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Changed sediment composition prevents recovery of macrobenthic community four years after a shoreface nourishment at the Holland coast

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ABSTRACT

Sand nourishment is a widespread management strategy to protect sandy coasts against erosion. Nourishments can impact the benthic fauna directly by burial and indirectly by changing environmental conditions such as bottom shear stress and/or sediment composition (grain size distribution). The macrobenthic community in soft-bottom environments is often strongly correlated with sediment composition, however, because of the strong correlation with other environmental conditions, it is difficult to determine the direct effects of sediment composition on the macrobenthic community from field observations. Nourishments can temporarily break this correlation allowing to study the relation between sediment composition and macrobenthic community more or less independent from other environmental factors. In 2017, a shoreface nourishment was constructed at the Holland coast near Callantsoog at a water depth of about 10 m. Because the influence of waves is limited at this depth, the nourishment is not very mobile. Sediment composition and macrobenthos was monitored at the nourished site and two reference locations before (2015 and 2016), and in 2021, four years after nourishment. In 2021, the sediment composition at the nourished site was much coarser (median grain size 330 ± 59 μm) than in the years before nourishment (195 ± 34 μm), while the sediment composition at the reference locations remained comparable over the years. The average number of taxa per sample at the nourishment decreased from 14.1 before nourishment to 3.0 taxa in 2021. Also the average total density at the nourishment location decreased from 12731 ind.m^{-2} before nourishment to 320 ind.m^{-2} in 2021. While before nourishment, the composition of the macrobenthic community at the nourished site was comparable to the southern reference location, in 2021 the macrobenthic community was more comparable to the community at the coarser sediments of the northern reference. Clearly, four years after the nourishment, the macrobenthic community has not recovered due to the presence of coarser sediments at the nourished site. Logistic regressions show that most of the dominant species have a negative correlation with median grain size, but some species are more sensitive to changes in sediment composition than others. The sensitivity of the macrobenthos to sediment composition illustrates the importance of using sediments of similar grain size as in the placement area, especially for nourishments in the deeper parts of the shoreface.

1. Introduction

Erosion of sandy coasts is a worldwide problem caused by a local imbalance between sediment supply and demand (Giardino et al., 2019). Presently, 24% of the sandy beaches in the world are eroding (Luijendijk et al., 2018). Repeated sand nourishments can provide a long-term and cost-efficient solution to coastline retreat in sandy coastal regions (Stronkhorst et al., 2018) and can be preferred over hard structural engineering as it is less disruptive to natural sediment dynamics (De Schipper et al., 2021). Sand nourishments, however, can also alter the natural morphodynamics of the coast and thereby affect the quality of nearshore habitats (Radermacher et al., 2018; Holzhauer et al., 2020). This is especially relevant for the macrobenthic community that resides in and close to the sea floor.

The sandy Dutch coast is prone to structural erosion at various locations (De Schipper et al., 2016). In order to preserve a safe,

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economically strong and attractive shoreline in the future, the coast is maintained by regular beach nourishments with typical volumes of 0.3–3 Mm^3 (Hanson et al., 2002; Brand et al., 2022), shoreface nourishments with typical volumes of about 1–3 Mm^3 (Baptist and Leopold, 2009; Brand et al., 2022), and occasionally mega-nourishments such as the Sand Motor with a total volume of about 21.5 Mm^3 (Stive et al., 2013; De Schipper et al., 2016). An overview of nourishment activities in the Netherlands since 1950 and the effectiveness in preserving the coastline can be found in Brand et al. (2022). In the Netherlands, nourishments are applied within the so called 'coastal foundation', stretching from the landward boundary of the dunes to the 20 m depth contour (Van der Spek et al., 2022). Since 2001, the yearly nourishment volume on the entire Dutch coast is about 12 Mm^3, of which 3.5 Mm^3 is nourished at the South-Holland and North-Holland coast (Giardino et al., 2019; Baptist and Leopold, 2009; Leewis et al., 2012; Brand et al., 2022). With the expected sea level rise, nourishment volumes are likely to increase in the future (Holzhauer et al., 2020; Stronkhorst et al., 2018; Lodder et al., 2023). Shoreface nourishments are typically applied in the active breaker bar zone in the upper part of the shoreface at a depth around three to eight m below NAP, i.e. Dutch Ordnance level, which is approximately Mean Sea Level (Van der Spek et al., 2022; Herman et al., 2021; Baptist and Leopold, 2009). Over time, the nourished sand will be redistributed by waves and currents over the active beach profile, thereby indirectly nourishing the beaches and dunes (De Schipper et al., 2021). The lifespan of nourishments ranges from one to four years for beach nourishments and three to six years for shoreface nourishments (Van Duin et al., 2004; Gijsman et al., 2019; Brand et al., 2022). The mega nourishment of the Sand Motor has an expected lifespan of more than 20 years (Stive et al., 2013).

Nourishments have direct effects on the macrobenthic community by burial of infauna and epifauna under a layer of sand. Indirectly, they may affect the community by changing the environmental conditions such as bottom shear stress and sediment composition in terms of grain size distribution (Schlacher et al., 2012; Colosio et al., 2007) that could influence the recovery potential of the original community. Recovery of the macrobenthic community may take place by immigration from surrounding environments and by settlement of larvae from the water column. Benthic communities have been found to recover as soon as the environmental conditions such as sediment properties have been restored to pre-nourishment conditions, a process which strongly depends on local morphological and hydrodynamic properties at the nourished site (Speybroeck et al., 2006). In the dynamic shoreface areas of the Holland coast, the macrobenthic community is well-adapted to highly dynamic conditions due to wave actions during storms (Newell et al., 1998; Kröncke et al., 2018; De Schipper et al., 2021). As a result, the macrofauna community will recover relatively fast (two to four years) from a single shoreface nourishment (Van Dalfsen and Essink, 2001; Leewis et al., 2012). However, changes in habitat characteristics such as sediment composition, wave action and/or current velocities due to nourishments might result in changes in the community structure, and consequently, longer recovery times (Van Tomme et al., 2013; Peterson et al., 2014).

Locally, nourishments may result in changes in sediment composition (grain size distribution) when the sediment grading at the borrowing location differs from the grading at the nourishment location or when sediment sorting occurs during or after nourishment. Although sediment from single nourishments in the active breaker bar zone will be taken-up in the system within a couple of years, repeated shoreface nourishments with sediment of a different sorting could change the sediment composition permanently.

