Review of manuscript bg-2020-17: "Persistent effects of sand extraction on habitats and associated benthic communities in the German Bight"

Reviewer #1:

General comments:

This paper intends to investigate the effects of historic and recent intensive dredging on habitats and benthic fauna in the German Bight in a dredging area near Sylt. This is a follow-up paper of Mielck et al 2018 where the focus was on morphological changes due to sand extraction for beach nourishment. This definitely is of scientific value and interest in the field of effect studies and increasing demand of sand for both industrial purposes and coastal protection.

However, I had to find out myself that this was a 'follow-up' study and really needed to read the Mielck paper to get better insights in this study and understand the situation of the area. At least, this could have been better referred to. Furthermore, the way it is written and presented now, especially the discussion adds little value compared to the previous study. Although, in itself, it really is a different study and could add interesting new scientific insights.

But therefore, this manuscript has to be thoroughly reworked with focus on the new aspects i.e. defining the different habitats related to the dredging history of the sites and characterizing the benthic communities related to these habitats. The introduction should therefore at least make a clear referral to the previous study and the conclusions of that one.

Moreover the manuscript should better introduce the available knowledge on the topic of impact of sand extraction on benthic habitats since too few references have been cited, while already quite some literature is available and this would situate the study in a broader perspective.

Objectives should also be better delineated to make clear what the main aim of this exact study was. This could also help maybe to explain the unconventional way of benthic sampling i.e. very small sample volume used for species identification compared to volume used for sediment analyses.

Results are too vague and too descriptive. Extra multivariate analyses should be done to characterize communities. Maybe acoustic data together with sediment data could be used in a PCA and these PCA results (=axis scores) can in their turn be used in the faunal analyses so that acoustic data are really used to determine benthic communities? This study would really benefit from a better combination of both datasets, since this is its strength. While in the current version of the manuscript, these two datasets are treated as separate entities.

Discussion is too superficial and adds very few new insights compared to the previous paper as well as said above. Plus it thus not really discuss the results of this study. I also do not agree with the conclusion made. The historic dredging actually caused a loss of habitat in my opinion. You even get a change in EUNIS habitat, so regeneration to the original habitat, without human intervention, will not be possible in that sense you cannot speak about regeneration/recovery. This could be discussed in the light of the MSFD, D6 seafloor integrity C1 habitat loss. See also specific comments for some extra input in the discussion that could lift it up to an interesting contribution for the scientific community. Also here, quite some literature is already available to put your results in a wider perspective but only very few references have been used. Looking into the existing body of literature

and putting your results in this wider perspective would give more body to the discussion. To conclude, the manuscript cannot be published in the current version, thorough revision is needed of all sections and some new analyses need to be done to make this a valuable contribution.

Dear Reviewer #1,

Thank you for your revision and the numerous helpful comments and suggestions for improvement. Indeed, this manuscript is something like a follow-up to one of our previous studies (Mielck et al. 2018). The focus of that study was set on morphological changes due to marine aggregate extraction in the same study area using bathymetric data between 1993 and 2017. For the new study presented here, we collected new data and intended to focus on the impact of sand extraction on the habitats and the associated benthic communities.

You are right that the conclusion of the previous work needs to be better communicated in the introduction. We addressed this in line 105:

"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."

Many thanks also for the provided literature and the hint to the ICES WGEXT reports, which were very helpful to improve our revised introduction with more facts and recent information about this topic, as well as for deeper discussion and a meaningful conclusion.

