Persistent effects of sand extraction on habitats and associated benthic communities in the German Bight

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Abstract. Sea-level rise demands for protection measures of endangered coastlines crucial for the local population. At the island of Sylt in the SE North Sea, shoreline erosion is compensated by replenishment with sand dredged from an offshore extraction site. We studied the long-term effects of sand extraction on bathymetry, geomorphology, habitats, and benthic fauna. Sand extraction created dredging holes about 1 km in diameter and up to 20 m below the ambient seafloor level. Directly after dredging the superficial sediment layer inside the pits was dominated by coarse sand and stones. Hydroacoustic surveys revealed only minor changes of bathymetry >35 years after sand extraction. Obviously, backfill of the dredging pits was very slow, at a rate of a few mm per year, presumably resulting from low ambient sediment availability and relatively calm hydrodynamic conditions despite high wave energy during storms. Thus, a complete backfill of the deep extraction sites is likely to take centuries in this area. Hydroacoustic surveys and ground truthing showed that the backfilled material is mainly very fine sand and mud, turning the previously coarse sand surface into a muddy habitat. Accordingly, grab samples revealed significant differences in macrozoobenthos abundance, species density and community composition between recently dredged areas (<10 years ago), recovery sites (dredging activity >10 years ago) and undisturbed sites (control sites). Overall, dredging turned the original association of sand-dwelling species into a muddy sediment association. Since re-establishment of disturbed benthic communities depends on previous re-establishment of habitat characteristics, the low sedimentation rates indicate that a return to a pre-dredging habitat type with its former benthic community is likely to be a matter of centuries as well. This, however, implies that coarser sediments from the adjacent areas can be displaced to the dredging pits by waves and currents. Since coarse sand is virtually immobile in this area, a regeneration towards natural conditions is unlikely without human interference (e.g. working with nature).

1 Introduction

Sea-level rise, with ever-increasing rates in the near future, demands protection measures of endangered coastlines crucial for the local population (Nicholls and Tol, 2006; Hinkel et al., 2014). In many cases, ecological awareness and sustainability considerations have led to the preference for ‘soft’ coastal protection measures like beach nourishment over ‘hard’ protection approaches such as dikes or revetments (Hamm et al., 2002; Pranzini et al., 2015; Staudt et al., under review). The resulting demand for marine aggregates needed for coastal protection has reached a high level, on a worldwide scale, and further increase is expected (Hamm et al., 2002; Kubicki, 2007; Danavaro et al., 2018; Schoonees et al., 2019). For the northern European Continental Shelf the extracted volume rose from some 53 million m^3 between 1998 and 2002 to a total of 73.2 million m^3 in 2018 (ICES, 2016, ICES, 2019).

Marine sand extraction changes local bathymetry and sediment composition (De Jong, 2016b, Mielck et al., 2018) and affects macrozoobenthic communities, both directly by killing or removal of benthic organisms during sediment extraction, and indirectly by altering the environmental conditions (Boyd et al., 2003; Foden et al., 2009). Further indirect effects of sediment dredging include increased turbidity, release of nutrients and toxins, changes in regional morphodynamics (Le Bot et al., 2010) and smothering of organisms due to sedimentation (van Rijn et al., 2004). Current attempts to minimize the area affected by dredging activities have led to greater extraction depths. The ecological effects of deep sand extraction (>10 m dredging depth), however, remain largely unknown (Boyd and Rees, 2004; De Jong et al., 2016a). Since sedimentological investigations showed tremendous change of the physical habitats, it must be expected that the macrozoobenthos changes at a similar level (Boyd et al., 2005; Kubicki et al., 2007; Foden et al., 2010). Whether or not the benthic communities recover, remain disturbed or even develop in unexpected directions is crucial information for a holistic assessment of the impact of such a coastal defense measure. It is thus essential to investigate the benthic communities of the affected areas to predict changes in species abundances and the structure of the benthic community.

After sediment extraction, morphological recovery of the local environment depends on the ambient sediment availability and hydrodynamic conditions. Additional crucial factors are extraction depth (i.e. deep drilling vs. shallow dredging) and the amount of material extracted (Cooper et al., 2007; De Jong et al., 2015). Re-establishment of the benthic community depends on the progress in morphological recovery and on the sensibility and resilience of the different benthic organisms and communities to anthropogenic impact (Desprez, 2000; Cooper et al., 2011). In general, a full re-establishment of benthic assemblages is possible but may take a long time and is strongly depending on sediment composition, original topography and the connection to similar habitats in the proximity (Desprez, 2000; Boyd et al. 2005). In addition, recovery may proceed over intermediate stages atypical for the original environment, e.g. when large amounts of fine materials are deposited in a sandy area (Boers, 2015).

The aim of this study was to further determine the impacts of extensive marine aggregate extraction on the regional macrozoobenthic communities. The main objectives were to (i) gain a deeper understanding of the correlation between the prevailing habitats and the recovery state of the associated benthic assemblages, to (ii) evaluate temporal recovery patterns along with short- and long-term changes in the community structures and to (iii) investigate the potential of a re-establishment of pre-dredging conditions regarding fine sand domains (coarse Pleistocene material cannot be re-established because of weak current velocities). Therefore, dredging pits of different ages and, as a control, the sandy areas surrounding the extraction site were compared for sediment and benthic faunal composition. Using hydroacoustic gear and sediment grab samples, habitat maps were created combining sediment properties with information about abundance and diversity of the macrozoobenthos.