The response of macrobenthos to sediment composition and bottom shear stress due to waves and tidal currents is studied at different locations in the shoreface of the North Sea coast (Speybroeck et al., 2006; Janssen and Mulder, 2005; Kröncke et al., 2018; Markert et al., 2015; Herman et al., 2021). It is shown that the composition of macrobenthic communities often correlates with sediment characteristics such as median grain size and mud content (Vanaverbeke et al., 2011; Van Hoey et al., 2004; Boon and Van Dalfsen, 2022; Cozzoli et al., 2013; Degraer et al., 2008; Gray, 1974; McLachlan, 1996). On the Belgian continental shelf, for example, Van Hoey et al. (2004) showed that macrobenthic communities of coarse sediments (median grain size > 300 μm) were characterized by low densities and low species diversity. Also species richness and the variability of species assemblage levels decreased with increasing grain size (Van Hoey et al., 2004; Vanaverbeke et al., 2011). Sediment composition is often strongly correlated to a wider set of environmental conditions, such as bottom shear stress, water depth and organic content of the sediment (Van Hoey et al., 2004; Snelgrove and Butman, 1994; Creutzberg et al., 1984; Anderson, 2008) and is, therefore, regarded as a suitable indicator for these environmental conditions. As a consequence, however, it is difficult to determine whether the response of the macrobenthic community reacts to sediment characteristics or to other co-varying environmental conditions (Snelgrove and Butman, 1994). Direct influence of the sediment composition itself is likely, as it constitutes the physical environment in which benthic organisms live, gather food and construct their burrows (Gray, 1974; Cozzoli et al., 2013). However, other co-varying factors also are known to have a direct influence, e.g. bottom shear stress that determines the mobility of the sediment in and around burrows. Nourishments can, temporarily, decouple the correlation between sediment composition and other physical environmental conditions by changing the morphology, and related to that the bottom shear stress (Herman et al., 2021) or by changing mainly the sediment composition. Mega nourishments like the Sand Motor, for example, not only have impact on sediment composition, but also on water depth and shear stress due to waves and tidal currents (Herman et al., 2021). As a consequence, the usual correlation structure between water depth, current velocities, wave impact, sediment composition and macrobenthic community structure is broken. The construction of the Sand Motor created deep locations with high flow rates, calm locations with relatively coarse sediments (Huisman et al., 2016), and more unusual combinations such as shallow sheltered areas in the lagoon (Van Egmond et al., 2018), which overall resulted in a higher diversity of habitats for macrobenthos (Van Egmond et al., 2018; Wijsman et al., 2022; Herman et al., 2021). The long-term (ten years) monitoring data from the Sand Motor (Herman et al., 2021) offers the opportunity to better estimate the relative contribution of these environmental variables to the macrobenthic community, independently of each other.

In 2017, a nourishment was applied off the coast of Callantsoog in the lower shoreface at a depth of about 10 m below NAP, with a crest height up to approximately 7.5 m below NAP. The location of the nourishment was at greater depth than regular shoreface nourishments, which are usually applied at a depth of about three to eight m below NAP in the active breaker bar zone of the upper shoreface (Baptist and Leopold, 2009). Because of the greater depth, below the fair-weather wave base, the effect of this nourishment on bottom shear stress is expected to be limited as mainly tidal currents and extreme storm waves dominate sand transport in this zone (Van der Spek et al., 2022; Van Duin et al., 2004). As a result, the nourishment will have a longer lifetime than regular shoreface nourishments and sediment composition of the nourishment will be influenced less by environmental conditions such as bottom shear stress due to waves. This makes it an interesting location to study the effect of sediment composition on the macrobenthic community with only limited interference of changes in other environmental conditions.

In this paper, we present and analyze the monitoring data of this deep shoreface nourishment, in order to test the hypothesis that there is a direct influence, only limitedly mediated through correlated other environmental variables, of sediment grain size on the composition of the macrobenthic community. Additionally, we use the long-term data from the Sand Motor that was presented in Herman et al. (2021) and which includes information on sediment composition as well as bottom shear stress. We use both datasets to investigate what are necessary

conditions, in terms of grain size distribution, for nourishments not to harm the recovery potential of the resident macrobenthic fauna.

2. Materials and methods

2.1. Study area

The Callantsoog nourishment is located in the northern part of the Holland coast, a 120 km sandy coast between Hoek van Holland in the South to Den Helder in the North (Fig. 1). The coast consists of a steep surf zone that is dominated by shore-parallel breaker bars and a less steep shoreface that extends to the −20 m contour (Van der Spek et al., 2022). The wave climate at the Holland coast is characterized by wind-driven waves that mainly come from Southwest to Northwest (Huisman et al., 2016). The sediment grain size is variable, both in space and time. Beach and dune sediments are fine sands (100–200 µm), swash and surf zone (0–8 m) have moderate sand (200–400 µm) while finer sands (100–300 µm) occur in the 8–10 m depth zone (Huisman et al., 2016). As many other sandy beaches in the Netherlands, the coastline near Callantsoog is subject to coastal erosion (Stronkhorst et al., 2018). In the last decades several beach and shoreface nourishments have been conducted in the area (Wijsman and Schotanus, 2022).

The deep shoreface nourishment that was constructed in 2017 had a total volume of 1 Mm^3 and is located 1200–1600 m from the coastline stretching parallel to the coastline over a length of 2 km. The sediment for the nourishment was mined at the location Q2C, approximately 10 km West of Callantsoog at a water depth of about 20 m below NAP. The median grain size of the sediments, varied between 130 and 360 µm (Marine Sampling Holland, 2011). At the receiving location, the median grain size varied between 158 and 245 µm before nourishment. As the nourishment was applied at greater depth than regular shoreface nourishments, it is expected that interference of previous nourishments in the same area is limited.

2.2. Sampling design

It is well known that macrobenthic communities in shallow coastal waters are characterised by strong spatiotemporal variability (Van Hoey et al., 2005, 2007). By adopting a BACI (Before/After and Control/Impact) sampling strategy (Underwood, 1992), we have partly corrected for the effect of this spatiotemporal variability.

The macrobenthic community was sampled using a Reineck box-corer (0.078 m^2) at the nourishment location and at two reference locations, North and South of the nourishment (Fig. 1). The reference locations were located in the vicinity (300–1500 m) of the nourishment at the same depth range. Sampling took place in Autumn in 2015, 2016 (before nourishment) and in 2021 (four years after nourishment). Each year, approximately the same 61 stations were sampled, 20 stations in each of the reference locations and 21 stations at the nourishment location. The sampling stations were located on 17 transects perpendicular to the coastline. Before nourishment (2015 and 2016), the average depth of the stations in the nourishment area (10.27 ± 0.14 m) was similar to the average depth of the stations in the reference areas North (10.30 ± 0.29 m) and South (10.27 ± 0.22 m).

2.3. Treatment of the samples

At each sampling station, a subsample with a total volume of about 3–6 L, was taken from the box-corer with three cores (total area 139.7 cm^2) for macrobenthos analysis. The samples were sieved using a 1 mm mesh sieve. The residue was stored in jars and preserved in 4% buffered formaldehyde to be analyzed later in the lab. All individuals were identified to the lowest possible taxonomic level. Damaged or very small individuals were sometimes identified to genus, family or higher level, while intact larger specimens could be identified to species level. In order to avoid bias in the diversity measures (number of taxa in a

sample) higher taxonomic levels were discarded from the counts of number of species whenever a lower taxon belonging to the high-level taxon was found in the sample, but it was counted as a species if this was not the case. All taxon names were checked against the World Register of Marine Species (WoRMs[1]) and synonymized with the accepted taxon names where needed.

