



Sedimentary and faunistic effects of medium-deep sand mining along the Dutch Coast

Rob Witbaard^{a,*}, Simeon Moons^b, Loran Kleine Schaars^c, Johan Craeymeersch^d

^a Rob Witbaard, NIOZ, dept. EDS, Korringaweg 7, Yerseke, 4401 NT, Netherlands

^b Simeon Moons, Rijkswaterstaat, Ministry of Infrastructure and Water Management, PO Box 2232, Utrecht, 3500 GE, Netherlands

^c L. Kleine Schaars, NIOZ, dept. COS, Landsdiep 4, den Hoorn, Texel, 1797 SZ, Netherlands

^d Johan Craeymeersch, WMR, Korringaweg 7, Yerseke, 4401 NT, Netherlands

ARTICLE INFO

Keywords:

Sandmining
Dutch coast
Macrobenthic fauna
Sedimentary change
Recolonization and recovery

ABSTRACT

This paper presents the results of a study into the ecological long-term effects of medium-deep sand extraction along the Dutch coast. A comparison was made of the benthic fauna in and outside medium deep extraction pits of various ages, ranging between 2 and 12 years. The pits and reference areas were also compared in terms of water depth, median grain size, silt content and percentage of organic matter.

The water depth of all sand extraction pits was on average 4 m larger than the surrounding reference areas. The average silt content in the extraction pits had increased by a factor 4 compared to the surrounding reference areas. The average silt content in the pits was 9.5 %. This increase differed between pits (0 and 46 %). The percentage of organic matter had almost doubled from 0.87 % in the reference areas to 1.50 % in the pits.

The medium-deep sand extraction pits are faunistically characterized by a higher average macro-benthic biomass and density but the number of species shows no clear difference with the reference areas. Faunistic heterogeneity in the pits is lower than in the surrounding reference areas. The macro-fauna in the pits is characterized by the greater abundance of deposit feeders and interface feeders while the benthic fauna in the reference areas is characterized by bivalves i.e. filter feeders. Small demersal fish did not show clear trends although some species, such as sandeel, showed a difference in abundance between pit and reference area. The effect of age of the mining pit on faunistic composition could not be separated from differences related to geographical position.

The results of this study show that recolonization of a newly mined medium deep sand extraction pit is fast but that the complete recovery and return of the original benthic fauna in these pits can be a very long process. The sedimentary differences between the pits suggests that recovery depends on the abiotic environment. The data suggest that by moving from shallow mining pits to medium deep pits a critical depth is passed beyond which hydrographical changes alter the settlement of fines and determine the composition of the macrofaunal community.

1. Introduction

The main use of sand as building material (Torres et al., 2021) and its use in land reclamation projects made sand to become a world wide scarce resource (Bendixen et al., 2019; Peduzzi, 2014). The demand is especially high in Asia with China and India having a leading role (Gavriletea, 2017). There is often a limited management of this resource (Ali et al., 2024).

In north west Europe the resource is better managed. Like in the

Netherlands where sand extraction has been identified as an activity of national importance (Anonymous, 2015). The sand is used for the realization of large infrastructural works (Borst et al., 2013) but mainly to protect the Dutch coast from effects of sea level rise (Brand et al., 2022; Lodder et al., 2023; Stive et al., 2013). In the Netherlands, 10 to 12 million m³ of sand is nourished annually to keep the predetermined basic coastline in place. This amount is likely to increase to about 25 million m³ (Anonymous, 2022; Lodder et al., 2023). To accommodate all future needs, the Dutch government has developed a sand extraction

* Corresponding author.

E-mail addresses: rob.witbaard@nioz.nl (R. Witbaard), simeon.moons@rws.nl (S. Moons), Loran.KleineSchaars@nioz.nl (L.K. Schaars), johan.craeymeersch@wur.nl (J. Craeymeersch).

<https://doi.org/10.1016/j.ecss.2025.109337>

Received 12 September 2024; Received in revised form 25 April 2025; Accepted 4 May 2025

Available online 8 May 2025

0272-7714/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

strategy which determines where and to what depth sand can be extracted (Brand et al., 2022). The strategy is not necessary in line with EU and national legislation to protect seafloor habitats and marine species (Vermolen, 2015).

Thus given the needs and effects of sand extraction for bottom life, a practical dilemma exists. A choice must be made between shallow (2–4 m) extraction with a relative rapid recovery but affecting large areas, or medium deep (4–6 m) extraction over smaller areas. The latter method of medium deep extraction is however facing a lack of information on the recovery rates of the benthic habitat and linked ecological effects.

There are many studies describing the immediate and short-term effects of shallow sand and gravel extraction on the macrobenthos. These show that immediately after exploitation, biomass and densities have decreased, but after several years there is usually no observable difference anymore (van Dalfsen and Essink, 2001; van Dalfsen et al., 2000; Newell et al., 1998; Boyd et al., 2003; Boyd et al., 2005). On basis of these studies it is estimated that the effects for such shallow mining pits are short-lived and that bottom life has fully recovered after four to six years (van Dalfsen and Essink, 2001). Similar recovery periods are assumed if sand extraction pits are made a few meters deeper as in medium deep mining.

For real deep mining pits it is however evident that extraction creates locally different physical conditions and therefore a different habitat (de Jong, 2016; Thatje et al., 1999). There is not much known about recovery rates of benthic fauna in medium-deep (4–6 m) mining pits. Increased water depth is likely to change hydrography and

sedimentation processes. Stratification may also result in anoxia which will locally change the nutrient dynamics. Removal of sediments to great depth may even expose geologically older sediments with different characteristics which will impact nutrient storage and exchange. Given such changes, the benthic communities will change as well.

On the long term the communities may return to their original composition only if the extraction pit fills itself with original surface sediments from its surroundings. If sediment characteristics change permanently, recovery towards the original fauna is unlikely, given the tight relationships between benthic fauna and sediments (Rees et al., 2007; Heip et al., 1992) and as evidenced by various studies on deep sand mining (>20m) (de Jong, 2016; Thatje et al., 1999).

Despite being among the most wide-spread human activities in coastal areas and shallow seas, sand extraction and its impacts on biodiversity are often overlooked or underestimated (Torres et al., 2025). It is for instance unclear whether the effects measured for real deep mining pits can extrapolated to medium-deep pits. Likewise, it is questionable if the static faunistic parameters as being measured for recovery of shallow mining pits can be extrapolated to estimate effects of medium-deep sandmining. For medium deep mining pits it is unclear how hydrographical, sedimentary and ecological processes change and interact and what the timescale of these changes is.

In this study we therefore explored the recovery, development and structure of faunal communities in four medium deep mining pits of different age with the aim to get information about the chrono-sequence of recovery. This against the background of reference areas surrounding

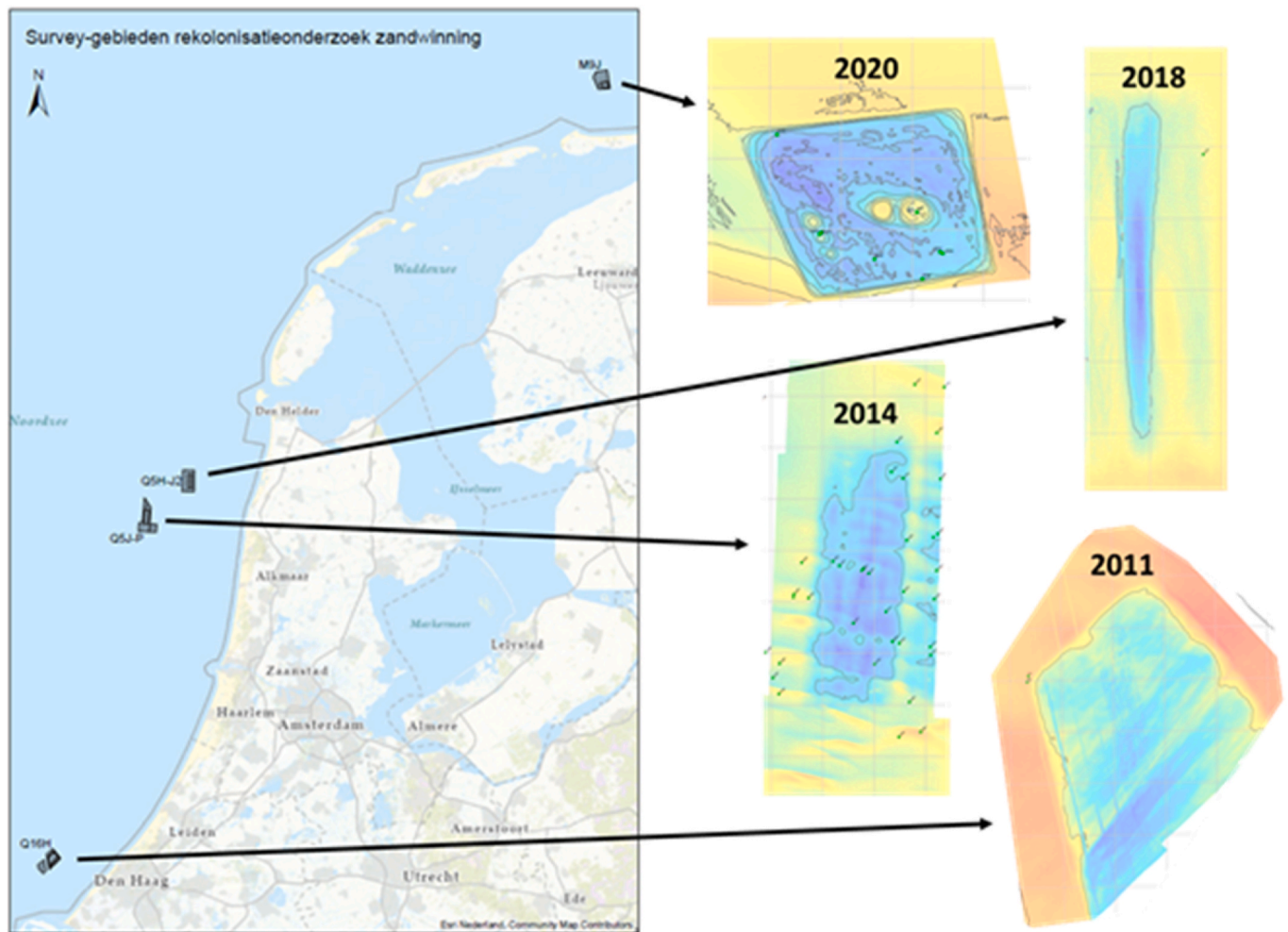


Fig. 1. The geographical positions of the mining pits. From North to South, M9J, Q5HJ2, Q5JP en Q16H. For each mining pit a bathymetric overview is given to show the orientation and bottom contours. Year of sand extraction is given with each bathymetric map.

each of the studied pits.