Hydroacoustic devices have proved highly useful remote sensing tools for seafloor classification and habitat mapping. Multibeam echosounders give information about water depth and morphology, and can thus be used to calculate backfill rates at the extraction pits (Harris and Baker, 2012; Jones et al. 2016; Mielck et al., 2018). Sonar systems such as sidescan sonars allow to investigate the backscatter intensity by transmitting an echo, which will be reflected by the seafloor and received by a transceiver. Backscatter allows to distinguish between hard/coarse (strong backscatter response from the seafloor) and soft/fine substrates (low backscatter response from the seafloor (Blondel and Murton, 1997; Blondel, 2003; Mielck et al., 2012, Mielck et al., 2015)), which is an additional parameter useful for seafloor classification. Interpretation and verification of sonar data always require ground truthing, e.g. by sediment samples and/or underwater video (Harris and Baker, 2012; Hass et al., 2016). Ground truthing can also give more detailed information on sedimentary properties such as the granulometric composition.

Benthos communities often largely correlate with sediment composition; however, a precise identification of communities is not yet possible by hydroacoustic methods because transitional zones between major habitat types may be populated by transitional communities and these zones are often not detectable by hydroacoustic methods (Markert et al., 2013). Thus, ground truthing by sediment samples is required to correctly identify the benthic communities.

2 Materials and methods

2.1 Study Area

The study area “Westerland Dredging Area” (WDA) is located in the German Bight (SE North Sea) approx. 7 km west off the island of Sylt (Fig.1). This island suffers strong erosion, notably along its wave-exposed western side. Since 1972, sediment losses are compensated by artificial beach nourishments and the investigated study site serves as a sand extraction area since 1984 (LKN-SH, 2012). Most of the seafloor west off Sylt is covered with Holocene fine sand (Figge, 1981; Zeiler et al., 2000). However, for shore nourishments coarse-to-medium grained Pleistocene sands are preferred (Temmler, 1983; 1994). These Pleistocene sediments come with gravel and stones deposited as a moraine core during the Saalian glaciation (~300–126 kyr BP). This moraine core strikes in NNW direction (Köster, 1979, see Fig. 1). The surface of the seafloor in WDA is characterized by bands of coarse-grained rippled sand, so called sorted bedforms (Diesing et al., 2006; Mielck et al., 2015).

The study area has an extent of ~5 km in north-south direction and ~3 km in east-west direction. Natural water depths range between ~14 and ~17.5 m while the pits left by sand extraction may reach down to 30 m water depth with diameters of approx. 1 km. Since 1984, more than 40 million m³ sediment was extracted from this area using Trailing Suction Hopper Dredgers (LKN-SH, 2012, 2020). With an actual annual material withdraw of 1–2 million m³, this area is the largest offshore sediment extraction site in Germany. The study area includes recent dredging zones, already exploited sand deposits, and - as control sites - unaffected seafloor regions. Meanwhile, the pits persist for more than 30 years (Mielck et al., 2018). The Pleistocene coarse sands exposed during sand extraction are rapidly covered by a layer of fine sand, which derived from the formerly steep rims of the pits (Zeiler et al., 2004; Mielck et al., 2018). After this initial phase, muddy sediments accumulate, however, due to the combination of a lack of mobile sediments and low transport rates (Valerius et al., 2015), at very low rates only. Accordingly, a complete backfill of the deep dredging pits was estimated to take many decades (Mielck et al., 2018).

This study is a follow-up to the previous study Mielck et al. 2018, which focused on morphological changes due to marine aggregate extraction in WDA using bathymetric data between 1993 and 2017. Hydroacoustic data and sediment samples were taken using the research vessel *Alkor* in January 2019. In order to acquire over-all information on the prevailing morphology and high resolution backscatter data of the study area, altogether 55 transects, each 5.5 km long, with a lateral distance of 50 m were surveyed in north-south direction at a vessel speed of ~5 knots. During the survey, which took place between January 25th and January 27th at calm weather conditions, multibeam echosounder and sidescan sonars were used simultaneously on all transects. Subsequently, 53 grab samples for grain-size and macrobenthic faunal analyses were collected on January 31th. Surveyed transects and position of the grab samples are provided in the section 'results' (Fig. 2 and 4a). Underwater videos could not be acquired as a consequence of high turbidity.

2.2 Multibeam echosounder

Bathymetric information of the investigation area was collected using a shallow water multibeam echosounder SeaBeam 1180 (180 kHz; swath width of 150°) which was installed on a plate in the ships' moonpool. Positioning and motion compensation was done using a Kongsberg SEATEX MRU-Z. During the survey three CTD-profiles were measured (conductivity, temperature, pressure) to calculate sound velocities. Multibeam data were post-processed using Hypack 2016a and ESRI ArcGIS10 resulting in a bathymetric map with a grid size of 2 m. For tidal correction, the gauge "Westerland Messpfahl" was used, which is located approx. 6 km east of WDA. Depth values in this study are given in meters below mean sea level.

2.3 Sidescan sonar

Two different sidescan sonars were deployed simultaneously to determine backscatter properties (roughness) of the seafloor across the study area during the survey. The devices were attached to each other and towed behind the vessel to avoid sound disturbances from the ship. They operated with different frequencies in order to collect backscatter information from the seafloor in two resolutions, which provides more detailed data regarding sediment composition and habitat character. The first sidescan sonar (Imagenex YellowFin 872) worked with a frequency 330 kHz resulting in a resolution of 12.5 cm/pixel in the digital imaging while reaching a swath of 160 m on the seafloor. The second sidescan sonar was a Tritech StarFish 990F that operated with a frequency of 1 MHz and reached a resolution of ~1 cm/pixel at a swath of 60 m. Using different frequencies leads to more detailed information on the seafloor environment. Sidescan mosaics recorded with a low frequency generally yield information on large-scale objects on the seafloor (e.g. facies changes, sandwaves, megaripples) while a high frequency gives more information on small-scale structures such as ripple marks or stones (Mielck et al. 2015). All recorded sidescan sonar data were post-processed using SonarWiz 5 (Chesapeake Technology) resulting in a grid resolution of 0.5 m for the YellowFin and 5 cm for the StarFish. Distinct areas (e.g. fine/coarse sand) and characteristic backscatter responses in the sonograms (e.g. stones) were manually digitized using ArcGIS aided by the collected ground-truth information. The sizes of the stones were determined by measuring slant angle and lengths of the acoustic shadow using the software EdgeTech Discover.