Additionally, sediment samples were taken from the top 5 cm of the box-corer with a cut-off 50 ml syringe and stored in a freezer for grain size analysis. The samples were freeze-dried, homogenized and sieved over a 1 mm sieve. No other pretreatment of the samples, such as removal of shell remains or organic material, took place. The sediment samples were analyzed using a laser diffraction Malvern Mastersizer to determine the median grain size from the grain size distribution.

2.4. Statistical analysis

All statistical analyses were performed in R4.2.1 (R Core Team, 2022). Community analyses were done using the package vegan (Oksanen et al., 2022). Differences in median grain sizes, number of taxa and densities were tested with Analysis of Variance (ANOVA) followed by Tukey post-hoc comparison where the density data were first transformed (fourth-root) to reduce skewness of the data.

The development of the patterns and changes in the macrobenthic community was evaluated by non-metric multidimensional scaling (nMDS) ordination in three dimensions using the vegan package in R (Oksanen et al., 2022) and the minimum stress values were reached after fifty iterations. Taxa at higher taxonomic levels than family were excluded from the analysis. Furthermore, the species *Paraonis fulgens* (only present at three stations at the nourishment in 2021) and *Macomangulus tenuis* (only present at one location at the nourishment in 2021 and one location at the reference North in 2021) were excluded from the nMDS analysis. Other rare species were included in the nMDS analysis, because they might include important indicator species for environmental conditions (Poos and Jackson, 2011). Prior to analysis, the density data were transformed (fourth-root) to correct the imbalance in significance of abundant and rare taxa to the similarity (Clarke, 1993). Ordination was done using the Bray-Curtis dissimilarity indices between the stations.

To study the response of individual species to grain size, logistic regressions were applied using generalized linear models (GLM) with a binomial distribution on the presence/absence data. For the regressions, twelve most occurring taxa were selected (Table 1), each observed at more than 25% of the sampled locations. The full model contained linear terms of the median grain size and the square of the median grain size, without interaction. Including the squared term allows for unimodal responses. Model selection was performed through a stepwise procedure based on the Akaike Information Criterium (AIC). From the logistic regression curves, the threshold value ($p_{(0.5)}$) is calculated, indicating the median grain size where the calculated probability of occurrence of a taxon is 0.5. The steepness of the curve ($\Delta p/\Delta \mu$) at the threshold value $p_{(0.5)}$ gives an indication of the sensitivity of the taxon to changes in median grain size at the threshold value.

In addition to the data from the Callantsoog nourishment, the Sand Motor data (Herman et al., 2021) was used to study the response of the macrobenthic community, summarised by scores on the first axis of the Principal Component Analysis (PCA), to variation in bottom shear stress and median grain size. Herman et al. (2021) showed that the scores on the first PCA-axis are mainly explained by the interaction between water depth and bottom shear stress, but that there is also a significant contribution of median grain size. For the dominant taxa, which were present at more than 10% of the 519 sampled stations at the Sand Motor, multiple linear regressions were made of the log-transformed density as

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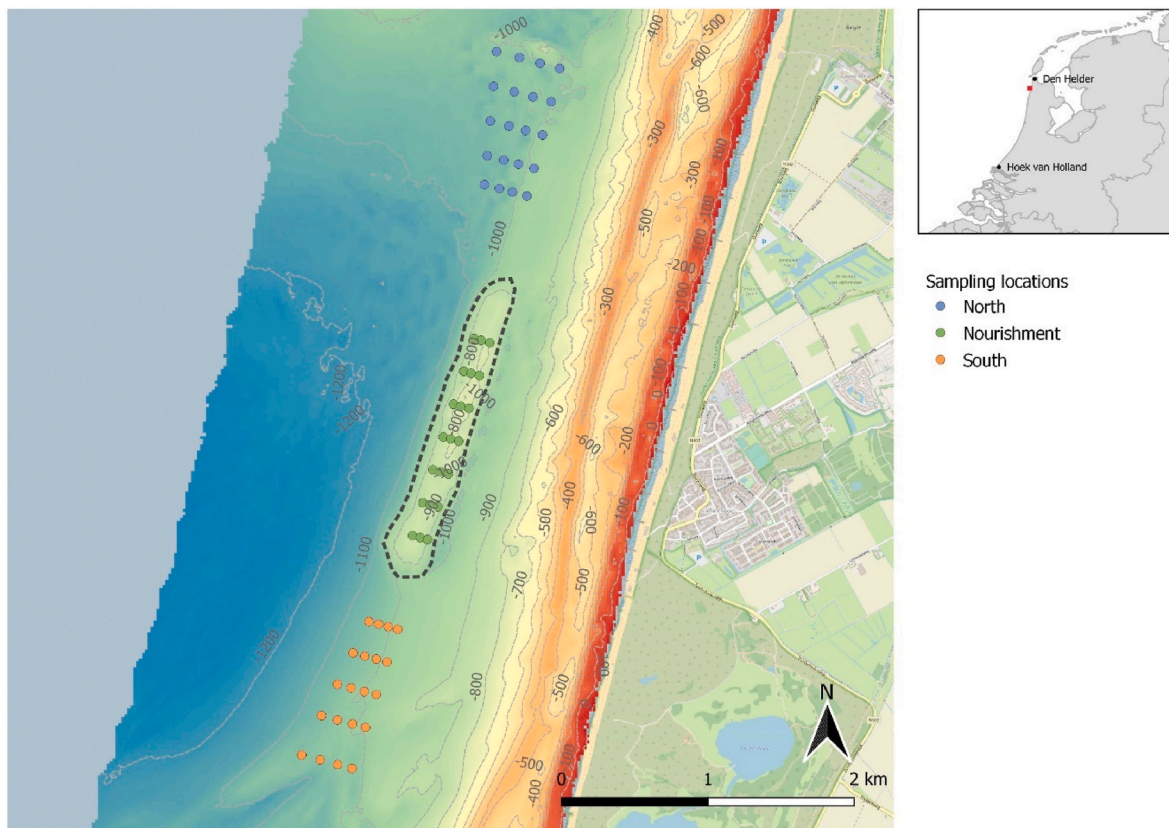
[1] www.marinespecies.org.

Fig. 1. Sampling locations at the nourishment location (green dots) and the reference locations North (blue dots) and South (orange dots). The broken line shows the contours of the nourishment. The inset shows the location of the Callantsoog nourishment (red square) in the northern part of the Holland coast. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Characteristics of the response curves of 12 most dominant (present at >25% of the stations) taxa. Column $p_{(0.5)}$ indicates the grain size (μm) where the probability of occurrence of the taxon is 0.5. Column $\Delta p/\Delta \mu$ indicates the slope of the curve at $p_{(0.5)}$ (μm^{-1}).

