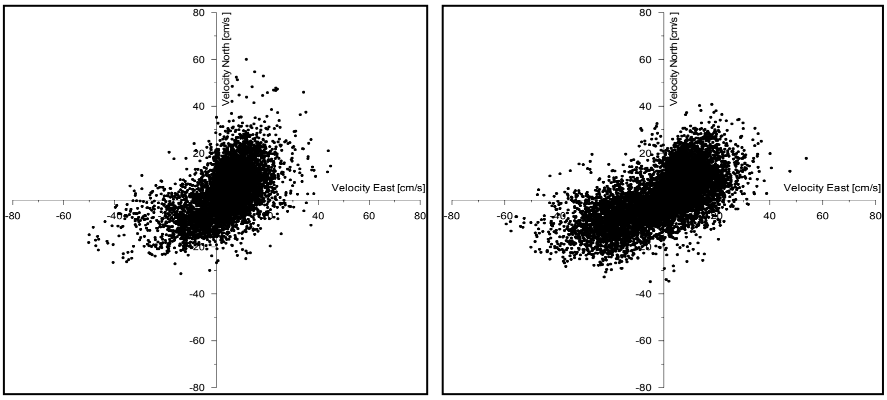

Fig. 6. Direction and speed of near-bottom currents in 2003 (left graph) and 2004 (right graph)

13.3.2 Colonisation of the Basement Model Substrates by Epifauna

After 143 days of exposure, 18 species of macro-fauna could be detected on the steel substrates, of which crustaceans and molluscs dominated, with six and five species, respectively. Less frequent were hydrozoans, polychaetes and echinoderms. Species number was highest (10) close to the bottom. The two main species were barnacles (*Balanus improvisus, Balanus crenatus*) with between 8,000 and 20,000 individuals per m^2, and blue mussels (*Mytilus edulis*), with 70,000 to 470,000 individuals per m^2.

The biomass was also dominated by these two species. While *Mytilus edulis* attained biomasses of between 1.7 and 22.3 g/m² ash free dry weight (afdw), due to the fact that the organisms had settled relatively recently, *Balanus* ssp. grew up to between 8.8 and 146 g afdw/m², peaking at the top plate at 5 m water depths with 169 g afdw/m² and 400,000 individuals. Figure 7 shows the water depth dependent development of biomass and abundance (no. of individuals) during different periods.

After an exposure of 246 days, 28 taxa were recorded, dominated by crustaceans, polychaetes and molluscs. Species number was highest at the base (22 species), and decreased towards the surface (10 species).
Figure 7 depicts the vertical distribution of biomass and abundance after this period. *Mytilus edulis* was the most abundant organism, with between 265,000 and 670,000 individuals per m², increasing by a factor of two as compared to the first sampling. It overgrew the barnacles, which eventually decreased in numbers. The biomass of the blue mussel increased to up to 1 kg afdw/m² in the surface layer. Barnacle biomass increased as well, but remained a factor of 10 lower than the mussels.

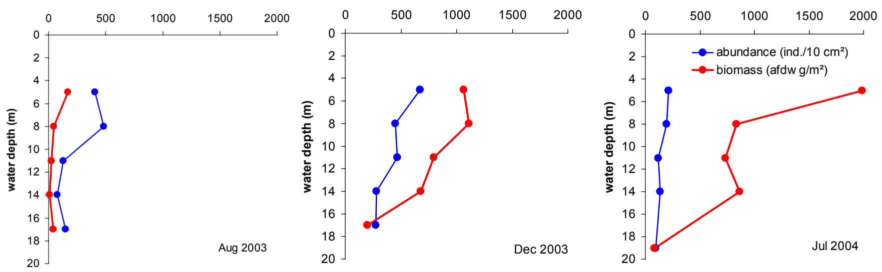

Fig. 7. Development of abundance (individuals per 10 cm²) and biomass (afdw per m²) after 143 (left), 243 (middle) and 470 (right) days of exposure of steel plates in different water depths

