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Experiments on the survival of six brackish macro-invertebrates from the Baltic Sea after dredged spoil coverage and its implications for the field

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Abstract

Physical disturbance by disposal of dredged materials in estuarine and coastal waters may result in burial of benthic fauna. Survival rates depend on a variety of factors including the type and amount of disposed materials and the life style of the organisms. Laboratory burial experiments using six common macrobenthic invertebrates from a brackish habitat of the western Baltic Sea were performed to test the organisms' escape reaction to dredged material disposal. Experimental lab-results were then extrapolated to a field situation with corresponding bottom topography and covering layer thicknesses at experimental field disposal study sites. Resulted survival rates were then verified by comparison with results of an earlier field study at the same disposal sites.

Our experimental design in the lab included the disposal of two types of dredged material (i.e. 'till' and 'sand/till mixture') and two covering layer depths (i.e. 10 – 20 cm and 14 – 40 cm). All three bivalves *Arctica islandica* (Linnaeus), *Macoma balthica* (Linnaeus), *Mya arenaria* (Linnaeus) and the polychaete *Nephtys hombergii* (Savigny) successfully burrowed to the surface of a 32 – 41 cm deposited sediment layer of till or sand/till mixture and restored contact with the overlying water. These high escape potentials could partly be explained by the heterogeneous texture of the till and sand/till mixture with 'voids'. The polychaete *Bylgides* (*Harmothoe*) *sarsi* (Malmgren) successfully burrowed through a 16 cm covering layer whereas the polychaete *Lagis koreni* (Malmgren) showed almost no escaping reaction. No general differences in escape behaviour after burial were detected between our test species from the brackish habitat and those reported in the literature for the same species in marine environments. However, a size-dependence in mobility of motile polychaetes and *M. arenaria* was apparent within our study. In comparison to a thick coverage, thin covering layers (i.e. 15 - 16 cm and 20 cm) increased the chance of the organisms (*N. hombergii* and *M. arenaria)* to reach the sediment surface after burial. This was observed for the other test species. While crawling upward to the new sediment surfaces burrowing velocities of up to 8 cm d^{-1} were

observed for the bivalves and up to 20 cm d^{-1} for *N. hombergii*. Between 17 and 79 % of the test organisms showed burrowing activity after experimental burial. The survival rate (defined as the ability to regained contact with the sediment surface) ranged from 0 to 33 %, depending on species and on burial depth. The organisms reached the sediment surface by burrowing (polychaetes and bivalves) and/or by extending their siphons to the new sediment surface (bivalves). The extrapolation of laboratory survival rates to the two disposal sites was obtained based on the *in situ* thicknesses of the dredged spoil layers measured by multi-beam echo sounder. This resulted in total average survival rate estimates for the test species of 45 and 43 % for the two disposal sites. The results obtained during the laboratory tests and the following extrapolation to the field were verified by the range of results from a previous field study, using grab sampling shortly before and after a disposal event in June 2001. The effect of dredged material disposal on the tested Baltic Sea benthic macrofauna was assessed by extrapolating the verified laboratory results to the field.

1. Introduction

Dredging and the disposal of dredged material constitute an important problem in coastal zone management worldwide (e.g. OSPAR 1998). Although, the disposal of dredged material amounts to only about 0.01 % of the man-induced disturbance of the marine seafloor – in contrast fishing activities make up about 54 % of the anthropogenic disturbances (de Groot 1996) – the high concentration of the disposal activities in the relatively small areas occupied by the world's estuaries and near-shore coastal regions means that it has a significant environmental impact.

The disposal of dredged material is usually associated with the covering of the marine seafloor, in which especially the thickness of the deposited sediment layer and the type of sediment are highly relevant for the survival of the benthic invertebrate community (e.g.

Maurer et al. 1986, Essink 1999). The “fatal depth” sensu Essink (1999), describes the limit for the different species to survive burial by burrowing to the new sediment surface. The fatal depth can range from a few millimetres to almost one metre (e.g. Maurer et al. 1986, Bijkerk 1988, c.f. Essink 1999, Schratzberger et al. 2000) and depends largely on the individual's age, size, motility, and its tolerance to oxygen deficiency and sulphide concentrations. The persistence of the covering sediment layer, its depth, the type of the deposited material, and the water temperature are also limiting factors (e.g. Essink 1999). Until now only a few results from laboratory experiments testing the escape behaviour of marine invertebrates have been published (e.g. Kranz 1974, Maurer et al. 1986, Chandrasekara and Frid 1998, Bijkerk 1988, c.f. Essink 1999, Hinchey et al. 2006) and *in situ* (Nichols et al. 1978, Norkko et al. 2002) investigations are even less well documented. The published investigations reveal that the highest tolerances to sudden coverage with sediment can be found in some large and highly motile polychaetes (e.g. *Nereis* sp. and *Nephtys* spp.) with maximum survivable sediment covers of 90 cm for sand and 60 cm for mud. These findings are supported by field studies which showed that different *Nephtys* species were the only survivors at several dredge spoil disposal sites (Howell and Shelton 1970, McGrorty and Reading 1984, Saila et al. 1972). In bivalves highest ‘fatal depths’ have been found in species having a long siphon with which they pipette their food from the sediment surface (e.g. *Macoma balthica*) or which feature a high motility within the sediment due to their pronounced muscular foot. Nevertheless, all studies thus far revealed high differences for maximally tolerable sediment cover, and, even more important, most of these studies have been carried out under marine conditions (salinity equal or above 30 PSU). Under brackish conditions (salinities below 15 PSU), as are common in estuaries around the world or in brackish inland seas like the Baltic Sea, only single experimental investigations have been performed yet (Hinchey et al. 2006). Here body sizes of marine invertebrates are usually reduced and shells of clams may be more fragile (Remane 1934, Remane and Schlieper 1971), and therefore potentially influence the species' tolerance to coverage by dredge spoil.