This study is the first in a series which looks into detail into the effects of medium deep sandmining along the Dutch coast.

2. Material and methods

In the summer of 2021, 4 medium deep sandmining pits (M9-J, Q16-H, Q5JP, Q5HJ2) situated along the Dutch coast were selected for this study (Fig. 1). Selection criteria to include the pits in this study were; 1-Sand was extracted up to 6 m. below the bed surface; 2-The year of the last sand extraction was the same throughout the pit; 3-The surface morphology of the pit was homogeneous; 4 – The orientation of the pits were comparable; 5 – The surrounding reference areas were undisturbed and had never mined before. The pits however differed from each other in terms of geographical position (see Table 1, Fig. 1) and age. Detailed bathymetric surveys in August 2021 determined the geomorphological features in and around the selected pits. Based on these data, a sampling scheme was planned.

2.1. Fauna sampling

Between February 7th and February 18th 2022, R.V. Arca from Rijkswaterstaat was used to sample the pits and the surrounding reference areas. For the most southern area a few stations in the reference area were resampled in March (2022), as the quality of the samples taken in February was insufficient due to a technical failure of the gear.

For sampling the NIOZ triple-D dredge (Bergman and van Santbrink (1994); Witbaard et al. (2013)) was used. In total 71 dredge hauls were made with a minimum of 8 stations in the pit and 8 stations in the corresponding reference area. Station details are given in Table 1.

The NIOZ Triple-D dredge is a fully quantitative dredge to sample large in- and epifauna, including sparsely distributed species ($\pm 1/\text{m}^2$) and small bottom fish. This category of benthic species are hard to quantify on basis of boxcore samples. The Triple-D dredge samples a highly selective set of organisms. The samples can be seen as complementary to box-core samples.

The dredge mouth contains a retractable cutting blade which is 20 cm wide, allowing opening and closing over a predetermined distance. It samples the seafloor to a depth of ~ 20 cm. and 20 cm. above. For this study, track lengths of 50 m were used, which means that 10 m^2 of seafloor is sampled. Track length and blade depth into the bottom are inferred from tilt sensor data.

During this sampling campaign an acoustic transponder on top of the dredge in combination with the ship's USBL system enabled the determination of the exact track position and track length. Here we report the calculated midpoint of haul when the cutting blade is in the sediment.

Directly after each haul of the dredge, performance parameters are recorded on basis of odometer counts, working pressures and a bottom detector. At the end of the day exact track lengths were calculated on basis of the tilt sensors in combination with USBL position data.

Before hauling the catch, the contents in the net are washed into the cod-end by towing the net a few minutes behind the ship. Once on board, the cod-end is emptied in large bins, catch volume is measured and photographed. The catch is sorted and when needed subsampling is part of the procedure. In case of subsampling it is assured that the catch is homogenized in advance as in the net, sorting on basis of density takes place. Specimens are sorted by species, pooled, weighed (scale: Marel, 2000 $\pm$ 0.5 gr.) and measured. Mollusks, echinoderms, fish are all individually measured to the nearest mm or 1/2 cm (de Jonge, 2020). Species which can not be identified on board, are taken to the lab. Later, species counts are transferred to densities and biomass per standard sampled area. Above procedure yields a data table on species occurrence, biomass and size distributions for each station or area. For species nomenclature, [WORMS](#) (World Register of Marine Species) is followed (Aug 15, 2022).

Between sampling in and outside the sandpits as well as between

Table 1

Sampling locations, mid position of the dredge haul together with depth (LAT).

Stationnr	Water Depth (meter; LAT)	Startbottom dd/ mm/yyyy	Lon.Midpoint (DD.ddd (E))	Lat.Midpoint (DD.ddd (N))
M9J-01- PIT_b	28.8	Feb 8, 2022	5.74065	53.56013
M9J-02- PIT	28.8	Feb 9, 2022	5.74549	53.55969
M9J-03- PIT	28.2	Feb 8, 2022	5.74942	53.56077
M9J-04- PIT	28.6	Feb 9, 2022	5.75404	53.55921
M9J-05- PIT	27.9	Feb 9, 2022	5.75762	53.56076
M9J-07- PIT	28.5	Feb 9, 2022	5.75909	53.55757
M9J-09- PIT	27.6	Feb 9, 2022	5.75153	53.55294
M9J-12- PIT	29.1	Feb 8, 2022	5.74308	53.55793
M9J-14- REF	23.9	Feb 9, 2022	5.72430	53.57051
M9J-17- REF	23.7	Feb 9, 2022	5.74511	53.57209
M9J-19- REF	23.5	Feb 9, 2022	5.75534	53.56762
M9J-20- REF	23.4	Feb 9, 2022	5.73473	53.56813
M9J-21- REF	25.3	Feb 8, 2022	5.72903	53.56242
M9J-22- REF	28.2	Feb 8, 2022	5.73469	53.55718
M9J-23- REF	23.2	Feb 8, 2022	5.74306	53.56497
M9J-24- REF	23.5	Feb 9, 2022	5.75745	53.57249
Q16H-01- PIT	26	Feb 14, 2022	4.06307	52.11217
Q16H-02- PIT	25.9	Feb 14, 2022	4.06598	52.10869
Q16H-04- PIT	25.7	Feb 13, 2022	4.06832	52.09961
Q16H-05- PIT	26.2	Feb 14, 2022	4.06068	52.10831
Q16H-07- PIT	26.6	Mar 28, 2022	4.06492	52.09975
Q16H-08- PIT	24.2	Feb 13, 2022	4.07245	52.10376
Q16H-10- PIT	25.5	Feb 13, 2022	4.07003	52.10844
Q16H-11- PIT	26.2	Feb 13, 2022	4.06655	52.09995
Q16H-13- REF	21.3	Mar 28, 2022	4.05598	52.11754
Q16H-14- REF	20.8	Mar 29, 2022	4.02983	52.09186
Q16H-15- REF	21	Feb 7, 2022	4.03723	52.08264
Q16H-17- REF	21	Feb 7, 2022	4.03461	52.08792
Q16H-19- REF	21.4	Feb 7, 2022	4.02976	52.08121
Q16H-19- REF	21.4	Mar 28, 2022	4.03014	52.08172
Q16H-20- REF	20.6	Mar 28, 2022	4.07906	52.10636
Q16H-22- REF	20.9	Feb 13, 2022	4.06084	52.11863
Q16H-23- REF	21.3	Feb 13, 2022	4.05540	52.11827
Q16H-24- REF	21.2	Feb 7, 2022	4.02477	52.08519
Q5HJ2- 01-PIT	26.4	Feb 10, 2022	4.46045	52.82176

(continued on next page)

Table 1 (continued)

Q5HJ2-02-PIT	27.1	Feb 10, 2022	4.46117	52.81847
Q5HJ2-03-PIT	26.4	Feb 12, 2022	4.46072	52.81210
Q5HJ2-04-PIT	25.9	Feb 10, 2022	4.46027	52.80571
Q5HJ2-05-PIT	26.8	Feb 10, 2022	4.46099	52.81867
Q5HJ2-06-PIT	27.2	Feb 10, 2022	4.46094	52.81682
Q5HJ2-09-PIT	23.8	Feb 12, 2022	4.46674	52.81752
Q5HJ2-10-PIT	24.3	Feb 12, 2022	4.46645	52.81151
Q5HJ2-11-PIT	26.8	Feb 12, 2022	4.46051	52.80861
Q5HJ2-12-PIT	26.7	Feb 10, 2022	4.46008	52.80748
Q5HJ2-13-REF	23.2	Feb 12, 2022	4.46047	52.83043
Q5HJ2-14-REF	22.9	Feb 11, 2022	4.46440	52.82795
Q5HJ2-15-REF	22.6	Feb 10, 2022	4.47133	52.82243
Q5HJ2-16-REF	NA	Feb 10, 2022	4.47119	52.81352
Q5HJ2-17-REF	22.3	Feb 10, 2022	4.47101	52.80328
Q5HJ2-18-REF	23.6	Feb 12, 2022	4.45426	52.82764
Q5HJ2-20-REF	22.8	Feb 11, 2022	4.44234	52.81204
Q5HJ2-21-REF	23.6	Feb 11, 2022	4.44436	52.81980
Q5HJ2-22-REF	22.2	Feb 11, 2022	4.45532	52.79791
Q5HJ2-23-REF	22.2	Feb 10, 2022	4.46277	52.79653
Q5HJ2-24-REF	22	Feb 12, 2022	4.44492	52.80411
Q5JPIT-01-PIT	24.8	Feb 15, 2022	4.32752	52.75470
Q5JPIT-03-PIT	26.7	Feb 16, 2022	4.33256	52.75303
Q5JPIT-04-PIT	26.4	Feb 16, 2022	4.32902	52.74586
Q5JPIT-05-PIT	27.5	Feb 15, 2022	4.32804	52.74374
Q5JPIT-06-PIT	27.7	Feb 15, 2022	4.33163	52.74493
Q5JPIT-07-PIT	25.8	Feb 15, 2022	4.32607	52.73695
Q5JPIT-11-PIT	26.8	Feb 15, 2022	4.33270	52.74855
Q5JPIT-12-PIT	28.1	Feb 16, 2022	4.33334	52.74098
Q5JPIT-13-REF	23.7	Feb 15, 2022	4.33449	52.72716
Q5JPIT-14-REF	22.2	Feb 15, 2022	4.32420	52.72779
Q5JPIT-15-REF	24.1	Feb 16, 2022	4.33181	52.72161
Q5JPIT-17-REF	23.6	Feb 15, 2022	4.32544	52.76319
Q5JPIT-19-REF	22.8	Feb 16, 2022	4.33478	52.76700
Q5JPIT-20-REF	21.8	Feb 16, 2022	4.34873	52.72235
Q5JPIT-22-REF	22.9	Feb 15, 2022	4.33215	52.76111
Q5JPIT-23-REF	23.4	Feb 16, 2022	4.32760	52.76750

different pits, the net was washed with an open cod-end to prevent potential cross contamination of the samples.

2.2. Sediment sampling

The triple D dredge is equipped with a miniature grab sampler to collect surface (2.5–5.0 cm depth) sediments. This sampler is triggered at the start of the actual dredge haul, i.e. when the cutting blade is pressed into the sediment a scoop of surface sediment is taken into a 60 ml jar. These samples are directly frozen on board. Once back in the laboratory, the content of the jars is freeze dried and a 2–7 g sample is used for the sediment grain size analyses on basis of laser diffraction on a Beckman Coulter LS 13 320 (Anonymous, 2018). The percentage of organic matter in the sediment was determined on basis of weight loss after ignition at 540 °C. Hereto the remaining sand fraction was used (3.5–9 g dried).