Taxon	Occurrence (−)	$p_{(0.5)}$ (μm)	$\Delta p/\Delta \mu$ (μm^{-1})
Ensis leei	0.63	259	−0.009
Spiophanes bombyx	0.61	255	−0.004
Magelona johnstoni	0.52	278	−0.006
Capitella spp.	0.50	235	−0.010
Spio martinensis	0.47	259	−0.007
Macoma balthica	0.44	219	−0.014
Lanice spp.	0.39	217	−0.012
Nephtys cirrosa	0.34	264	0.005
Eumida spp.	0.30	199	−0.014
Nephtys spp.	0.30	167	−0.003
Urothoe poseidonis	0.26	209	−0.003
Abra alba	0.26	194	−0.017

a function of the log-transformed bottom shear stress and median grain size. The regression parameters are related to the macrobenthic community, expressed as the values on the first PCA-axis.

3. Results

3.1. Nourishment

In 2021, four years after the nourishment, the average depth at the nourishment location had decreased by 2 m to 8.28 ± 0.30 m while the average depth at the reference locations North and South remained similar (10.26 ± 0.29 and 10.21 ± 0.24, respectively) to the depth

before nourishment. The depth measurements at the nourishment site, four years after the nourishment, illustrate the very limited mobility of the nourished sediment at this depth. The annual cross-shore elevation profiles (JARKUS, see supplementary material) show that the height of the nourishment has decreased approximately 60 cm between 2018 and 2022 due to erosion and/or compaction.

3.2. Sediment composition

Before nourishment (2015 and 2016), median grain sizes recorded at the reference location North were on average 264 μm (±17 μm) which was significantly (p < 0.01) larger than at the nourishment location and reference location South (195 ± 34 μm and 208 ± 30 μm, respectively) (Table 2). There was no significant difference in median grain sizes between the nourishment location and the reference location South before nourishment. In 2016, the median grain sizes at both the nourishment and the reference South were significantly (p < 0.01) smaller than in 2015. This is mainly due to the presence of finer sediments in the southern part of the nourishment area and the northern part of reference South in 2016 (Fig. 2). In 2021, four years after the nourishment, the average median grain size at the nourished location was much coarser (330 ± 59 μm) than before the nourishment (195 ± 34 μm). Given the

Table 2
Average median grain size (SD50, μm ± standard deviation) at the three locations in 2015, 2016, and 2021.

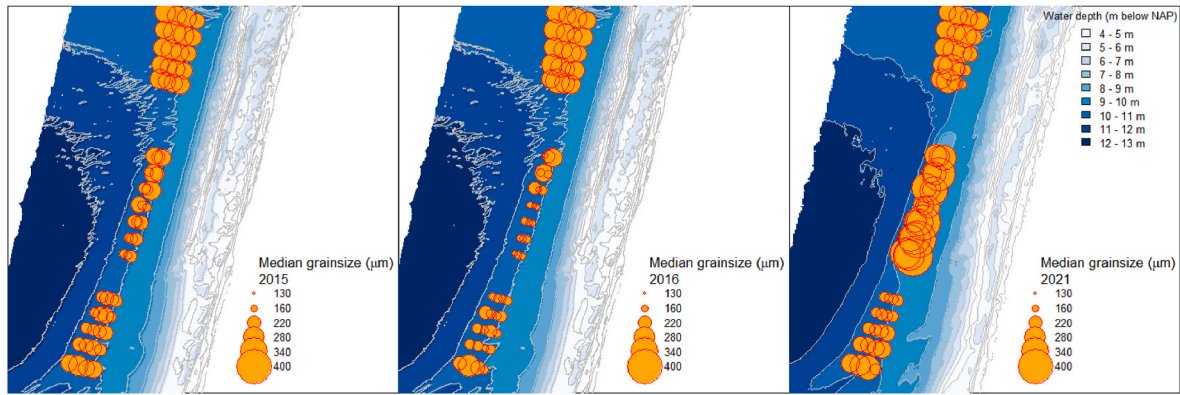| Year	North	Nourishment	South
2015	263 ± 15	212 ± 28	223 ± 23
2016	266 ± 18	179 ± 31	193 ± 29
2021	260 ± 35	330 ± 59	221 ± 34

Fig. 2. Spatial distribution in median grain size (μm) in 2015, 2016 and 2021. The map in the background shows the water depth (m below NAP).

long residence time of the nourished sand, this is most likely a direct result of the nourishment. The average median grain size at the nourishment in 2021 was significantly (p < 0.01) larger than at the reference location South (221 ± 34 μm) but also significantly (p < 0.01) larger than at the reference location North (260 ± 35 μm). Also, the variation in median grain size was relatively high at the nourishment location in 2021 (Table 2, Fig. 3), indicating a mixture of very coarse and finer sand, with median grain sizes ranging from 230 to 447 μm. It is not likely that the coarsening of the sediment at the reference location South in 2021 in comparison to 2016 is caused by the nourishment, because the coarsening of the sediments mainly occurred in the most southern transects of the reference location South. At the reference location North, relatively fine sediments are recorded at the shallowest stations of the southern transect in 2021 (Fig. 2), resulting in an increased variability in grain sizes at this location compared to 2015 and 2016 (Fig. 3). It is not clear if this is directly or indirectly related to the nourishment. At the reference locations South and North, the average median grain sizes in 2021 were not significantly different from the average median grain sizes in 2015

and 2016, before nourishment.

