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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 excavation site. We studied the long-term effects of sand extraction on bathymetry, geomorphology, habitats, and benthic fauna. Hydroacoustic surveys revealed that changes of bathymetry and habitat characteristics caused by sand extraction can be still detected after >35 years while the investigation of grab samples revealed persistent changes in sediment composition and benthic faunal composition. The comparison of recently dredged areas (<10 years ago), recovery sites (dredging activity >10 years ago) and undisturbed sites exposed significant differences in the number of individuals and species of macrozoobenthic organisms as well as in the mud content, indicating a persistent successional stage of the communities in the dredged areas. The slow backfill of the dredging pits results from low ambient sediment availability and relatively calm hydrodynamic conditions, despite high wave energy during storms. Based on current sedimentation rates, we conclude that a complete backfill of the deep excavation sites and re-establishment of the benthic communities is likely to take centuries in this area. Since re-establishment of the benthic communities depends on previous re-establishment of habitat characteristics, habitat mapping with remote sensing techniques is suggested as a cost-effective means to monitor the state of regeneration.

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 worldwide demand for marine aggregates needed for coastal protection reached a high level, and further increase is expected (Hamm et al., 2002; Kubicki, 2007; Danavaro et al., 2018; Schoonees et al., 2019). Currently, some 40 million m³/year of sand and gravel are being extracted from the northern European Continental Shelf (Bonne, 2010, Velegrakis et al., 2010).
Marine sand extraction changes local bathymetry and sediment composition (De Jong, 2016, Mielck et al., 2018) and affects macrozoobenthic communities, both directly by killing or removal of benthic organisms during sediment extraction, and

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indirectly by altering the environmental conditions. Further indirect effects of sediment dredging include increased turbidity, release of nutrients and toxins, changes in regional morphodynamics and smothering of organisms due to sedimentation (van Rijn et al., 2004). Current attempts to minimize the area affected by dredging activities led to greater extraction depths. The ecological effects of deep sand extraction (>10 m dredging depth), however, remain largely unknown. While sedimentological investigations yield tremendous change of the physical habitats, it must be expected that the benthic communities change at a similar level. Whether or not the benthos regenerates, remains disturbed or even develops 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 regeneration 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). Regeneration 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, full regeneration of benthic assemblages is possible but may take a long time (Desprez, 2000). 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).

In order to classify the seafloor and to map the prevailing benthic habitats at dredging sites, hydroacoustic devices are considered as an useful remote sensing tool. While 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 as an additional parameter useful for seafloor classification (Blondel and Murton, 1997; Blondel, 2003; Mielck et al., 2014, Mielck et al., 2015). Extensive ground truthing (e.g. taking sediment samples and/or underwater videos) is an important precondition to verify the sonar data interpretations, and to gain further important information on the sedimentary properties (Harris and Baker, 2012; Hass et al., 2016).

Hydroacoustic seafloor classification also enables to derive information on the benthic habitat types and the associated benthic communities. However, a precise identification of communities is not yet possible because transitional zones between major habitat types may be populated by transitional communities and these zones or often not detectable by hydroacoustic methods (Markert et al., 2013). Thus, ground truthing by sediment samples is also required to correctly identify the benthic communities.

The aim of this study is to compare the composition of the macrozoobenthic communities within dredging pits of different ages with those found in the sandy (more or less pristine) areas surrounding the extraction site. Differences in the benthic communities are deemed to reflect the refilling processes. The use of hydroacoustic gear allows to create habitat maps which

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- combined with sediment grab samples - will be used to evaluate the long- and short-term impact of dredging on the benthic habitats and the potential of regeneration in an area characterized by a lack of mobile sediments and weak sediment transport rates.

This study is part of the project STENCIL ('Strategies And Tools For Environment-Friendly Shore Nourishments As Climate Change Impact Low-Regret Measures'), a collaborative coastal and shelf research program which aims to make further steps towards the establishment of an sustainable Integrated Coastal Zone Management (ICZM) and an Ecosystem Approach to Management (EAM) in Germany.