2.3. Statistical analyses

2.3.1. Univariate analyses

To get a first impression of the differences between the mining pits and their surroundings as well as between the different areas, a comparison is made on basis of univariate parameters. This was done for dredge performance (track length, blade depth), site and sediment parameters (water depth, D50, % silt, % org.C) and fauna parameters (catch volume, density, biomass and diversity). The latter separately for macro benthos and bottom fish. For a few numerical abundant species, length frequency diagrams for pit and reference samples in combination with density differences have been compared. Biodiversity indices were calculated according to Krebs (1999) and Hammer et al. (2001).

2.3.2. Multivariate analyses

The multivariate analyses focused exclusively on macrobenthos because their mobility is much more limited than for fish and are thus more likely to reflect differences between pits and ref areas. The degree to which the species composition are similar, is firstly analyzed for the four different areas where the mining pits with reference areas were located. An indirect gradient analyses, which is an ordination method, was used i.e. Detrended Correspondence Analyses (DCA). In this method the multidimensional space is reduced to a limited number of axis giving the relationship between samples and species occurrence (Borcard et al., 2011; Jongman et al., 1987). In the analyses we first focused on potential differences between the geographically separated mining pits and secondly on the differences between mining pits and the corresponding reference areas.

In the next step we tried to relate the observed faunistic differences to environmental variables. Hereto we used Canonical Correspondence Analyses (CCA). This was done for the entire data set, i.e. all combined pit and reference areas together, as well as for each pit and corresponding reference area separately. For the first instance, partial CCA was used so that first a correction is being made for the differences in benthos community caused by the spatial differences between the areas. (Jongman et al., 1987; ter Braak, 1988; Borcard et al., 1992). The environmental variables we used in this analyses were: water depth, d50, % silt, and % organic matter. Additionally we used the distance of the sampled location to the center of the mining pit. This as proxy for conditions which have not been measured such as spatially differentiated fishing intensity or faunistic spill-over effects from pit to reference area, or hydrographical effects.

The significance of the observed relationships with all variables has been tested by a Monte-Carlo permutation test (999 permutations). Both forward and backward selection of environmental variables was used to select variables and to construct the optimal model explaining the observed faunistic differences. Correlation between environmental variables was checked on basis of the Pearson's correlation coefficient.

All analyses were performed on fourth root transformed species

densities to reduce the effect of quantitative dominant species (Field et al., 1982). Only species were used which were found at a minimum of three locations and at least contributed for 1 % of the total density in the sample. This to get a robust estimate of differences in fauna composition between geographical areas and between mining pits and reference locations instead of a difference based on rare species as part of accidental catches.

Both DCA and CCA analyses and statistical testing of the differences were done in R (R Core Team, 2020) with the Vegan package (Oksanen et al., 2022). Other packages used in the analyses were; doBy (Halekoh and Højsgaard, 2025), ggplot2 (Wickham, 2016), gridExtra (Auguie, 2017), gtable (Wickham and Pedersen, 2024), readxl (Wickham and Bryan, 2025), reshape2 (Wickham, 2007), dplyr (Wickham et al., 2023), lattice (Sarkar, 2008), geosphere (Hijmans, 2024), data.table (Barrett et al., 2025), ggrepel (Slowikowski, 2025) and corrplot (Wei and Simko, 2024).

3. Results

3.1. Dredge performance

The dredge performance parameters show that the average track lengths over all successful hauls was 49.8 m. There was no systematic difference in track lengths between areas or between mining pits and their reference areas. There were neither differences between pits and reference areas for the penetration depth of the cutting blade although at site M9J (2020) the cutting blade penetrated slightly deeper in the softer sediments in the pit itself.

3.2. Abiotic environment

The average depth difference between the extraction pits and the reference areas varied between 3.4 and 4.7 m (Table 2). Measured over all locations the average difference was 3.9 m. Thus without exception water depth in the pit was considerably larger than in its surroundings.

Table 1 and Fig. 2 give the summary statistics for the sampled stations and the differences between the extraction pits and their reference areas. It shows that the median grainsize (d50) in mining pit M9J decreased from 299 μm to 199 μm and in Q16H had decreased from 288 μm to 119 μm . For mining pits Q5JP and Q5HJ2 such difference was less evident. Percent silt increased in all mining pits on average with a factor

4, but especially in the oldest pit (Q16H) where the % silt increased from ~5 % in the ref. areas to over 40 % in certain locations in the pit. A monoco sample in this area showed a 30 cm thick layer of soft mud (35–52 %). The average increase in the pits of the % organic matter was a factor 1.5. There was a weak but not significant inverse relationship between water depth and d50. Percentage organic matter and percentage silt did neither show a relationship with depth. Both were however strongly coupled to the categorical difference between mining pit and reference area. The benthic environment within the pit thus differs from its neighboring reference areas in terms of depth, grainsize, silt and organic matter (Fig. 2, Table 2).

3.3. Fauna

3.3.1. Univariate

For all areas the appearance of the dredge catch in and outside differed markedly. The catch from the M9J pit contained large amounts of sub-fossil *Cerastoderma* and *Macoma*, which are not found alive in the area today. Their presence suggests that former tidal channel deposits have been sampled (van (van der Spek et al., 2022) originating from an era with lower sea levels.

Over all pit samples summarized, the most common macro-benthic species were the echinoderm *Echinocardium cordatum*, the brittle stars *Ophiura albida* en *Ophiura ophiura* and the polychaete *Owenia fusiformis*. From mining pit Q16H four adult and living *Yoldia limatula* were found. This is an introduced species already known from the Westerschelde (Dauvin et al., 2022; Craeymeersch, 2021, Driessen and van Looijen-goed, 2020), but new for the offshore North Sea.

Per sampled location between 22 and 44 invertebrate species were encountered in the dredge samples. Over all stations an average number of 32 species were found. There were large differences in faunal densities between the four areas. In and around the youngest sandpit (M9J, 2 years) the average density was 46.9 ind.m⁻² while in and around the southern and oldest sandpit (Q16H, 12 years) an average of 2623 ind. m⁻² was found. Latter high densities could be attributed to the presence of a hotspot with *Spisula subtruncata* in the reference areas and dense beds with *Abra alba* in the pit Q16H. The other two (Q5HJ2, Q5JP) areas off the coast of North Holland, had intermediate average densities of respectively 159 and 57 ind.m⁻².

Macro-benthic biomass (wet weight) in and around Q16H was on average 224 g. m⁻², mainly caused by the dense shellfish beds. Biomass

Table 2

Overview of the main sedimentary characteristics of the sampled mining pits and their reference areas together with relevant details such as the geographical position (DD.ddd) of the pits, surface area, average water depth (LAT, M) and year from which it originated. Where relevant values are given with their standard error. Mean density in individuals.M⁻² and Biomass in Wetweight gr.M⁻². * Half of this average density is related to one sample (Q16H-24-R) taken from a *Spisula* shellfish bank.

Location	M9J		Q5HJ2		Q5JP		Q16H	
Sample	pit	ref	pit	ref	pit	ref	pit	ref
Nr of Samples	8	8	10	11	8	8	8	10
Year	2020	–	2018	–	2014	–	2010	–
Lat. (N)	53.559	–	52.814	–	52.746	–	52.105	–
Lon.(E)	5.750	–	4.462	–	4.330	–	4.0665	–
Year	2020	–	2018	–	2014	–	2010	–
km2	1.9	–	1.9	–	2.8	–	4.1	–
Depth(LAT m.)	28.4 ± 0.2	24.3 ± 0.6	26.1 ± 0.4	22.7 ± 0.2	26.7 ± 0.4	23.1 ± 0.3	25.7 ± 0.3	21.1 ± 0.1
Avg. d50 μm	199 ± 38	299 ± 36	256 ± 11	239 ± 2.2	319 ± 11	319 ± 12	119 ± 15	288 ± 18
Avg. %<63 μm	2.6 ± 0.2	1.3 ± 0.2	2.5 ± 0.6	0.3 ± 0.2	1.2 ± 0.1	0.43 ± 0.2	34 ± 3.5	6.2 ± 1.7
%org.	0.7 ± 0.05	0.58 ± 0.06	0.9 ± 0.1	0.88 ± 0.02	0.59 ± 0.02	0.48 ± 0.02	3.93 ± 0.37	1.42 ± 0.15
N-taxa Macro	21.4 ± 1.3	25.1 ± 0.6	30.0 ± 0.9	25.5 ± 1.0	21.9 ± 1.8	20.0 ± 1.0	22.6 ± 0.5	26.8 ± 1.4
Density Macro	45.8 ± 6.0	48.1 ± 22.9	298 ± 66	32 ± 6.4	105 ± 61	9.4 ± 1.4	3345 ± 684	2045 ± 1095*
Biomass Macro	8.3 ± 1.1	12.3 ± 3.7	32.6 ± 7.1	7.3 ± 0.7	22.9 ± 6.2	4.0 ± 0.8	134 ± 26	297 ± 139
N-taxa Fish	9.5 ± 0.6	11.5 ± 0.3	9.9 ± 0.7	6.2 ± 0.6	7.5 ± 0.8	5.9 ± 0.6	3.9 ± 0.6	5.1 ± 0.5
Density Fish	9.7 ± 1.2	16.1 ± 1.5	3.6 ± 0.4	3.1 ± 0.4	8.2 ± 0.8	4.7 ± 0.4	0.53 ± 0.1	2.2 ± 0.7
Biomass Fish	4.5 ± 0.5	5.5 ± 0.5	3.9 ± 0.7	2.5 ± 0.5	4.5 ± 0.9	2.4 ± 0.4	1.6 ± 0.4	7.4 ± 2.5