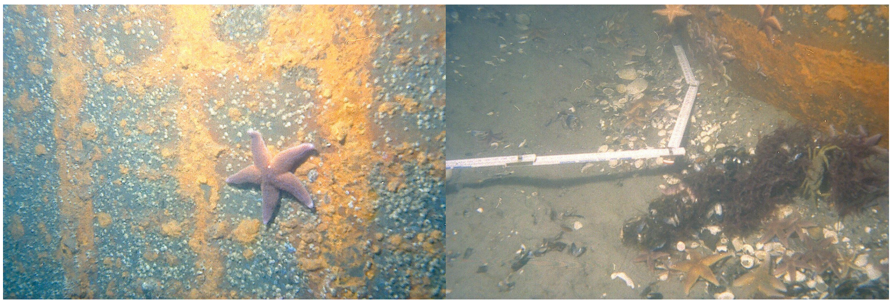

Fig. 8. Settling patterns on the bottom cylinder after 264 days. The starfish (*Asterias rubens)* becomes more frequent on the cylinder walls (1-2 individuals per m²). The left photograph shows that reddish rust flakes have formed, and are starting to peel from the wall, with the attached organisms. The right picture shows the basement of the cylinder, where the currents have created a trough by sediment erosion which has started to fill with the debris from the cylinder walls, thereby attracting large predators, such as crabs (*Carcinus maenas*) and starfish. The larger shells of some mussels have been washed out of the sediment

It is evident, that the settling density, abundance and biomass are much higher in the surface mixed layer then at the base of the installation. This is probably also effected by increasing predation pressure by large predators like *Asterias rubens* and *Carcinus maenas*, as can be seen in Fig. 8.

The values in the bottom water levels are lower by a factor of five. The overall colonisation numbers are extremely high, considering the short exposure time. Maximal abundance after 246 days is in the range of 700,000 individuals m^2, with a biomass of 1.1 kg afdw, equivalent to about 18 kg of wet weight per m^2.

In July 2004, the succession on the bottom steel cylinder was further advanced. There was hardly any space left not covered by organisms. The abundance here was dominated by polychaetes (*Polydora ciliate*) and barnacles (*Balanus crenatus*). Unlike on the steel plates, blue mussels could be detected at the steel cylinder only in the juvenile stage. This difference can be attributed to the predation pressure of crabs and starfish, for which the bottom structure was much easier to access than the steel plates suspended in mid-water. They were also favoured by the salinity conditions in the bottom water, where they met their salinity dependent distribution boundaries. Other frequent predators of blue mussels observed in video sequences were 1 - 2 year old species of Baltic cod, which found excellent shelter and prey in and around this structure.

The abundance of *Balanus crenatus* was highest, with about 40 % of all species and 90 % of total biomass. At the surface substrates, this species was replaced by the brackish (*Balanus improvisus*). The scratch samples at the cylinder yielded 15 different taxa.

On all substrates, a total of 41 macro-zoobenthos taxa could be detected after 470 days of exposure. With nine and twelve different species, crustaceans and polychaetes dominated; molluscs and hydrozoans followed with five species each.

The biomass at the deeper levels seemed to have reached an equilibrium after three months, but the increase continued at the surface (Fig. 9). This was due to the growth of *Mytilus edulis*, which reached a biomass of close to 1.9 kg afdw per m^2 and 95 % of total biomass at the 5 m depth level.

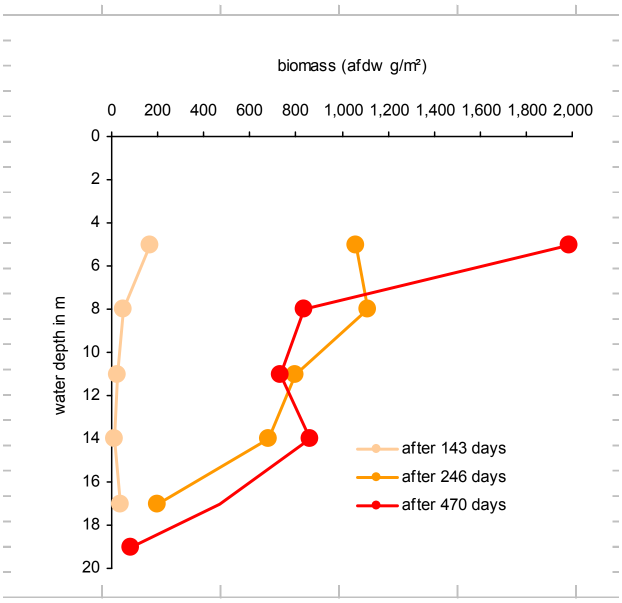

Fig. 9. Development of biomass in different water depths after 143, 246 and 460 days of artificial substrate exposure (from April 2003 to July 2004)

In order to estimate the dependence of colonisation dynamics on the seasonal positioning of the experiments, three new sets of steel tiles were installed in July 2004, and the first of them retrieved and analysed after 177 days in January 2005. The primary exposure period for the first experiment was during summer, while the second set collected species settling in autumn and winter. The differences between the experiments were not significant concerning species diversity. In the first study, 18 taxa were recorded after 143 days; in the second, 20 taxa after 177 days. In both cases, molluscs, polychaetes and crustacean dominated, but while the order of dominance was crustaceans first, then molluscs, and finally polychaetes during summer exposition, the autumn ranking was polychaetes first, then crustaceans, and finally molluscs (Fig. 10).