2 Study Area

The study area is located in the German Bight (SE North Sea) approx. 7 km west off the island of Sylt (Fig.1). This island suffers from strong erosion, notably along its wave-exposed west side. Since 1971, sediment losses are compensated by artificial beach nourishments and the investigated study site serves as a sand extraction area since 1984 (LKN-SH, 2012). Its extent reaches ~5 km in north-south direction and ~3 km in east-west direction; water depths ranges between 14 and 30 m. With an annual material withdraw of 1–2 million m³, this area is the largest offshore sediment extraction site in Germany. It includes recent dredging zones, already exploited sand deposits, and unaffected seafloor regions. The pits left after dredging activity reach up to 20 m below ambient sea floor with diameters of approx. 1 km. Meanwhile, the pits persist for more than 30 years (Mielck et al., 2018).

Freshly dredged pits show 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, accumulation of muddy sediments prevails at very low sedimentation rates. This is due to the combination of a lack of mobile sediments and low transport rates (Valerius et al., 2015). Accordingly, a complete backfill of the deep dredging pits was estimated to take many decades (Mielck et al., 2018).

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). The surface of the seafloor in the study area is characterized by bands of coarse-grained rippled sand, so called sorted bedforms (Diesing et al., 2006; Mielck et al., 2015).

2 Materials and methods

For this study, hydroacoustic data and sediment samples were taken using the research vessel *Alkor* in January 2019. In order to acquire all-over information on the prevailing morphology and high-resolute 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

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knots. Ground truthing comprised 53 grab samples for grain-size analysis and macrobenthic fauna. Underwater videos could not be acquired as a consequence of high turbidity.

2.1 Multibeam echosounder

Bathymetric information of the investigation area were 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 the study site. Depth values in this study are given in meters below mean sea level.

2.2 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. The 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. The sizes of the stones were determined by measuring slant angle and lengths of the acoustic shadow using the software EdgeTech Discover.

2.3 Grab sampling and analysis

A total of 53 grab samples were taken for ground truthing 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. 4). At two positions, it was not possible to take a sediment sample due to very steep slopes or the presence of stones on the seafloor that prevented the sampler to shut 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).

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For faunal analyses, a sub-sample of 100 cm² surface area 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 of all individuals of a species within single grab samples.

For statistical analysis, the sampling sites were classified according to their history of sand extraction: Class "0" with sites never dredged 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. 2 (a)). These classes were used as a categorical variable in univariate analysis 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.

3 Results

3.1 Habitat mapping

All of the past dredging pits are still visible in the hydroacoustic survey executed in January 2019 by bathymetric lows down to 30 m water depth (Fig. 2 left, multibeam echosounder measurements). Although sand excavation in the northern part of the study area already started in 1984 (Fig. 2 (a)) the depressions have only partially refilled with sediment after 35 years. In 1995 the dredging activity started in the southern part of the study site (b) and between 2008 and 2017, aggregates were extracted in the western part of the area (c). Since 2017 a new dredging area was established in the middle part of the study site (d).

The sidescan sonar measurements (Fig. 2, right) showed numerous features across the study area (Fig. 3). Grain-size analyses of the sediment samples (Fig. 4(a), (b)) revealed that high backscatter stands for coarse sand, intermediate for fine sand, and low backscatter for muddy sediments. In addition, numerous stones were detected.

Based on the sidescan sonar mosaics, the seafloor was 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. 3 (b)) occurred within this rippled coarse sand zone while there were virtually no stones present in the fine sand zones or dredging pits (Fig. 4 (c) 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. 3 (a)). (3) Extended areas of mud were only identified in the dredging pits in the northern and in southern parts of the study site (Fig. 3 (c)). (4) In the center of the study area, where sand extraction is still ongoing, cone-shaped funnels were

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observed in the sonograms which were caused by recent dredging activities (Fig. 3 (d)). The habitat maps (Fig. 4) represent the spatial arrangement of these features in the studied area.

3.2 Benthos analysis from grab samples

After sand extraction, the macrozoobenthic abundance and species density was significantly lower in class "1" whilst after >10 years (class "2") only a slightly increase became apparent when compared to class "1" (Fig. 5, Table 1). Biomass was also lower in the sand extraction sites, however, this difference was statistically not significant (Fig. 5). Additionally, the composition of the macrozoobenthic community strongly changed during the recovery phase.