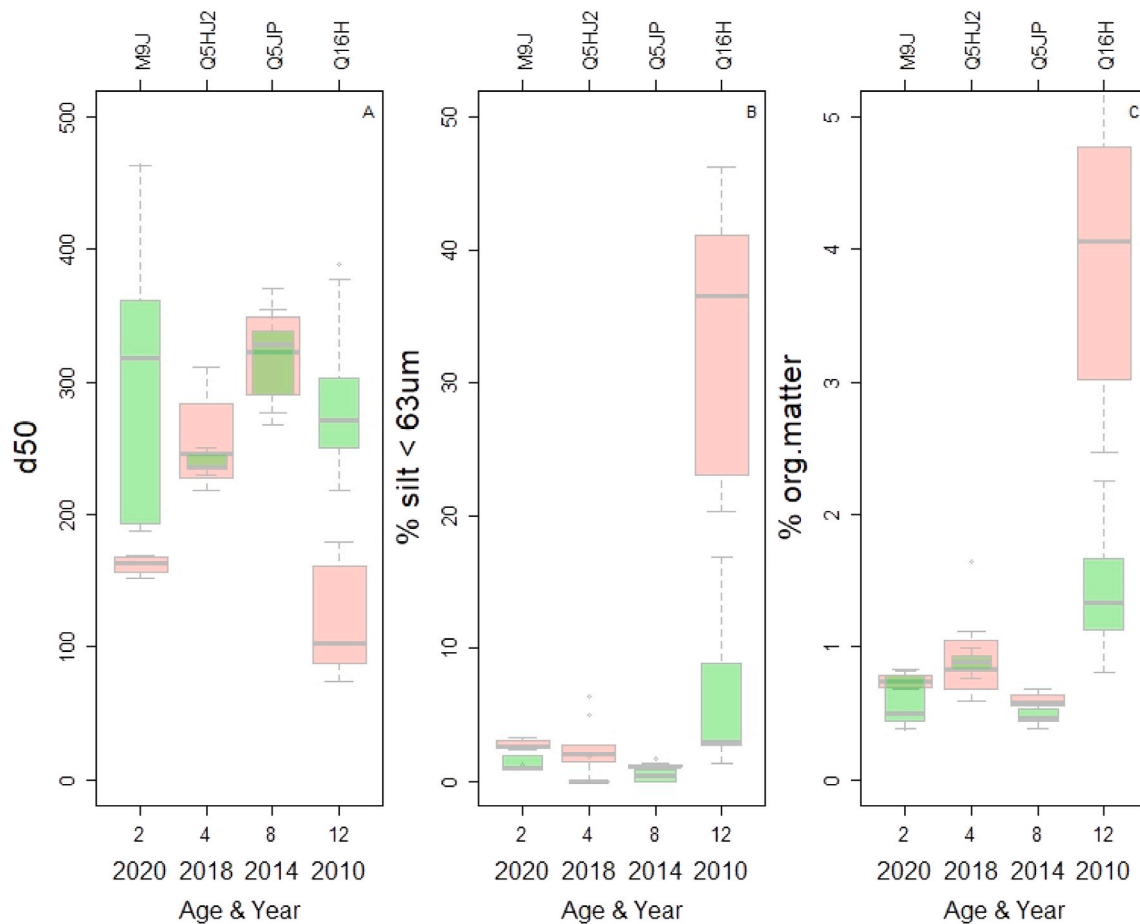


Fig. 2. Boxplots showing the differences in sedimentary parameters between the mining pit (red) and the reference areas (green). Along the x-axis the age in years and the year of sand extraction are given. On top of the graph the location names are given. **Fig. 2A;** Median grainsize, **2B;** Percentage silt, **2C;** Percentage Organic matter. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in the other areas ranged between 10.3 and 19.4 g. m⁻².

The "averaged" differences between extraction pit and their surroundings are summarized in Fig. 3, showing that both log(density) and log(Biomass) differ significantly (Tukey HSD post hoc, $p < 0.05$). This trend is however inconsistent when looked at individual pits (Table 2). While macro-benthic densities are always higher in the pits, the difference in average biomass between pit and reference area is mainly caused by the difference in Q5HJ2 and Q5JP.

Studying the diversity and dominance patterns (index of numerical distribution of specimens over the pool of species) gives a more robust difference (Fig. 4). The macro-benthic faunas in the reference areas are without exception more diverse than in the mining pits. Dominance in the pits is invariably higher when compared to the reference areas. Only for Q16H there is overlap in dominance, caused by the abundant occurrence of *Spisula subtruncata* in the reference areas and *Abra alba* in the pit itself.

Over all samples 26 species of bottom fish were found. *Gobiidae* and *Ammoditidae* were the most abundant species groups. No significant difference was found between the pooled pit and pooled reference areas in terms of average fish biomass or average fish density (Tukey HSD, $p = 0.36$ & $p = 0.59$ respectively). Number of species between pit and ref area neither differed. There were however differences for individual pits or species groups but these were not unequivocal when compared over all pits. Fish densities in pit M9J and Q16H were lower than in the surrounding ref areas. The mining pits Q5HJ2 and Q5JP showed the opposite trend with higher fish densities in the pit. In the reference areas sandeels (*Ammoditidae*) and the pooled flatfishes tend to be more abundant. *Callionymus lyra* was more abundant in the pit areas.

3.3.2. Size distributions and densities

For a few key species which were identified from the multivariate analyses length frequency diagrams and a comparison of densities in and outside the pit(s) were made (Fig. 5). *Abra alba* is such a species and is indicative of organically enriched fine sediments. It is extremely abundant in the pits with an average density of 641 ind.m⁻². The average density for the reference stations was 54 ind.m⁻². Mean shell length within the pits is slightly smaller than in the reference areas. *Donax vittatus* is another bivalve species which contributes to the observed differences between pit and the surroundings. This species is hardly found within the pits. Their shell lengths in the reference areas were slightly bigger. The filter feeding bivalve *Spisula subtruncata* which was mainly found in the southernmost location (Q16H) demonstrated a distinct size separation between pit and reference area. The variation in densities of the sampled locations in the reference areas were however so large that the observed average density difference between pit (898 ind.m⁻²) and surroundings (2 ind.m⁻²) became insignificant.

A typical echinoderm species found in the mining pits was *Echinocardium cordatum*. The average densities in mining pits was 82 ind.m⁻² while outside the pits the average density was 14 ind.m⁻². Average length in the reference stations has a unimodal distribution and is larger than in the pits where 2 size classes were present. Another echinoderm which was commonly found in the mining pits is *Ophiura ophiura*. Mean density over all pits was 25 ind.m⁻² while outside the pits its density was as low as 6 ind.m⁻². Average size in the pits was smaller, mainly because larger animals were almost absent. *Crangon crangon* had similar size class distributions within and outside the pit. Densities in the pit are suggested to be slightly higher ($p < 0.05$). *Philocheilus trispinosus*, a small

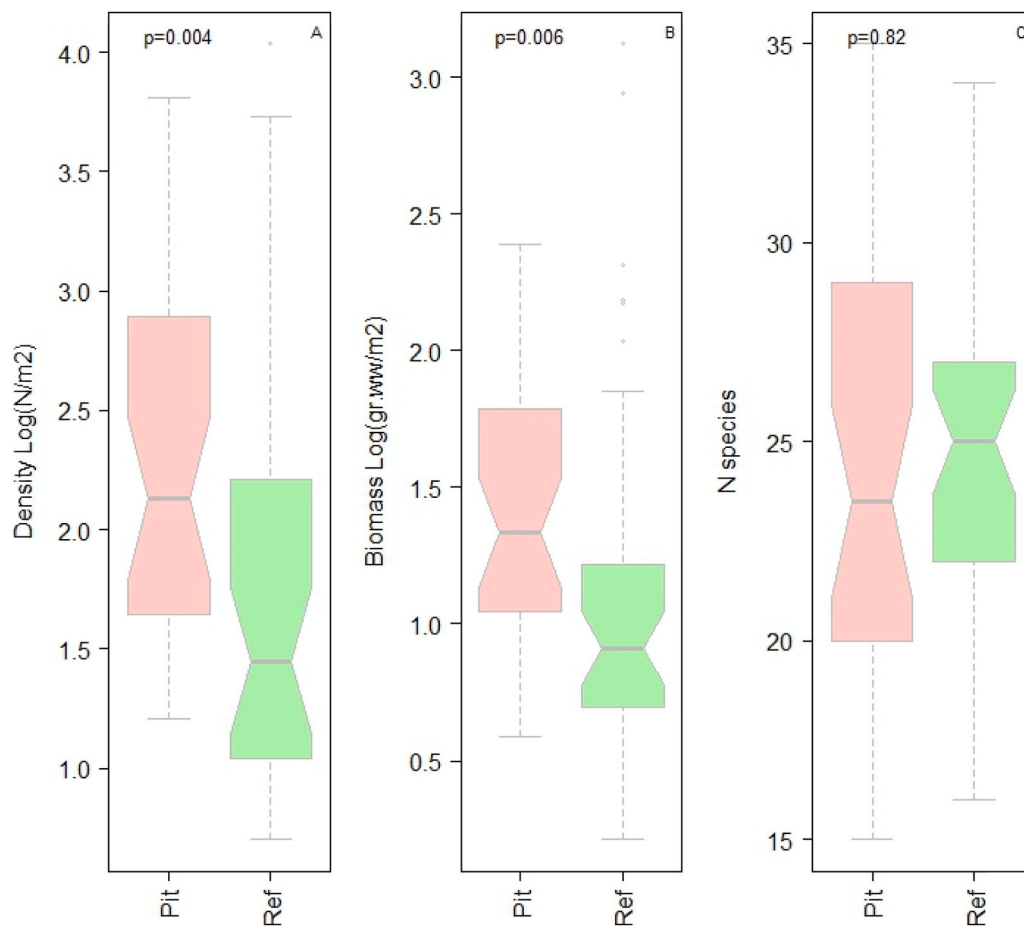


Fig. 3. Notched box and whisker plots which give the differences between mining pit (red) and its surroundings (green). Non overlapping notches indicate a significant difference (McGill et al., 1978). 3A: Macrofaunal density, 3B: Macrofaunal biomass; 3C: Number of macrofaunal taxa. On basis of a post-hoc Tukey HSD test the p-values are given in the top left corner of each panel. Both faunal density and biomass differed significantly. There was no difference in the number of taxa. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

shrimp species neither differed in size, but densities, although low, were in the pits significantly lower ($p < 0.05$) (no graph).

Largest difference in fish fauna were found for the M9J pit mainly due to the $5 \times$ lower sandeel densities in the pit (1.5) when compared to the reference areas (8.3). The difference was highly significant (TukeyHSD- $p = 0.006$).

3.3.3. Multivariate

The univariate analyses do only give a limited insight in the compositional differences of the communities sampled. This is illustrated by the almost identical species numbers found in the mining pits and the reference areas. The diversity indices (Margalef, Shannon-H, Dominance) however show a distinct difference and show that the specimens are numerically differently spread over the species when pit and reference areas are compared.

To detect and summarize the subtle changes in faunistic composition, multivariate techniques are better suited and offer the possibility to link the differences to measured environmental variables. Hereto we used DCA and CCA.

Fig. 6 shows the results of the DCA applied on the macro-benthic data set and suggests that three distinct types of communities were sampled. The 95 % ellipses for the reference areas (containing original fauna) of M9J, Q16H and Q5HJ2 + Q5JP do not show any overlap suggesting that they represent distinct different benthic communities. This separation is most likely related to the large geographical range over which the areas are spread. The only community overlap which was found concerned the two locations off the coast of North Holland (Q5HJ2 & Q5JP),

suggesting that around these two pits the original fauna is similar.