In the present study we conducted laboratory burial experiments with several species typically found at the experimental 'DYNAS disposal site' in Mecklenburg Bay (western Baltic Sea) and exposed them to different covers of glacial till and a sand/till mixture. Glacial till is a characteristic component of western and southern Baltic surface sediments (e.g. Lemke et al. 1994). Approximately 300,000 t/a dredged material is deposited on the sea floor during maintenance dredging of the navigational waterways and harbour construction works in the German Baltic region. Even combined with sand this material is quite different from the pure sand, mud or clay evaluated in all previous studies, as it is very compact and after disposal appears in clumps of different sizes and shapes (up to approximately 4 cm in length) creating an inhomogeneous covering layer with some 'voids' which can be used by many invertebrate species as a refuge. In order to estimate survival rates of the dominant macrofauna species under field conditions we combined our findings from the laboratory experiments with multi-beam echo sounder measurements of the thickness of deposited layers on the sea floor after dredged material disposal at two experimental disposal sites close-by in June 2001 ('DYNAS disposal sites'; for further information see this volume or http://www.io-warnemuende. de/projects/dynas/). Furthermore survival rates from a field study including two grab sampling campaigns from the above mentioned disposal sites (Powilleit et al. 2006) were used to verify the experimentally derived survival rates in the present study.

The aims of the present study are: (1) to experimentally determine species-specific survival rates of six common brackish invertebrates after burying with two different types of typical covering material common in local dredged material disposals (till and sand/till mixture), and compare these to published data from fully marine habitats, (2) to extrapolate survival rates to an *in situ* situation at the 'DYNAS disposal sites', where elevation levels of surface sediments were measured after the disposal event in August 2001, and (3) to compare experimentally derived survival rates with rates determined from two grab sampling campaigns shortly before and shortly after the above mentioned dredged material disposal.

2. Material and Methods

2.1. Sampling

Macrofauna for the laboratory experiments was collected during several cruises of RVs 'Alexander v. Humboldt' and 'Gadus' in the Mecklenburg Bay (western Baltic Sea) between January and July 2001. The species selected for the experiments were among the dominant species of the local benthic invertebrate community and were partly different in terms of life style, mode of locomotion, and feeding mode. They included the infaunal bivalves *Arctica islandica*, *Macoma balthica*, *Mya arenaria*, and the polychaetes *Bylgides* (*Harmothoe*) *sarsi* (scale worm – epibenthic predator), *Lagis koreni*, *Nephtys hombergii*. Specimens of *A. islandica* were collected by dredging, whereas all other species were caught by a Van Veen grab (75 kg; 0.1 m²) and were separated from sediments with a 1.0 mm sieve. Sorting and taxonomic determinations were accomplished under magnification with a stereo microscope in the laboratory.

Two sediment types were used for our experiments: a fine uncontaminated till (median grain size 8 µm) which occurred as compacted clumps of different sizes, and a mixture of fine sand, till, coarse sand, and mud (median grain size 220 µm, hereafter referred to as 'sand/till mixture') both dredged from a local sediment trap close to the entrance of Rostock harbour (Friedrichs 2003). These two types of sediments were also used as disposal material in the *in situ* DYNAS dredged material disposal experiment at two sites in the south eastern part of Mecklenburg Bay (19 m) (Powilleit et al. 2006). Additionally to each of these sediment types a 1 mm sieved, defaunated fine sand originating from a sandy sediment (16 m water depth) near the sediment trap was added in a ratio of 2:1 to obtain the necessary amounts of covering material.

2.2. Experimental setup and statistical analyses

Laboratory experiments were carried out in perspex tubes of 10 cm inner diameter, which were open at the top and submerged in a closed large-volume tank containing aerated seawater of 4 °C and a salinity of 13.5 PSU (according to the *in situ* situation in January during collection of bivalves). The experiments were performed in the dark corresponding to the natural conditions at the disposal sites. The perspex tubes were filled with an initial 6 to 10 cm substratum layer of the same defaunated fine sand described earlier, upon which the test species were placed. Prior to the experiments test organisms were cultivated for up to four month in the laboratory and adapted to experimental conditions. The experimental design consisted of three replicates with two types of dredged material and with two covering layer thicknesses each. Thereby each species was treated separately (i.e. results based on 72 single tubes, 12 tubes per species). Depending on animal sizes 1 to 5 specimens per taxa were placed into each Perspex tube. One week after adding the test specimens the two types of dredged material were carefully disposed into the tubes. Table 1 summarises the experimental configuration including total numbers of specimens, numbers of test species per tube, body size, and covering layer depths.

Based on the expected motility of the organisms, the duration of the experiments was set to 28 days for the bivalves *A. islandica* and *M. arenaria*, to 38 days for *M. balthica*, and to 7 days for the polychaetes. Due to their expected lower tolerances to burial, reduced covering layer depths were chosen for the polychaetes *B. sarsi* and *L. koreni* (table 1). After covering with the dredged material, a daily photographic documentation of the sediment surface was completed to assess the time when a test species reached the surface by burrowing through the covering layer. In tubes with bivalves, weekly observations of laterally visible burrow structures were made to evaluate burrowing velocities, whereas these observations were not possible in most of the polychaete tubes.

After the end of the experiments, the sediments were extruded from the Perspex tubes and sliced into 1 cm sections. Living specimens and their positions and orientations were monitored. Burrowing distances were evaluated for the respective positions of polychaete heads (*B. sarsi, N. hombergii*) or tube tip (*L. koreni*) and anterior parts of bivalve shells. Polychaete sizes and bivalve shell lengths were measured to the nearest mm with a calliper rule. Three types of organism responses to burial were classified: ‘no locomotion’, burrowing without reaching the sediment surface (‘burrowing’), and complete recovery (‘reaching the sediment surface’). The latter response included cases in which siphon tips of bivalves reached the sediment surface. Only complete recovery (regaining contact with the new sediment surface) was defined as survival. Finally specimens were mechanically tested for survival.

Burrowing velocities were calculated (cm d^{-1}) for all test species by using either visible burrowing structures during the experiments or information on burrowing distances at the end of the experiments. Due to the limited information for the polychaetes and *A. islandica* more detailed analyses were only possible for *M. arenaria* and *M. balthica*. The non-parametric Mann-Whitney-U test was applied to test differences between burrowing velocities in the two different disposal materials till and sand/till mixture. Linear regression analyses were performed to test for significance between individual shell lengths and either burrowing velocities or burrowing distances. Statistics were conducted using the SPSS v13.0 software package.