While undisturbed ambient sediments were mostly fine sands with intermingled patches of coarse sand, the bottom of the holes left by sand extraction were characterized by coarse sands that were rapidly covered by a layer of fine sand and later by muddy sediments. The increase in mud content was significantly higher after 10 years of recovery (Fig. 5).

Regarding the quantity of individuals in the grab samples, the total number was significantly lower for the dredged sites when compared to the undisturbed sites (Scheffe post-hoc test, $p<0.01$ 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 ($p=0.53$). 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 and recently dredged sites was statistically significant ($p<0.01$). The percentage mud content of the sediment significantly differed between all combinations of disturbance classes ($p<0.05$). The highest mud content occurred in recently dredged sites and the mud-loving polychaete *Notomastus latericeus* made most profit from the mud accumulation (Table 2).

After ten years of re-filling the bivalve *Kurtiella bidentata* and the brittle star *Ophiura ophiura* benefitted from the intermediate level of mud enrichment. However, most profit in this successional state made the polychaete *Lagis koreni* which was not present in our samples alive but revealed its presence by abundant remainders of its characteristic conical tubes. A community composition equivalent to ambient conditions was not reached in any of the extraction pits.

4 Discussion

The potential for natural regeneration 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). Regeneration of the benthic fauna in addition depends of the character of the newly accumulated material as well as on the sensibility and recruitment behavior of the involved benthic species (De Jong, 2016).

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 area was

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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, 3 (a), 4). The dredging pits themselves reveal a muddy surface, even 35 years after sediment excavation. This is due to low sedimentation rates in the southern North Sea and the study area (Dominik et al., 1978; von Haugwitz et al., 1988; Mielck et al., 2018) brought about by the combination of a lack of mobile sediments and weak transport rates (Valerius et al., 2015). 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 re-filling of the pits is likely to take centuries (Mielck et al., 2018).

Even then, natural regeneration cannot restore full pre-dredging conditions, for two reasons. The first are differences in sediment composition. In particular, coarse sand is relatively immobile on the seafloor (Tabat, 1979; Werner, 2004; Mielck et al., 2015). Therefore, natural regeneration of the surface layer may take a long period of time until the previous bathymetric condition is reached back again. But even then 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 - 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 most likely 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.

Generally, recovery of the benthic fauna at dredging sites depends on the regeneration state of the sediment, and complete recovery is only possible if the native sediment characteristics are restored (Zeiler et al., 2004). Since even the oldest dredging pits have neither re-filled with sediment nor attained ambient sediment composition, the benthic communities in these areas are still in an intermediate state of biological regeneration. Given the low rates of natural sedimentation, the extraction site communities are likely to remain in a successional state for the next centuries.

As a strategy to monitor the further development in the excavation sites, we suggest to investigate the different habitat types by hydroacoustic means combined with the occasional analysis of the benthic communities. Though hydroacoustic mapping at present cannot detect the full range of benthic habitats (e.g. in transition zones, Markert et al., 2013) it can indicate the time when restoration of the seafloor may be sufficient for restoration of the communities. Monitoring approaches should also evaluate potential effects of enriched contents of polycyclic aromatic hydrocarbons (PAHs) and chlorine hydrocarbons (Brockmeyer and Theobald, 2016) on the benthic organisms in the mud-rich dredging pits of the study area.

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5 Conclusion

In the study area west off the island of Sylt (SE North Sea) sand extraction takes place since 1984. Before the mining started, a mix of fine and coarse sand patterns could be found on the seafloor with occasional occurrences of hard substrates. Hydroacoustic surveys showed that even the oldest mining pits are still detectable after more than 35 years and the backfill is very slow while grab sampling revealed that the fill material is rather muddy. Investigation regarding the benthic community composition showed that mud-preferring species benefit from the altered habitats, however, sand-preferring organisms sometimes disappeared or were largely decimated. After more than 10 years, the benthic communities are still in an intermediate state of biological regeneration. We assume that they remain in this state for the next centuries, since a regeneration of the dredged areas towards pre-dredging conditions seems not to be possible in the near future because of low backfill rates and the immobility of medium-to coarse sand which prevent a re-accumulation. However, the sand mining is concentrated on a relatively small area and the surrounding seafloor shows numerous of similar untouched benthic habitats. Hence, a threat to the prevailing species is not expected.