2.4 Grab sampling and analysis

The surface sediments and morphology across WDA are already well-known from the prior study (Mielck et al. 2018) and were taken representative for all occurring seafloor environments. For ground truthing of hydroacoustic data, a total of 53 grab samples were taken using a van Veen grab (HELCOM; 30 x 30 cm; 0.1 m²). The sampling positions generally followed a regular grid but some positions were also selected on the basis of the bathymetric information in order to take samples both from the older dredging pits (older than 10 years) and the newer ones (see Fig. 1). At two positions, sampling was not possible due to very steep slopes or the presence of stones on the seafloor, respectively, that prevented the sampler to close completely. Grain-size analyses were done using a CILAS 1180L diffraction laser particle-size analyzer, which provides grain-size information between 0.04 and 2500 µm. The statistical parameters (referring to vol-%) are based on Folk and Ward (1957) and were calculated using GRADISTAT (Blott and Pye 2001).

For faunal analyses, a sub-sample of 100 cm² surface area (max. depth of 18 cm; limited by the Van Veen grab) from each of the grabs was fixed in 5 % buffered formaldehyde-in-seawater solution. In the lab, the sample was sieved through 1 mm square meshes and the residual fauna determined to species level and counted. Biomass was determined as fresh weight per species and sample. For statistical analysis, the sampling sites were classified according to their history of sand extraction: Class “0” with sites never dredged or indirectly impacted by sand extraction and thus serving as a control for undisturbed conditions; class “1” with the sites where sediment was extracted during the past 10 years; and class “2” with the sites where sand extraction terminated at least 10 years prior to sampling (cf. Fig. 2A). These classes were used as a categorical variable in univariate analyses of variances (ANOVAs) to test for effects on macrozoobenthic abundance, biomass, and species density. Significant differences between the variables were further investigated with Scheffe’s post hoc test. Prior to statistical analyses, abundance and biomass data were log(x+1)-transformed while Cochran C test indicated that no transformation was needed for species numbers. All calculations were done using STATISTICA® 6.1 software. Variations in community structure were analyzed by similarity percentage routine (SIMPER) and analyses of similarities (ANOSIM) procedures using the software package PRIMER 6 (PRIMER-E, Ivybridge, U.K.). All benthos data and results of the statistical analyses are included in the supplementary materials.

3 Results

3.1 Habitat mapping

The hydroacoustic survey executed in January 2019 revealed that all of the past dredging pits are still visible by bathymetric lows down to 30 m water depth (Fig. 2 left, multibeam echosounder measurements) and the pits of the various periods are still distinguishable from each other. The pits in the middle part of the study area derived from dredging since 2017, the western ones from the 2009 to 2016 period, the southern ones from 1995 to 2008, and the northern ones from 1984 onwards (Fig. 2). Thus, even these oldest depressions have only partially refilled with sediment after 35 years (c.f. Zeiler et al. 2004; Mielck et al. 2018).

The sidescan sonar measurements (Fig. 2, right) showed numerous features across the study area (Fig. 3). Ground truthing with grain-size analyses of the sediment (Fig. 4A and B) revealed that relatively high backscatter stands for coarse sand, intermediate for fine sand, and relatively low backscatter for muddy sediments. In addition, numerous stones were detected. Based on these sidescan sonar mosaics, the seafloor could be classified into four types (Fig. 3):

(1) The darker domains are rippled coarse sand zones (sorted bedforms). Several thousands of stones with diameters from ~10 cm to >1 m (best seen in the high-resolution data set, (Fig. 3B) occurred within this rippled coarse sand zone while there were virtually no stones present in the fine sand zones or dredging pits (Fig. 4C and D). Stones in sidescan sonogram are characterized by a strong dark reflection followed by a bright acoustic shadow.

(2) Intermediate backscatter stands for fine sand, which mostly occurred in the areas unaffected by sand extraction (Fig. 2 right). Coarse and fine sand zones were often demarcated by sharp borders (Fig. 3A).

(3) Extended areas of mud were only identified in the dredging pits in the northern and in southern parts of WDA (Fig. 3C).

(4) In the center of the study area, where sand extraction is still ongoing, cone-shaped funnels were observed in the sonograms, which were caused by recent dredging activities (Fig. 3D).

The habitat maps (Fig. 4) represent the spatial arrangement of these features in the studied area. While undisturbed ambient sediments were mostly fine sands with intermingled patches of coarse sand, the bottom of the holes left by sand extraction was characterized by coarse sands that were rapidly covered by a layer of fine sand and later by muddy sediments. The increase in mud content in >10 year old pits was highly significant (Fig. 5A).

3.2 Benthos analysis from grab samples

Sand extraction significantly changed macrozoobenthic abundance and species density while there was no significant effect on biomass (ANOVA, Table 1). Scheffe post-hoc tests revealed that abundance was significantly lower in the dredged compared to the undisturbed sites ($p<0.01$ for the recently dredged sites and $p<0.05$ for the recovery sites) while there was no significant difference between recently dredged and recovery sites ($p=0.53$; Fig. 5A and B). After >10 years of recovery, the number of species returned to a level as high as for the control site ($p=0.10$), while the difference between undisturbed (control) and recently dredged sites was statistically significant ($p<0.01$). These changes in macrozoobenthic species density and abundance were accompanied by significant changes in sediment composition, as exemplified by the percentage mud content which significantly differed between all combinations of disturbance classes ($p<0.05$; Fig. 5A).