2.3. Multi-beam echo sounder measurements at the ‘DYNAS disposal sites’

The bed relief of the surveyed area at the ‘DYNAS disposal sites’ was mapped several times by coupling MBES-technique with high accuracy positioning. Bed detection was carried out by means of the multi-beam echosounder EM 3000™ from Simrad-Kongsberg. It operates at a frequency of 300 kHz with a ping repetition rate of 15 Hz. The nominal apex angle is 1.5° along-track and 120° across-track during transmission, and 30° along-track and 1.5° across-track during receiving. This results in an array of 127 individual beams with an effective 1.5° • 1.5° apex angle per single beam arranged with some overlap over an arc of 120°. A gyro-compass (Anschütz 20™, 4™) and a motion sensor (DMS-05™, TSS UK LTD.) monitored the movement of the vessel to compensate for the orientation of the sonar head at each time incident. Three dimensional ship positions were accurately determined by real-time kinematic global positioning (Trimble 4000 ssi™). Vertical sound velocity profiles were recorded daily. The resulting soundings were compensated for ship motion and ray-refraction. Positions and altitudes are output in World Geodatic System 1984 (WGS 84). For mapping horizontal positions were projected on to Universal Transverse Mercator 32 (UTM32) map projection and altitudes transformed with respect to the normal chart datum. The individual measurements were further processed in a digital terrain model (DTM) with a grid size of 1 m × 1 m. Details of the methods and error estimations are described elsewhere (Stockmann et al., this volume).

For a precise determination of the thickness of the deposited layer, bathymetric surveys were carried out directly before and after the disposal. Due to rough wave conditions and subsequent technical problems these data had to be discarded, however. The first successful survey was completed on August 20 and 21, 2001, about two months after the disposal. As typical time-scales for morphological development are on the order of years (Stockmann et al., this volume), the observed bed features of the dumping mounds should be quite similar to the situation shortly after the disposals. As a substitute for direct observation before disposal, "uncovered planes", representing the undisturbed seabed below the dumped material, were constructed by a bilinear interpolation between four boundaries defined around the deposition areas. The local thickness of the deposited layer was then computed by the altitude differences between the DTM and the “uncovered plane”. This procedure is justified by the observation that the seabed outside the dumping mounds was remarkably smooth.

The surface area of different deposited layer heights at the ‘DYNAS disposal sites’ was finally calculated in intervals of 5 centimetres in order to give estimates of the survival rates in the field based on our laboratory results.

3. Results

3.1. Behavioural response to experimental burial

Results of the 7-day laboratory burial experiment with the polychaetes *Bylgides sarsi*, *Lagis koreni*, and *Nephtys hombergii* are summarized in table 2. When comparing the three behavioural responses (i.e. ‘no locomotion’, ‘burrowing’, and ‘reaching the sediment surface’), it is most obvious that *L. koreni* is highly sensitive to covering (no survivors), whereas 24 to 32 % of the other two polychaetes survived the burial. Responses to different covering material seem to be taxa-specific. Taking into account ‘escaping activities’ (i.e. ‘burrowing’ + ‘reaching the sediment surface’), *N. hombergii* showed the highest resistance to burial in till and sand/till mixture, whereas till obviously had less negative effects on its survival rates. *B. sarsi* profits from the sand/till mixture, where *N. hombergii* has no survivals.

A thin covering layer of till allowed more specimens of the motile burrower *N. hombergii* to reach the sediment surface after burial than a thick layer. In *B. sarsi* this effect was not found - probably because of the small differences in the covering layer depth between 10 – 12 cm and 14 – 16 cm (i.e. 2 to 6 cm) in the experimental setup (table 2). The larger body size of *B. sarsi* resulted in higher survival rates, i.e. body size of survived specimens ranged between 2.0 and 3.0 cm whereas smaller worms between 0.6 and 1.8 cm showed either no locomotion or minor burrowing behaviour. For the head-down deposit-feeding *L. koreni* only 17 % of the test specimens showed very low burrowing activities and a high degree of tube damage was observed after the end of the experiments. No differences, either in covering material or in covering layer depth, were found for this species (table 2).

Table 2 also shows results of the 28 (38)-day covering experiments with the three bivalves *Arctica islandica*, *Mya arenaria*, and *Macoma balthica*. Independent of the covering layer material and depth, the percentage of specimens which showed ‘escaping activities’ (i.e. ‘burrowing’ + ‘reaching sediment surface’) was high in *M. arenaria* and *M. balthica* (63 to 79 %). Survival rates in the two covering layer materials varied between 0 and 42 % for all three bivalves and were highest for *M. balthica*. No survival and low burrowing activities were found for *A. islandica* after burial with the sand/till mixture.

No clear effects of the covering layer depth were observed for *A. islandica* and *M. balthica*. For *Mya arenaria* higher ‘escaping activities’ were only found with the lower covering layer of the sand/till mixture.

3.2. Burrowing velocities in experiments

Upward burrowing velocities calculated for test species were lowest in *L. koreni* (0.29 - 0.57 cm d^{-1}, n = 4). *M. balthica*, *A. islandica* and *B. sarsi* showed burrowing velocities of 0.37 – 3.89 cm d^{-1} (n = 16), 3.7 (n = 2), and 2.5 to 5.3 cm d^{-1} (n = 2) respectively. Highest burrowing rates were found in *M. arenaria* with up to 8.0 cm d^{-1} and *N. hombergii* (10.0 - 20.0 cm d^{-1}).

Small specimens of *M. arenaria* (i.e. shell lengths < 2.5 cm) couldn’t successfully move to the sediment surface after burial either with their entire shell or with the siphons, although burrowing distances varied between 0 and 14 cm with a mean of 4.1 ± 4.4 cm (SD; n = 10). For larger specimens (i.e. shell lengths between 2.5 and 4.3 cm) the mean burrowing distance nearly doubled (i.e. 7.0 ± 6.5 cm; n = 23). Within the latter group no significant relations between body size and either burrowing velocity or burrowing distance were found (table 3). Burrowing velocities of single specimens during the first week of experiments with the sand/till mixture ranged between 0.44 and 0.56 cm d^{-1} whereas the overall mean velocity for this covering material was 1.24 ± 0.50 cm d^{-1} (n = 4). A higher, but statistically not significant, mean burrowing velocity was evaluated for the till set-ups (i.e. 3.94 ± 2.89 cm d^{-1}; n = 4) (table 3).