3.3. Macrobenthos

In total 106 unique taxa were observed in the 183 samples that were taken during the three years of monitoring. The total number of taxa at the reference location North (40 taxa) was much lower than at the reference location South (85 taxa) and the nourishment location (77 taxa). Before nourishment, the average number of taxa per sample was lower at the reference location North (average 3.9 ± 1.2 taxa per sample) compared to the reference location South (average 18.7 ± 11.0 taxa per sample) and the nourishment location (average 19.6 ± 8.3 taxa per sample) (Fig. 4). In 2021, four years after the nourishment, the average number of taxa per sample at the nourishment location dropped to 3.0 ± 1.5 taxa, which was comparable to the average number of taxa at the reference North (average 3.5 ± 1.7 taxa), but less than half the number of taxa at the reference location South (average 6.7 ± 2.0 taxa per sample).
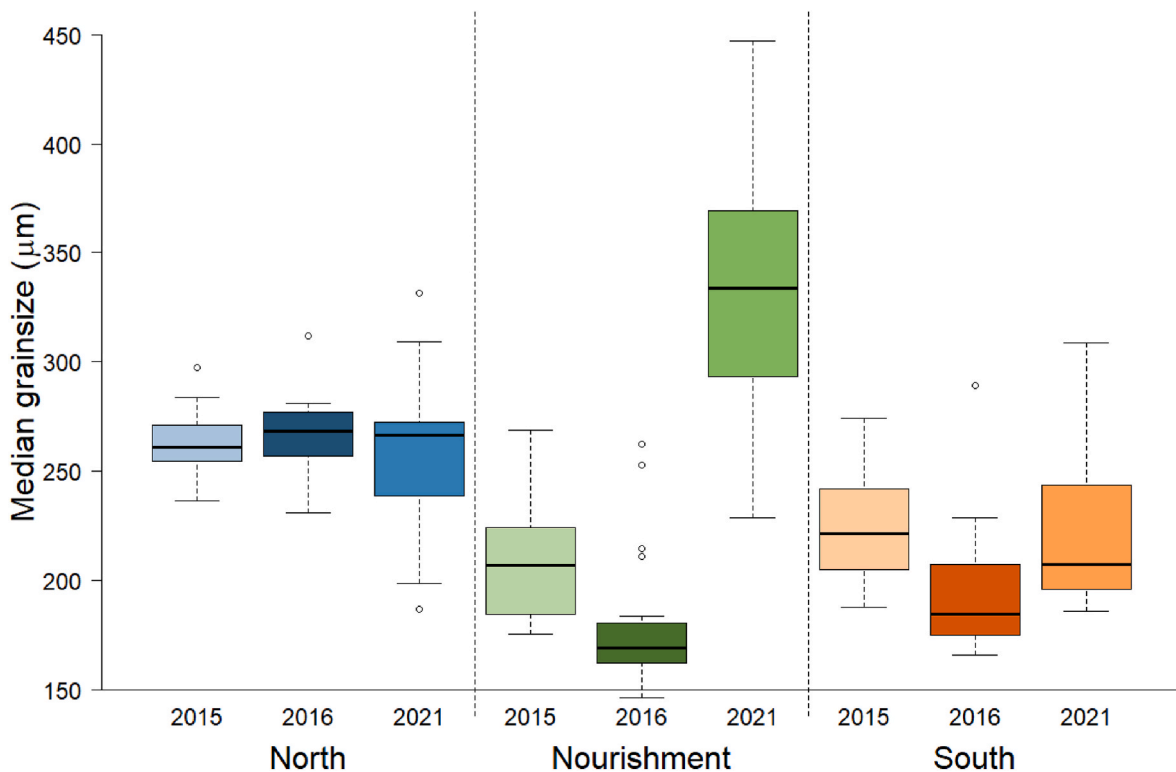

Fig. 3. Median grain size (μm) in 2015, 2016 and 2021 at the nourishment and reference locations North and South.
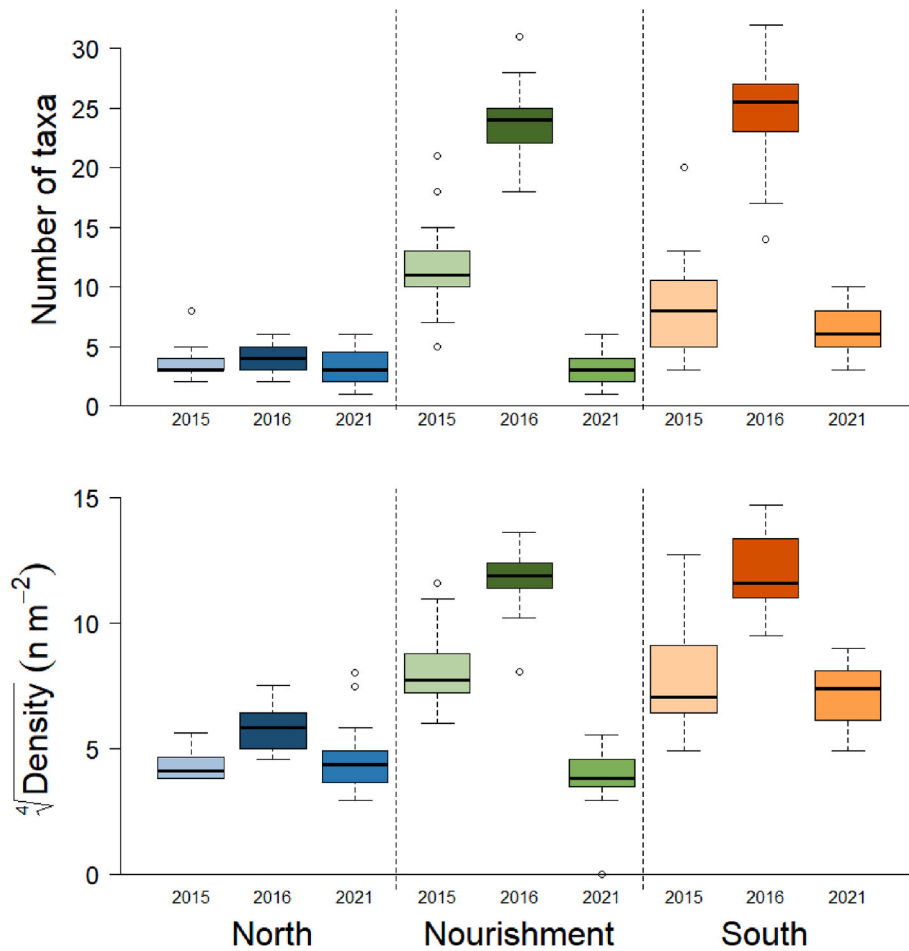
Fig. 4. Number of taxa and total density in 2015, 2016 and 2021 at the nourishment and reference locations.

The overall average total density per location was 6869 (±10026) ind.m^{-2} and the median density was 2004 ind.m^{-2}. The maximum density observed was 50608 ind.m^{-2} at a station sampled in 2016 in the reference location South. Most dominant species were *Lanice conchilega*, *Ensis leei* and *Spio martinensis* accounting for 21.0%, 11.4% and 10.3%, respectively, of the total density. There was a large variation over the years with maximum densities in 2016 (Fig. 4). Like the total number of taxa, the average density was lowest at the reference location North (783 ± 821 ind.m^{-2}). Before nourishment, in 2015 and 2016, the total density at the nourishment location (12731 ± 9139 ind.m^{-2}) was comparable to the total density at reference location South (15141 ± 13574 ind.m^{-2}) and much higher than at reference location North (832 ± 693