More significant differences between the experiments could be recorded in relation to macro-fauna abundance and biomass development. The deployment of substrates in a later seasonal phase led to a faster increase in biomass and abundance. The biomass on these substrates reached the one year level of the earlier depositions already after 173 days, and the values at that time were higher by a factor of between 3 and 45, depending on water depth. A comparison is shown in Fig. 11.

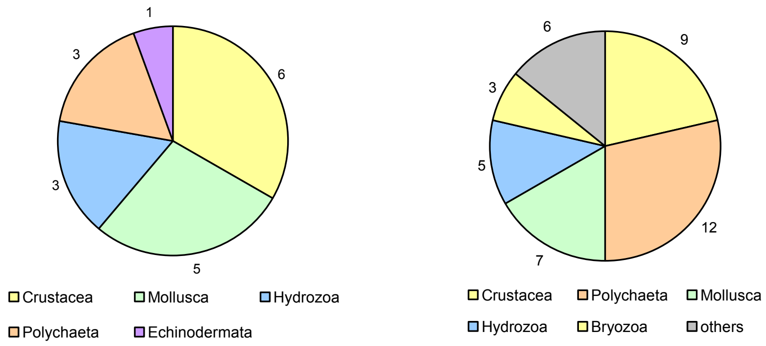

Fig. 10. Succession of macrobenthic diversity on artificial hard substrates (steel plates) after summer exposure from April to August 2003 (left graph) and after winter exposition from July 2004 to January 2005 (right graph). The substrates were retrieved after 143 and 173 days, respectively

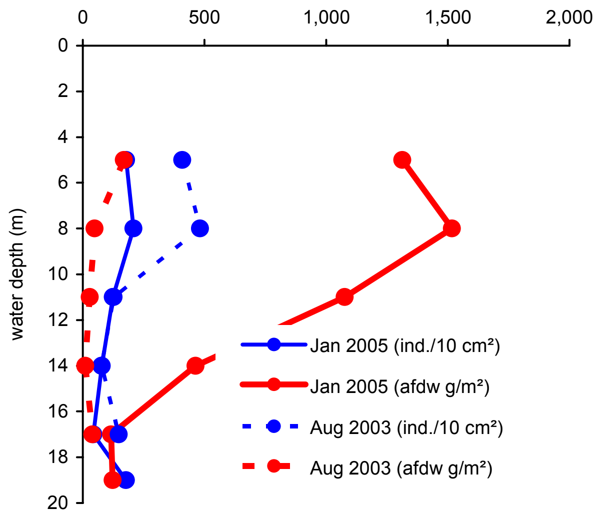

Fig. 11. Abundance and biomass development on substrates with approximate the same exposure time (177 days, Jul. 2004 to Jan. 2005, and 143 days, Apr. 2003 to Aug. 2003), but different seasonal starting dates (July vs. April). Note, that biomass (afdw) is given on a m² base, whereas abundance values are based on 10 cm²

Evidently, the dynamics of colonisation are, at least in the first phase, highly dependent on the seasonal point of deployment of the installation. Figure 12 provides a visual impression on the settling dynamics after retrieval of the substrates from different depths in January 2005.