No significant differences in mean burrowing velocities of *M. balthica* were found for the two covering materials till (i.e. 1.13 ± 1.02 cm d^{-1}; n = 10) and sand/till mixture (i.e. 1.45 ± 0.87 cm d^{-1}; n = 6) (table 3).

3.3. Measurements of accumulated sediment elevation levels after an experimental disposal of dredged material in the field

On the 20th and 21st of August, two month after the dredged material disposal at the two disposal sites in Mecklenburg Bay, multi-beam echo sounder measurements revealed distinct mounds with diameters of up to 28 m on the sea floor at the DYNAS disposal site 1 (till) and mound-like structures with diameters of up to 9 m at the DYNAS disposal site 2 (sand/till mixture), respectively (figure 1). The maximum height of these mounds was about 1.5 m. Total affected areas of the two sites “till” and “sand/till” were 8,602 m² and 15,438 m², respectively. Table 4 summarizes the surface areas of each 5 cm class of deposition depth. 25 % of the total affected area of site 1 revealed deposition levels higher than 40 cm whereas this deposition was found only at 3 % of the affected area at site 2. Five to ten centimetre elevation levels were found at 18 and 31 % of the affected area at the sites 1 and 2, respectively.

When comparing these sediment elevation levels at the disposal sites with the chosen covering layer depth in the experiments, our lower covering layer depth (between 10 and 20 cm) corresponds to a spatial percentage between 14 and 20 % whereas the high covering layer depth in experiments with bivalves and *N. hombergii* (i.e. 32 – 41 cm) corresponds to an area of less than 7 % at the disposal sites. Looking at organism's survival rates derived from our experiments in comparison to rates found at the 'DYNAS disposal sites' 2 weeks after the experimental disposal in June/July 2001 (data from Powilleit et al. 2006), we found lower survival rates of test species in laboratory experiments (table 5). However, these rates match better with *in situ* survival rates if all those organisms are included, which have shown any type of 'escaping activity' in the laboratory experiments (i.e. 15 – 81 %).

4. Discussion

Our results documented a high burrowing potential after experimental burial of the three bivalve species *Arctica islandica*, *Macoma balthica* and *Mya arenaria* as well as the polychaete *Nephtys hombergii*. A considerable number of the test organisms were able to successfully burrow to the sediment surface through a covering layer of 32 – 41 cm. As described by Maurer et al. (1986) for North Atlantic organisms, shallow burrowing siphonate suspension feeders, young deep-burrowing siphonate suspension feeders, and large polychaetes with well developed proboscis and parapodia are well-adapted to burial. These organisms may survive experimental burial depths of up to 0.5 m when covered with fine sand at a temperature of 19 °C and a salinity range between 20 and 26 PSU. Despite their smaller body size in the brackish western Baltic Sea as a result of lower salinity our results reveal that *M. balthica*, *M. arenaria*, *N. hombergii*, and partly *A. islandica* belong to this group of organisms in Mecklenburg Bay. In contrast, tube-building deposit feeders (e.g. *L. koreni*) are most susceptible to the lethal effects of burial (Maurer et al. 1986).

4.1 Burrowing behaviour

The soft shell clam *Mya arenaria* is a deep burrowing suspension-feeder inhabiting boreal sandy sediments up to 20 m water depth and is very common in estuaries (e.g.

Hayward and Ryland 1990). In its natural habitat there is a positive relation between body size and burial depth. This is probably due to trade offs between feeding opportunity and mortality risk due to predation (e.g. Zwarts and Wanink 1989, Zaklan and Ydenberg 1997).

Burrowing behaviour of *M. arenaria* after burial could be observed in our experiments in cases when the clams were located in the vicinity of the transparent tube walls. Two types of locomotion were observed: especially in larger specimen the anterior edge of the valve was directed towards the sediment surface, the siphon was actively used to flush sediments and together with some foot contractions the bivalve stems itself towards the sediment surface ('hydraulic burrowing' sensu Checa and Cadee 1997). As it is known from literature, smaller specimen were observed to be using their extended foot directed to the sediment surface during burrowing, i.e. they pulled their valves upwards (e.g. Bromley 1996). Generally *M. arenaria* stopped its burrowing activity when siphons have reached the overlying seawater. Thus the burrowing activity of this clam partly depends on its body size or on the length of its extended siphon.

In the present study we found a considerable recovery potential even for the larger size class of *M. arenaria* (i.e. 2.5 – 4.3 cm shell lengths) (table 3). Burrowing distances were even higher in these larger specimens compared to the size class < 2.5 cm in shell length.

Otherwise it is reported that fully grown *M. arenaria* from marine habitats are rather immobile (e.g. Bromley 1996). A covering layer of about 10 cm of sand was stated in Wadden Sea sediments as its fatal depth (Bijkerk 1988, c.f. Essink 1999), indicating a low tolerance of this clam to burial. These low tolerances, also found by Kranz (1974) in suspension feeding bivalves, seem to be more valid for large sized adults from marine environments. Our findings for a Baltic Sea *M. arenaria* population revealed that even a covering layer depth between 15 and 35 cm could be survived by about 20 % of the tested *M. arenaria*. These results are more in accordance with the findings of Emerson et al. (1990), who experimentally examined smothering and re-burrowing of 3 different size classes of an intertidal *M. arenaria* population in Nova Scotia, Canada (shell length < 3 cm, 3-5 cm, and > 5 cm). Emerson et al. (1990) reported that when buried under 75 cm of sand (i.e. maximum burial depth) up to 40 % mortality in clams of less than 5 cm shell length, and 60 % mortality of the largest clams were found. No mortality was reported at a burial depth of 50 cm of sand for the two lower clam size classes and up to 20 % for the largest clams. Tyler-Walters (2003) on the other hand classified *M. arenaria* as probably being of intermediate intolerance to smothering by 5 cm of sediment, with additional dependence on the nature of the smothering material.

