



# Short-term impact of deep sand extraction and ecosystem-based landscaping on macrozoobenthos and sediment characteristics



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## ABSTRACT

We studied short-term changes in macrozoobenthos in a 20 m deep borrow pit. A boxcorer was used to sample macrobenthic infauna and a bottom sledge was used to sample macrobenthic epifauna. Sediment characteristics were determined from the boxcore samples, bed shear stress and near-bed salinity were estimated with a hydrodynamic model. Two years after the cessation of sand extraction, macrozoobenthic biomass increased fivefold in the deepest areas. Species composition changed significantly and white furrow shell (*Abra alba*) became abundant. Several sediment characteristics also changed significantly in the deepest parts. Macrozoobenthic species composition and biomass significantly correlated with time after cessation of sand extraction, sediment and hydrographical characteristics. Ecosystem-based landscaped sand bars were found to be effective in influencing sediment characteristics and macrozoobenthic assemblage. Significant changes in epifauna occurred in deepest parts in 2012 which coincided with the highest sedimentation rate. We recommend continuing monitoring to investigate medium and long-term impacts.

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## 1. Introduction

The demand for marine sand in the Netherlands and internationally is rising (Stolk and Dijkshoorn, 2009; ICES, 2014). In the Netherlands, 24 million m<sup>3</sup> marine sand is used annually for coastal nourishments and construction. An increase of annual nourishments up to 40–85 million m<sup>3</sup> of sand for counteracting effects of future sea level rise is anticipated (Deltacommissie, 2008). The potential for deep sand extraction was investigated in a deep temporary extraction site (PUTMOR) in front of 'the Port of Rotterdam' with 6.5 million m<sup>3</sup> of sand extracted, an initial water depth of 23 m and extraction depths between 5 and 12 m. There were no indications that deep sand extraction would lead to unacceptable effects and recovery of benthic assemblages could be possible (Boers, 2005). For a 20 km<sup>2</sup> seaward harbour expansion Maasvlakte 2 of the Port of Rotterdam, the Dutch authorities permitted extraction deeper than the common 2 m extraction depth, primarily to decrease the surface area of direct impact. Approximately 220 million m<sup>3</sup> of sand was extracted between

2009 and 2013, with an average extraction depth of 20 m. To maintain sufficient supply of marine sand in the intensively used coastal zone, the authorities started promoting deeper sand extraction for future sand extraction projects larger than 10 million m<sup>3</sup> (IDON, 2014). Ecological impacts of deep sand extraction, however, are largely unknown and still under investigation. In general, sand extraction has direct impacts on the seabed since benthic organisms are damaged or removed and the bathymetry and seabed composition is changed considerably. Indirect effects are increased turbidity, release of nutrients or toxins and smothering by sedimentation. In 1979, the first studies on the impacts of large-scale dredging in the North Sea appeared (de Groot, 1979b, 1979a). Since then, many international studies have investigated various ecological aspects of shallow sand extraction (Newell et al., 1998, 2004; Seiderer and Newell, 1999; Desprez, 2000; van Dalfsen et al., 2000; Boyd et al., 2003, 2005; Phua et al., 2004; Boers, 2005; Barrio Froján et al., 2008; Desprez et al., 2009; Le Bot et al., 2010; De Backer et al., 2014). The recovery time of benthic assemblages to pre-dredge conditions after shallow sand extraction in the North Sea is estimated to be 4–6 years (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001; Boyd et al., 2005). In a region with high-intensity sand and gravel extraction off the south-east coast of England, higher macrozoobenthic variability was observed and complete recovery was not reached 11 years

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after the cessation of extraction (Wan Hussin et al., 2012). For muddy areas however, Newell et al. (1998) estimated that recovery time is around 6–8 months. The recovery time of benthic assemblages after deep and large-scale sand extraction is not yet determined. In this study, we report on the short-term (0–2.5 yr.) changes in macrozoobenthos in the deep and large-scale borrow pit for Maasvlakte 2. As an experiment, two sandbars were excavated copying naturally occurring bedforms to increase habitat heterogeneity and benthic species richness (Baptist et al., 2006; van Dijk et al., 2012; de Jong et al., 2014). We tested the hypothesis that deep and large-scale sand extraction and ecosystem-based landscaping approaches will lead to significant changes in macrozoobenthic assemblage. Furthermore, we hypothesise that the macrozoobenthic assemblage in the Maasvlakte 2 extraction site will resemble the highly productive and species-rich macrozoobenthic white furrow shell (*Abra alba*) clusters which were found in 2006 and 2008 in the 8 m deepened shipping lane and the lowered disposal sites for dredged fine sediment in front of the Port of Rotterdam (de Jong et al., in press). We aim to answer the following questions:

- (1) What is the short-term (0–2.5 yr.) impact of deep sand extraction on macrozoobenthos?
- (2) What are the changes in sediment characteristics and bathymetry?
- (3) Which environmental and hydrodynamic variables are influencing macrozoobenthos?
- (4) Are ecosystem-based landscaping techniques effective in influencing macrozoobenthic assemblages and sediment characteristics?

## 2. Materials and methods

### 2.1. Borrow pit and surrounding area

The Maasvlakte 2 borrow pit is situated in front of Rotterdam harbour outside the 20 m depth contour and is 6 km long and 2 km wide (Fig. 1). The research area stretches over approximately 100 km<sup>2</sup> in front of the Port of Rotterdam. The seabed consists of fine to medium sand with a small fraction of mud, very fine sand and sediment organic matter (SOM).

Sand waves are present in the surrounding area, with wave lengths of 100–800 m, amplitudes up to 5 m and crests orientated perpendicular to the tidal current (Hulscher, 1996). In the exclusion area, amplitudes are around 4 m (Fig. 2).

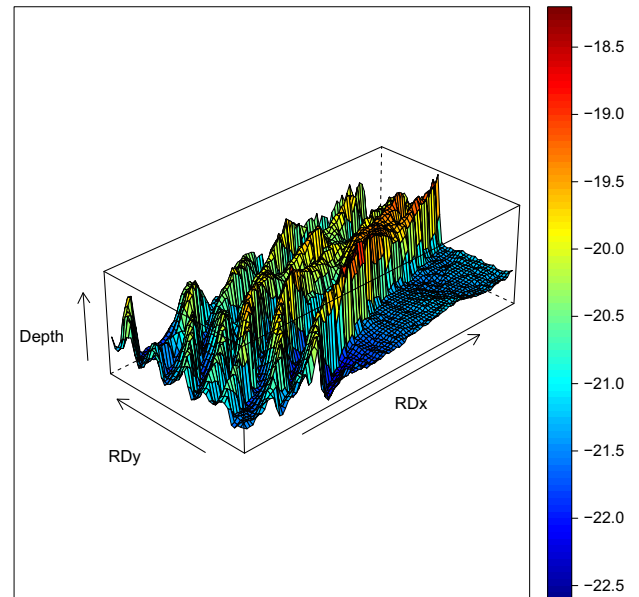


Fig. 2. Natural sand wave field in the exclusion area of the Maasvlakte 2 borrow pit from north-western direction.

Approximately 220 million m<sup>3</sup> of sand was extracted between 2009 and 2013 with an average extraction depth of 20 m. A large northern and smaller southern borrow pit is separated by an exclusion area.

Macrozoobenthos in the North Sea correlates with a variety of sediment characteristics (Heip et al., 1992; Künitzer et al., 1992; Holtmann et al., 1996; Van Hoey et al., 2004, 2007; Degraer et al., 2008; Verfaillie et al., 2009). Naturally occurring bed forms, such as sand waves and shoreface-connected ridges influence macrozoobenthos on smaller spatial scales (Baptist et al., 2006; van Dijk et al., 2012).