Paralleling the changes in sediment composition, the composition of the macrozoobenthic community strongly changed during the recovery phase (Supplementary material: Table 2). Compared to the ambient sediments, abundance of *Magelona johnstoni, Pisione remota, Aonides paucibranchiata, Polygordius appendiculatus,* and *Goniadella bobretzkii*, all sand dwelling species, sharply dropped in fresh (class 1) dredging holes (SIMPER, average dissimilarity 96.95%). Older (class 2) compared to fresh dredging holes (class 1) show increases of abundance in mud dwellers such as *Lagis koreni* and *Ophiura ophiura* with its associate *Kurtiella bidentata* (SIMPER, average dissimilarity 96.38%; see Supplementary material Table 5). Both periods combined, faunal composition in older dredging holes is an assemblage of mud dwellers and strongly differs from the ambient assemblage of sand dwellers (average dissimilarity 90.94%). A community composition equivalent to ambient conditions was not reached in any of the extraction pits.

4 Discussion

The potential for natural recovery of the seafloor morphology after sediment dredging depends on local sediment availability, hydrodynamic conditions determining transport rates, and the extraction procedure (Desperez, 2000; Cooper et al., 2011; Goncalves et al., 2014; De Jong et al., 2015). A recovery of the benthic fauna in addition depends on the character of the newly accumulated material as well as on the sensibility and recruitment behavior of the involved benthic species (De Jong, 2016b).

For the sand mining area west of Sylt, hydroacoustic surveys and sediment analyses revealed that the impact of dredging on the seafloor morphology persists since many decades. Before the dredging activity started in 1984, the study site was characterized by patterns of fine and coarse sand (sorted bedforms), which are very common in this area (e.g. Figge, 1981, Mielck et al., 2015). These pre-dredging conditions are still present between the dredged areas and east of them (Fig. 2, 3A, 4).

The dredging pits, in contrast, have different surface layers. Directly after dredging the surface is composed of coarse sand and stones. Soon afterwards, this layer is covered by fine sand probably deriving from the (formerly steep) rims of the pits

(Zeiler et al., 2004; Mielck et al., 2018). Finally, the strong decrease of current velocities inside the pits allow for sedimentation of suspended mud (Zeiler et al., 2004) turning the pits into mud areas. However, sedimentation rates are typically low in the southern North Sea and the study area (Dominik et al., 1978; von Haugwitz et al., 1988; Mielck et al., 2018), which is brought about by the combination of a lack of mobile sediments and weak transport rates (Valerius et al., 2015). Therefore, mud accretion is a very slow process. The comparison of the 2019's bathymetry of the oldest pits with earlier measurements in 2016 and 2017 (Mielck et al., 2018) revealed no significant change indicating that the annual sedimentation rate was below the resolution of our multibeam device (~10 cm). This is in accordance with the very low sedimentation rate (2–18 mm per year) recorded from a muddy depression near the Island of Helgoland, ~80 km south of the study area (Dominik et al., 1978; von Haugwitz et al., 1988). Based on such low rates of sedimentation, a complete backfill of the pits is likely to take centuries (Mielck et al., 2018).

Even then, natural backfill cannot restore full pre-dredging conditions, for two reasons. The first are differences in sediment composition. While sand was removed during dredging, the backfill material is fine sand with a high mud content. This is so because coarse sand is relatively immobile on the seafloor (Tabat, 1979; Werner, 2004; Mielck et al., 2015). Therefore, backfill to the previous bathymetric situation is already slow but restoration of the previous mixture of fine- and coarse sand surface layer may take even longer. However, the previous accumulations of fine material in deeper layers of the sediment will persist, potentially also affecting the living condition for deeper-dwelling fauna.

The second reason relates to the numerous stones found in the coarse sand areas. These are – as well as the coarse sand itself - natural relicts of Pleistocene moraines (Köster, 1979; Zeiler et al., 2008) highly unlikely to be transported by tidal currents. However, they provide the only natural hard substrates in a soft-sediment environment, giving a habitat to some sessile species and serving as stepping-stones in the dispersal of others (Sheehan et al., 2015; Michaelis et al., 2019). During sand mining, stones >10 cm are filtered out and remain on the seafloor (LKN-SH, pers. com.). However, virtually no stones could be detected in the older dredging pits (Fig. 4 (c), (d)), as they were already buried by slope failures shortly after the dredging activity (Mielck et al. 2018). Thus, these patches of hard substrata are inevitably lost for the benthic epifauna.

The species composition of the macrozoobenthic infauna changed according to sediment composition in the dredging holes, once more demonstrating the well-known animal-sediment relationships deriving from the dynamic sedimentary and hydrodynamic environment (Snelgrove and Butman, 1994). Generally, recovery of the benthic fauna at disturbed sites depends on the recovery state of the sediment, and complete recovery is only possible if the native sediment characteristics are restored (Zeiler et al., 2004). Thus, complete recovery is only possible within the restrictions given above for the habitat characteristics. Until then, the original sandy habitat is lost for the benthic infauna, and thus as a feeding ground for higher trophic levels such as fish or diving birds. Currently, it is replaced by a transient habitat type with a shallow muddy surface layer on top of a sandy sub-surface layer. This allows some surface-dwelling mud-fauna to come in, but still excludes deep-dwelling mud-fauna such as *Callianassa subterranea* occurring in the muddy depression near the Island of Helgoland mentioned above. It may take some further decades of mud accumulation to reach habitat characteristics comparable to the

Helgoland depression. The feeding-ground function for higher trophic levels may then be restored, but for a different set of users: predators limited to sandy sediments will be excluded while the larger water depth will limit profitability for others such as diving birds.