ind.m^{-2}). In 2021, after nourishment, however, the average density at the nourishment location (320 ± 251 ind.m^{-2}) was even lower than the average density at reference location North (684 ± 1044 ind.m^{-2}) and only ten percent of the average density at reference location South (3146 ± 1810 ind.m^{-2}). Only sixteen taxa were observed in that year at the nourishment location with dominant species *Nephtys cirrosa*, *Spiophanes bombyx*, *Bathyporeia pelagica* and *Magelona johnstoni* accounting together for more than 75% of the total density. The species *P. fulgens* was unique for the nourishment site in 2021 (observed at three stations). The spatial distribution of the macrobenthos density over the years (Fig. 5) also shows the strong reduction of the macrobenthos density at the nourished location. In the reference area North, relatively higher densities were
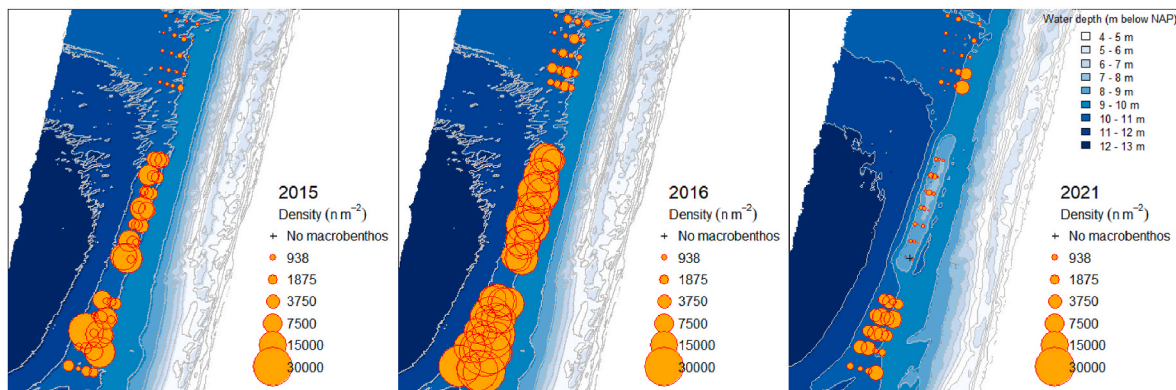

Fig. 5. Density macrobenthos 2015, 2016 and 2021 at nourishment and reference locations.

found at the finer sediments at the shallowest stations of the southern transect. The dominant species at these stations were *S. martinensis*, *E. leei* and *Capitella* spp.

It is clear from the nMDS plot (Fig. 6) that the macrobenthic community in the area varies both over time and space. At the reference location North, the macrobenthic community differed from the reference location South (all years) and the nourishment location (2015 and 2016). Characteristic species for reference location North is *N. cirrosa*. In 2015 and 2016, the macrobenthic communities at the reference location South and at the nourishment location were quite similar to each other but varied between the years. In 2021, the macrobenthic community at the reference location South became more similar to the macrobenthic community in 2015 at that location. At the nourishment location, however, the macrobenthic community in 2021 deviated from the community of reference location South and became more similar to the macrobenthic community at the reference location North.

All twelve dominant taxa that were selected for logistic regression (Table 1) show a significant relation with median grain size. Fig. 7 shows two examples: the probability of occurrence of *E. leei* (negative relation) and *N. cirrosa* (positive relation) as a function of median grain size. The curves represent the best GLM models (lowest AIC) fitted through all data. For visualization of the observations, the 183 stations are grouped into ten groups of equal size based on median grain size. The decreasing

occurrence of *E. leei* with increasing grain size, reflected by a negative value of $\Delta p/\Delta \mu$ (Table 1) suggests that sediments with a median grain size larger than 260 μm are less preferred by this species. On the other hand, *N. cirrosa*, seems to have a preference for coarser sediments, as is reflected by a positive value of $\Delta p/\Delta \mu$, and sediments with a median grain size less than 180 μm are supposed to be less suitable for this species. From the twelve dominant taxa, only *N. cirrosa* show a positive response with median grain sizes (Table 1). The other taxa show, like *E. leei*, a decreasing probability of occurrence with increasing grain size. For *Abra alba*, *Nephtys* spp. and *Eumida* spp. this threshold value ($p_{(0.5)}$) is low (< 200 μm) indicating that these taxa prefer relatively fine sediments while species like *M. johnstoni*, *E. leei*, *S. martinensis* and *S. bombyx* tolerate larger median grain sizes which is reflected in the higher threshold value. Especially *A. alba*, *M. balthica*, *Lanice* spp. and *Eumida* spp. seem to be sensitive to small changes in median grain size at the threshold value, which is reflected in the large absolute value of $\Delta p/\Delta \mu$. The probability of occurrence of these taxa decreases with 0.14 to 0.17 with an increase of 10 μm in median grain size at the threshold value. *Nephtys* spp., *Urothoe poseidonis*, *S. bombyx* and *N. cirrosa* are less sensitive to small changes in median grain sizes at the threshold value, as 10 μm difference in median grain size will change the probability of occurrence with only 0.03 to 0.05 for these taxa.

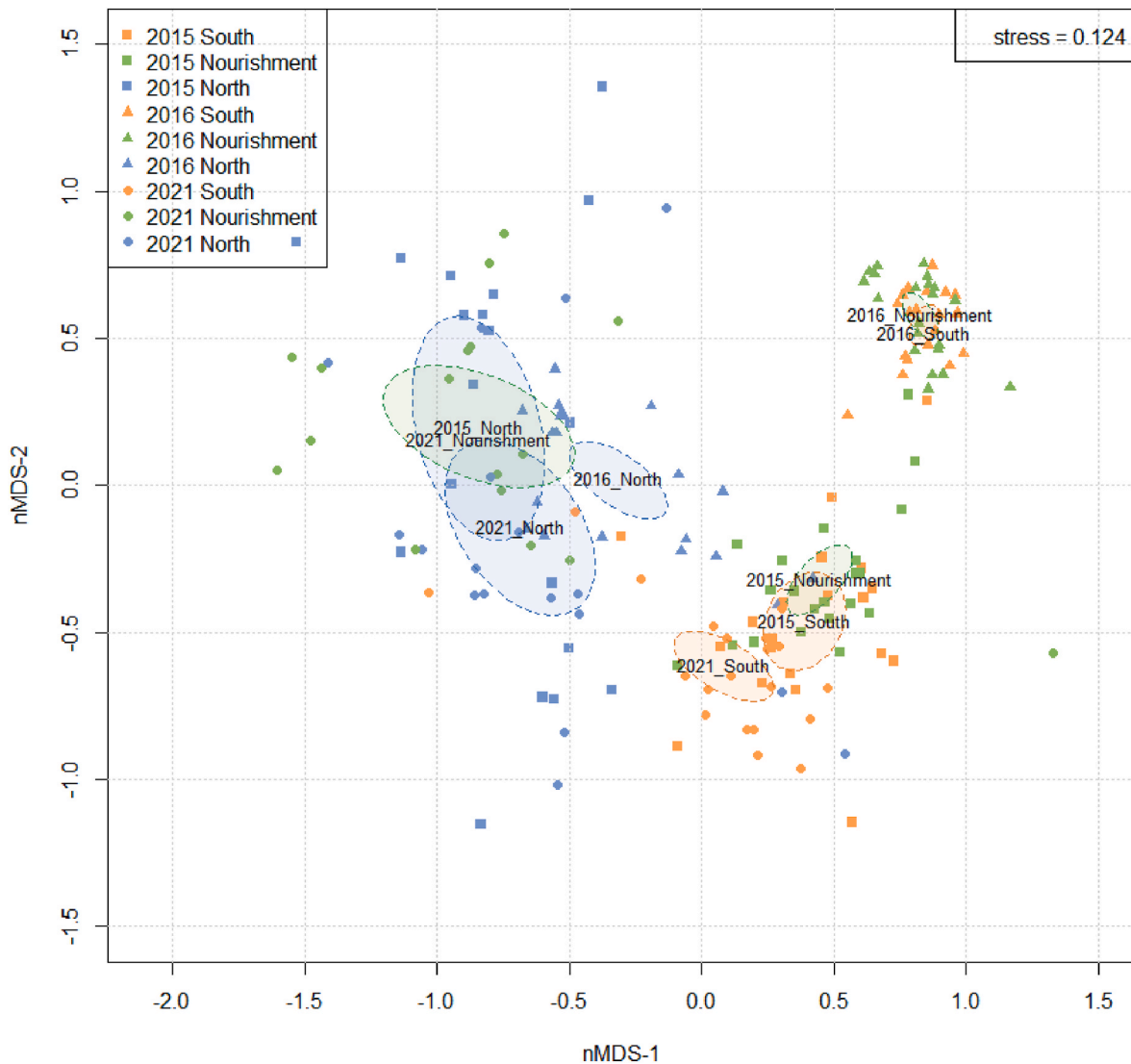The sensitivity of macrobenthic species to changes in sediment