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		

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Table 2: Macrozoobenthic species composition and community statistics.

Site class	**all**	**"0"**	**"1"**	**"2"**
No of stations	53	25	8	20
Total individuals	518	423	16	79
Abundance per core, mean	9.8	16.9	2.0	4.0
Abundance per core, sd	19.7	26.8	3.0	4.4
Total species	35	26	9	19
Species per core, mean	2.7	3.5	1.1	2.3
Species per core, sd	2.0	1.9	1.4	1.9
	total	**Ø No. of individuals per core**		
Pisione remota	152	5.84	0	0.30
Aonides paucibranchiata	138	5.36	0	0.20
Polygordius appendiculatus	60	2.28	0	0.15
Goniadella bobrezkii	25	0.76	0.12	0.25
Magelona johnstoni	25	0.92	0.12	0.05
Nephtys cirrosa	23	0.40	0	0.65
Notomastus latericeus	13	0	**0.75**	0.35
Kurtiella bidentata	12	0.04	0	**0.55**
Ophiura ophiura	10	0.04	0	**0.45**
Scoloplos armiger	7	0.08	0	0.25
Oligochaeta	7	0.04	0.12	0.25
Spiophanes bombyx	6	0.16	0	0,10
Capitella minima	5	0.12	0.12	0.05
Fabulina fabula	4	0.08	0	0.10
Urothoe poseidonis	4	0.16	0	0
Eteone longa	3	0.08	0	0.05
Mytilus edulis	3	0	0.37	0
Malacoceros fuliginosus	2	0.08	0	0
Spio filicornis	2	0.08	0	0
Nemertea	2	0.08	0	0
Eumida juv	1	0	0.12	0
Ophelia limacina	1	0	0	0.05
Scolelepis bonnieri	1	0	0	0.05
Ensis leei	1	0.04	0	0
Macomangulus tenuis	1	0	0	0.05
Spisula elliptica	1	0.04	0	0
Spisula subtruncata	1	0.04	0	0
Tellimya ferruginosa	1	0.04	0	0

Crassicorophium crassicorne	1	0	0	0.05
Diastylis bradyi	1	0.04	0	0
Monopseudocuma gilsoni	1	0.04	0	0
Nototropis falcatus	1	0.04	0	0
Anthozoa	1	0	0.12	0
Asterias rubens	1	0	0.12	0
Branchiostoma lanceolatum	1	0.04	0	0
Lagis koreni tubes*		0.04	0.12	**1.00**

* class of relative frequency; bold values indicate significantly increased ($p<0.05$) abundance per core on the species level

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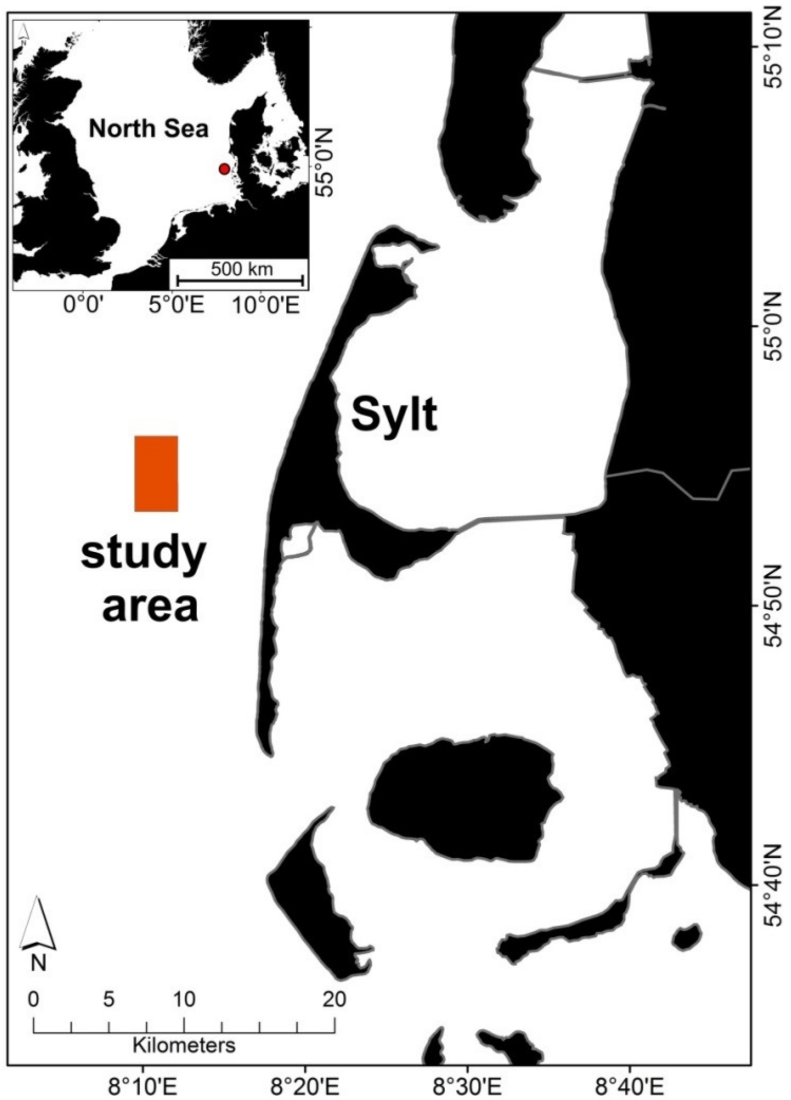