To investigate the applicability of ecosystem-based landscaped sandbars in sand extraction projects, two sandbars were excavated on the seabed of the extraction site. One sandbar parallel to the tidal current was completed in spring 2010 (Fig. 3: denoted with 1). The parallel sandbar has a length of 700 m, a width at the crest of 70 m and slopes of 140 m length. The crest of the sandbar is located at a water depth of 30 m and the troughs are more than 40 m deep.

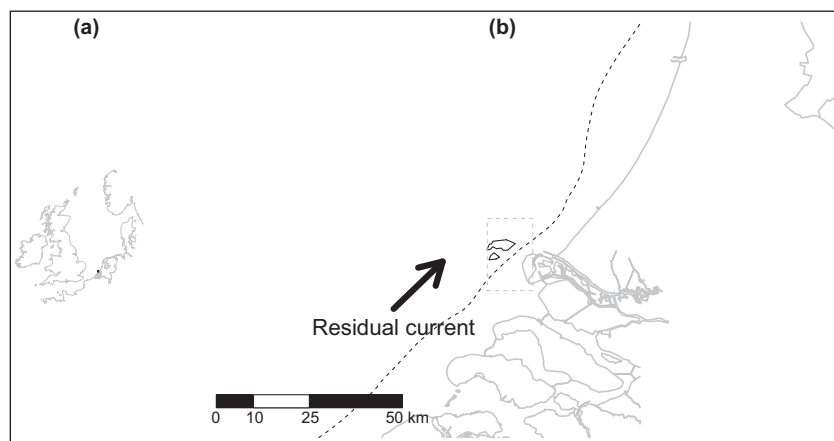
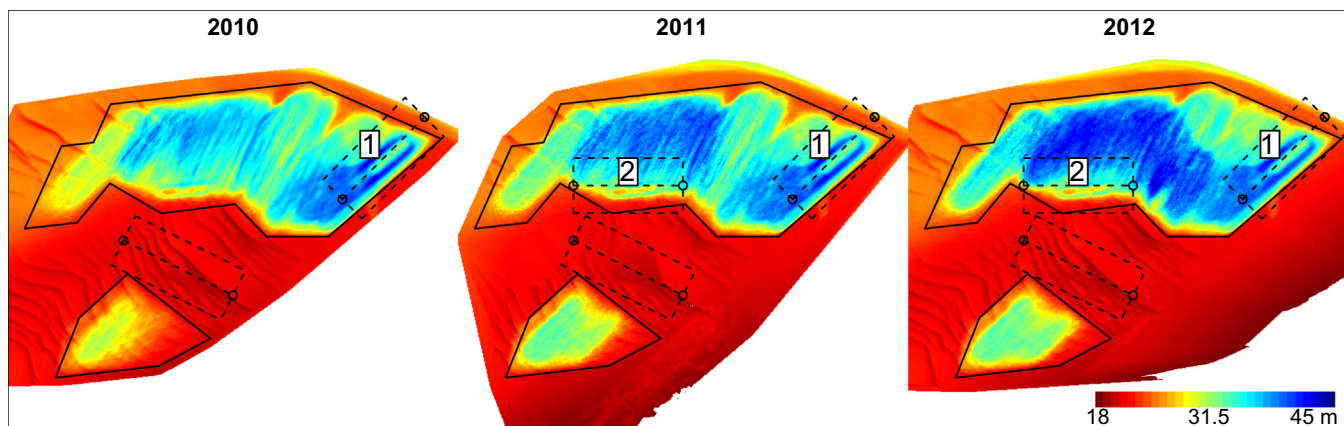
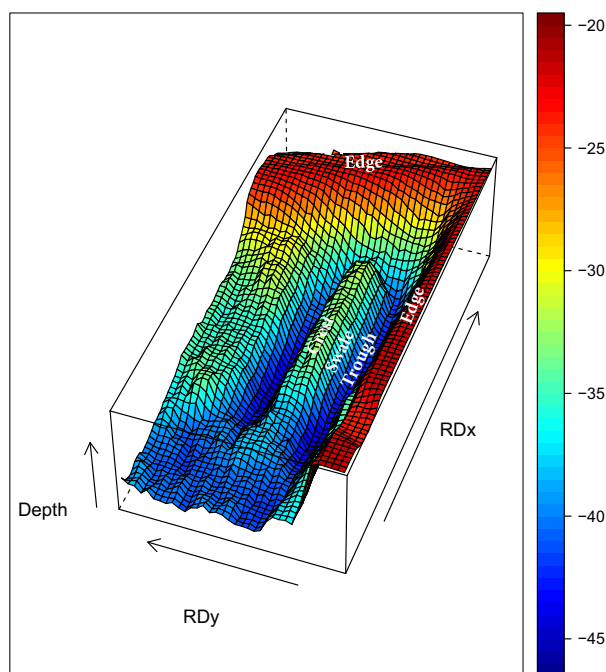


Fig. 1. (a) North Sea, (b) Dutch coastal zone with Maasvlakte 2 borrow pit and harbour extension with 20-m isobath (black dashed line), residual tidal current and survey area (grey-coloured dashed rectangle).



**Fig. 3.** Bathymetry of Maasvlakte 2 borrow pit during the sand extraction with the parallel sandbar (1) and the oblique sandbar in 2011 and 2012 (2). The dashed rectangles are the three-dimensional projections of the sand waves (Fig. 2) and the parallel sandbar (1) and oblique sandbar (2).

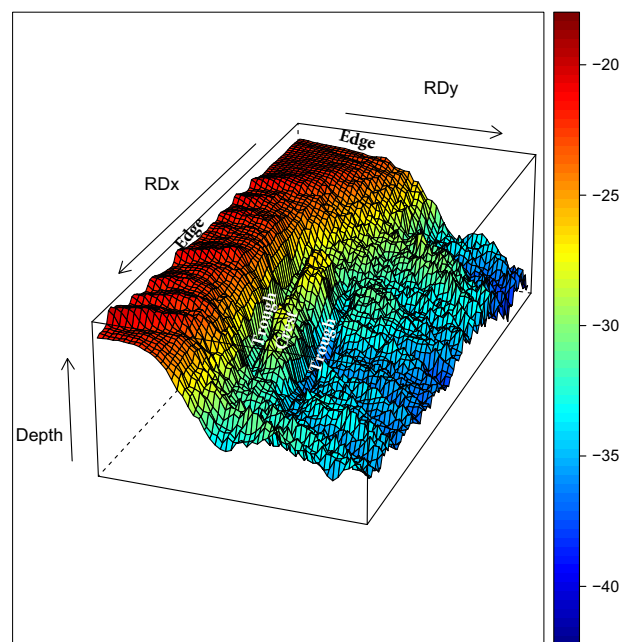


**Fig. 4.** Parallel sandbar in the Maasvlakte 2 borrow pit with the edge of the borrow pit and sample locations: crest, slope and trough. The slopes of the parallel sandbar are only investigated in 2010.

In 2011, the second sandbar was completed with an orientation oblique to the tidal current (Fig. 3 denoted with 2 and Fig. 5). The length and width are similar to the parallel sandbar but, due to time constraints, the difference in depth between crest and trough is less pronounced. The crest is situated at a water depth of 28 m and the northern trough is 36 m deep. A narrow and 32 m deep trench separates the crest from the slope of the borrow pit.