Fig. 6. nMDS plot macrobenthos for the years 2015, 2016 and 2021 at nourishment and reference locations. The polygons indicate the 95-% confidence intervals.
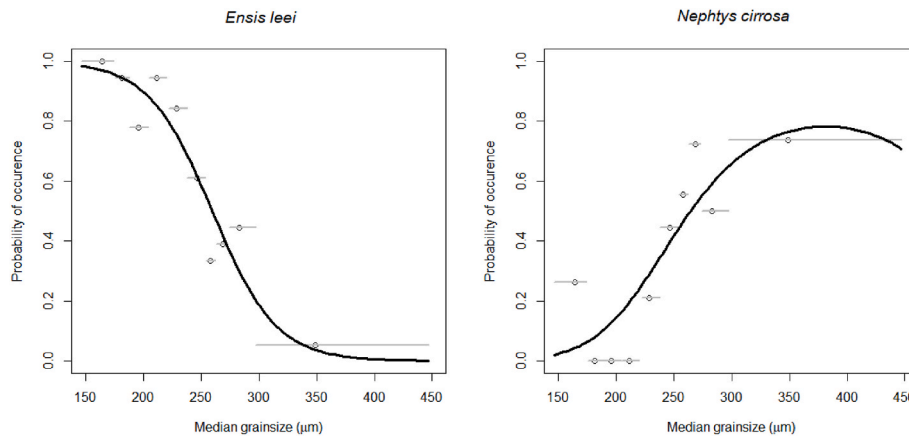
Fig. 7. Examples of the results of logistic regression for the probability of occurrence of *E. leei* and *N. cirrosa* as a function of median grain size (μm). Dots and horizontal lines represent the mean value and range, respectively, of the ten classes of median grain sizes.

composition can also be seen in the Sand Motor data (Fig. 8), where the slopes of the regression coefficients for bottom shear stress (left panel) and median grain size (right panel) of the different species are plotted against the species' scores on the first PCA axis. The figure shows a strong correlation (r = −0.92) between the scores of the species on the first PCA axis with the direction and strength of their response to bottom shear stress (left panel). Species like *E. leei*, *M. johnstoni* and *S. bombyx* that have a high positive score on the first PCA axis become less abundant as the bottom shear stress increases. Specialists of the dynamic surf zone like *Scolelepis (Scolelepis) squamata*, *Haustorius arenarius*, *Gastrosaccus spinifer*, *P. fulgens* and *Portumnus latipes* have a negative score on the first PCA axis and become more abundant with increasing bottom shear stress. The strength of the correlation is striking – response to bottom shear stress seems to be an important characteristic of this macrobenthic community. This is in line with the interpretation of Herman et al. (2021).

Although less pronounced than for bottom shear stress, there is also a clear correlation (r = −0.76) between the species scores on the first PCA axis and the response to changes in median grain size (right panel). For roughly half of the taxa, an independent response to median grain size, on top of the response to bottom shear stress, is found (p < 0.1). This is almost exclusively the case on the positive side of the first PCA axis: i.e. in species that prefer relatively sheltered conditions (low bottom shear stress). Species with the strongest negative relation with median grain size are *Nephtys hombergii*, *Fabulina fabula* and *M. johnstoni*. These species are the most selective for grain size and cannot be expected where the grain size is coarser. Positive responses to grain size have only been

found in three taxa (*Microphthalmus similis*, *N. cirrosa* and Nemertea). Two of these species are specialists of coarse sediments, which depend on the (large) interstitial spaces between the coarse grains of sand. These species are normally not found in the shoreface along the Holland coast, but are present in the zone of the Sand Motor in the patches with very coarse sediment.

4. Discussion

The Callantsoog nourishment that was located in the lower shoreface at the Holland coast provides an ideal opportunity to study the effect of sediment composition on macrobenthos, more or less independent of bottom shear stress. Although the nourishment resulted in a decrease in water depth from 10.3 m in 2016 to 8.28 m in 2021 at the location, it is expected that effects of bottom shear stress due to waves at this water depth remain limited. Annual cross-shore elevation profiles (JARKUS data, Southgate, 2011) show that the crest height of the nourishment has decreased with about 60 cm between 2018 and 2022 due to erosion and/of compaction.

The fact that most of the sediment remained in place at the nourishment, four years after it was applied, demonstrates the limited mobility of the sediment at the nourishment. This may raise questions on the utility of a nourishment at such depth, but most importantly for the present discussion, it suggests that the nourishment did not result in large differences in physical stress on the sediment.