The Baltic tellin *Macoma balthica* is a mobile brackish-water bivalve widely distributed over the northern hemisphere and throughout the Baltic Sea, which is able to switch between suspension-feeding and deposit-feeding. With its foot, it is able to burrow vertically and horizontally through the sediment. Furthermore it is observed that specimens surface periodically, move about and then rebury themselves into the substrate. This behaviour pattern may permit location of a better site for feeding (Brafield and Newell 1961), or could be an advantage when changing the feeding mode to surface deposit-feeding. Generally the clam is considered tolerant of hypoxia (Dries and Theede 1974). To avoid predation by epibenthic predators at the sediment surface ('siphon-cropping') this species has a high burrowing capacity (e.g. Bonsdorff et al. 1995, Tallqvist 2001). However predator avoidance can conflict with feeding needs (Zwartz 1986). For *M. balthica* a fatal depth between 40 and 60 cm was recorded for the Wadden Sea (Bijkerk 1988, c.f. Essink 1999), which complied with our findings for the lower point of this range. Hinchey et al. (2006) reported that even juveniles of *M. balthica* (size classes between 2.0 and 5.9 mm) were able to move through a silty sand layer of up to 25 cm thickness after burial within a few hours and these authors classified *M. balthica* as highly tolerant to burial. According to Olenin (1992) this species was among the most resistant species in Baltic Sea sediments near the Lithuanian coast after dredged spoil dumping. Budd and Rayment (2001) stated that it is likely, that *M.*

balthica is not sensitive to smothering by a layer of sediment 5 cm thick. Even with its small body size of about 1.0 to 1.5 cm compared to the burrowing distance in the experiments, this species seems to be very well adapted to escaping activity induced by burial.

Nephtys hombergii, as an active polychaete, that uses its eversible proboscis to dig rapidly through the sediment, infaunally hunts for prey. In case of burial, even with viscous or impermeable materials, it therefore may be able to travel a sufficient distance and survive for a long period of time beneath these materials (Budd and Hughes 2005). The reported high burrowing potential of *Nephtys hombergii* with fatal depths between 60 and 85 cm (Bijkerk 1988, c.f. Essink 1999) could be confirmed by our measurements with survival rates of more than 60 % for the sand/till covering material. Field observations at a dump site in the Ems estuary (North Sea) after a three-week period of dumping in December 1989 however revealed a clear decrease in abundance of *N. hombergii*, when the sediment layers deposited were thicker than ca. 0.3 m (Kleef et al. 1992).

The ocean quahog *A. islandica* is a burrower in muddy/sandy sediments, which requires sediment surface contact with its short inhalant siphon for feeding and respiration. After burial, it is able to switch from aerobic to anaerobic respiration and is generally considered to be tolerant of anoxia (e.g. Theede et al. 1969). According to Sabatini and Pizzola (2004) this species is classified as intermediate intolerant to an 'incidental' disposal of dredged material. Although its very compact shell protects the bivalve against mechanical damage during initial burial the type of covering material in the present study probably raises a lot of burrowing difficulties for *A. islandica* because of the texture and the derived low permeability of the till.

The tube-building polychaete *Lagis koreni* is a characteristic inhabitant of inshore muddy to sandy substrates in north-western European waters. As a head-down subsurface deposit-feeder its narrow posterior end of the cone-shaped tube is either flush with the surface or protrudes slightly. The worm normally collects subsurface sediment but can also forage with its tentacles at the sediment-water interface too (Dobbs and Scholly 1986). As indicated in our investigation by low burrowing velocities (0.29 - 0.57 cm d^{-1}), *L. koreni* has the ability to excavate itself if lightly buried (e.g. Rees et al. 1992). This probably could be managed with its contractile tentacles together with flushing activity of the tube. Due to a high risk of mechanical tube damage during the initial burial process, especially with compact till clumps and a covering layer depth of more than 10 cm, no specimens were able to excavate themselves. This was also true for the covering with the sand/till mixture.

The scale worm *Bylgides sarsi* is known as an active semi-pelagic swimmer normally foraging for prey on the sediment surface and characterized by a high tolerance against hydrogen sulphide and oxygen deficiency (e.g. Sarvala 1971, Laine et al. 2003, Janas et al. 2004). It is a dominant member of sub-halocline soft-bottom communities in the Baltic Sea and often among the first macrozoobenthic species which re-colonizes azoic sediments (e.g. Laine et al 1997). As an epibenthic species, *B. sarsi* is sensitive to mechanical disturbance during the initial process of disposal of dredged material. For the scale worm the process of covering with the compacted till clumps was probably the critical moment in our experiments. If not directly damaged, its chance of re-burrowing to the sediment surface might be good. As it is observed in our study, body size seems to be an additional parameter which favoured survival in this species, as well as in mobile infaunal species (e.g. *Nephtys* spp.).

4.2 Effects of different covering materials

Differences in the deposited material between till and a sand/till mixture resulting in modified surface structures after disposal and differing compositions of the covering layers may have affected the benthic fauna in a variable way. For example the cohesive till clumps would provide good support for upward extension but inhibit shell penetration of bivalves. Probably due to an inhomogeneous till covering layer with ‘resting holes’ in our experimental setups we found higher survival rates of bivalves and *N. hombergii* compared to a mixture of sand/till. The characteristics of both types of covering material might explain some of the differences in survival in comparison to published data.

Looking at the species-specific level under field conditions, there is also evidence that several species at the ‘DYNAS disposal site’ with the sand/till mixture as deposited material showed higher decreases in macrofaunal densities shortly after the disposal, indicating higher detrimental effects on the fauna (Powilleit et al. 2006).

The dependence of survival on sediment type might additionally result from faster depletion of oxygen and accumulation of toxic reduced compounds (e.g. hydrogen sulphide) in finer sediments (e.g. Maurer et al. 1986, Norkko et al. 2002). Essink (1999) reported a lower tolerance of invertebrates in case of mud deposition instead of fine sand during continuing sedimentation. Experimental burial under mud resulted in high mortality in all size classes of clams *M. arenaria* and under all burial depths tested by Emerson et al. (1990).

4.3 Comparability of experimental setups

Contradictory results in the literature as found for *M. arenaria* and *N. hombergii*, may have resulted from the different sediments tested but could also be due to differences in acclimation time and in the method of burial.

A prerequisite for the cultivation of test specimens for longer time periods is the choice of optimal laboratory conditions to avoid any negative effect on nutrition state and condition indices. A long acclimation time (e.g. one month) was recommended by Emerson et al. (1990) because organisms had to recover from the collection procedure. An acclimation time of one week in the test tubes in our study is in concordance with that of Maurer et al. (1986), who held test organisms for 7-14 days to acclimate them to laboratory conditions. Additional variation in published mortality data may be caused by the burial procedure and the type of covering material.