The same figure (6A) shows that the ellipses for all the mining pits and corresponding reference areas have minimal or no overlap. This is even the case for the areas Q5HJ2 and Q5JP and illustrates that benthic communities in mining pits deviate from their "undisturbed" references. The ordination furthermore shows that the most northern sampling location (M9J) deviates strongest from the other areas.

In Fig. (6B) the most influential species are plotted in the same 2 dimensional space. Overlaying these graphs shows which species are characteristic for the communities identified by the ellipses. The most southern location Q16H and its reference area are characterized by *Abra alba*, *Owenia fusiformis*, *Spisula subtruncata* and *Ophiura albida*. The mid stations (Q5HJ2 and Q5JP) can be characterized by *Ensis ensis*, *Thia scutellata*, *Fabulina fabula* and *Ensis magnus*. The most northern location (M9J) is characterized by the abundance of *Astropecten irregularis*, *Donax vittatus*, *Ensis siliqua*, *Ensis leei* and *Ophelia borealis*.

Similar analyses have been performed on each area separately. They show that for all areas big differences exist in the benthic communities from the mining pit when compared to the corresponding reference areas. Percentage explained variance for the different areas range between 45 and 65 % and can all be related to the abiotic variables (Fig. 7).

For the multivariate analyses of the bottom fish the rare species were excluded from the analyses (as for the macrobenthic species) to prevent spurious results based on the occurrence of one or two single specimens caught. The results of that analyses showed that there are regional (latitudinal) differences in the composition of the fish fauna between the four areas sampled. Especially the composition of the fish fauna in the

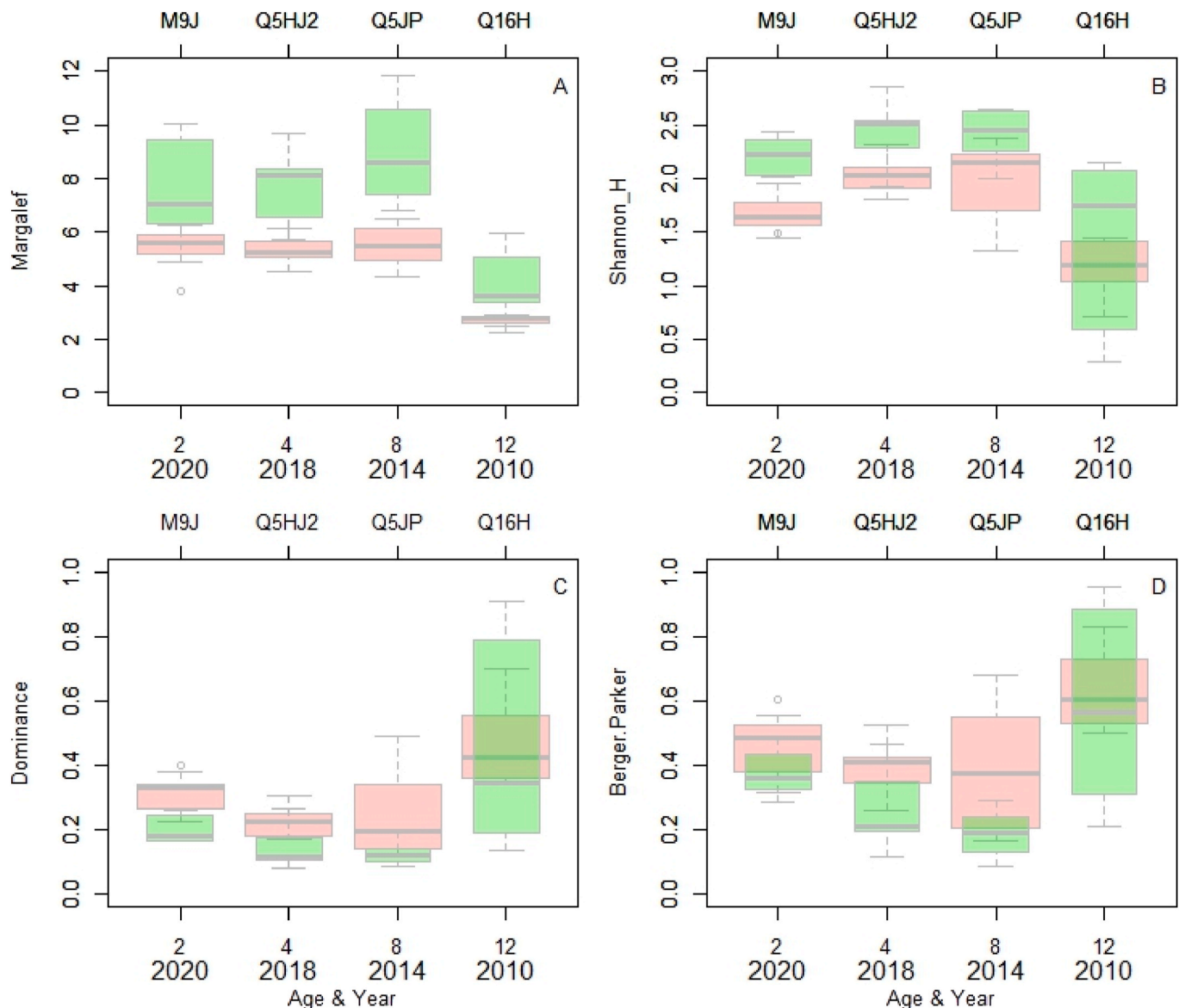


Fig. 4. Boxplots giving an overview of the differences in diversity and dominance indices between mining pit (red) and reference areas (green). The mining pits have been left-right arranged in order of age. The name of area has been plotted above each [graph 4A](#): Margalef's diversity index; [4B](#): Shannon_H diversity; [4C](#): Dominance; [4D](#): Berger parker dominance of the most abundant species in each of the areas. The high dominance in the reference area of Q16H pit is linked to the local mass abundance of *Spisula subtruncata*. In the pit itself the dominance is related to the high densities of *Abra alba*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

southern (Q16H) and most northern location (M9J) differs markedly from the intermediate area. Differences in composition of the fish fauna between mining pit and reference areas were weak or absent. Only for some single species such as sandeel, the densities between pit and reference area differed significantly.

Thus especially the macro-benthic data shows that there are clear signs of a faunistic change in the pits in comparison to the surrounding reference areas. This difference (over a small spatial scale) overlays the a huge natural geographical variation in community structure between the four sampled areas.

4. Discussion

In the Netherlands shallow sand extraction (2–4 m) is nowadays replaced by extraction to slightly greater depths (4–6 m). This guarantees future needs and limits the space needed for sandmining. In Dutch coastal waters the spatial demand for sand extraction appears small in

relation to the total surface area of the Dutch EEZ but relative to the typical coastal sandy habitats its spatial proportion can be scaled differently as extraction takes place in a strictly bounded depth zone ([Brand et al., 2022](#)) which hosts typical benthic communities.

Extraction to somewhat greater depths, is facing a lack of information on the ecological and hydrographical consequences such as recovery of the macro-benthic communities.

According to [de Jong et al. \(2016\)](#) and [van der Werf and Giardino \(2009\)](#) major hydrographic effects can also occur if a series of contiguous (medium) deep sand extraction pits develop along the coast in the direction of the flow. Such situation could potentially disturb the sedimentation-erosion balance and trigger unintended biological, hydrological and geomorphological effects. An example of such effect has been described for Kwinte Bank in the Belgian North Sea ([Bonne, 2010](#)).

For deep mining (~20 m), [de Jong et al. \(2016\)](#) also concluded that it will likely take decades for the benthos community to fully return to its original state, if ever possible. Today, it is also the question whether the

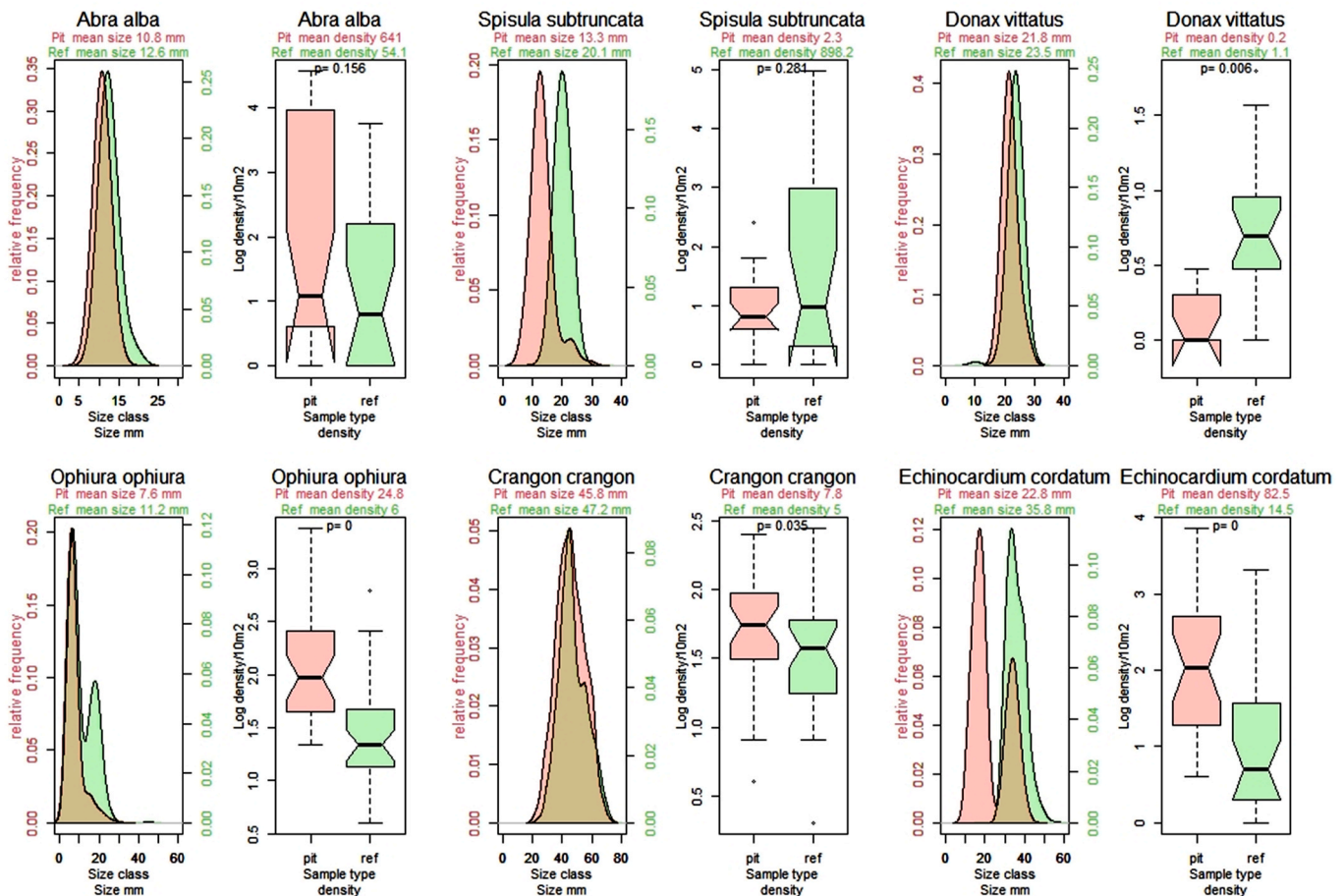


Fig. 5. A comparison of size frequency distribution and density differences of selected species between pit and reference area. In the top right corner of each graph key numbers are given. For the differences in average density p values are given to indicate statistical significance.

fauna in medium deep (4–6 m) extraction pits can fully recover and how long such recovery may take.