A better delineation of the aims of this study towards a combination of the used data sets (benthos analysis and hydroacoustic data) was a very good way to improve the whole study. Additional revisions and statistical analysis were done (see below). Table 2 was shifted to the supplementary material (as well as SIMPER and ANOSIM*).*

A recovery towards the original pre-dredging conditions is of course not possible, since the coarse Pleistocene sediment cannot be replaced without a new ice age. When sand mining started in 1984, the coastal authorities and also some scientist assumed the so-called "Wanderfeinsand" (migrating fine sand, Tabat, 1979; Köster 1979), which is ubiquitous in the German Bight, will refill the pits relatively quick. This has not happened until now due to weak sedimentation rates. However, a recovery to a fine-sand habitat might be possible (maybe in decades or centuries). When the pits are flattened enough, also current velocity (which decreased significantly in the pits) will increase again. This would prevent an accumulation of muddy material. We added these aspects to the manuscript (see below).

Specific comments in chronological order:

Introduction

L30-31: 'current' with references from 2010 is somewhat outdated in my opinion. I would suggest to check ICES WGEXT reports where recent figures are yearly reported for NE Atlantic countries. Latest report has figures from 2018 even making a distinction between extraction for coastal protection and for industrial purposes, see https://www.ices.dk/community/groups/Pages/WGEXT.aspx

The number has been corrected with data from the suggested ICES WGEXT report from 2019 and the references have been changed accordingly:

Line 35:

"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)."

L30-42: very few references while quite some papers have been published on these topics so would be good to support these lines with extra references. Just naming a few: Le Bot et al 2010, Foden et al 2009, Kubicki et al 2007, Van Lancker et al 2015, also in cooperative research report of ICES WG on extraction a lot of references are incorporated in chapter on ecological impact of sand extraction (http://ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/CRR330.pdf)

The quoted references were expanded by the ones suggested above, as well as by others within the whole introduction.

L64-66: refine/rephrase your objectives – maybe better in the form of hypotheses, research questions?

This section has been thoroughly revised and is now presented earlier in the introduction.

Line 59:

"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."

L70 and further: this part should be moved to acknowledgements

This part has been moved to acknowledgements.

Study area

L74: make 'study area' a section under M&M

We moved the section "study area" to "Material and Methods" (line 84).

L75 - Fig1: Please include location of reference area(s) plus add information (best in a more detailed zoom) on e.g. geological layers, bathymetry and past and 'recent' dredged areas on the map, so it is more in line with the information provided in study area paragraph

We revised Fig 1 and added bathymetric information, as well as the border of the Saalian moraine from which the sediment has been extracted. Additionally, we included the locations of differently aged extraction areas and the reference area. The zoom-factor was also increased.

L78: water depths between 14 and 30 m, is this natural depth range or does this include extraction pits already? Confusing, I would suggest to report 'natural' depth

The stated water depths include the extraction pits. The seafloor in the study area and also in the surroundings is very flat. The natural water depth ranges between 14 and 17.5 m in the research site.

We revised this in line 94:

"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."

L79: would be good to add cumulative amount of sand that has been extracted since 1984

Since 1984, ~41 Mio m³ were extracted.

Revision in line 96:

"Since 1984, more than 40 million m³ sediment was extracted from this area using Trailing Suction Hopper Dredgers (LKN-SH, 2012, 2020)."

L82: what type of dredging is done? Static or trailer dredging?

Dredging was achieved using Trailing Suction Hopper Dredgers.

We added this information to the manuscript (see above).

L83: typo add IS derived

revised

L84: 'prevails' strange wording, better 'takes place'?

revised

Material and methods

L94 'all-over' replace by 'over-all', 'high-resolute' replace by 'high resolution'

revised

L95-96: Please put transects and location of grab samples on a map.

Transects and positions of the grab samples are provided in the section 'results'. We added this information to the manuscript at line 112. (Captions of Fig. 2 and Fig. 4a were modified to highlight this information.):

Line 537:

"The exact positions of the taken grab samples lie in the middle of the pie charts;"

Line 529:

"Surveyed transects become visible as longish dark grey stripe proceeding in N-S direction."

L95: These 55 transects were done for both multibeam and sidescan? Simultaneously or on different days? Please provide information on this in M&M section. Also not clear how long survey was, all in one week, several days throughout January? January can be quite heavy weather and shallow area so weather can have influence on measurements, certainly when spread over several days. Info needed.