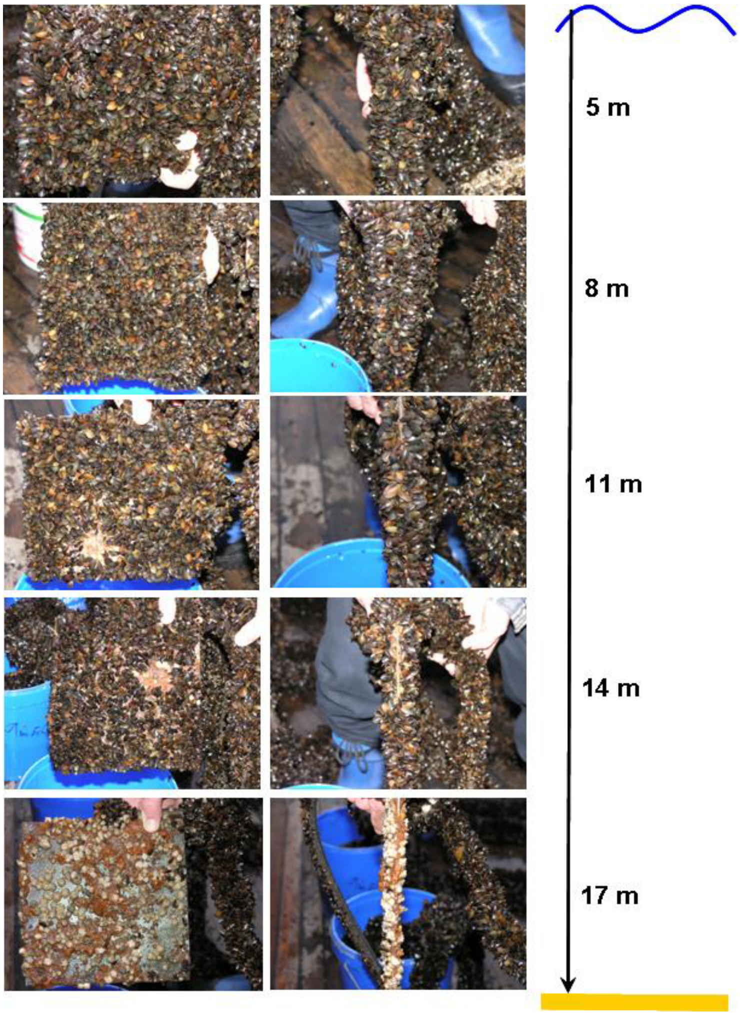

Fig. 12. Epibenthos on settling substrates in different water depths after 177 days of exposure in January 2005. The front and side views of the steel tiles show the increased density of organisms at water levels near the surface

13.3.3 Impact on Sediment Structure and its Living Community

A secondary effect of offshore structures on benthic distribution patterns is exerted by the hydrodynamic changes of turbulence and currents at the base of installations. Figure 13 shows the sediment thickness around the test cylinder after a few months of deposition and an underwater picture of more than 40 cm deep erosion troughs after 246 days.

After this stage, the trench was consolidated by larger shell pieces, and its depth stabilized at 40 cm. The trough then slowly began to fill up with organic debris supplied by flakes of rust with attached organisms from the upper part of the cylinder. Initially, this rich organic load attracted predators (Fig. 14), but later, it created oxygen deficiency, even in the well aerated sediment area. Finally, the organic overload promoted microbial sulphate reduction and the formation of toxic hydrogen sulphide. Figure 14 shows the immediate vicinity of the cylinder after 697 days, with white mats of sulphide oxidising bacteria dominating the picture.

The development of macro-benthic (endo- and epi-benthic) species in the sediment surrounding the steel cylinder was monitored during the entire period of the experiment. In general, the faunistic composition was similar to that of the long term reference station (Stn. 030) nearby. In the beginning, species composition and frequency of appearance were comparable to the reference, whereas in a later stage, differences started to develop. After an exposure of 417 days, no significant difference in diversity and biomass could detected, while after 697 days the effects of the increasing input of biomass from the higher parts of the cylinder began to affect the infauna of the surrounding sediments. Up to that date, the overall effect on the integrated biomass around the cylinder had been positive due to the increase in food supply. Negative trends due to the increased spread of anoxia from the immediate base of the pile were at that time not yet detectable for the wider surrounding area. The quantitative analysis of endo-benthos data was, however, generally hampered by the small number of parallel samples, which could be taken around our comparatively small model substrate, without changing the environment itself. Taken into account the large natural spatial heterogeneity of endo-benthos in such sediments, the results cannot satisfy statistical standards. At this point, the limits of small model substrates have obviously been reached and the necessity for a full size research structure becomes obvious.

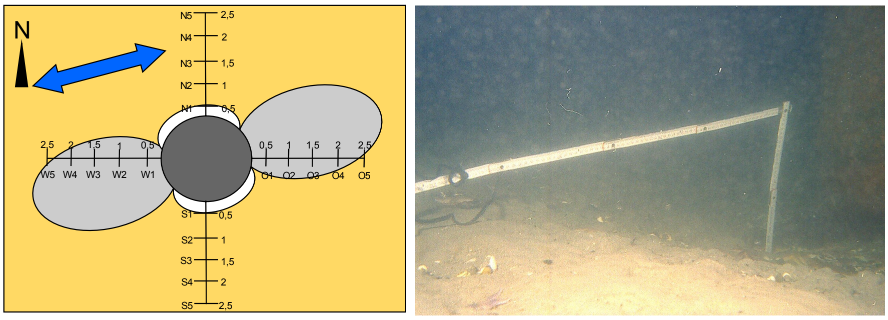

Fig. 13. Direction and spatial extent of sediment erosion (white area) and deposition (grey area) around the test cylinder (dark grey). After 246 days, an erosion depth of more than 40 cm at the cylinder walls could be recorded. The spatial pattern and intensity of the erosion/redeposition process is closely related to main direction of current and speed of current