## 2.2. Macrozoobenthos and sediment sampling

To ensure comparable data, sampling was carried out using identical protocols as during the baseline study and the current recolonisation study of the Environmental Impact Assessment (EIA) for the construction of Maasvlakte 2. A boxcorer with a surface area of 0.077 m<sup>2</sup> was used to sample sediment and macrobenthos, larger than 1 mm and mainly living in the seabed. A bottom sledge was used to sample macrobenthic in- and epifauna with a



**Fig. 5.** Oblique sandbar in the Maasvlakte 2 borrow pit with the southern edge of the borrow pit and sample locations: crest and troughs.

size range of 0.5–10 cm. Bottom sledge samples are hereafter called epifauna (EP) although large infauna is collected as well. Perdon and Kaag (2006), Craeymeersch and Escaravage (2010), de Jong et al. (2014).

Sampling with the boxcorer was executed by the Royal Netherlands Institute for Sea Research (NIOZ) on 29–30th June 2010, 2–5th May 2011 and 23–25th April 2012. In 2010 and 2011, 45 and in 2012, 64 boxcore samples were collected. To reach a higher spatial resolution in- and outside the extraction site in 2012, a subsample of the boxcore was analysed which reduced the sampled surface area to 0.015 m<sup>2</sup>. Four samples were collected in the deep parts of the extraction site, 14 samples in the reference area (near and far field) and four samples in the shipping lane area (Table 1).

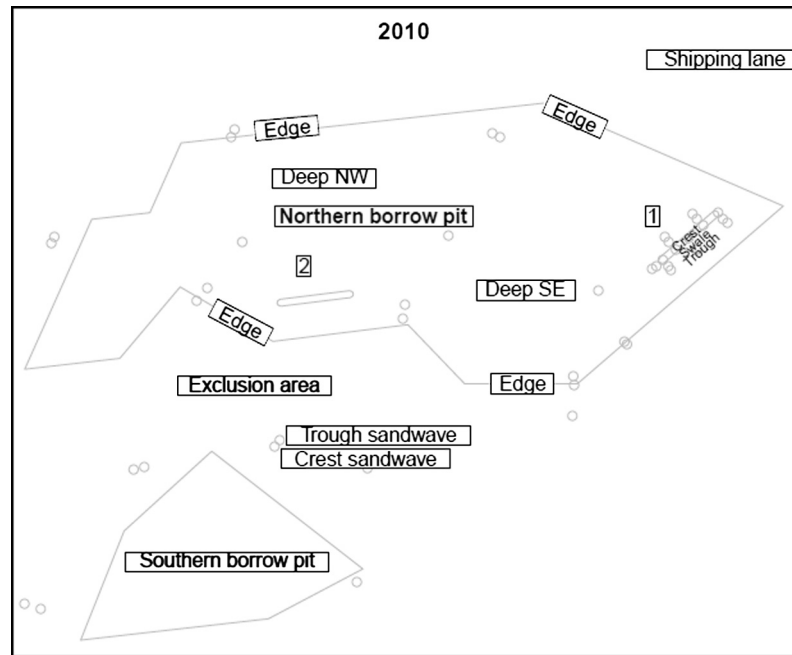
No maintenance dredging was executed in the shipping lane according to Rijkswaterstaat. Specimens were identified up to species level when possible and ash-free dry weight biomass (g AFDW m<sup>-2</sup>) was analysed by means of loss on ignition, 2 days at 80 °C followed by 2 h at 520 °C.

Number and location of boxcore samples. Locations are visualised in Fig. 6.

Number and location of bottom sledge samples.

Year	Reference				Borrow pit							
	Crest	Troughs	Slope	Shipping lane	Parallel Sand bar			Oblique sand bar		Deep		Total
					Crest	Slope	Trough	Crest	Trough	South-east	Rest	
2010	5	6	4	–	2	3	3	–	–	–	3	26
2011	–	1	10	–	2	–	4	2	4	1	2	26
2012	5	1	5	3	2	–	4	2	4	3	3	32





**Fig. 6.** Southern and northern borrow pit, with the sampling locations and boxcore sampling positions in 2010. The parallel sandbar (1) with sub locations crest, swale and trough and the oblique sandbar (2) which was not sampled in 2010.

of package 'pgirmess' was used to determine significant differences in biotic and abiotic variables between sub locations. Significance of differences in macrozoobenthic species composition between location and time after cessation of sand extraction was tested with permutational multivariate analysis of variance using distance matrices (ADONIS) of package 'vegan'. Due to the lack of post-hoc multi-comparison tests in the ADONIS function, we manually selected sets of locations and analysed each comparison. We applied Non-Metric Dimensional Scaling (nMDS) using the metaMDS function in R package 'vegan', based on Bray–Curtis dissimilarities of macrozoobenthos abundance data, to visualize differences in benthos assemblages in the extraction site and reference area (Oksanen, 2013). 3-Dimensional (3D) ordinations were used due to high stress values. The bioenv.default function was used to determine the best subset of continuous and categorical environmental variables, so that the Euclidean distances of scaled environmental variables have the maximum Spearman rank correlation with the macrozoobenthic community dissimilarities. The subset of environmental variables were linearly fit onto the 3D ordinations using the ENVFIT function in package 'vegan' (999 permutations). When Spearman rank correlation coefficients between a set of variables exceeded 0.9 one of the variables was dropped (Zuur et al., 2007). Package 'marmap' version 9.0.2 was used to make the bathymetric 3D plots and setSQL and subsetSQL was used to load the high resolution bathymetry data of 2011 and 2012 (Pante and Simon-Bouhet, 2013). We used package 'MGCV' for the GAM analyses, using Gaussian distribution. We selected the best explaining variables with the Akaike information criterion (AIC) and used only non-correlated variables. We checked the assumptions for GAM with the gam.check function and used log10-transformed biomass values.