We added the missing information to the manuscript:

Line 109:

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.

L111: please add what focus is of 330 kHZ and what of 1MHz sonar

Information was added to the manuscript:

Line 130:

"Using different frequencies leads to more detailed information about the seafloor environment. Sidescan mosaics recorded with a low frequency generally yield information about large-scale objects on the seafloor (e.g. facies changes, sandwaves, megaripples), while a high frequency gives more information about small-scale structures such as ripple marks or stones (Mielck et al. 2015)."

L126: very unconventional way of sampling benthos, very small samples for macrobenthos…I would expect the other way around big enough subsample for sediment and main sample for benthos? Why was this done this way? Clear justification is needed

Initially, this study was planned as a follow-up to investigate the further sedimentation characteristics of the dredging holes. When deep sediment dredging was first applied, the deeper water layer and sediment inside the dredging holes temporarily depleted in oxygen and became close to azoic (Armonies & Buschbaum 2008, unpublished report for the national authorities). This was thought to be due to the diameter/depth aspect favouring stagnant conditions in relatively small but deep holes. As a consequence, the national authorities decided that further dredging should use the same holes, i.e. increase their diameter instead of creating many small holes. The present study was an opportunity to check whether or not the larger diameter of the dredging holes would facilitate water

circulation and thus enable permanent establishment of a macrozoobenthic community in the depths of the holes. Accordingly, the main questions to answer were:

(1) is there life macrozoobenthos in the dredging holes?

(2) if yes, typical sediment-specific (i.e. mud-dwelling) fauna or just temporary opportunists washed into the holes from ambient sediments?

(3) is the benthic biomass inside the holes already comparable to ambient sediments, i.e. is the function as a potential feeding ground for higher trophic levels already restored?

To answer these questions, small sediment cores taken along with the sediment ground-truthing samples were considered to be adequate. A full description of the benthic communities in- and outside the dredging holes was not intended in this study. Only after the present results, it is clear that the current state of macrozoobenthic development warrants further studies with focus on the benthic communities, and therefore, with a sampling design adequate to reveal far more details of benthic community composition.

Armonies, W. , Buschbaum, C. (2008): Fachgutachten Makrozoobenthos im Rahmen der UVS für das Sandentnahmegebiet "Westerland III" westlich von Sylt. Im Auftrag des Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein, pp. 1-94.

L129-130: class 0 control, is this really control, undisturbed conditions?? What about indirect/secondary impacts? Can you be certain that these are not at all affected by the dredging?

We know the seafloor west of Sylt very well. In Mielck et al. 2015, for example, we made a study in an area ca. 6 km northeast of the dredging area. Additionally, during the joint research project WIMO (2010-2015), we investigated several study areas more than 20 km south of it. The investigation shows, that the seafloor conditions are very similar to the conditions in class "0" (patterns of fine and coarse sand -> so called sorted bedforms). During the dredging process in our study area, only small portions of very fine material are released to the water. This fraction was not detected in the grain-size spectrum of our sediment samples in this area west of Sylt. It seems that the material is transported away by tidal currents into northern direction.

A direct impact due to dredging activities in class "0" can be excluded, since this is not permitted by the coastal authorities. In addition, the bathymetry does not show any signs of dredging.

Revision line 152:

"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;"

Results

L140: replace ‘excavation’ by ‘extraction’ – try to be consistent throughout the manuscript

Replaced

L141: how do you know they are only partially refilled? What was depth after cessation of extraction? What is depth now? Please support your statements with numeric data.

We showed the refill process in a previous paper about the dredging area (Mielck et al. 2018: Morphological changes due to marine aggregate extraction for beach nourishment in the German Bight (SE North Sea)). Here, we also used data from 1993, that showed water depth of ~26 m in the northern pit. At this point of time, dredging activities were still conducted in this part of the study area. In 2008, water depths were at ~22 m and 10 years later, no measureable differences in water depth occurred. Moreover, we made investigations with a seismic device that revealed old slope failures in the subbottom, which are an indicator for a refill process.