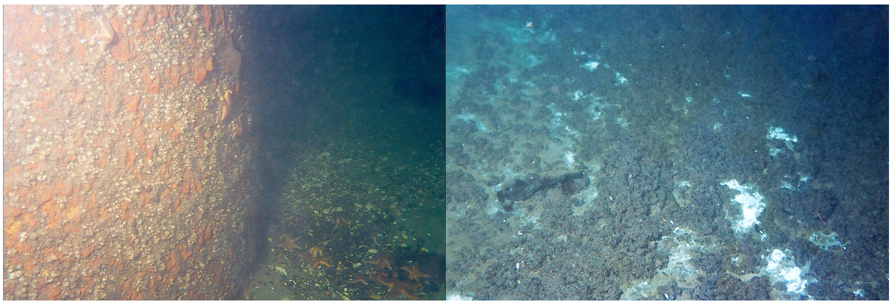

Fig. 14. Succession of biota at the base of the cylinder. After 417 days of exposure (left picture), predators gather at the base, profiting from the first organic material dropping from the upper part of the structure. After 697 days, (right picture) the organic load exceeds the oxygen supply, and the sediment turns anoxic

13.4 Discussion

As a primary effect of the installation of steel structures in the western Baltic waters, a general increase in diversity, abundance and biomass of benthic macro-fauna on the new substrate over time was observed. It is important to note, that the dynamics of colonisation and biomass development are highly dependent on the point in time of the first deployment within the seasonal cycle of larval settlement. The species diversity was dominated by the taxonomic groups of crustaceans, polychetes and molluscs. The total number of species increased during the observation period to 41, with still increasing tendency. The inverse relationship between diversity and biomass with water depth is striking, and is depicted in Fig. 15.

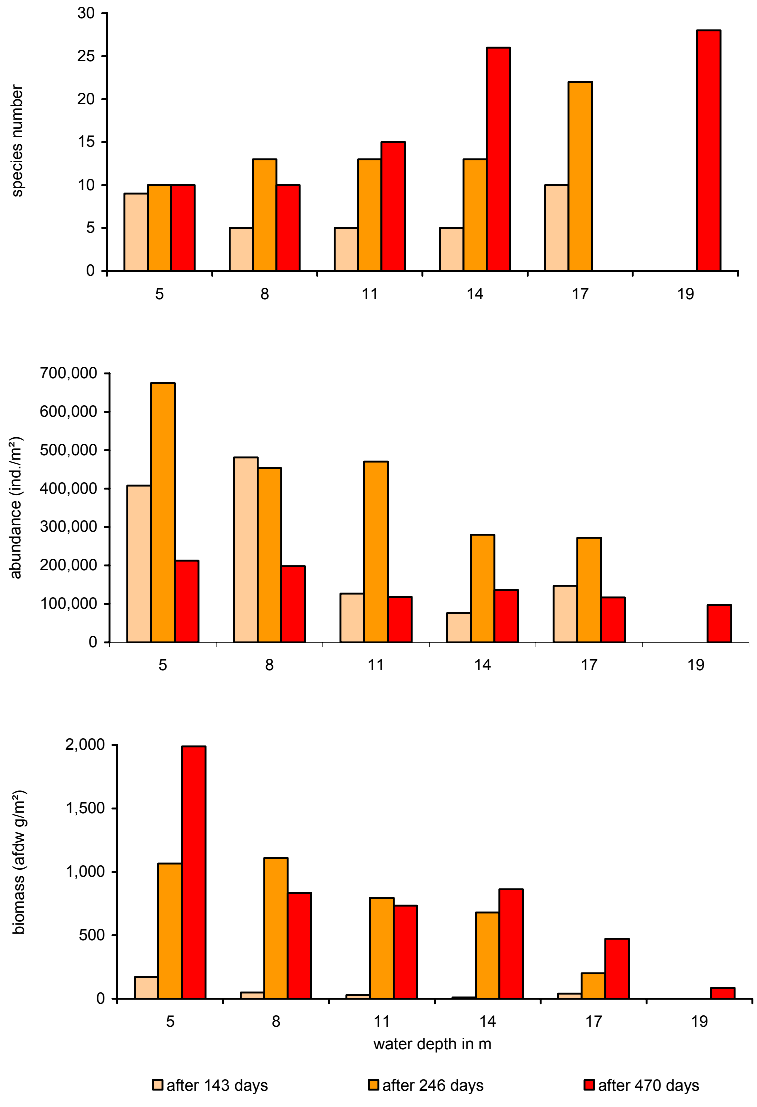

Fig. 15. Temporal development of species diversity, species abundance and biomass during the colonisation experiments at different water depths

Due to missing comparable substrates at the same water depth of a wider surrounding area, the species composition at the model pile is very different from the more endo-benthic species dominated sandy sediments of the Mecklenburg Bight or the Darss Sill (Zettler et al. 2000, 2004). As the vertical extension of the water column coincides with the salinity gradient (Fig. 5), the general decline of species diversity towards poorer brackish conditions (Remane 1955) is mirrored in this development. The increased maturity of the macro-benthos populations at all depths is reflected in the return of the abundance from a steep increase in the first phase to lower numbers, that develops along with the size structure of a mature population (Rumohr et al. 1996). In the context of this development, the biomass in the deeper layers also reached an equilibrium level after 246 days. An exception was the surface population, which increased its biomass through the last sampling period.