### 3. Results

#### 3.1. Abiotic data

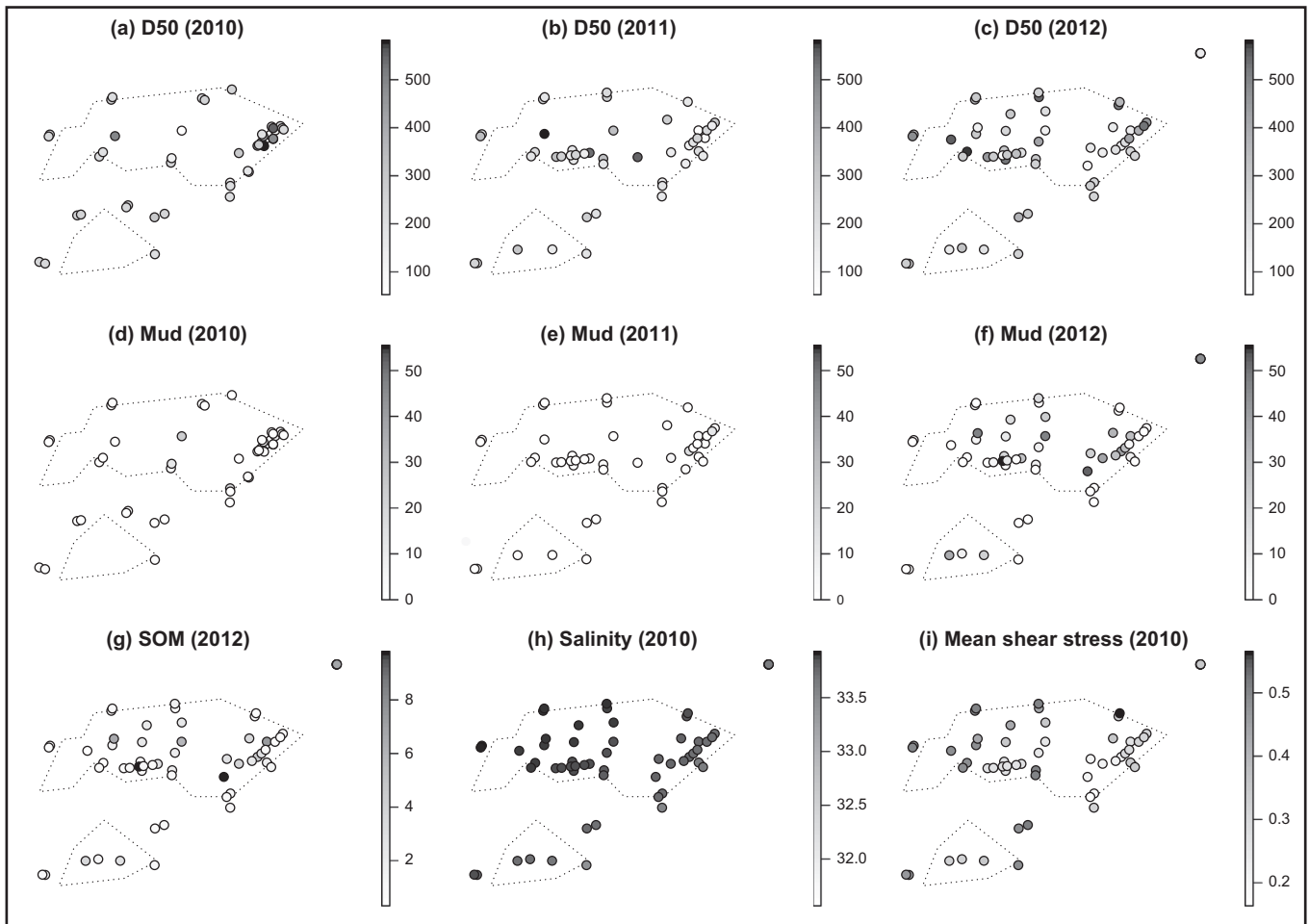
Decreasing median grain size and increasing mud values were observed in the borrow pit (Fig. 7a–f, Appendix II). Sediment

organic matter was only measured in 2012 but shows a similar distribution as for mud (Fig. 7f and g). The conditions in the deep parts of the borrow pit are very similar to those of the 1970s deepened shipping lane area. The circumstances in the shipping lane itself remained very similar during the monitoring campaign. Water depth at the sampling site within the shipping lane in 2006, 2008 and 2012 was, respectively, 29.6, 29.0 and 26.8 m (Appendix II). Median grain size decreased from 228.8 to 193.9 and 135.1  $\mu\text{m}$  and mud content changed from 7.5 to 2.5 and 23.1 vol% and SOM from 1 to 1.4 to 4.7 mass%. Due to ongoing sand extraction in the borrow pit, only one  $t_2$  location in the north-western deep part was sampled. The sediment characteristics in this area are similar to the  $t_2$  samples from the south-eastern deep part. The high value of mud and SOM on the crest of the oblique sandbar (II) however is not related to sedimentation of fines but to remains of old peat or wood fragments. In 2010, significant higher very fine sand values were detected on the parallel sandbar (I) compared to the reference area (Kruskal–Wallis  $<0.05$ ). In 2012, very fine sand and mud values differed significantly between the shipping lane area and the edge and the reference area and between the deep south eastern part – edge and reference area (Kruskal–Wallis  $<0.05$ ). The largest water depth was found in the south-eastern trough of the parallel sandbar (1) and was respectively 44.7, 44.4 and 43.2 m in 2010, 2011 and 2012. Between 4 October 2010 and 4 August 2011, the sedimentation rate in the troughs of the parallel sandbar (1) was relatively small (Table 3, N: +0.16 and S: +0.05 m). The deep SE area and the crest of the parallel sandbar eroded slightly (–0.02 m and –0.10 m).

The sedimentation rate in the troughs of the parallel sandbar between 4 August 2011 and 20 July 2012, increased considerably (N: +0.43 and S: +0.75 m). In the deep SE area 0.18 m of sediment settled and 0.27 m on the crest of the parallel sandbar.

#### 3.2. Infaunal data

Highest species richness was found in the reference area in 2010 (Fig. 8a). Species richness in 2010 was significantly lower at



**Fig. 7.** Environmental variables. (a–c): Median grain size ( $D_{50}$ ,  $\mu\text{m}$ ), (d–f): Fraction mud (vol%), (g): SOM for 2012 (mass%), (h and i): Mean near-bed salinity (ppt) and mean bed shear stress ( $\text{N m}^{-2}$ ) based on 2007 weather conditions and 2010 bathymetry.

**Table 3**

Water depth and sedimentation rate at sub locations in the borrow pit (–: erosion, +: sedimentation).

Year	Average sedimentation rate			
	Deep SE	N trough par. sandbar	Crest par. sandbar	S. trough par. sandbar
2010	–41.04	–41.89	–35.76	–41.55
2011	–41.06 (–0.02)	–41.73 (+0.16)	–35.87 (–0.10)	–41.50 (+0.05)
2012	–40.88 (+0.18)	–41.30 (+0.43)	–35.60 (+0.27)	–40.75 (+0.75)