When looking at temperature as a decisive factor for the burial tolerance of macrofauna, higher temperatures favour escaping from burial due to the higher metabolic activity of poikilothermic macrofauna in summer (Bijerk, 1988 cf. Essink, 1999). In contrast, our experimental temperature of 4 °C rather simulated a typical winter situation in bottom waters of the western Baltic Sea. Corresponding burrowing activities and resulting survival rates of the test species in the laboratory should therefore have remained considerably below *in-situ* survival rates from the disposal sites in Mecklenburg Bay, where the temperatures in June/July 2001 ranged between 9 – 14 °C. On the other hand lower temperatures would favour higher tolerances to oxygen deficiency due to the organism's lower metabolic activity. Although not measured, oxygen deficiency might have occurred in our experiments shortly after the disposal. The latter temperature effect would have prolonged the test species time to escape from burial.

Another difference between different laboratory studies and in comparison to field conditions is the spatial containment of the test species in the experimental tubes with a surface area of only about 78 cm² each in the present study. This situation lowers the chances of an organism to escape laterally instead of a direct vertical motion towards the sediment surface after burying (i.e. the volume/surface area of experimental containers in connection with test species body sizes might be a critical factor in determining survival rates after burial). *In situ*, the buried macrofauna could easily take a more transverse escape path, which may possibly be an easier way out of the sediment.

4.4 Survival rates and implications for the field

In addition to survival rates of macrofauna determined by grab sampling 2 weeks before and 2 weeks after the experimental disposal, our laboratory survival rates were combined with precise measurements of the dredged material elevation levels on the sea floor at the DYNAS disposal sites which enabled us to spatially and independently quantify the survival chances of macrofauna in the field. Two main sources of error in the determination of the *in situ* thickness of the deposited layer must be taken into account: (1) altitude differences between the real seabed before disposal and the constructed “uncovered plane” and (2) depression of the seabed due to compaction by impact of the disposed material. The magnitude of the first error source was estimated by comparing the altitudes between the digital terrain model (DTM) outside the dumping mounds and an “uncovered plane” that was constructed by bilinear interpolation in the same way as described for the dumping mounds. On average the difference was less than 2 cm per individual DTM grid cell. For the percentages of the sediment elevation levels, however, this error scales with the inverse square root of the number of DTM cells involved, and reduces typically to a few mm, and is therefore negligible. A possible surface depression by the disposal is of more significance, as it resembles a constant, systematic bias. In a worst case scenario the magnitude of the depression may be estimated from differences in the volumes of the material disposed from the barks and the material detected by the multi-beam echo sounder. This assumes that no loss of material took place in the water column, which can not be confirmed by observations during the disposals (Siegel et al. 2003). For the glacial till, the loss in volume was about 400 m^3, which is 13.8 % of the total till discharge (Stockmann et al., this volume). With the total area of the glacial till mounds of about 8000 m^2 (compare table 5) this would result in an overall thickness of the depressed material of 5 cm. For the sand/till site only the till chunks had the potential to cause bed depressions. Most of the material loss of 900 m^3 (Stockmann et al., this volume) should be due to material dispersion during the disposal process. In lack of any other information, a potential depression of 5 cm is thus assumed here. Adding an increased layer with an area identical to the lowest 5 cm bin in table 5, the spatial coverage for a thickness of the deposited layer from 10 to 20 cm would drop from 14 % to 11 % for the till site and from 20 % to 15% for the sand/till site.

We can assume that a sediment elevation level between 0 – 5 cm has no detrimental effect on the macrofauna of the two DYNAS disposal sites. For disposal site one 72 % of the area (6,206 m² vs. 8,602 m²) are affected by covering layer depths of > 5 cm with survival rates probably similar to those derived from our laboratory results. For the disposal site 2 (sand/till mixture) an area of 10,428 m² (i.e. 68 % of the total affected area) had a covering layer depth > 5 cm. Hence, there are still minor disturbed sediments which can initiate a fast re-colonization by immigration of motile adult macrofauna from the neighbouring sea floor.

When calculating density changes of the test species according to the spatial extension of affected areas with thicknesses of the coverage layer > 5 cm, total average survival rates of 45 and 43 % were achieved at disposal sites 1 and 2 respectively. These rates are closer to our laboratory results combining survivals and burrowing specimens (i.e. 52 and 48 %) than those found in grab samples 2 weeks after the disposal at the two sites in Mecklenburg Bay (western Baltic Sea) with single values of more than 100 % for *M. arenaria* and *M. balthica* and mean values of 77 and 38 % (table 5). In addition to methodological constraints of grab sampling when dealing with patchy distributions of benthic organisms, less spatial limitations and immigration from unaffected neighbouring areas or within the disposal sites are possible causes for higher *in situ* survival rates of the macrofauna compared to experimental rates.

Looking at the temperature in summer 2001, when the DYNAS dredged material disposal took place, and at laboratory conditions (4 °C), where microbial activity is greatly reduced, the latter lower temperature would decrease the sediment oxygen demand (SOD) considerably, as the major part of the SOD is caused by temperature-dependent microbial processes (e.g. Meyer-Reil et al. 1983). Consequently the organisms would have a prolonged time period for escaping from burial before unfavourable anoxic conditions might have established. As some of the tested invertebrates are well adapted to low temperatures, or are even arctic species (*A. islandica*, *B. sarsi*), their escaping potential at low temperatures is still at hand. It could be recommend that field disposal activities in the western Baltic Sea should be limited to the cold season, when low temperatures and high hydrographical dynamics support favourable oxygen conditions for the macrofauna at the sea floor.

In addition to the primary effects of the sediment deposition discussed so far the secondary and possible long-term effects of disposals like increased turbidity, enhanced suspended particulate matter (SPM) concentrations, and higher nutrient levels may result in considerable habitat changes and should be mentioned briefly. Generally these latter effects play a less important role in cases where only single disposal events were investigated in comparison to sites with repeated disposals. Nevertheless increased turbidity may effect the functioning of phytoplankton and benthic primary producers as well as visual predators. Enhanced SPM-concentrations may lead to a decrease in the net food intake per unit of time in filter-feeding organisms or can cause suboptimal functioning of gills. Also the release of additional nutrients from the disposed material (e.g. ammonia, phosphates) may accumulate to harmful levels and favour increased growth of epiphytes (e.g. Essink 1999, Ellis et al. 2002, Thrush et al. 2003). Such habitat changes are likely to affect sediment characteristics, biogeochemical fluxes as well as food-webs. For our lab experiment secondary effects of disposal were not investigated in detail but it is most likely that enhanced SPM-concentrations after the disposal might have negatively influenced the nutrition state of the suspension-feeding test species.