The fact that the increase in abundance and biomass is highest at the upper parts of the installations is most probably due to two reasons. The availability of food of good quality and quantity is much higher in the surface mixed layer, where filter feeders can take it out of an abundantly producing pelagic system. The inhabitants of the lower levels of the frame have to content themselves with food that has already left the productive cycle, is less in mass and less nutritive. The feeding process in the vicinity of the sediment may, at the measured current speeds, often be inhibited by large amounts of resuspended mineralic particles which further reduce the nutritive value of the prey. A second factor is the presence of large benthic predators, like starfish, crabs and juvenile cod, which are all restricted to the lower water levels, due to the low saline conditions at the surface. So the observed depth gradient in biomass development of epifauna is easy to explain, and in the first phase of development poses no environmental problems. However, in the more advanced states of fouling at structures, precisely these conditions lead to severe environmental drawbacks, specifically under stratified Baltic conditions.

If, due to the inhibiting surface salinities, predators like starfish, crabs and cod are absent or barely active, but the prey, in this case mainly blue mussels, is not affected, then the typical biological regenerative cycle does not work. There is no biological limit to *Mytlis edulis* growth, so that no biomass equilibrium can develop. At other natural hard substrates, space would sooner or later become the limiting factor, and the growth rate would then adapt. On uncoated steel structures, there is a continuous provision of new substrate whenever the population size and the weight of the epifauna reaches a critical value and disengages the rust flake from the steel surface. This sequence leads to continuous exponential growth and biomass formation on the upper part of steel structures. The biomass is then transferred to the base of these structures as attachment to the large rust flakes. Due to the great weight, this transfer is rapid, and restricted to the immediate surroundings of the piles. In a first phase, the high organic input is appreciated, used and converted by predators, which tend to accumulate at the base (Fig. 14, sketch Fig. 16). In this process, an imbalance between the local supply of organic mater and the availability of oxygen will develop. At the onset of anoxia, microbial metabolism will dominate the decomposition, and oxidants other than oxygen will be used (Fig. 14). As sulphate is present in seawater in large quantities, sulphate reduction very quickly becomes the primary decompositional pathway. The resulting formation of hydrogen sulphide, as a dissolved gas, which is toxic to higher organisms by inhibiting their respiratory chain, initiates a vicious cycle in the enclosed bottom layer which ultimately results in a situation which is already in a critical state in many areas. As a result of increased surface productivity and export of food to the sediments, the macro-fauna biomass has generally increased over the past decades in the southern Baltic (Cederwall and Elmgren 1980, Cederwall et al. 2002, Rumohr et al. 1996) and with it, the demand for oxygen by the sediments (Karlson et al. 2002, Powilleit and Kube 1999, Weigelt and Rumohr 1986). As frequent stratification prohibits additional supply of oxygen by vertical mixing, the benthic systems in these stratified areas have already drifted towards oxygen deficiency over the past decades. If this imbalance is further aggravated by additional input of organic matter, and free hydrogen sulphide starts to spread in the bottom water, large stocks of benthic biomass will be poisoned, and will likewise be subject to anaerobic decomposition, resulting in the emission of even higher amounts of sulphide. If this self powered process gains momentum, a whole marine region can turn into an area devoid of higher animal life. Such a process was observed in the Kiel Bight at the beginning of the 1980s (Weigelt and Rumohr 1986) and in the western Pomeranian Bight in 1994, where just a short term extension of thermal stratification caused a sediment area of several square kilometres to turn sulphidic (Powilleit and Kube 1999). The implications for economy like fisheries and tourism were grave, and the macro-fauna required about half a decade to recover to normal diversity and biomass conditions.

Our model-pile is situated in a better aerated and weaker stratified environment than the areas that are currently disclosed for wind park planning. It is collecting slower growing organic material from far beneath the surface mixed layer, where access for larger predators was possible and it was of a considerably smaller size, that the planned constructions. Nevertheless, the effects became obvious after a short period. Therefore, our observations of the successive negative development in the benthic environment around this test pile led us to assess the construction of large numbers of adjoining full size piles in closer vicinity to the Danish Sound as a potential threat to the benthic habitat in this area.