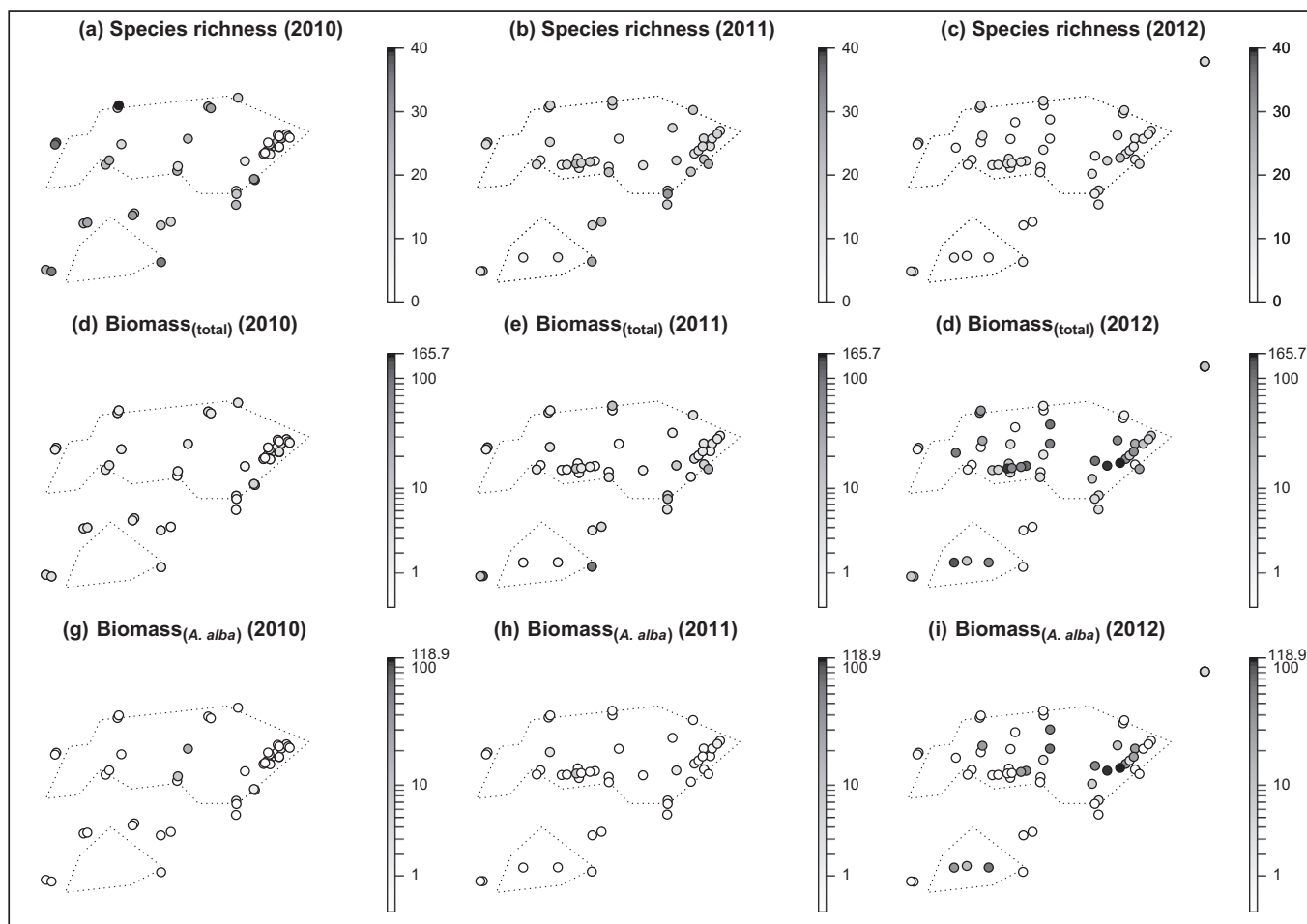
the crest and swale of the parallel sandbar when compared to the reference area (Kruskal–Wallis,  $<0.05$ ). Species richness in the extraction site in 2012 was similar to the reference area. Directly after sand extraction, species richness in the troughs of the sandbars was significantly lower compared to reference level, respectively, 3.7 instead of 8 species per haul. Comparisons of species richness in the shipping lane in 2006 and 2008 with 2012 is not possible due to the smaller samples sizes obtained in 2012. Species richness peaked at median grain sizes of around  $200 \mu\text{m}$  and 18 m water depth, time after cessation also contributed significantly and the generalised additive model (GAM) explained 40.3% of the total deviance (Fig. 9b, Appendix V, Table 2).

Infaunal biomass decreased in the reference area during the monitoring campaign and the 3-year average was  $16.1 \text{ g AFDW m}^{-2}$  (Appendix IV). Directly after sand extraction, biomass values in the

borrow pit are generally significantly lower compared to reference values. In 2012, high infaunal biomass values were detected in the deep parts of the extraction site (Fig. 4). Biomass values were significantly higher in the deep SE part of the borrow pit when compared to the edge (Kruskal–Wallis,  $<0.05$ ). In 2011, biomass values in the trough of the oblique sand bar were significantly lower than reference values. In the deep SE part in 2012, biomass reached high levels (maximum:  $165.7 \text{ g m}^{-2} \text{ AFDW}$ ) mainly due to white furrow shell (Fig. 4d and i). Values were significantly higher compared to the reference area and the edge (TukeyHSD,  $p < 0.05$ ). In the middle of the crest of the oblique sandbar, another hotspot in infaunal biomass emerged. The average biomass value was significantly higher than the value at the edge (TukeyHSD,  $p < 0.05$ ). Biomass of the crests of the parallel and oblique sandbars differed, respectively, 14.9 and  $51.1 \text{ g AFDW m}^{-2}$ . Infaunal biomass showed a significant negative correlation with median grain size and time after sand extraction, which explained 48.5% of the total deviance (Fig. 9a, Appendix V Table 1).

### 3.2.1. Infaunal species composition

In total, 109 infaunal species were detected in the reference area and borrow pit. Paddleworms (*Eteone* sp.), bristleworm *Spiophanes bombyx*, spaghetti worms (*Terebellidae* sp.), amphipod *Urothoe poseidonis* and sea urchins (*Echinoidea* sp) numerically dominated infauna of the reference area. In terms of biomass, infauna was dominated by sea potato (*Echinocardium cordatum*),



**Fig. 8.** Biological parameters of boxcore sampling for 2010, 2011 and 2012. (a–c) Species richness ( $n$  species boxcore $^{-1}$ ), (d–f) total biomass boxcore ( $g$  AFDW  $m^{-2}$ ) and (g–i) biomass *A. alba* boxcore ( $g$  AFDW  $m^{-2}$ ).

**Table 4**

Differences in infaunal species composition in 2012 between locations (permutational multivariate analysis of variance using distance matrices (ADONIS)).

	Ref	Edge	Crest par	Trough par	Crest oblique	Trough oblique	Deep SE	Deep NW	Shipping lane
Ref	–		*	**	*	*	**	**	**
Edge		–				.	**	**	**
Crest par			–				*	*	
Trough par				–					
Crest oblique					–				
Trough oblique						–	.		
Deep SE							–		
Deep NW								–	
Shipping lane									–

Significance codes:

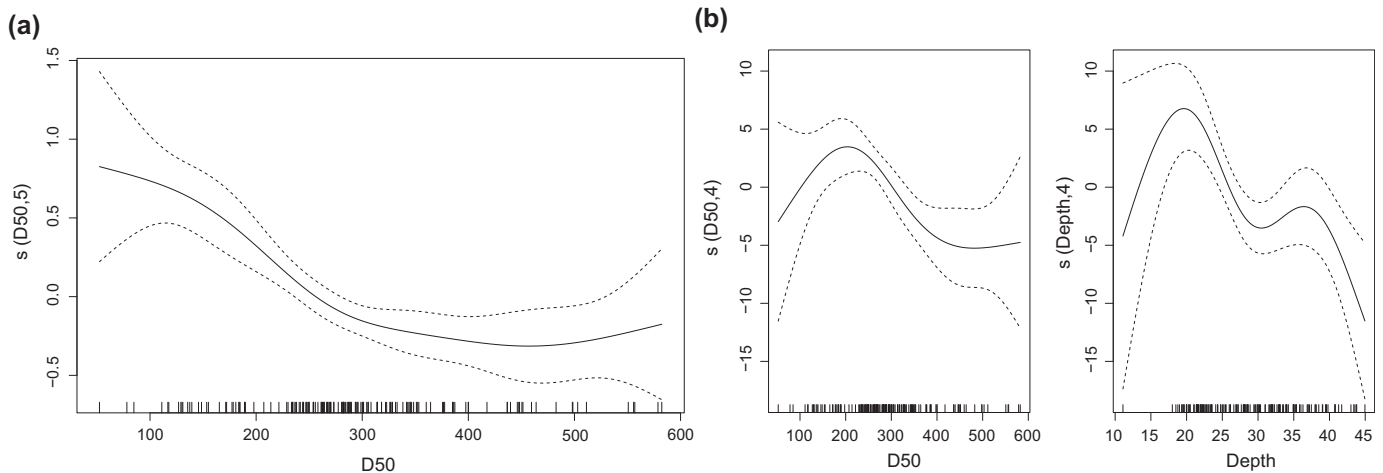
\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