Figure 1: Study area "Westerland dredging area" located west of the Island of Sylt in the SE North Sea.

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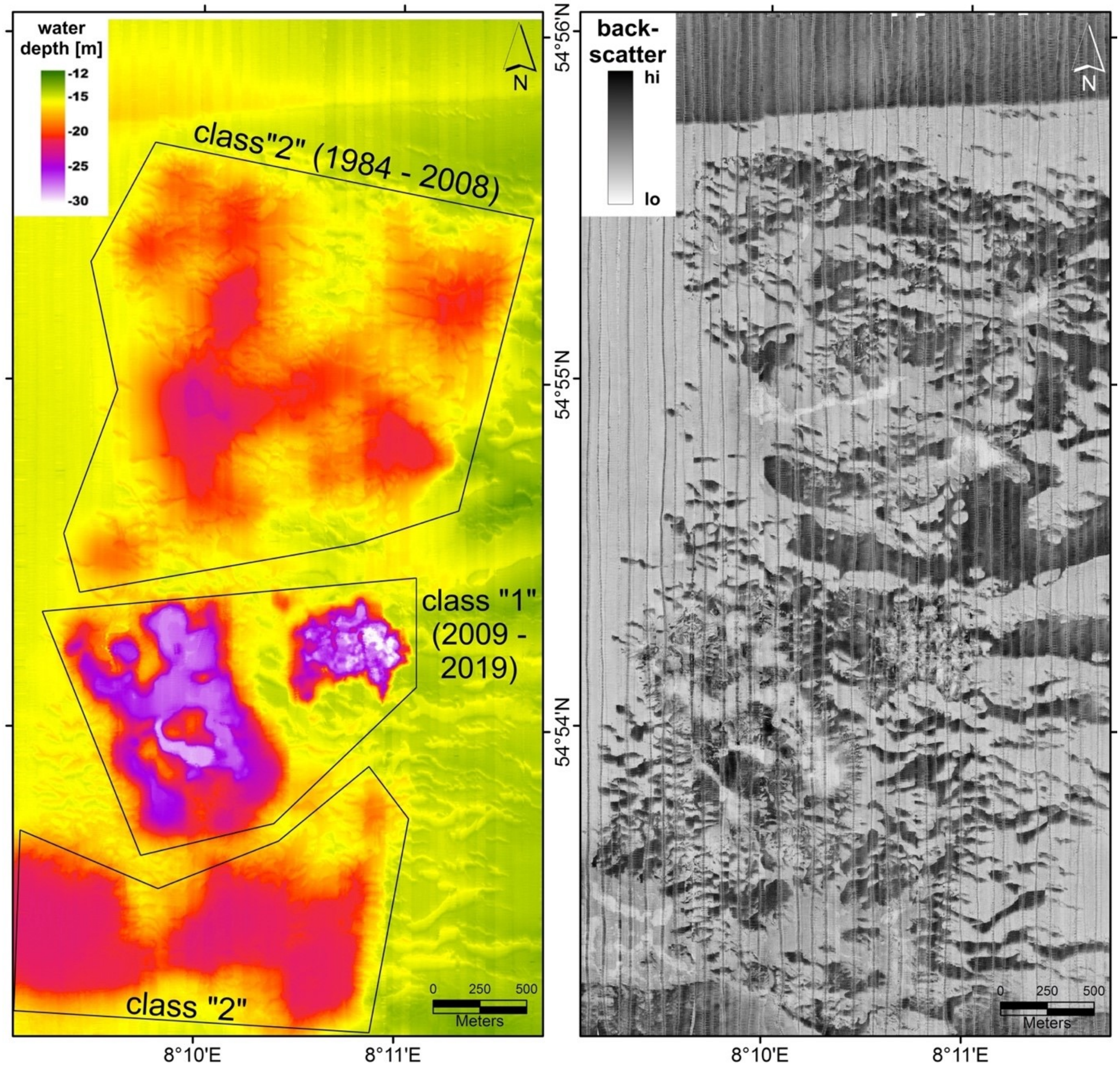