From the data gathered in our experiment, we calculated the increase of biomass per unit area after the deployment of substrates to range between the factors of 14 and 140. Similar results have been found at Danish installations in the North and Baltic Seas (Birklund and Petersen 2004, Leonard and Pedersen 2004), and in artificial reef systems in Polish waters (Chojnacki 2000). Studies at the Dutch coast have shown that stability of the fouling community is reached after a period of five to six years, which can be extended by storm events and other disturbances (Leewis et al. 2000, Leewis and Hallie 2000).

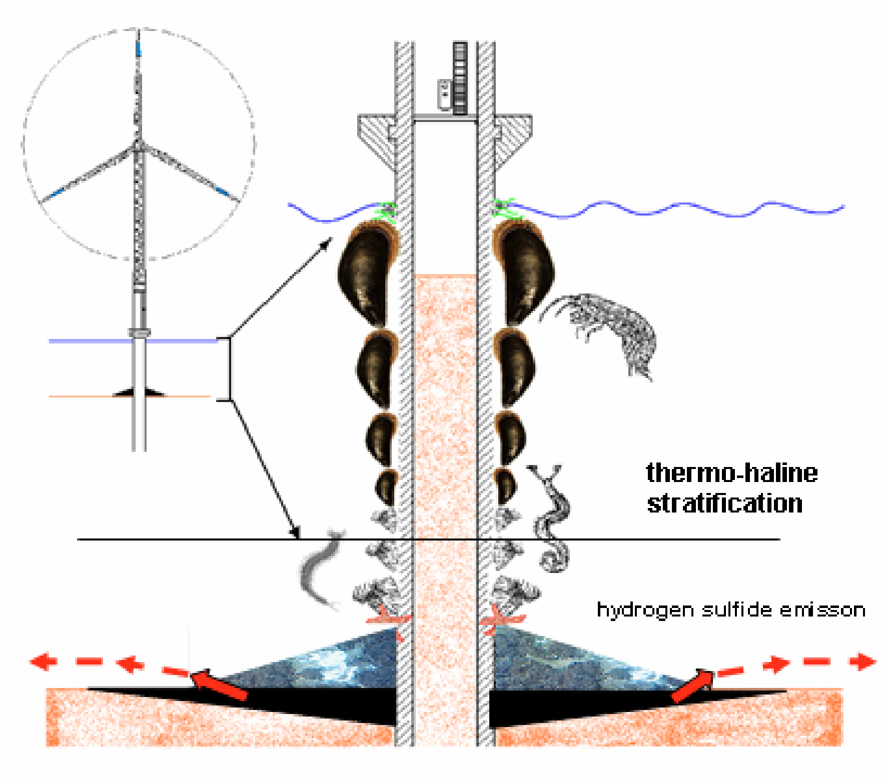

Fig. 16. Sketch of the projected colonisation dynamics on a full-sized wind turbine pile in the western Baltic, based on the results of the present study

The present study shows that in comparison to other areas, biomass increase per unit time in the western Baltic is much higher than elsewhere (Table 1). Biomass decreased with water depth, but was still considerably higher than the initial value of the soft bottom community (see reference station in Table 1).

Taking into consideration the development of biomass on the steel tiles and the bottom cylinder, a steel tube (mono-pile construction) of 2 m diameter in a water depth of 20 m would yield a biomass (wet weight) of 150 kg after 143 days and 1.6 tons after 246 and 470 days. Assuming a pile (tripod) to have a threefold colonisation area in all, and a mid-sized wind farm to have 100 turbines (actual planning in the Baltic calls for between 20 and 400 per farm), the initial annual yield per wind farm comes to about 500 tons. If this is the yearly equilibrium growth rate, balanced by the loss of biomass due to flake detachment, this amount is selectively deposited in small sediment areas, and would certainly have enough impact to start the reaction chain described above and indicated in Fig. 16.

Table 1. Total biomass (wet weight) at the reference station, the pile model (after one year of exposure) and literature values from other pile structures in the North and Baltic Seas

Pile structures	wwt in [g/m²]
5 m	20,000
8 m	15,000
11 m	11,500
14 m	13,000
17 m	4,000
19 m	2,000
Monitoring (030), 2003-2004, reference station	140
Nysted, Baltic, Pile after 1 year[a]	3,000
Nysted, Baltic, Mast after 6 years[a]	14,500
Horns Rev, North Sea, Pile after 1 year[b]	2,800

a = from Birklund and Petersen (2004). Wet weights were calculated from dry weights by a factor of 2.55

b = from Leonard and Pedersen (2004)

Strategies for mitigation of these problems include the proper distancing of the piles to prohibit the accumulation of single-pile effects to a combined area. Another strategy, which might even be economically sustainable, is to let the mussels grow on removable substrates on the upper part of the piles and harvest them.