Additionally, data from Zeiler et al. (2004) reveal, that similar dredging depths (~ 33 m water depth) were also achieved in the year 1991. The dredging depth after cessation seemed to be generally at this level in order to limit the size of impact.

Zeiler M, Figge K, Griewatsch K, Diesing M, Schwarzer K (2004): Regenerierung von Materialentnahmestellen in Nord- und Ostsee. Die Küste 68:67–98. https://doi.org/10.2314/GBV:599000627

We added the reference (Zeiler et al., 2004) behind the phrase in line 169.

L141-145: in text, you mention letters a, b, c , d but these are not indicated on figure2. Please make sure that your figures and text match.

We modified the text and removed a,b,c,d.

Line 165:

“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).”

– actually these are results from a previous study so delete here? Or clarify, since now it is confusing because you refer to/compare with earlier published study and description of these dredging pits is not the aim of this study.”

You are right, that the refill process is a result from the previous study. However, we think that it is important to show at least a bathymetric map of the study area and to give a hint to the refill process. Hence, we added a reference to Mielck et al. 2018.

Note: The bathymetry shown here was recorded in 2019 and was not published in Mielck et al. 2018.

L146-147: please define what is high, intermediate and low backscatter

The backscatter of the seafloor is illustrated in a grey-scale. When taking a look on Fig. 2 (right) you can see, that there are three different backscatter classes in the sonar-mosaic consisting of a range of grey values (high, intermediate, low backscatter). They represent three domains: coarse sand, fine sand, and mud. Since the backscatter in hydroacoustics is a complex process, it is not easy to define exact borders at the 8-bit color palette. There were many attempts in the past; however, the backscatter could be affected by very many parameters: e.g. the slope of the seafloor, the distance between the seafloor and the transducer, the slant range and angle of inclination, the gain-settings etc.

The post-processing software SonarWiz used in this study provides a function for automatic classification. However, there are always some artefacts in the resulting maps. Hence, we prefer to show the "raw" data in a sonar mosaic and do a supervised classification of the habitats with ARCGIS aided by our ground-truth data.

We changed this phrase in the manuscript, in order to clarify this aspect:

Line 171:

"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):"

L156-157 – Fig4: would be good to have delineation of different dredging zones cf. old, new ones this would make interpretation of the maps more clear.

These delineations are already included in Figure 2 (left). Fig. 4 already yields many features and we think that it is not a good idea to paint more lines in the figure. However, we put a hint in the caption regarding the ages:

Line 538:

"For age of the dredging zones cf. Fig. 2 (left)."

L162: on which results this statement is based? Data in results are needed to support this? E.g. multivariate analyses or cluster analyses.

We provided additional SIMPER and ANOSIM statistics/results. This information was added to the manuscript:

Line 159:

"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."

Line 198:

"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 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."

L163-165: ? would think this is a result that should be under habitat mapping? This is ground truthing of your sidescan results

Yes, indeed. We moved this part to 3.1 Habitat mapping.

Line 184:

"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)."

L166-170: unclear – is there a difference between undisturbed and control? First time mentioned in the paper. Please rephrase.

No, there is no difference. We rephrased this throughout the whole manuscript.

L174-177: idem as comment above, please use multivariate analyses to back up these statements with SIMPER to demonstrate which species are making the difference between the groups

We provided additional SIMPER and ANOSIM statistics to the result section (see above).

Discussion

L190: okay, low sedimentation rates but how does the mud comes in? Do these pits not act as traps for mud?

Yes, this is correct. They act as sediment traps. The current velocity decreases inside the pits and muddy material, which is in suspension (most likely coming from rivers), accumulates in the pits. This is one result from the previous study (Mielck et al. 2018) and was also a finding from Zeiler et al.,

2004, who measured current velocities inside the dredging pits. We added this information to the manuscript.