Currently, sand mining is restricted to a relatively small part of the SE North Sea with vast surrounding areas with similar habitats and fauna. Because of deep dredging operations instead of extensive dredging, a vast habitat loss is therefore not expected and not a threat to all the sand-dwelling benthic species living in the area as it was the case in other marine areas (Varriale et al. 1985; Borja et al. 2006).

Instead, the deep mining pits provide a spot of muddy sediment, which is among the rarer habitat types in the SE North Sea. Judgement of prevailing pros and cons therefore depends on the item in focus but should always include that sand mining is just one of many types of anthropogenic exploitation in the area. Since faunal composition largely correlates with sediment composition, hydroacoustic habitat mapping is suggested as a cost-effective monitoring approach for the further development of the extraction sites. Though, at present, hydroacoustic mapping cannot detect the full range of benthic habitats (e.g. in transition zones, Markert et al., 2013) it can indicate structural differences large enough to activate additional faunal studies.

Besides the fauna, mud accretion in the dredging pits may also affect the chemical environment. Mud often shows enriched contents of polycyclic aromatic hydrocarbons (PAHs), chlorine hydrocarbons (Brockmeyer and Theobald, 2016) or heavy metals (Lakhan et al., 2003). In addition, hydrodynamic conditions allowing for mud accretion might also facilitate microplastic deposition. Whether or not the deep dredging pits seems to act as a sink for pollutants (Zeiler et al. 2004) and whether or not the pollutants affect the benthic fauna remains to be studied intensively. As a strategy to monitor the further development in the extraction sites, we suggest semiannual investigations of the occurring habitat types by hydroacoustic means combined with the analysis of the benthic communities every two years.

5 Conclusion

In the study area west off the island of Sylt (SE North Sea) the seafloor is characterized by a mix of fine and coarse sand patterns with occasional occurrences of stones. Sand extraction started in 1984 and created extraction pits about 1 km in diameter and up to 20 m depth below ambient seafloor level. These mining pits remained virtually unchanged even after 35 years, with low rates of backfill by muddy sediment. The change in sediment composition from sand to mud causes changes in benthic community composition, turning the previous community of sand dwellers into a mud-preferring assemblage. Further development into a typical mud community may take some more decades, until the mud layer has become thick enough for deep-dwelling species. This state may then remain for the next centuries, until the pits are largely backfilled and attain a surface sediment layer similar to original. But even then, living conditions may deviate from the surroundings, because the fine backfill sediments will persist deeper in the sediment. In addition, stones, gravel and coarse sand originally occurring at the sediment surface are unlikely to be replaced; without human interference (e.g. working with nature) their function as a habitat for epibenthic species is inevitably lost.

Author contribution. FM, HCH, WA designed the scientific study. FM, SH and CG collected the data during the research survey AL-519. SH, WA and FM processed and analyzed the data. FM, WA, RM and HCH prepared the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1: Univariate ANOVAs for macrozoobenthos parameters versus site classes (undisturbed control / disturbance >10 years ago / disturbance during past 10 years). SSQ sum of squares, DF degrees of freedom, MSQ mean square, F F-statistic.

Parameter	**SSQ**	**DF**	**MSQ**	**F**	**p**
Abundance (log_{10}-transformed)					
Constant	15.2998	1	15.2998	74.8265	0.0000
Site class	2.8096	2	1.4048	6.8704	0.0023
Error	10.2236	50	0.2045		
Biomass (log_{10}-transformed)					
Constant	0.15174	1	0.15174	5.44012	0.0238
Site class	0.01202	2	0.00601	0.21546	0.8069
Error	1.39466	50	0.02789		
Species density					
Constant	221.763	1	221.763	67.0728	0.0000
Site class	38.232	2	19.116	5.7817	0.0055
Error	165.315	50	3.306		
Percentage mud					
Constant	2.86595	1	2.86595	75.1721	0.0000
Site class	1.72991	2	0.86495	22.6872	0.0000
Error	1.86813	49	0.03813		