5. Conclusions

In our laboratory experiments all three bivalves *A. islandica*, *M. balthica*, *Mya arenaria* and the polychaete *N. hombergii* showed high escaping potentials as they successfully moved through the deposited sediment with a covering layer of 32 – 41 cm.

Our results increase the few available data sets for macrofauna response to burial in brackish environments. The comparison with literature data shows that the smaller size of our brackish water species seem to have no negative effects on the organisms' ability to escape from burial.

The extrapolation of laboratory survival rates gained in burial experiments to the field situation using high-precision echo sounder measurements of the burial depth at disposal sites proved successful and enables realistic estimates of the *in situ* survival rates. By using this combination it is possible to perform an independent evaluation of survival rates in addition to results obtained by the classical approach of grab sampling before and after disposal of sediments.

In cases of already published species-specific survival rates one can roughly estimate the benthic re-colonization of these species at disposal sites by relying on consecutive precise measurements of changes in bottom topography before and after burial without the necessity for repeated grab samplings and time-consuming sorting and identification procedures. Nevertheless a prerequisite for this method is the use of a highly sophisticated measuring system in order to obtain the necessary burial depth resolution of a few centimetres.

Our approach of combining high-precision multi-beam echo sounder measurements of elevated bottom topography with laboratory-derived survival rates of macrofauna complements classical grab sampling programmes at disposal sites. Especially when using already published survival rates, this may contribute to a less time consuming procedure in monitoring and assessment of spoil disposal sites.

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Figure captions

Figure 1: Results of multi-beam echo sounder measurements of the two DYNAS disposal sites 1 (till) (upper panel) and 2 (sand/till mixture) (lower panel) in Mecklenburg Bay (western Baltic Sea) from August 2001, two months after an experimental disposal of dredged material. Elevations above the original zero seafloor level before the disposal activities are given in metres and geographical positions as Universal Transverse Mercator 32 (UTM32) centre coordinates.

Table 1: Total specimen numbers, numbers per tube, body sizes ranges (shell lengths in bivalves, body length in polychaetes) and covering layer depths (cm) in the burial experiments with a subset of 12 tubes for each of the six different test species.

	Arctica islandica	***Macoma balthica***	***Mya arenaria***	***Bylgides sarsi***	***Lagis koreni ****	***Nephtys hombergii***
n	39	49	39	22	24	29
n $tube^{-1}$	2 - 5	2 - 4	4 - 5	1 - 3	2	2 - 3
body size (cm)	1.0 - 4.2	0.9 - 1.6	1.3 - 4.3	0.5 - 3.0	1.0 - 4.3	1.0 - 6.0
low covering layer depth	15-17	15-16	15-16	10-12	10-12	20
high covering layer depth	35-41	35-40	32-35	14-16	14-17	40

*: animal size given as tube length

Table 2: Burrowing behaviour of test organisms in laboratory covering experiments with the 2 different covering materials till and sand/till mixture and 2 different covering layer depths. Numbers of specimen in each behavioural category are given. Depending on animal sizes the numbers of specimen per trial slightly varied.

	Till low coverage	**Till high coverage**	**Till/sand low coverage**	**Till/sand high coverage**
Bylgides sarsi (n = 22)				
no locomotion	6	2	3	2
burrowing	1	1	0	0
reaching sediment surface	0	2	2	3
Lagis koreni (n = 24)				
no locomotion	6	4	5	5
burrowing	0	2	1	1
reaching sediment surface	0	0	0	0
Nephtys hombergii (n = 29)				
no locomotion	2	3	2	3
burrowing	0	3	5	4
reaching sediment surface	6	1	0	0
Arctica islandica (n = 39)				
no locomotion	6	4	9	8
burrowing	5	1	0	3
reaching sediment surface	0	3	0	0
Macoma balthica (n = 49)				
no locomotion	7	1	6	4
burrowing	2	4	2	7
reaching sediment surface	3	7	5	1
Mya arenaria (n = 39)				
no locomotion	2	2	1	3
burrowing	4	6	8	5
reaching sediment surface	3	1	3	1

Table 3: Individual burrowing velocities of *Mya arenaria* and *Macoma balthica* survivors after burial derived from laboratory covering experiments at 4 °C with successfully re-burrowed specimens.

Tube label	**Covering layer depth (cm)**	**Shell length (cm)**	**Burrowing distance (cm)**	**Duration of complete re-burrowing (d)**	**Burrowing velocity (cm d^{-1})**
M. arenaria					
till 1A	15.0	4.2	9.0	4	3.75
till 1C	16.5	2.7	10.0	6	2.75
till 1C	16.5	3.2	8.0	13	1.27
till 2C	32.0	3.8	26.0	4	8.00
sand/till 1A	15.5	2.7	8.0	18	0.86
sand/till 1B	15.0	4.2	7.0	8	1.88
sand/till 1C	15.0	2.5	8.0	18	0.83
sand/till 2A	32.0	3.9	23.0	23	1.39
M. balthica					
till 1 A	16.5	1.4	14.0	38	0.37
till 1 B	15.0	1.2	14.0	38	0.37
till 1 C	15.5	1.0	13.0	9	1.44
till 2 A	36.0	1.5	33.0	38	0.87
till 2 A	36.0	1.6	33.0	38	0.87
till 2 A	36.0	1.0	33.0	38	0.87
till 2 A	36.0	1.2	33.0	38	0.87
till 2 B	40.0	1.5	35.0	9	3.89
till 2 C	39.0	1.2	36.0	38	0.95
till 2 C	39.0	1.2	29.0	38	0.76
sand/till 1A	15.0	1.4	14.0	8	1.88
sand/till 1A	15.0	1.2	14.0	8	1.88
sand/till 1B	15.0	1.1	15.0	38	0.39
sand/till 1B	15.0	1.2	15.0	38	0.39
sand/till 1C	15.0	1.2	15.0	6	2.50
sand/till 2C	35.0	1.2	30.0	21	1.67

Table 4: Sediment elevation levels in August 2001 two month after the experimental disposal of dredged material at two disposal sites in Mecklenburg Bay (western Baltic Sea). Total affected areas of the two sites "till" and "sand/till" were 8,602 m² and 15,438 m², respectively. For discussion of associated errors see text.