Figure 2: Results of the hydroacoustic survey along 55 N-S transects executed in January 2019. Left: post-processed bathymetric map of the study site measured with multibeam echosounder; class "1":sites where sediment was extracted during the past 10 year (1984 – 2008); class "2": sites where sediment extraction terminated at least 10 years prior to the sampling (2009 – 2019); class "0": sites which were never 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.

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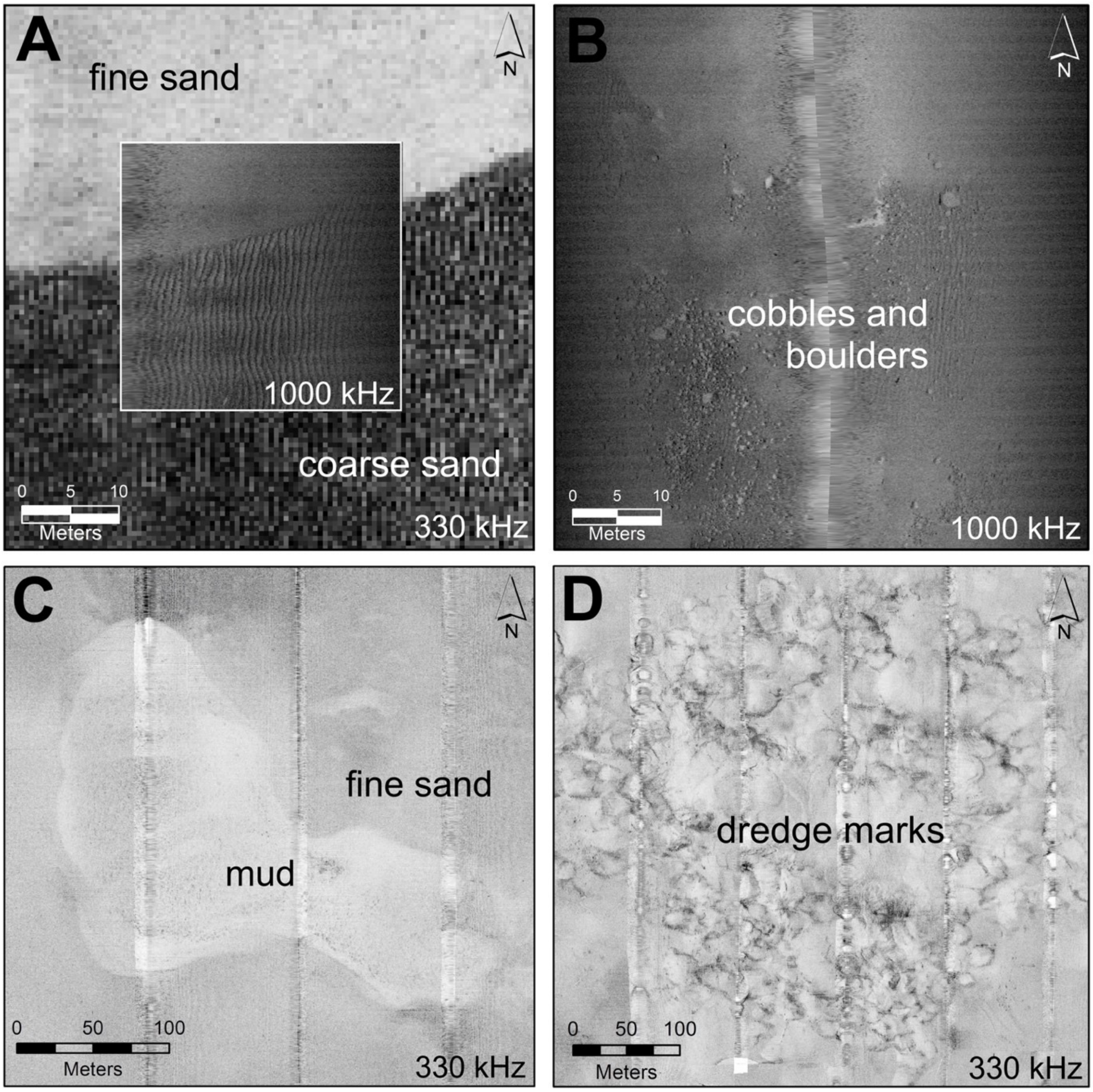