Table 2 was moved to supplementary material

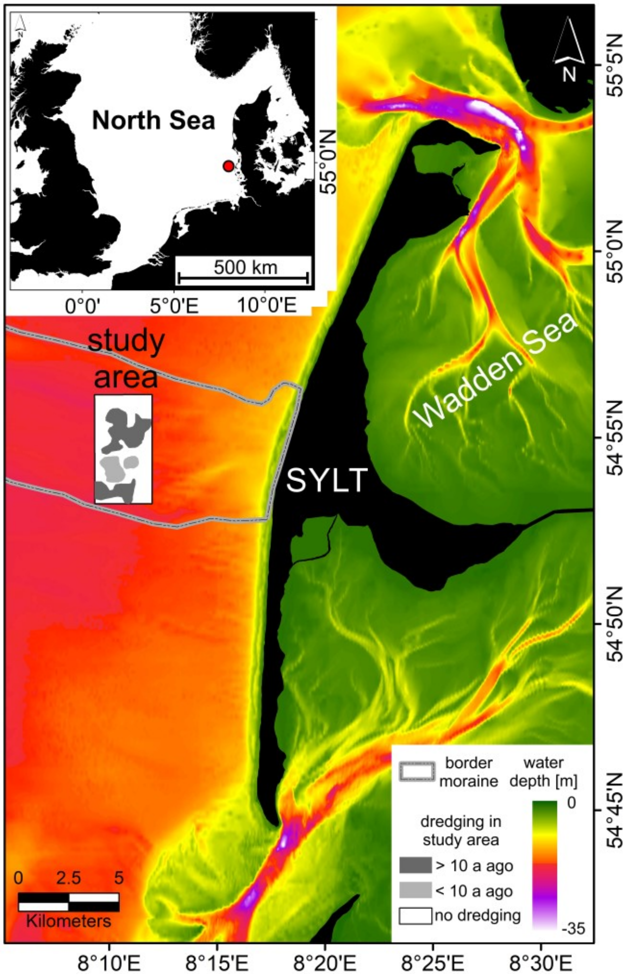


Figure 1: Study area "Westerland dredging area" (WDA) located west of the Island of Sylt (SE North Sea). Bathymetric information were provided by the German Federal Maritime and Hydrographic Agency (BSH, 2018) and own measurements. Geological data were modified after Streif and Köster, 1978 (subaquatic border of the Saalian PISA-moraine).

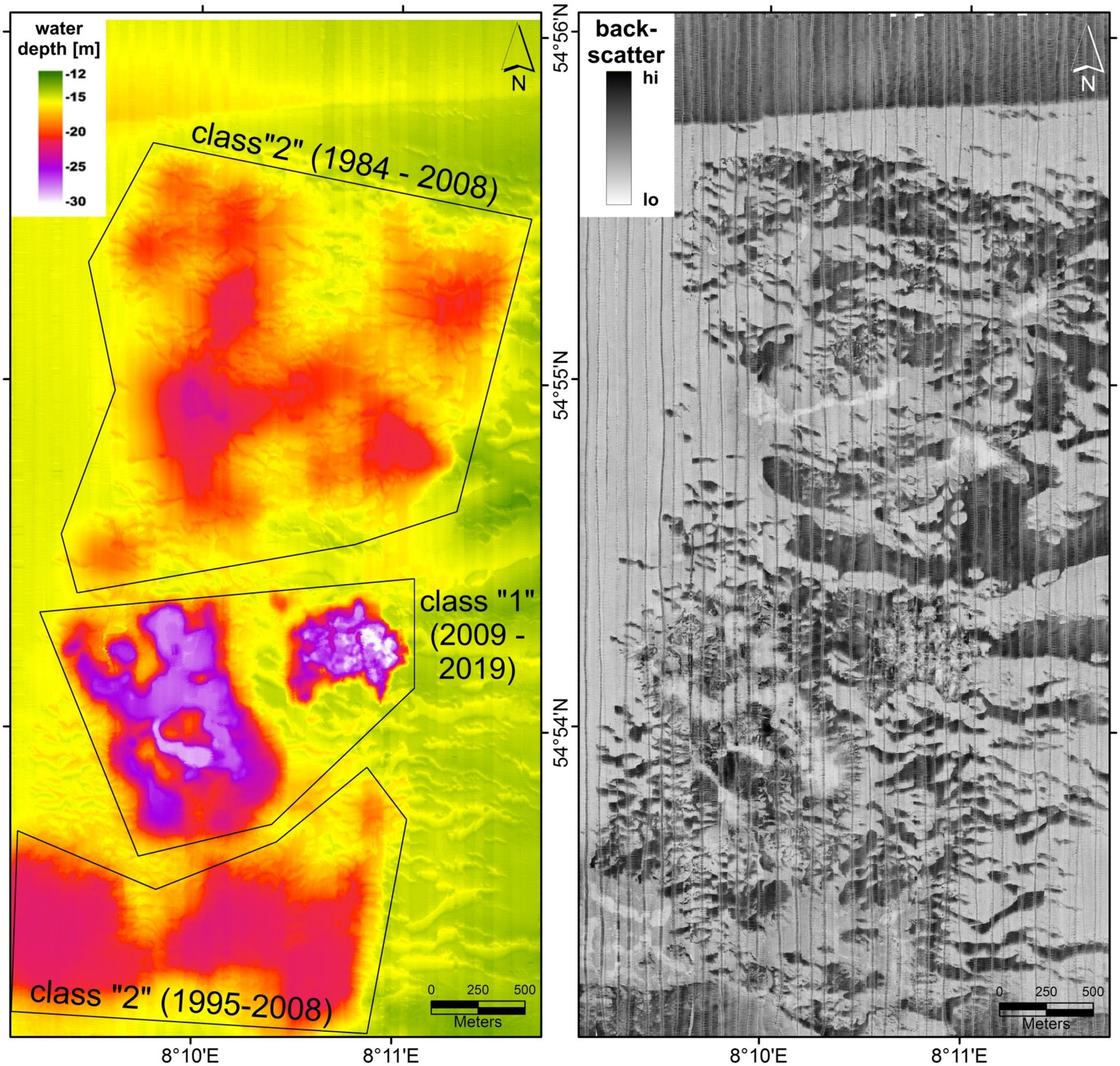


Figure 2: Results of the hydroacoustic survey along 55 N-S transects executed in January 2019. Left: post-processed bathymetric map of the study site measured with multibeam echosounder; class "1":sites where sediment was extracted during the past 10 year (1984 – 2008); class "2": sites where sediment extraction terminated at least 10 years prior to the sampling (2009 – 2019); class "0": control sites which were unaffected by dredged (area outside the boxes). Right: Backscatter response of the seafloor recorded with sidescan sonar (here: 330 kHz); dark grey = high backscatter, light grey = low backscatter. Surveyed transects becomes visible as longish dark grey stripe proceeding in N-S direction.