Line 220:

"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. "

L191-193: this is for the first time you mention the earlier study with which you compare the 2019 measurements – this causes the reader to be very confused all the way throughout the paper. Should be made clear from the beginning, even in introduction results of previous study should be situated.

To set it in a better context, we added a hint to the earlier study to the section 2.1 Study area.

Line 105:

"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."

L212: is this a successional state? In my opinion, this is just an altered habitat which will never recover to the old state and reach a different equilibrium or has already reached it in the historic dredging pits. I would call this physical loss of benthic habitat (cf. MSFD descriptor 6 C1) due to dredging, even at the EUNIS level. For more background information see reports on this topic http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/Fisheries%20Resources%20Steering%20Group/2019/WKBEDPRES2/WKBEDPRES2_Report_2019.pdf + related info. Very weak discussion regarding the benthic results/benthic habitats. This is focus of the paper but it fails to add body to this topic while it actually should be the main part of the discussion. Combining the acoustic data with the biological data, is the interest of this paper.

As already mentioned above: A recovery to a common fine sand habitat is possible, although the coarse sand is lost forever. When the pits are flattened enough, also current velocity will increase again. This would prevent an accumulation of muddy material.

However, your statements are very important and we hope that we added these aspects to our strongly revised discussion.

e.g. line: 249 and additional parts of the discussion:

"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."

e.g. line 280:

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.

L213-214: what are these habitat types? Where do you find which one? How related to dredging history? This is what should be discussed? Which habitat type, you found where and what are the indicator species for this type of habitat? As said above, this should be focus of discussion.

Based on your suggestions, we revised the discussion. See above.

L216: do you want restoration? Naturally, it will probably not be possible? So if you want restoration maybe mitigation through human intervention is needed? Or if not, leave it like it is, other suggestions?

See above (line 280).

What would be frequency needed for monitoring, yearly, every 5 years? Every 10

During our investigations in the past years, we did a semiannual monitoring program in this area. The dredging season is generally between May and September. Before they started the extraction, we did measurements to evaluate the situation and what happened to the new dredging pits from the last season during winter storms. When the dredging season was finished in September, we did a second survey to detect the new dredging pits. Since the analysis of the benthic communities is a relatively great effort, we would do this only every two years in the future.

We added this Information to the manuscript:

Line 271:

"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. "

years? As you suggest, rate of infilling is very slow so why put money in a monitoring study where you already know the result? Wouldn't it be better to put the money in other research questions or mitigation measures or 'working with nature' designs? Or studies to prevent this happening again with the ongoing dredging? I am just putting forward some ideas, topics that could be included in the discussion and that would give it more scientific value. Now the discussion is too superficial, it could be lifted up by going more into depth in the main topics of your study.

A regular monitoring is very meaningful, as the dredging activities will take place each year. We believe, hence, that these activities should be monitored by collecting hydroacoustic and benthic data on the same temporal scale. It will further allow us to control for other potential external influences,

such as storm events. However, we will come up with ideas, how the impact of dredging might be reduced.

When we started the monitoring program, it was the first time that sophisticated multibeam devices were used in this area. We already knew that the accumulation rate is very slow. However, we did not know that it is that slow. Additionally, we had no idea what happened to the benthic communities after more than 30 years after the impact.

The aspect "working with nature" was added to the manuscript.

Reviewer #2

Review of manuscript bg-2020-17: "Persistent effects of sand extraction on habitats and associated benthic communities in the German Bight"

General comments:
This paper investigates the recovery of benthic invertebrate fauna following dredging for beach replenishment in the German Bight. The under lying premise of this work is that eventually the habitat condition will return to pre-dredging condition, and this will allow the re-establishment of predredging benthic fauna, which is found in nearby undisturbed areas. The author suggests that any benthic assemblage that differs from the unimpacted zones is a successional stage.