To study this, four medium deep mining pits in the Dutch coastal zone had been selected which differed in age and were free of sand mining in their close vicinity. It was furthermore assumed that the reference areas around each pit contained the original fauna and could function as background against which the development of the fauna in the pits could be compared. It can however not be excluded that bottom-trawling has contributed to faunal differences between pit and reference areas. Especially if bottom fisheries preferentially targets either the pits or the reference areas. We have however no data available of fishing intensity and history at the same spatial scale as our study sites. In our opinion it will therefore be too speculative to attribute observed differences between pit and reference areas to spatial differences in bottom fishing in and around pits or between areas. We furthermore added a factor "distance" in the analyses to be able to catch unknown variation in the dataset, like a potential fishing effect.

Based on the multivariate analyses, it was immediately evident that geographic latitude and age of the pits behaved as covariates. Therefore the effects of age and geographical latitude were impossible to separate from each other. This is illustrated by the ordination (Fig. 6) showing that for the reference stations three distinct macrobenthos communities could be recognized without showing overlap of the 95 % confidence ellipses. Thus the reference areas by no means reflect the same type of benthic community, implying that the initial question about recovery rate of medium deep mining pits could not be answered. Still lessons can be learned from the comparison of the pits and reference areas and among the locations.

The existence of a "pit effect" is evident for all sampled areas.

Between 45 % and 65 % of the variance in the faunal communities in the pits and reference areas can be explained on basis of depth, % silt and d50 (Fig. 7). The percentage of organic matter added little to the explained variance and was therefore omitted although it may play a crucial role (see below). The % org. matter strongly correlates with % silt (0.96) and the percentage of organic matter is the most likely factor responsible for the observed faunal differences as it is an indirect measure of food supply.

The medium deep mining pits studied here, show an increase of the % silt which ranged between 2 and 8 times. The increase in organic matter content ranged from a few percent to nearly a factor 3.

Boxplots show that benthic density and biomass (Fig. 3) in the mining pits is higher than in the reference areas. This suggests that the amount of available food, to sustain the community, is higher in the pits. This idea is confirmed by the observations of Burd et al. (2012). They showed that the organic flux was the most important predictor for benthic biomass and production in the Strait of Georgia (west coast of Canada). There are many other studies showing that the supply of organic matter is a critical factor to explain higher densities and biomass (de Jong et al. (2015); de Jong (2016); Rosenberg, 1995; Boon et al., 1999; Creutzberg et al., 1984; Rees et al., 2006; Thatje et al., 1999; Sardá et al., 2000; de Jong et al. (2015); de Jong (2016)).

The mining pits studied here had especially higher biomasses and densities of (subsurface) deposit feeders such as *Echinocardium cordatum* or *Abra alba* (Fig. 5). These species are relatively short lived and typically respond quickly to disturbance and food enrichment (Rosenberg, 1995, 2001; Pearson and Rosenberg, 1978; Gray and Elliot, 2009). Outside the pits which were not disturbed by mining and lacked extra sedimentation of food, filter feeding species like *Ensis* spp., *Donax vittatus*

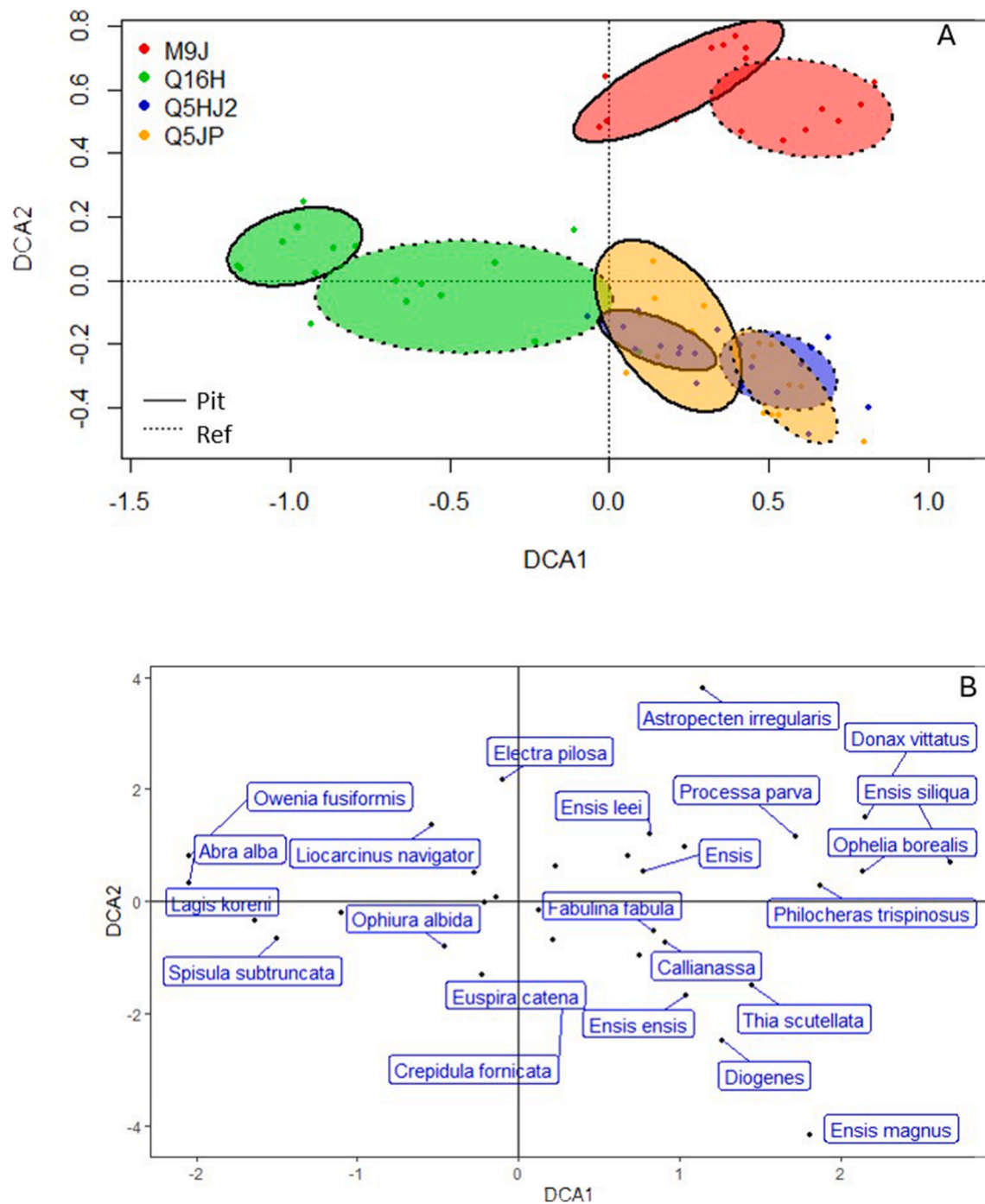


Fig. 6. Graphical representations of the results of a detrended correspondence analyses on basis of macrofaunal species composition and densities. 6A: Positioning of the 95 % confidence boundaries between the pits and reference areas which are indicated by the line type encircling the hull. Colors indicate the four different areas (pits and reference). 6B: Projection of the species occurrence in the same two dimensional ordination space as in Fig. 6A showing which species contribute to the observed differences in the communities. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and *Spisula subtruncata* dominated the fauna.

Our data furthermore show that the species heterogeneity in the pits is reduced (Fig. 4) with a few deposit feeding species being dominant. This is also a typical sign of a disturbed environment (Pearson and Rosenberg, 1978) and often triggered by the higher food supply related to the settlement of fine particles.

In the Dutch shallow coastal zone with permanently mixed waters, fine particles (silt & organic) can only settle in conditions where flow velocities or wave impact is low. Such conditions seem to develop in medium deep mining pits and are in line with the observations of Krause

et al. (2010) for the western Baltic. The local deepening leads to changed hydrographical conditions with locally lower currents, less wave impact and possibly stratification. These factors strongly regulate sedimentation of fines. The same process also influences settlement (and survival) of macrobenthos as their larvae behave as rather passive particles in relation to wave action and currents in this coastal setting. The slightly deeper environment of a sandpit might act as shelter and prevent their resuspension or further transport. Increased food availability might increase their growth and survival but above all can support a higher biomass.

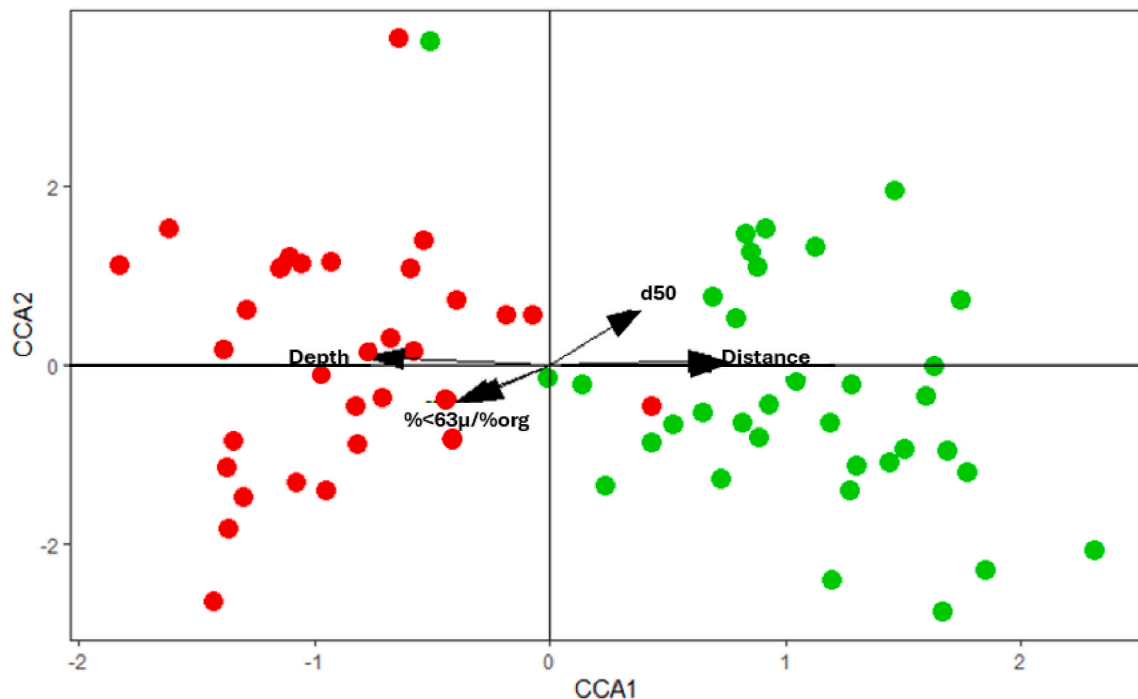


Fig. 7. Results of the pCCA where mining pits and reference areas are conditionally (area) arranged on basis of the explaining variables. Water depth and %silt strongly correlate with the pit stations and not unexpectedly the reference stations correlate with higher d50 and with greater distances to the centre of the pit. Area as conditional factor already explains 38 % of the total variance in the entire dataset (abiotics-species-stations matrix). Of the remaining variance 17 % can be explained by abiotic conditions.