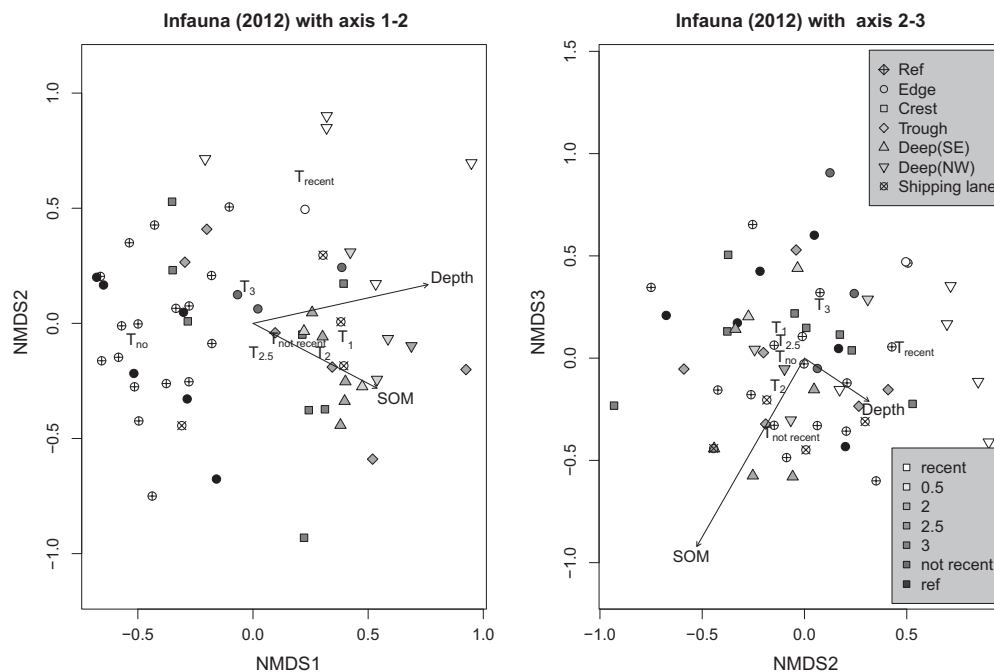
\*\*\*  $p < 0.001$ .

Atlantic jackknife clam (*Ensis directus*), mud shrimp (*Pestarella tyrrhena*), *Ensis* sp. and swimming crab (*Liocarcinus holsatus*). At the crests of the parallel sandbar, bristleworm *Notomastus latericeus*, white furrow shell (*Abra alba*) and bean-like tellin (*Tellina fabula*) dominated in terms of weight. At the crest of the oblique sandbar, infauna was dominated by white piddock (*Barnea candida*), unidentified bivalves, white furrow shell, the sea potato and *Notomastus latericeus*. Infauna in the troughs of sandbars and the deep areas was dominated by Tellinids and *A. alba*. In the SE trough of the parallel sandbar, boxcore failed due to a thick semi-fluid muddy layer on top of the sediment. The species composition in

the shipping lane area changed considerably between 2006–2008 and 2012. The most abundant species of 2006–2008 were: *Owenia fusiformis* (2010.7 ind.  $m^{-2}$ ), *A. alba* (862.4 ind.  $m^{-2}$ ), *Lanice conchilega* (610.5 ind.  $m^{-2}$ ), *Tellinoidea* spp. (381.1 ind.  $m^{-2}$ ), *Heteromastus filiformis* (311.7 ind.  $m^{-2}$ ), *Caprellidae* spp. (192.2 ind.  $m^{-2}$ ), *Actiniaria* spp. (271.3 ind.  $m^{-2}$ ) (de Jong et al., in press). In 2012, infauna was dominated by *Heteromastus filiformis* (516.7 ind.  $m^{-2}$ ), *Tellinoidea* sp. (383.3 ind.  $m^{-2}$ ) and *A. alba* (200 ind.  $m^{-2}$ ). Due to differences in sample size in 2012, a statistical analysis was not possible. Species composition differed for all years amongst location and time after cessation of sand extraction



**Fig. 9.** Smoothing functions of GAMs. (a) Biomass boxcore (g AFDW m<sup>-2</sup>). (b) Species richness (n species boxcore<sup>-1</sup>).



**Fig. 10.** Dimensional ordination plots of 2012 with sites and significant correlations of continuous variables depth and SOM and categorical variable time after cessation of sand extraction. The left panel is a ordination with axis 1 and 2, and the left panel axis 2 and 3.

(ADONIS,  $p < 0.01$ ). The infaunal composition at the crest of the parallel sandbar differed significantly from the deep SE and NW whereas the trough of the parallel sandbar was not significantly different. Due to the parallel sandbar, significant differences in species composition occurred (Table 4). *A. alba* was the most abundant species at the infaunal biomass hotspots reaching values of 118.87 g AFDW m<sup>-2</sup>. One location on the crest of the oblique sandbar with a biomass value of 129.08 g AFDW m<sup>-2</sup> was dominated by white piddock (*Barnea candida*) (72.79 g AFDW m<sup>-2</sup>) and American piddock (*Petricolaria pholadiformis*) (4.35 g AFDW m<sup>-2</sup>) which both feed on old wood and peat fragments. Infaunal data is summarized in Fig. 16 upper panel.

### 3.2.2. Infaunal nMDS ordination and correlations with environmental variables

The stress value of the 2-dimensional ordination of 2012 was 0.25. Therefore, 3-D ordination was performed and stress was

decreased to 0.17. In 2012, 39.3% of the variance is explained by depth, SOM and time after the cessation of sand extraction (Fig. 10). The reference locations and the locations from the edge are clustered on the left side of the ordination. The locations from the south-eastern and north-western deep area, the troughs and crests group in the right part of the ordination and are strongly correlated to increased SOM levels. The samples from the deep north-western part of the extraction site, with recent sand extraction are separated from the south-eastern samples. Three of the four samples from the shipping lane area grouped in the same area as the south-eastern samples while one sample was more similar to the reference area. Infaunal samples from the troughs of the sandbars are located in the right part of the ordination. *Abra alba*, *Actiniaria* and *Owenia fusiformis* grouped together. Piddocks are located in the lowest part of the 2-dimensional ordination, due to the high abundance on the crest of the oblique sandbar (Fig. 11). *Tellina fabula* is more located in the middle due to higher abundance at the



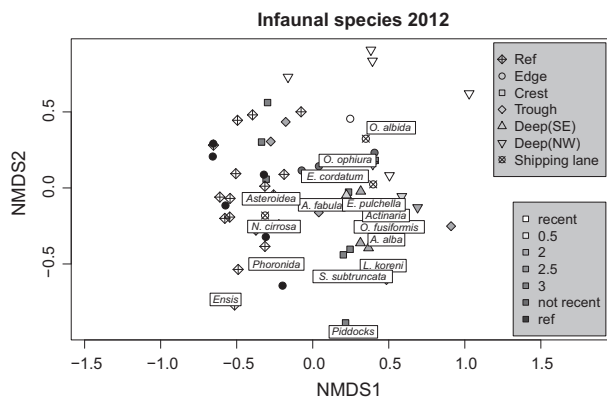


Fig. 11. 2-Dimensional ordination plot of 2012 (first 2 axis) with most abundant or characteristic species.

crest of the parallel sand bar. *Asteroidea* spp., *N. cirrosa* and *Phoronida* are found in the reference area and the edge of the extraction site.

### 3.3. Epifaunal data

Highest species richness (14.3 species per haul) was observed in the shipping lane whereas for the reference area on average, 7.5 species per haul were observed (Appendix VII, Fig. 12). The species

richness in the shipping was significantly higher compared to the reference area, edge and deep NW part of the borrow pit (Table 5).