Figure 3: Seafloor features detected within the two sidescan sonar mosaics.

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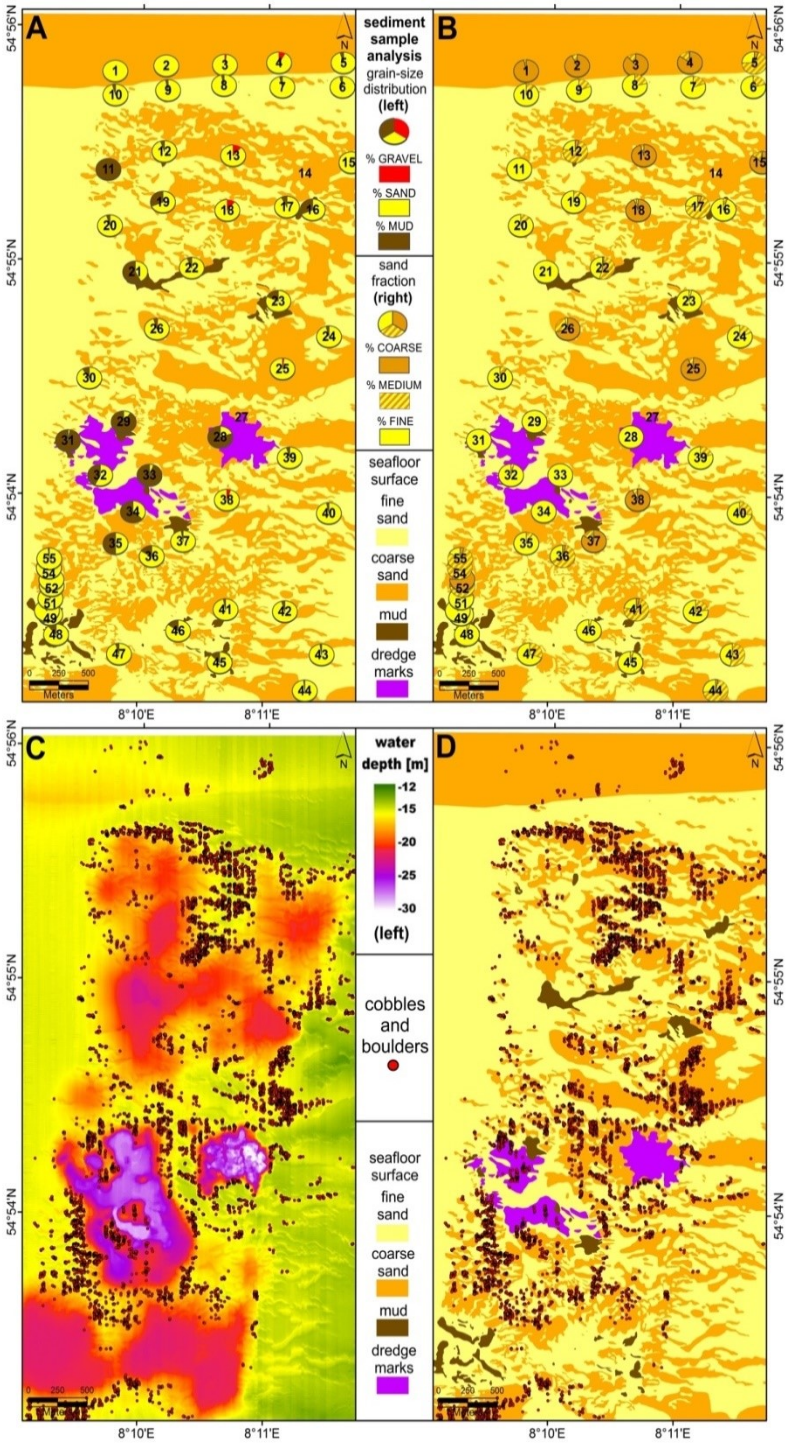