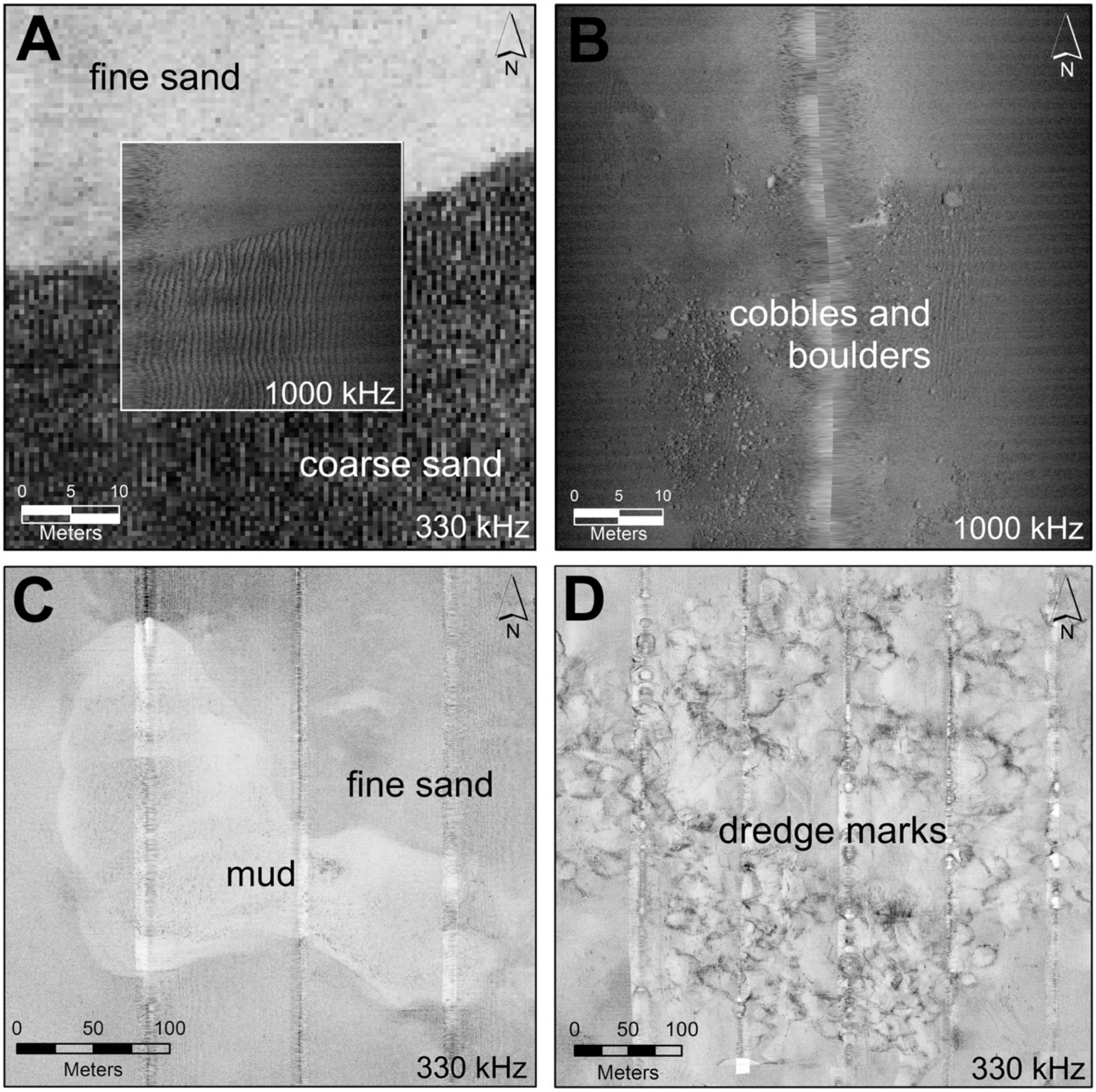


Figure 3: Seafloor features detected within the two sidescan sonar mosaics.