The relatively large water depth of reference area North (ca 10 m below NAP), which is in the same range as the reference area South and
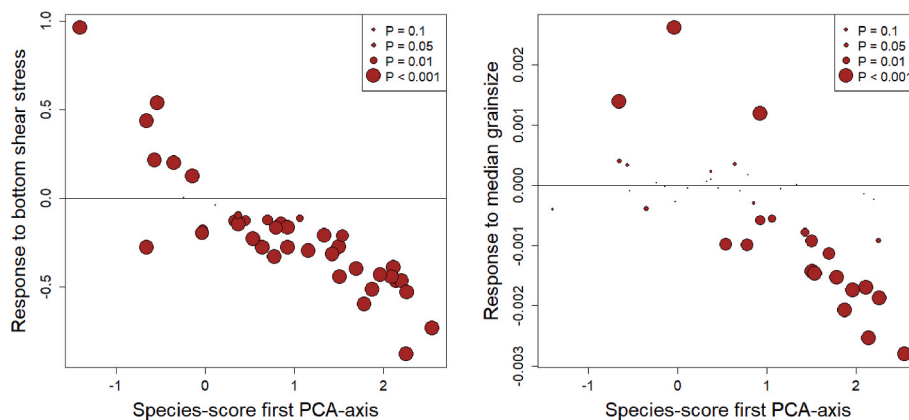

Fig. 8. Relation between species response of to bottom shear stress (left panel) and median grain size (right panel) and the score on the first PCA axis. The response is given as slope of the regression coefficient in the multiple linear regression. Dots indicate individual dominant species. Size of dot indicates significance of regression. Data from Sand motor monitoring (Herman et al., 2021; Wijsman et al., 2022).

the nourishment area before nourishment, suggests that the different sediment sorting and macrobenthic community in this reference area is not caused by differences in bottom shear stress due to waves. However, from the data it cannot be derived whether the differences are caused by bottom shear stress due to tidal currents or if there is another cause for the relatively coarse sediments. Also at the nourishment, where the water depth decreased by 2 m between 2016 and 2021, the relatively coarse sediments are expected not to be the result of increased bottom shear stress due to waves. Most probably the coarse sediments are a direct effect of the nourishment.

In general, the data from the Callantsoog and Sand Motor nourishments have the advantage of breaking partly the correlations that normally exist between physical forces, sediment composition and macrobenthic community. This offers more opportunities to investigate the factors independently. Data from the Sand Motor show that bottom shear stress is the most important factor in understanding the composition of the macrobenthic community (Herman et al., 2021). In addition, sediment composition also plays a role, but not all species have a significant response to sediment composition. In the exposed surf zone, where the bottom shear stress is high, most species are not very sensitive to changes in sediment composition. This sensitivity increases in the more sheltered areas of the deeper shoreface. Versatility of shallow-water species with respect to sediment grain size is confirmed in experiments, where the species show innate preferences to certain sediment size, but easily adapt these preferences, e.g. in the presence of other species (Van Tomme et al., 2013).

Most studies on the effect of grain size in nourishments were conducted with beach nourishments (Menn et al., 2003; Peterson et al., 2006; Jones et al., 2008), as the practice of shoreface nourishments is not very widespread. They do agree, however, that the use of sediment with a grain size similar to the resident sediment is advisable (Kindeberg et al., 2023). McLachlan (1996) showed in a well-chosen experimental situation that effects of grain size on the beach fauna result from the interaction between grain size of the sediment and physical stress. Coarser sediment deposited on a fine sand beach attained a steeper slope, leading to a more reflective beach in what used to be a dissipative morphology (Hanson et al., 2002). This in turn led to a type of assemblage known from reflective beaches, with (fewer) species adapted to more energetic conditions. This conclusion was confirmed by later monitoring results in the same area (Pulfrich and Branch, 2014), and extended in similar situations elsewhere (Brazeiro, 2001). Reverse conditions may apply where nourishments use too fine sediment, leading to poor stability of the nourished sediment and increased turbidity of the water, but again with a complex of physical and sediment-related factors that, together, determine the outcome for the resident fauna (Manning et al., 2014). In the deeper shoreface, the direct impact of waves is much less prominent. Our study shows that, at least in these conditions, sediment grain size alone can have a profound influence on the macrobenthic community. Moreover, as the residence time of the sediment in these locations is large, recovery to the original community may be slow or absent. The high stability of the sediment suggests that nourishment at a water depth of 10 m is not very meaningful. However, if performed, it would require additional care to select the appropriate grain size.

Little quantification can be found in the literature for what constitutes an 'appropriate' similarity in grain size between nourishment sand and the sediment at the place of nourishment. Our study shows that for the most sensitive species, e.g. *A. alba*, *Eumida* sp. or *M. balthica*, with calculated sensitivities $\Delta p/\Delta \mu$ of around -0.015 μm^{-1}, a difference in median grain size as small as 50 μm, causes a difference in probability of occurrence of 0.75 – which is basically the difference between almost always present and almost always absent. This sets high requirements to the precision used in selecting borrow sites for nourishments. Due to horizontal and vertical variability in sediment composition at the scale of tens to hundreds of meter (horizontally) and a few m (vertically), it is almost impossible to predict the composition of the nourishment sand

taken from a specific borrow site with this required precision. For the Dutch coast, the most refined voxel model of sand resources gives a 3D picture of the distribution of four classes of sand (<105 μm, 105–210 μm, 210–420 μm and >420 μm) (Vermaas, 2020). The width of these classes, added to the frequent presence of intermittent layers of different composition within the depth of sand mining, make it virtually impossible to select a suitable location based on available databases. A certain degree of trial and error in selecting borrow locations seems to be unavoidable. However, *in situ* investigation of the sediment layers in plausible borrow locations does allow for a more reliable selection on grain size. Moreover, further development of the sand resource model, i. e. making it more reliable and redefining the grain size classes seems recommendable for the Dutch situation.

For shallower nourishment locations, where residence time of the nourished sand is shorter and bottom shear stress becomes a more dominant factor, it can be anticipated that the selection of borrow locations may be less important. However, if a significant coarse fraction is present in the nourished sand, there is a risk that this will remain in place while the finer fractions are mobilized. At the Sand Motor, Huisman et al. (2016), found coarsening by tidal currents at deep sites up to 150 μm in median grain size, although the effect was lessened after deep-reaching storms. Such sorting might lead to a coarsening in the longer term when a site is repeatedly nourished. Given the high degree of sensitivity of the fauna to this factor, this may cause long-term changes in the faunal communities.

5. Conclusions

Four years after the nourishment in the lower shoreface off Callantsoog, the macrobenthic community has not recovered. Because the nourishment is located at greater water depths than regular shoreface nourishments, waves have less impact on the nourishment resulting in a relatively stable situation. As a consequence, the relatively coarse material of the nourishment has not been taken-up in the system and a macrobenthic community has developed on the nourishment that is characterized by a low density and a low species diversity. Due to the calm morphodynamic conditions, it is not likely that the situation will change in the near future. The sensitivity of the macrobenthos to sediment composition illustrates the importance of using sediments of similar grain size to the placement area, especially for nourishments in the shoreface. Despite of all practical difficulties, we recommend for future nourishments especially in the lower shoreface, to put more effort on using sediments of similar grain size as in the placement area. Also losses of fine sediment fractions during dredging and nourishing should be reduced to prevent coarsening of the sediment during the activities.

CRediT authorship contribution statement

Jeroen W.M. Wijsman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Theo C. Prins:** Writing – review & editing, Methodology. **J.J. Simeon Moons:** Writing – review & editing. **Peter M. J. Herman:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wijsman, J.W.M. reports financial support was provided by Rijkswaterstaat Water Traffic and Living Environment.

Data availability

Data are available at 4TU repository (https://data.4TU.nl)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2023.108521.

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