435 **Figure 4: Habitat maps created with a combination of hydroacoustic data and ground-truth information. (a), (b): Position and sediment composition of the grab samples. (c), (d): appearance of stones.**

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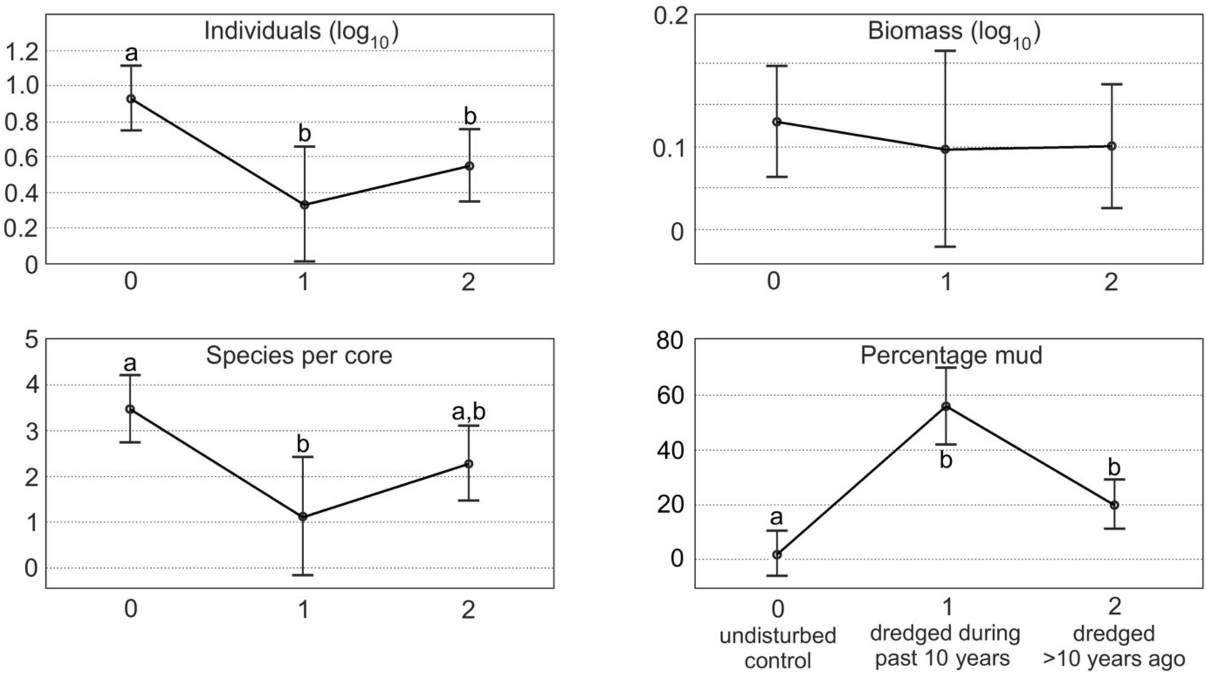

Figure 5: Macrozoobenthos abundance, biomass, species density and the mud content of sampling stations across the sediment extraction area. Site class 0 = control sites unaffected by sediment dredging; class 1 = sites dredged within the last 10 years; class 2 = sites >10 years after dredging.