Siltation and organic enrichment in really deep mining pits (<20 M) as previously described, is not a short-term effect but persists for decades. Pit effects appear to be long lasting (Mielck et al., 2021; Mielck et al., 2019; Thatje et al., 1999). Our data suggests that this might also be the case for medium deep pits as we see effects irrespective of their age (2–12 years). de Jong's (2016) suspicion of the permanent character of faunistic changes in deep mining pits thus also seems to hold for medium-deep (6 m) pits.

Older studies on the effects of "shallow" (2–4 M) sandmining (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001) concluded that after 4–6 year the fauna had completely recovered but even for the oldest pit studied here (Q16H-12 years old), such recovery was not evident. In this pit it might be due to the "gyre" like hydrography, concentrating fines in the area (Stutterheim, 2002). The absence of a fully recovered fauna in two of the other pits (Q5HJ2 and Q5JP) however suggests that the lack of recovery might have to do with the greater excavation depths as the currents in that area are unidirectional. Pit M9J was too young to take into account as it still was in its earliest phase of recovery and recolonization.

Potentially a critical threshold for sedimentation and resuspension of fine material is surpassed when mining goes from 4 m. to 6 m. below bed level. All pits, irrespective of age show this happening. It might well be that the effects also depend on pit orientation, pit shape and size and the depth zone where the pits are made.

Apart from the biodiversity perspective, the change in benthic community is also likely to have consequences for the benthic secondary production, the structure of the food web and exchange processes between seafloor and overlying water (See Fig. 2 in Torres et al., 2025). This certainly needs attention as sandmining will be an ongoing activity in the future, but might have unexpected and large effects on the ecology in shallow coastal zones.

5. Conclusions

Without exception, median grain size in the extraction pits decreased

and silt and organic matter content increased when compared to the reference locations.

The data illustrate that the slightly deeper pits act as a sediment trap for fines. The sedimentary change in the pits translates into increased total abundance and total benthic biomass of especially "deposit feeders" and "surface deposit feeders". Diversity in the pits is lower than in the surroundings, which is related to the dominance of a few species such as *Echinocardium cordatum*, *Abra alba* and *Ophiura ophiura* while the fauna in the reference areas is characterized by filter feeding bivalves such as *Spisula* and *Ensis* species.

The data suggest that sedimentary and faunistic change in the extraction pits represent a general process as the sampled pits covered a wide geographical range and differed greatly in age. The latter suggests that recovery takes a long time and it remains unknown if the sediments and fauna in the pits will ever return to their original state.

CRedit authorship contribution statement

Rob Witbaard: Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation. **Simeon Moons:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Loran Kleine Schaars:** Data curation. **Johan Craeymeersch:** Writing – review & editing, Visualization, Methodology, Formal analysis.

Declaration of competing interest

This work has been commissioned by Rijkswaterstaat as part of a research program to increase our knowledge about the effects and effectiveness of sandmining (www.zanduitzee.nl) along the Dutch coast. S. Moons is representing this organization but was not involved in the data-analyses, reporting and the writing of the original draft of this manuscript. As members of independent research organizations, R. Witbaard, L. Kleine Schaars and J. Craeymeersch have no interests which could have influenced the outcomes of this work.

Acknowledgements

This study has been made possible by the funds made available by the Dutch national "Zand uit Zee" program (www.zanduitzee.nl) (Zaak 31175858). The authors thank the support of National Marine facilities (NMF) department of NIOZ for their involvement and continuous dedicated help in the development of the Triple D. Data collection would not have been possible with the help of Eva Immler, Evaline van Weerlee, Jeroen van Daalen and Bram Parmentier. The crew of R.V. Arca is thanked for their indispensable help on board.

The data to this article can be found online at: <https://doi.org/10.25850/nioz/7b.b.pj>.

Data availability

The underlying data have been Archived in the institutes digital Archive and have been assigned a DOI: 10.25850/nioz/7b.b.pj.