The average epifaunal biomass in 2012 in deep SE parts was 32.8, 18.83 at the shipping lane area and 6.6 g WW m<sup>-2</sup> for the reference area (Appendix VII). Highest epifaunal biomass values (601.4 g WW m<sup>-2</sup>) was detected in 2012 in the parallel trough mainly due to high wet weight values of *Ophiura ophiura* (483.7 g WW m<sup>-2</sup>), *Ophiura albida* (46.3 g WW m<sup>-2</sup>) and *A. alba* (44.9 g WW m<sup>-2</sup>). In 2012, the trough of the parallel sandbar harboured a significantly higher epifaunal biomass compared to the reference area and edge of the borrow pit (Table 6).

Epifaunal species richness is significantly correlated with time after extraction, which explained 51.6% of the total deviance (Appendix V, Table 3). Epifaunal biomass showed a significant correlation with mud (peaked at 30 vol%), mean salinity and time after sand cessation and explained 53.2% of the total deviance (Fig. 13, Appendix V, Table 4).

#### 3.3.1. Epifaunal species composition

In total, 26 species were detected with the bottom sledge in the reference area and borrow pit. Epifauna in the exclusion area was numerically dominated by brittlestar (*Ophiura ophiura*) and cut trough shell (*Spisula subtruncata*). The edge of the extraction area is numerically dominated by *O. ophiura* and bean-like tellin (*Tellina fabula*) and biomass was 8.0 g WW m<sup>-2</sup> with nine species. The epifauna at the crest of the parallel sandbar was numerically dominated by white furrow shell (*Abra alba*), *Ophiura albida*, common necklace shell (*Euspira nitida*), *O. ophiura* and netted dog

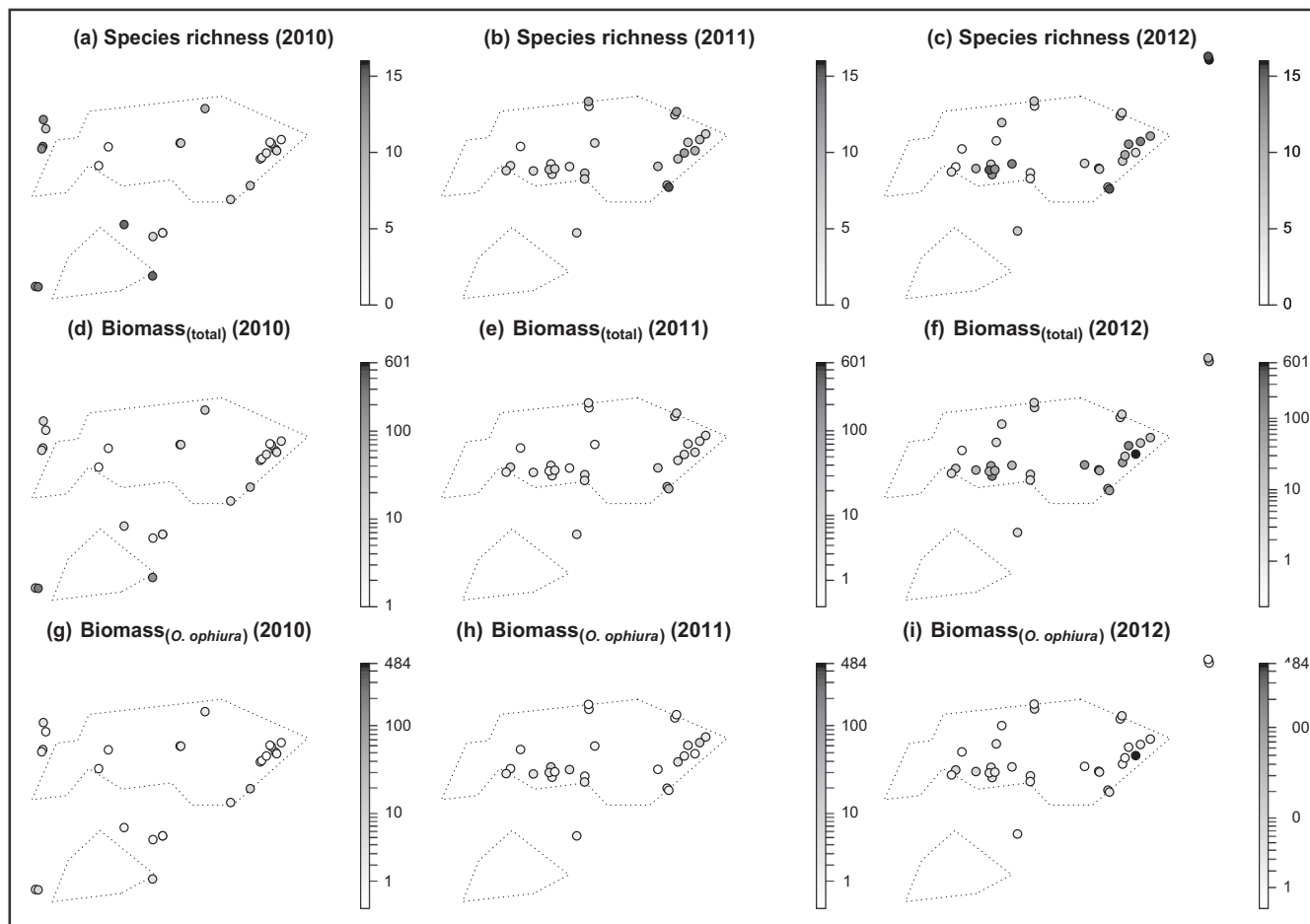


Fig. 12. Biological parameters of bottom sledge sampling for 2010, 2011 and 2012. (a–c) Species richness (n species boxcore<sup>-1</sup>), (d–f) total biomass boxcore on a logarithmic scale (g WW m<sup>-2</sup>) and (g–i) biomass *O. ophiura* boxcore on a logarithmic scale (g WW m<sup>-2</sup>).

**Table 5**

Differences in epifaunal species richness in 2012 between locations, based on ANOVA followed by TukeyHSD multi pairwise comparisons.

	Ref	Edge	Crest par	Trough par	Crest oblique	Trough oblique	Deep SE	Deep NW	Shipping lane
Ref	–								*
Edge		–							**
Crest par			–						
Trough par				–					
Crest oblique					–				
Trough oblique						–			
Deep SE							–		
Deep NW								–	**
Shipping lane									–

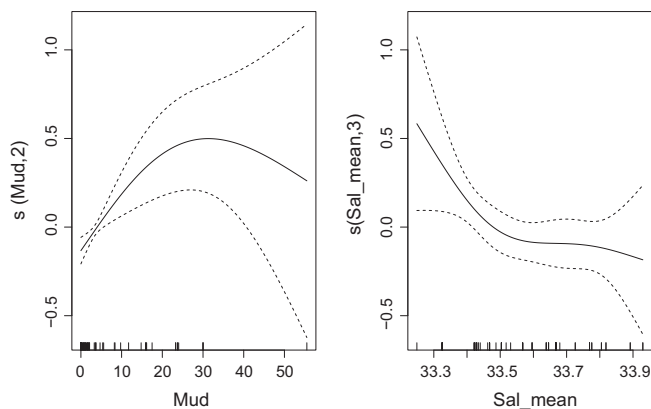
Significance codes:

\*  $p < 0.05$ .\*\*  $p < 0.01$ .\*\*\*  $p < 0.001$ .**Table 6**

Differences in (log transformed) epifaunal wet weight in 2012 between locations, based on ANOVA followed by TukeyHSD multi pairwise comparisons of log transformed mean values.