This premise has 2 flaws:
1. The author states that the sands being dredged are Pleistocene in age, and that the existing hydraulics of the system and sediment supply limits deposition to very fine sand and mud at very low rates of deposition. This information highlights that the hydraulics and sediment supply of the area has fundamentally changed since the sands were deposited in the Pleistocene, so it is difficult to understand how the author expects these conditions to be restored, even over many decades/centuries/millenia. In effect, Pleistocene marine conditions and sediment supply would need to be re-established for the pre-mining conditions to be re-established. What these changes do highlight is that the dredging is an unsustainable mining activity – e.g. the material being extracted will not be replenished, so the dredging is resulting in a permanent change in habitat conditions. The implications of this permanent change should be the focus of the paper.

Dear Reviewer #2,

Thank you for you revision and your helpful comments.

You are right. Investigations show, that something like a new ice age with strong glacification and interglacials are necessary to reach pre-dredging conditions. However, this knowledge is relatively new regarding this study area. When sand mining started in 1984, it was assumed, that the so-called "Wanderfeinsand" (freely translated: moving fine sand, Tabat, 1979; Köster 1979) would refill the pits relatively quick. Of course, the Pleistocene material is gone forever, but a refill with fine sand would not indicate such a strong change in habitat characteristics when compared to muddy domains, since fine sand domains are relatively common west of Sylt. When you have a look at Figure 4 you can see, that the fine sand superimposes the Pleistocene material quite regularly. Hence, also a complete refill

with fine sand (maybe after many decades?) might be a re-establishment towards pre-dredging conditions. However, this recovery did not take place until now. A refill with muddy material at very low sedimentation rates seems to be the major problem, which was not predicted in the 1980s. However, maybe after many decades, the pits are adequately flattened, that current velocity might be high enough to prevent an accumulation of muddy material. This might lead to a higher accumulation-rate of fine sand. We provided the information in the strongly revised manuscript, that Pleistocene material cannot be re-stablished.

Line 242:
"Thus, these patches of hard substrata are inevitably lost for the benthic epifauna".

2. The benthic assemblages present at the mined sites are not a successional stage that will ultimately lead back to the pre-mining assemblage. If the muds are not replaced by sand (which is highly unlikely given the quiescent hydraulics and limited sediment supply), then the mud loving assemblage will remain in perpetuity. The paper suggests that there is a successional order of benthic infauna, while at the same time saying the infauna reflects the sediment characteristics. Mud is not a successional stage to sand. The change in benthos due to the change in sediment, and why this matters, should be the focus of the discussion, not that it is an intermediate step leading back to the original assemblage.

This work should be re-framed to highlight the permanent changes that are occurring to the sediments, how the infauna has changed due to these impacts, and what are the implications of these changes. The author states that the sandy benthos is wide-spread and the mining is not a threat to the prevailing species – so the question is what are the implications, if any, of the conversion of sandy habitat to muddy habitat and the loss of sessile habitat? Discussing how these changes might affect other trophic levels or food webs, such as through the uptake of PAHs or other contaminants from the mud, would be more relevant than focussing on the (lack of) re-establishment of the original fauna.

It would also provide more context for the comment about monitoring PAH's which is otherwise unrelated to anything discussed in the paper.

We changed the aims of this paper and the refill-processes is not in the focus of this manuscript anymore (as also claimed by reviewer #1). We set the objectives on the habitat change and the associated benthic communities. To emphasize this, we did further statistical analysis. Moreover, a re-framing of the introduction and the discussion (using more references, making more statistical analysis regarding a combination of the two datasets hydroacoustic and benthos analysis) was done. The impact on food webs was taken into account in the discussion: (e.g. regarding diving birds and predators).

Line 243:
The species composition of the macrozoobenthic infauna changed accordingly to the 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.

Revision regarding the impact of PAH:

Line 267:
"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 may act as a sink for pollutants and whether or not the pollutants affect the benthic fauna remains to be studied."