Sediment deposition (cm)	**Sediment area (m^2)**		**Percent of elevated area (%)**		**Cumulative percentage**	
	till	sand/till	till	sand/till	till	sand/till
0 - 5cm	2396	5010	28	32	28	32
5 - 10cm	1559	4788	18	31	46	63
10 - 15cm	701	1814	8	12	54	75
15 - 20cm	521	1163	6	8	60	83
20 - 25cm	343	772	4	5	64	88
25 - 30cm	329	691	4	4	68	92
30 - 35cm	329	431	4	3	72	95
35 - 40cm	281	306	3	2	75	97
> 40cm	2143	463	25	3	100	100

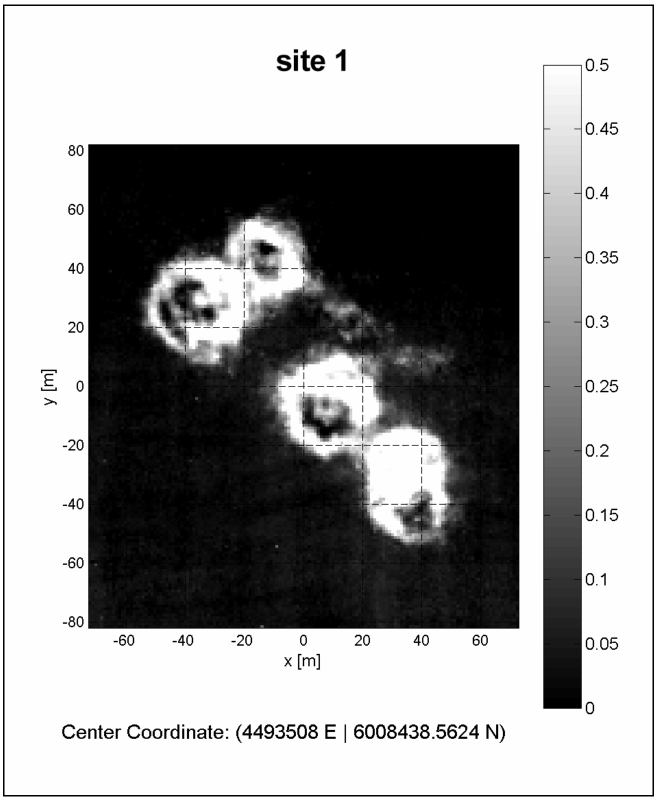
Table 5: Comparison of survival rates and 'escaping activity' (values in brackets; i.e. 'survival rate' + 'burrowing'; %) of selected invertebrates after experimental burial in the laboratory and at the 'DYNAS disposal site' (Mecklenburg Bay, western Baltic Sea, in the latter case data from Powilleit et al. 2006 were used). Laboratory survival rates are defined as percentage of specimen completely re-burrowed after burial whereas survival rates at the 'DYNAS disposal sites' are relative density differences of specific taxa shortly before and shortly after the disposal event in June 2001.

	survival rates ('escaping activity') (%) laboratory experiments [1]		**survival rates (%) 'DYNAS disposal site' [2]**	
	till	sand/till	station 1 till	station 2 sand/till
Arctica islandica	16 (47)	0 (15)	78	26
Mya arenaria	22 (78)	19 (81)	167	100
Macoma balthica	42 (67)	24 (60)	119	17
Bylgides sarsi	17 (33)	50 (50)	30	29
Lagis koreni	0 (17)	0 (17)	0	0
Nephtys hombergii	47 (67)	0 (64)	67	53
means	24 (52)	16 (48)	77	38

[1]: combined data for both covering layer thicknesses

[2]: original data from Powilleit et al. 2006

Fig. 1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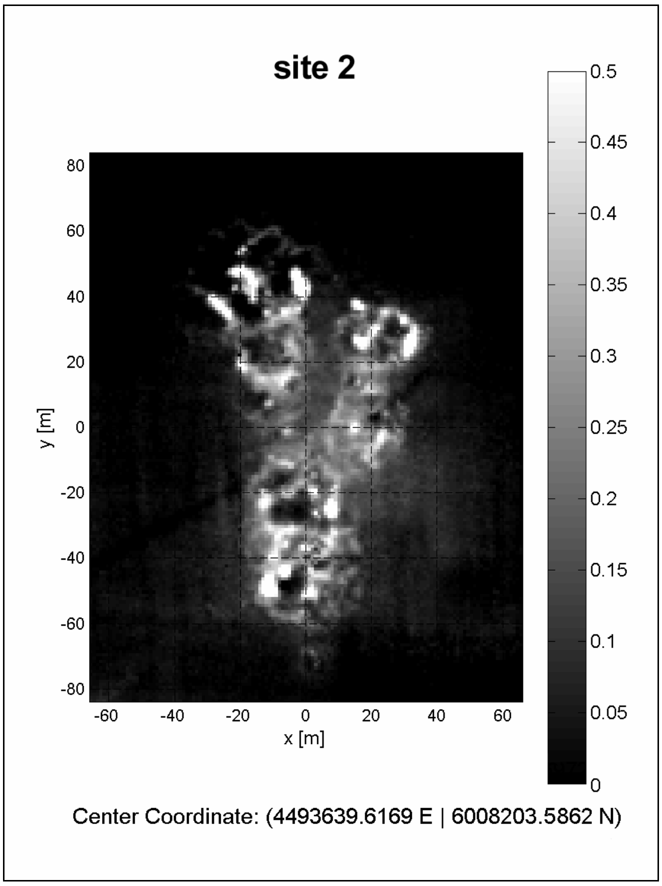
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
80
60
40
20
0
-20
-40
-60
-80
y [m]
-60
-40
-20
0
20
40
60
x [m]
Center Coordinate: (4493508 E | 6008438.5624 N)


site 2
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
80
60
40
20
0
-20
-40
-60
-80
y [m]
-60
-40
-20
0
20
40
60
x [m]
Center Coordinate: (4493639.6169 E | 6008203.5862 N)