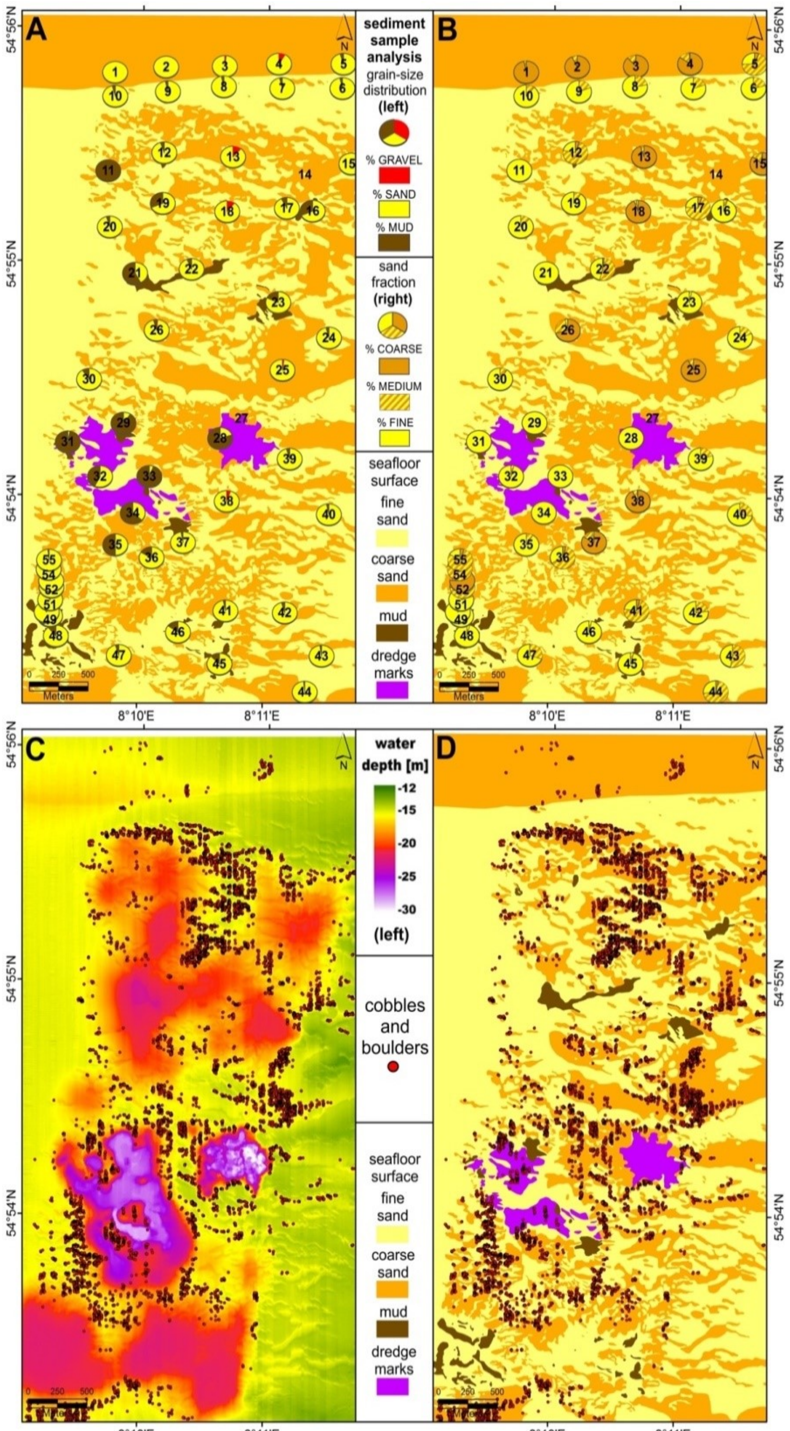
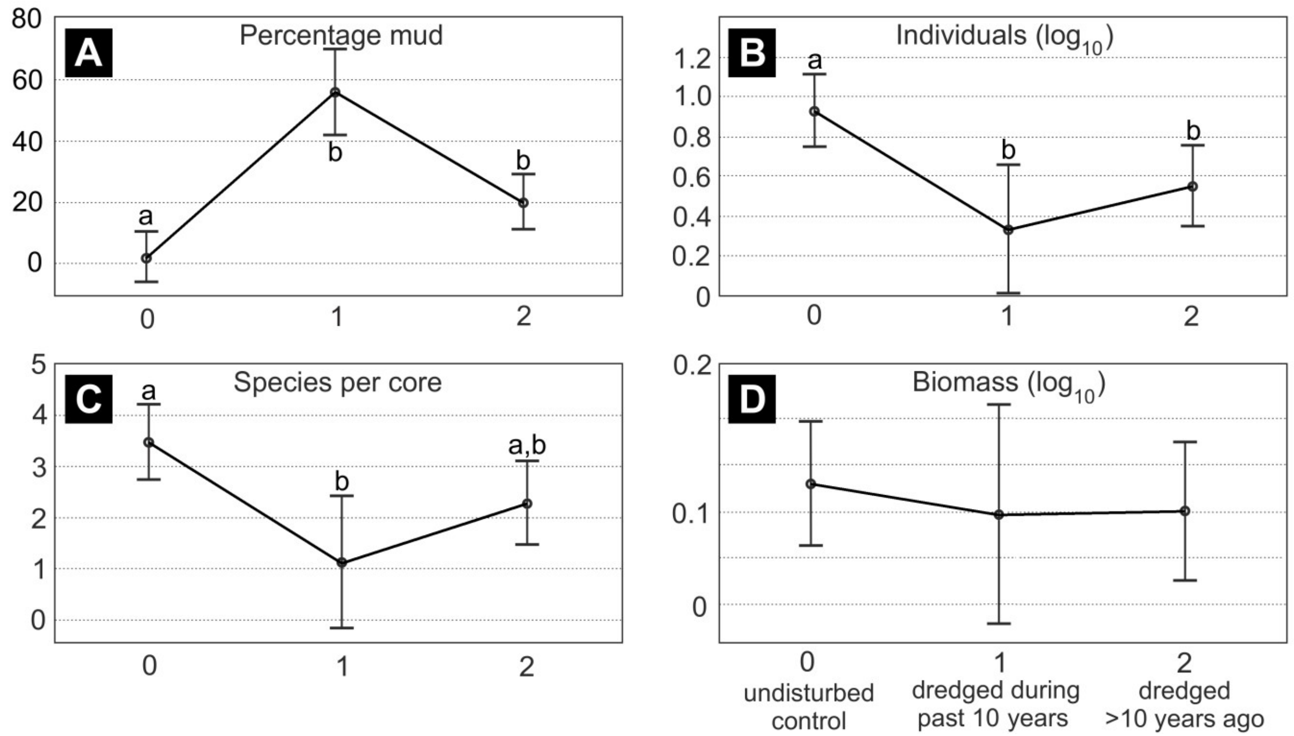


Figure 4: Habitat maps created with a combination of hydroacoustic data and ground-truth information. (a), (b): Position and sediment composition of the grab samples. The exact positions of the taken grab samples lie in the middle of the pie charts; (c), (d): appearance of stones. For age of the dredging zones cf. Fig. 2 (left).



540 **Figure 5: Mud content (A), macrozoobenthos abundance (B), species density (C) and biomass (D) of sampling stations across the sediment extraction area. Site class 0 = control sites unaffected by sediment dredging; class 1 = sites dredged within the last 10 years; class 2 = sites >10 years after dredging.**