References

- Ali, P.F., Gan, G.G.G., Asmawi, S., 2024. The management of offshore sand mining: a systematic literature review. *J. Sust. Sci. Manag.* 19, 161–191.
- Anonymous, 2015. North sea policy document 2016-2021. The Dutch Ministry of Infrastructure and the Environment the Dutch Ministry of Economic Affairs, p. 120. The Hague The Netherlands. www.government.nl/enm/www.noordzeeloket.nl.
- Anonymous, 2018. NIOZ, Werkinstructie Benthos 13. Analyseren sediment monsters, p. 35.
- Anonymous, 2022. Mariene Strategie voor het Nederlandse deel van de Noordzee 2022-2027. Bijlage onderdeel van het Nat. water progra. 2022-2027 164.
- Auguie, B., 2017. gridExtra: miscellaneous functions for "grid" graphics. R package version 2.3. <https://CRAN.R-project.org/package=gridExtra>.
- Barrett, T., Dowle, M., Srinivasan, A., Gorecki, J., Chirico, M., Hocking, T., Schwendinger, B., Krylov, I., 2025. data.table: extension of "data.frame". R package version 1.17.0. <https://CRAN.R-project.org/package=data.table>.
- Bendixen, M., Best, J., Hackney, C., Lönsmann Iversen, L., 2019. Time is running out for sand. *Nature* 579, 29–31. <https://doi.org/10.1038/d41586-019-02042-4>.
- Bergman, M.J.N., van Santbrink, J., 1994. A new benthos dredge ("triple D") for quantitative sampling of infauna species of low abundance. *Neth. J. Sea Res.* 33 (1), 129–133. [https://doi.org/10.1016/0077-7579\(94\)90057-4](https://doi.org/10.1016/0077-7579(94)90057-4).
- Bonne, W., 2010. Macrobenthos characteristics and distribution, following intensive sand extraction from a subtidal sandbank. *J. Coast Res.* 51, 141–150. <https://doi.org/10.2112/SI51-013.1>.
- Boon, A.R., Duineveld, G.C.A., Kok, A., 1999. Benthic organic matter supply and metabolism at depositional and non-depositional areas in the North Sea. *Estuar. Coast Shelf Sci.* 49, 747–761. <https://doi.org/10.1006/ecss.1999.0555>.
- Borcard, D., Legendre, P., Drapeau, P., 1992. Partialling out the spatial component of ecological variation. *Ecology* 73 (3), 1045–1055.
- Borcard, D., Gillet, F., Legendre, P., 2011. Numerical Ecology with R. Springer, New York.
- Borst, W., Vellinga, T., van Tongeren, O., 2013. The monitoring programme for the Maasvlakte 2 construction at the port of Rotterdam-Part II. *Terra Aqua (Engl. Ed.)* 130, 20–32.
- Boyd, S.E., Limpenny, D.S., Rees, H.L., Cooper, K.M., Campbell, S., 2003. Preliminary observations of the effects of dredging intensity on the re-colonization of dredged sediments off the southeast coast of England (Area 222). *Estuar. Coast Shelf Sci.* 57, 209–223. [https://doi.org/10.1016/S0272-7714\(02\)00346-3](https://doi.org/10.1016/S0272-7714(02)00346-3).
- Boyd, S.E., Limpenny, D.S., Rees, H.L., Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES J. Mar. Sci.* 62, 145–162. <https://doi.org/10.1016/j.icesjms.2004.11.014>.
- Brand, E., Ramaekers, G., Lodder, Q., 2022. Dutch experience with sand nourishments for dynamic coastline conservation – an operational overview. *Ocean Coast Manag.* 217, 106008. <https://doi.org/10.1016/j.ocecoaman.2021.106008>.
- Burd, B.J., Macdonald, T.A., van Roodseelaar, A., 2012. Towards predicting basin wide invertebrate organic biomass and production in Marine sediments from a coastal Sea. *PLoS One* 7 (7), e40295. <https://doi.org/10.1371/journal.pone.0040295>.
- Craeymeersch, J.A.M., 2021. When does the file Yoldia reach the Wadden Sea? <https://www.wur.nl/en/research-results/research-institutes/marine-research/show-marine/when-does-the-file-yoldia-reach-the-wadden-sea.htm>.
- Creutzberg, F., Wapenaar, P., Duineveld, G., Lopez Lopez, N., 1984. Distribution and density of benthic fauna in the southern North Sea in relation to bottom characteristics and hydrographic conditions. *Rapp. P.-V. Reun. Cons. Int. Explor. Mer.* 183, 101–110.
- Dauvin, J.-C., Gofas, S., Raoux, A., Bouchet, V.M.P., Pavard, J.-C., Pezy, J.-P., 2022. The American protobranch bivalve Yoldia limatula (Say, 1831) in European waters. *BioInvasions Rec* 11 (2), 473–481. <https://doi.org/10.3391/bir.2022.11.2.20>.
- de Jong, M.F., 2016. The ecological effects of deep sand extraction on the Dutch continental shelf. Implications for Future Sand Extraction. PhD Thesis, Wageningen, p. 164.
- de Jong, M.F., Baptist, M.J., Lindeboom, H.J., Hoekstra, P., 2015. Short term impact of deep sand extraction and ecosystem based landscaping on macrozoobenthos and habitat characteristics. *Mar. Pollut. Bull.* 97 (1–2), 294–308. <https://doi.org/10.1016/j.marpolbul.2015.06.002>.
- de Jong, M.F., Borsje, B.W., Baptist, M.J., van der Wal, J.T., Lindeboom, H.J., Hoekstra, P., 2016. Ecosystem-based design rules for marine sand extraction sites. *Ecol. Eng.* 87, 271–280.
- de Jonge, D., 2020. <https://raw.githubusercontent.com/dswdejonge/TripleD/master/inst/extdata/morphologies.png>.
- Diessen, F., van Looijengoed, W., 2020. De gladde snavelneut een nieuwe tweekleppige in Nederland. WWW.naturetoday.com/nl/nl/nature-reports/message/?msg=26297.
- Field, J.G., Clarke, K.R., Warwick, R.M., 1982. A practical strategy for analyzing multispecies distribution patterns. *Mar. Ecol. Prog. Ser.* 8, 37–52.
- Gavrilletea, M.D., 2017. Environmental impacts of sand exploitation. *Analyses of sand market. Sustainability* 9, 1118. <https://doi.org/10.3390/su9071118>.
- Gray, J.S., Elliot, M., 2009. Ecology of Marine Sediments; from Science to Management, second ed. Oxford University Press, p. 225.
- Halekoh, U., Højsgaard, S., 2025. doBy: groupwise statistics, LSmeans, linear estimates, utilities. R package version 4.6.25.9036. <https://github.com/hojsgaard/doby>.
- Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. Past: paleontological statistics software package for education and data analysis. *Paleontol. Electron.* 4 (1). http://palaeo-electronica.org/2001_1/past/issue1_01.htm.
- Heip, C., Basford, D., Craeymeersch, J.A., Dewarumez, J., Dörjes, J., de Wilde, P., Duineveld, G., Eleftheriou, A., Herman, P.M.J., Nierman, U., Kingston, P., Küntzer, A., Rachor, E., Rumohr, H., Soetaert, K., Soltwedel, T., 1992. Trends in biomass, density and diversity of North Sea macrofauna. *ICES J. Mar. Sci.* 49 (1), 13–22. <https://doi.org/10.1093/icesjms/49.1.13>.
- Hijmans, R., 2024. Geosphere: spherical trigonometry. R package version 1, 5–20. <https://CRAN.R-project.org/package=geosphere>.
- Jongman, R.H.G., ter Braak, C.J.F., van Tongeren, O.F.R., 1987. Data Analysis in Community and Landscape Ecology. Pudoc, Wageningen, p. 299.
- Krause, C.J., Diesing, M., Arlt, G., 2010. The physical and biological impact of sand extraction: a case study of the western Baltic Sea. *J. Coast Res.* 51, 215–226. <https://doi.org/10.2112/SI51-020.1>.
- Krebs, C., 1999. Ecological Methodology, second ed. Addison Wesley Educational publishers Inc. California, p. 620.
- Lodder, Q.J., Slinger, J.H., Wang, Z.B., van der Spek, A.J.F., Hijma, M.P., Taal, M., van Gelder-Maas, C., de Looft, H., Litjens, J., Schipper, C.A., Löffler, M., Nolte, A.J., van Oeveren, C., van der Werf, J.J., Grasmeyer, B.T., Elias, E.P.L., Holzhauer, H., Tonnon, P.K., 2023. The coastal genesis 2 research programme: outputs, outcomes and impact. *Ocean Coast Manag.* 237. <https://doi.org/10.1016/j.ocecoaman.2023.106499>.
- McGill, R., Tukey, J.W., Larsen, W.A., 1978. Variations of box plots. *Am. Statistician* 32 (1), 12–16.
- Mielck, F., Hass, H.C., Michaelis, R., Sander, L., Papenmeier, S., Wiltshire, K., 2019. Morphological changes due to marine aggregate extraction for beach nourishment in the German Bight (SE North Sea). *Geo Mar. Lett.* 39, 47–58. <https://doi.org/10.1007/s00367-018-0556-4>.
- Mielck, F., Michaelis, R., Hass, H.C., Hertel, S., Ganai, C., Armonies, W., 2021. Persistent effects of sand extraction on habitats and associated benthic communities in the German Bight. *Geosciences* 18, 3565–3577. <https://doi.org/10.5194/bg-18-3565-2021>.
- Newell, R.C., Seiderer, L.J., Hitchcock, D.R., 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanogr. Mar. Biol. Annu. Rev.* 36, 127–178.
- Oksanen, J., Simpson, G.L., Blanchet, F., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Solymos, P., Stevens, M.H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, B.A., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M.O., Lahti, L., McGinn, D., Ouellette, M.H., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C.J.F., Weedon, J., 2022. Vegan: community ecology package. R package version 2, 6–2. <https://CRAN.R-project.org/package=vegan>.
- Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Annu. Rev.* 16, 229–311.
- Peduzzi, P., 2014. Sand, rarer than one thinks. Article reproduced from united nations environment prgram (UNEP) global environmental alert service (GEAS). *Environ. Dev.* 11, 208–218. <https://doi.org/10.1016/j.envdev.2014.04.001>.
- R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL: <https://www.R-project.org/>.
- Rees, H.L., Pendle, M.A., Limpenny, D.S., Mason, C.E., Boyd, S.E., Birchenough, S., Vivian, C.M.G., 2006. Benthic responses to organic enrichment and climatic events in the western North Sea. *J. Mar. Biol. Assoc. U. K.* 86 (1), 1–18. <https://doi.org/10.1017/S002531540601280X>.
- Rees, H.L., Eggleton, J.D., Rachor, E., Vanden Berghe, E. (Eds.), 2007. Structure and Dynamics of the North Sea Benthos. ICES Cooperative Research Report, vol. 288. ICES, Copenhagen, p. 258.
- Rosenberg, R., 1995. Benthic marine fauna structured by hydrodynamic processes and food availability. *Neth. J. Sea Res.* 34, 303–317. [https://doi.org/10.1016/0077-7579\(95\)90040-3](https://doi.org/10.1016/0077-7579(95)90040-3).
- Rosenberg, R., 2001. Marine benthic faunal successional stages and related sedimentary activity. *Sci. Mar.* 65 (Suppl. 2), 107–119. <https://doi.org/10.3989/scimar.2001.65s2107>.
- Sardá, R., Pinedo, S., Gremare, A., Taboada, S., 2000. Changes in the dynamics of shallow sandy-bottom assemblages due to sand extraction in the Catalan Western

- Mediterranean Sea. ICES J. Mar. Sci. 57, 1446–1453. <https://doi.org/10.1006/jmsc.2000.0922>.
- Sarkar, D., 2008. Lattice: Multivariate Data Visualization with R. Springer, New York. ISBN 978-0-387-75968-5. <http://lmdvr.r-project.org>.
- Slowikowski, K., 2025. Ggrepel: automatically position non-overlapping text labels with 'ggplot2'. R package version 0.9.6.9999. <https://github.com/slowkow/ggrepel>.
- Stive, M.J.F., de Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., van Gelder-Maas, C., van Thiel de Vries, J.S.M., de Vries, S., Henriquez, M., Marx, S., Ranasinghe, R., 2013. A new alternative to saving our beaches from sea-level rise: the sand engine. J. Coast Res. 29 (5), 1001–1008. <https://doi.org/10.2112/JCOASTRES-D-13-00070.1>.
- Stutterheim, S., 2002. van Noord tot Noordwest. Een studie naar de berging van baggerspecie op loswallen. Rapport RIKZ/2002.047. Ministerie van verkeer en waterstaat, p. 310.
- ter Braak, C.J.F., 1988. Partial canonical correspondence analysis. In: Bock, H.H. (Ed.), Classification and Related Methods of Data Analysis. Elsevier Science Publishers B. V., Amsterdam.
- Thatje, S., Gerdes, D., Rachor, E., 1999. A seafloor crater in the German Bight and its effects on the benthos. Helgol. Mar. Res. 53, 36–44. <https://doi.org/10.1007/PL00012136>.
- Torres, A., Simoni, M.U., Keiding, J.K., Müller, D.B., zu Ermgassen, S.O.S.E., Liu, J., Jaeger, J.A.G., Winter, M., Lambin, E.F., 2021. Sustainability of the global sand system in the Anthropocene. One Earth. <https://doi.org/10.1016/j.oneear.2021.04.011>.
- Torres, A., Jouffray, J.-B., Van Lancker, V., Velpen, A.V., Liu, J., 2025. Reducing sand mining's growing toll on marine biodiversity. One Earth 8, 101202. <https://doi.org/10.1016/j.oneear.2025.101202>.
- van Dalen, J., Essink, K., 2001. Benthic community response to sand dredging and shoreface nourishment in Dutch coastal waters. Senckenberg. marit. 31 (2), 329–332. <https://doi.org/10.1007/BF03043041>.
- van Dalen, J., Essink, K., Madsen, H.T., Birklund, J., Romero, R., Manzanera, M., 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. ICES J. Mar. Sci. 57, 1439–1445. <https://doi.org/10.1006/jmsc.2000.0919>.
- van der Spek, A., Forzoni, A., Vermaas, T., 2022. Holocene deposits at the lower shoreface and inner shelf of the Dutch Coast. Ocean Coast Manag. 224. <https://doi.org/10.1016/j.ocecoaman.2022.106203>.
- van der Werf, J.J., Giardino, A., 2009. Effect van zeer grootschalige zandwinning langs de Nederlandse kust op waterbeweging, zandtransporten en morfologie. Deltares Rapport, p. 74.
- Vermolen, R.A.F., 2015. Zandwinning, zandsuppletie en kaderrichtlijn Mariene Strategie Over de juridische betekenis van de KMS en de mogelijkheid Nederland te beschermen in verband met klimaatadaptatie door zandwinning en zandsuppleties voor de kust. Tijdschrift voor omgevingsrecht 1. <https://doi.org/10.5553/TO/156850122015015001004>.
- Wei, T., Simko, V., 2024. R package 'corrplot': visualization of a correlation matrix. Available from, Version 0.95. <https://github.com/taiyun/corrplot>.
- Wickham, H., 2007. Reshaping data with the reshape package. J. Statist.-software 21 (12), 1–20. <http://www.jstatsoft.org/v21/i12/>.
- Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. ISBN 978-3-319-24277-4. <https://ggplot2.tidyverse.org>.
- Wickham, H., Bryan, J., 2025. Readxl: read excel files. R package version 1.4.5. <https://CRAN.R-project.org/package=readxl>.
- Wickham, H., Pedersen, T., 2024. Arrange 'grobs' in tables. R package version 0.3.6. <https://CRAN.R-project.org/package=gtable>.
- Wickham, H., François, R., Henry, L., Müller, K., Vaughan, D., 2023. Dplyr: a grammar of data manipulation. R package version 1.1.4. <https://CRAN.R-project.org/package=dplyr>.
- Witbaard, R., Lavaleye, M.S.S., Duineveld, G.C.A., Bergman, M.J.N., 2013. Atlas of Megabenthos (Including Small Fish) on the Dutch Continental Shelf of the North Sea, p. 223. NIOZ-rapport 2013-4.
- WoRMS, World Register of Marine Species. <https://www.marinespecies.org>.