The introduction and presentation of the scientific question should be revised and strengthened, and the aim of the investigation should be clearly stated earlier in the paper. It would also be useful to provide more discussion about why deeper extraction pits might have a different recolonization trajectory as compared to shallower disturbances. Providing some hypothetical examples of how deeper disturbance could have different impacts as compared to shallow extraction would provide more context for the results. The paper would benefit from additional, and more recent references.

We revised the whole introduction and specified the aims. Additional references were used for both the introduction and the discussion. Your suggestion regarding deep vs. extensive dredging operations was taken into account in our strongly revised discussion:

Line 256:

"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 Italy for example (Varriale et al. 1985)."

Table 2 was removed to supplementary material.

Specific comments in chronological order:

Introduction:

1. **This paper discusses regeneration whereas it might be more applicable to use re-establishment.**

"Regeneration" has been substituted with "recovery" and "re-establishment".

2. **Line 29 – has reached a high level? Examples of the growth in extraction rates would be useful if it is considered that ongoing sand mining will pose a threat.**

Numbers from recent ICES reports were added to strenghten this statement.

Line 35:

"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)."

3. **Line 36 – activities have led**

The sentence has been corrected.

4. **Line 54 - sonars allow the analysis of backscatter intensity – how? This needs more explanation.**

Further explanation has been added.

Line 70:

"Sonar systems such as sidescan sonars allow investigating 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."

Line 59 – poor English

The sentence has been removed because it was a repetition.

5. **Line 64 introduces aim of paper – should be presented much earlier**

This section was moved and revised:

Line 59:

"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."

6. Line 67 -will be used? Have been used.

Revised.

7. 53 grab samples for 55 x 5 km transects are not a lot of samples. A more detailed description of the sampling strategy should be presented to demonstrate the samples are representative of the different areas.

The size of the study area is approx. 5 x 3 km. This is not very huge for hydroacoustics. It would be possible to survey the whole study site using sidescan sonar with ~12 transects, since our sidescan sonar could measure with a swath range of ~250 m. The reason for the high amount of transects was the multibeam echosounder. It has only a small swath range in shallow water. In order to reach full-cover bathymetry, 55 transects were necessary.

Regarding the sampling strategy we already mentioned in the manuscript:

Line 142:
"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)."

The area and the occurring surface sediments are well known due to a prior study (Mielck et al. 2018). In the manuscript presented here, we aimed to describe the habitats including the benthic communities.

The following information was added to the manuscript:

Line 140:
"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."

Mielck, F., Hass, H. C., Michaelis, R., Sander, L., Papenmeier, S., and Wiltshire, K. H.: Morphological changes due to marine aggregate extraction for beach nourishment in the German Bight (SE North Sea), Geo-Mar. Lett., 39(1), 47–58, doi:10.1007/s00367-018-0556-4, 2018.

10. Line 99 - area was collected

revised

11. Some justification should be provided that all of the past mining pits are still visible. Were the locations compared to maps? How would you know if a pit was no longer visible?

We did a previous investigation, which focused on morphological changes due to marine aggregate extraction in this study area using bathymetric data between 1993 and 2017.

Additionally, other investigations took place in this area (e.g. Zeiler et al. 2004). Moreover, the mining locations are well known by the coastal authorities (LKN-SH), so we can be sure that there are no complete refilled mining pits, which are not visible anymore.

Zeiler M, Figge K, Griewatsch K, Diesing M, Schwarzer K (2004): Regenerierung von Materialentnahmestellen in Nord- und Ostsee. Die Küste 68:67–98. https://doi.org/10.2314/GBV:599000627

This information is now included in the manuscript:

Line 105:
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.

12. Benthos -line 159 – what is class 1 lower than? Class 0?

Yes, it is lower than in class "0". We rephrased the whole section 3.2:

Line: 190:

"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 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 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."

13. Line 169: Polychaete profited? Polychaete exploited suitable environment.

Revised (see above).