Then the succession of adverse processes would be terminated right at the beginning and turned into a positive direction. At the moment, it cannot be predicted how a pile or a set of piles could influence vertical turbulent mixing processes and thus increase the oxygen supply to the sediments. To increase the vertical oxygen transport by pile design or other technical means and hence foster sediment aeration as a countermeasure would certainly lead to local improvements at the hot spot areas. It would, however, initiate a large scale density change of the bottom water by mixing in warm, less saline water. This could in turn prevent the inflowing water from entering the deeper Baltic basins and aerating them.

All these examples show that Baltic problems related to offshore structures are highly diverse from oceanic or North Sea situations, due to a fundamentally difference in physical transport conditions in this sea. Changes in basic transport patterns in one key locality of the delicate transition zone of the western Baltic may propagate through the ecosystem on a basin-wide scale. We therefore believe that for a proper assessment of the ecological effects of large wind farms in the stratified waters of the western Baltic, it is necessary to take all of these processes into consideration, study and balance them, and model the resulting impact on a basin scale.

References

Birklund J, Petersen AH (2004) Development of the fouling community on turbine foundations and scour protections in Nysted Offshore Wind Farm, 2003. Energi E2 A/S Report June 2004: 39 pp

Cederwall H, Elmgren R (1980) Biomass increase of benthic macrofauna demonstrates eutrophication of the Baltic Sea. Ophelia 1: pp 287-304

Cederwall H, Diziulis V, Laine A, Osowiecki A, Zettler ML (2002) Eutrophication and related fields: Baltic Proper: benthic conditions. In: Fourth periodic assessment of the state of the marine environment of the Baltic Sea area 1994-1998. Baltic Sea Environm Proc 82B: pp 0-55

Chojnacki JC (2000) Experimental effects of artificial reefs in the southern Baltic (Pomeranian Bay). In: Jensen AC et al. (eds) Artificial Reefs in European Seas. Kluwer Academic Publ, pp 307-317

Feistel R, Nausch G, Matthäus W, Hagen E (2003) Temporal and spatial evolution of Baltic deep water renewal in spring 2003. Oceanologia 45 (4): pp 623-642

Gill AB (2005) Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J Appl Ecol 42:605-615

Karlson K, Rosenberg R, Bonsdorff E (2002) Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavian and Baltic waters – a review. Oceanogr Mar Biol Annu Rev. 40:427-489

Leewis R, Hallie F (2000) An artificial reef experiment off the Dutch coast. In: Jensen AC et al. (eds) Artificial Reefs in European Seas. Kluwer Academic Publ, pp 307-317
Leewis R, van Moorsel G, Waardenburg H (2000) Shipwrecks on the Dutch continental shelf as artificial reefs. In: Jensen AC et al. (eds) Artificial Reefs in European Seas. Kluwer Academic Publ, pp 307-317
Leonard SB, Pedersen J (2004) Hard bottom substrate monitoring Horns Rev Offshore Wind Farm. Annual Status Report 2003. Elsam Engeneering
Powilleit M, Kube J (1997) Effects of severe oxygen depletion on macrobenthos in the Pomeranian Bay (southern Baltic Sea): a case study in a shallow, sublittoral habitat characterised by low species richness. J Sea Res 42:221-234
Remane A (1955) Die Brackwasser-Submergenz und die Umkomposition der Coenosen in Belt- und Ostsee. Kieler Meeresforschung 11: pp 59-73
Rumohr H, Bonsdorff E, Pearson, TH (1996) Zoobenthic succession in Baltic sedimentary habitats. Arch Fish Mar Res 44:179-214
Weigelt M, Rumohr H (1986): Effects of wide-range oxygen depletion on benthic fauna and demersal fish in Kiel Bay 1981-1983. Meeresforschung 31:124-136
Zettler ML, Bönsch R, Gosselck F (2000) Das Makrozoobenthos der Mecklenburger Bucht – rezent und im historischem Vergleich. Meereswissenschaftliche Berichte 42:144 pp
Zettler ML, Röhner M (2004) Verbreitung und Entwicklung des Makrozoobenthos der Ostsee zwischen Fehmarnbelt und Usedom – Daten von 1839 bis 2001. In: Bundesanstalt für Gewässerkunde (ed) Die Biodiversität in Nord- und Ostsee, Vol 3. Report BfG-1421, Koblenz: 175 pp