	Ref	Edge	Crest par	Trough par	Crest oblique	Trough oblique	Deep SE	Deep NW	Shipping lane
Ref	–			*					
Edge		–		*					
Crest par			–						
Trough par				–				**	
Crest oblique					–				
Trough oblique						–		*	
Deep SE							–	*	
Deep NW								–	
Shipping lane									–

Significance codes:

\*  $p < 0.05$ .\*\*  $p < 0.01$ .\*\*\*  $p < 0.001$ .**Fig. 13.** Smoothing functions of GAMs. Epifaunal biomass (g WW m<sup>-2</sup>).

whelk (*Nassarius nitidus*) with a wet weight of 7.6 g WW m<sup>-2</sup> and 10 species per haul. *Abra alba*, *Tellina fabula*, *O. ophiura*, elliptic cut trough shell (*Spisula elliptica*), *Nassarius nitidus* numerically dominated epifauna on the crest of the oblique sandbar, wet weight was 17.5 g WW m<sup>-2</sup> with 12.5 species per haul. Epifauna at the trough of the parallel sandbar was dominated by *O. ophiura*, *Abra alba*, *O. albida* and *Euspira nitida* with a wet weight of 175.4 g WW m<sup>-2</sup> and 8.3 species per haul. *Abra alba*, *O. ophiura* and *Tellina fabula* dominated the trough of the oblique sandbar with a wet weight of 31.0 g WW m<sup>-2</sup> and 9.8 species per haul. White piddock (*Barnea candida*) which was detected with the box-corer on the crest of the oblique sandbar was not detected with the bottom sled but the biomass of epifauna was also higher. *A. alba*,

*Tellina fabula*, hermit crab (*Pagurus bernhardus*), *O. ophiura* and *Nassarius nitidus* dominated the deep south-eastern part and wet weight was on average 32.8 g WW m<sup>-2</sup> and 7.7 species per haul. Epifauna of the shipping lane area in 2006–2008 was numerically dominated by *Abra alba* (143.9 ind. m<sup>-2</sup>), anemones *Actiniaria* sp. (88.8 ind. m<sup>-2</sup>), *O. albida* (40.7 ind. m<sup>-2</sup>), pullet carpet shell (*Venerupis senegalensis*) (5.9 ind. m<sup>-2</sup>) and *Nassarius reticulatus* (3 ind. m<sup>-2</sup>). In 2012, *Abra alba* dominated epifauna of the shipping lane area and wet weight decreased from values above 100 g in 2006 and 2008 to 18.8 g WW m<sup>-2</sup> in 2012.

The species composition of epifauna inside the extraction site and shipping lane area differed significantly from the edge of the extraction site and the reference area (Tables 5 and 7). The species composition of the oblique crest differed significantly (ADONIS < 0.05) from the shipping lane area (Table 7).

### 3.3.2. Epifaunal nMDS ordination and correlations with environmental variables

Stress values for the 2-dimensional ordinations of epifauna in 2012 was 0.08, which is very satisfactory. For the last year, time after the cessation of sand extraction, the fraction very fine sand and mean and maximum bed shear stress explained 62.9% of the variance (Fig. 14). Reference samples are located in the right part of the ordination, while the samples from the shipping lane areas ended in the upper left part. Samples from areas with recent extraction are similar to the reference locations. One sample collected in the trough of the parallel sandbar in 2012 ended at the left side of the ordination, and is characterised by the highest epifaunal biomass, 601.36 g WW m<sup>-2</sup> and *O. ophiura* as most abundant species, 483.67 g WW m<sup>-2</sup>. Epifaunal data is summarized in Fig. 16 lower panel.

Table 7

Differences in epifaunal species composition in 2012 between locations (permutational multivariate analysis of variance using distance matrices (ADONIS)).

	Ref	Edge	Crest par	Trough par	Crest oblique	Trough oblique	Deep SE	Deep NW	Shipping lane
Ref	–		*	**	*	*	**		**
Edge		–	.	*	.	**	*	.	*
Crest par			–					.	.
Trough par				–				.	.
Crest oblique					–				*
Trough oblique						–			
Deep SE							–		
Deep NW								–	
Shipping lane									–

Significance codes:

\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

\*\*\*  $p < 0.001$ .

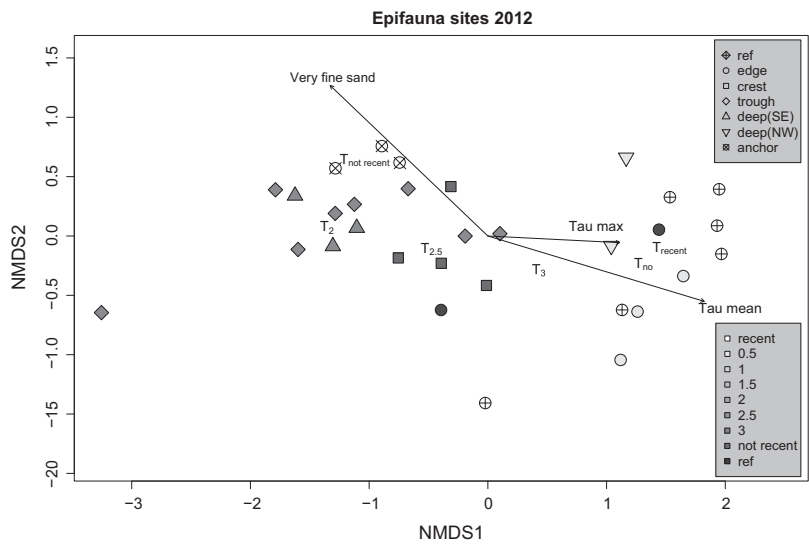


Fig. 14. 2-Dimensional ordination plot of epifauna in 2012 with sites and significant correlations of continuous variables very fine sand, mean and maximum bed shear stress and categorical variable time after cessation of sand extraction.

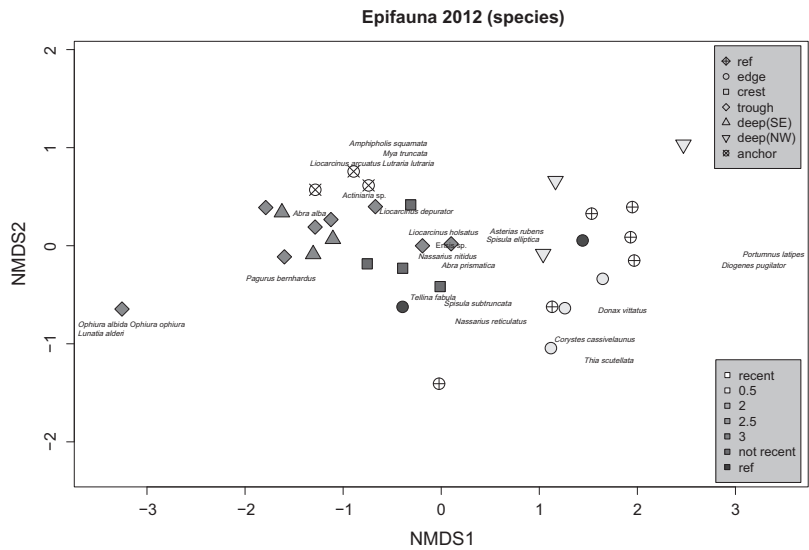


Fig. 15. 2-Dimensional ordination plot of 2012 most abundant or characteristic species.

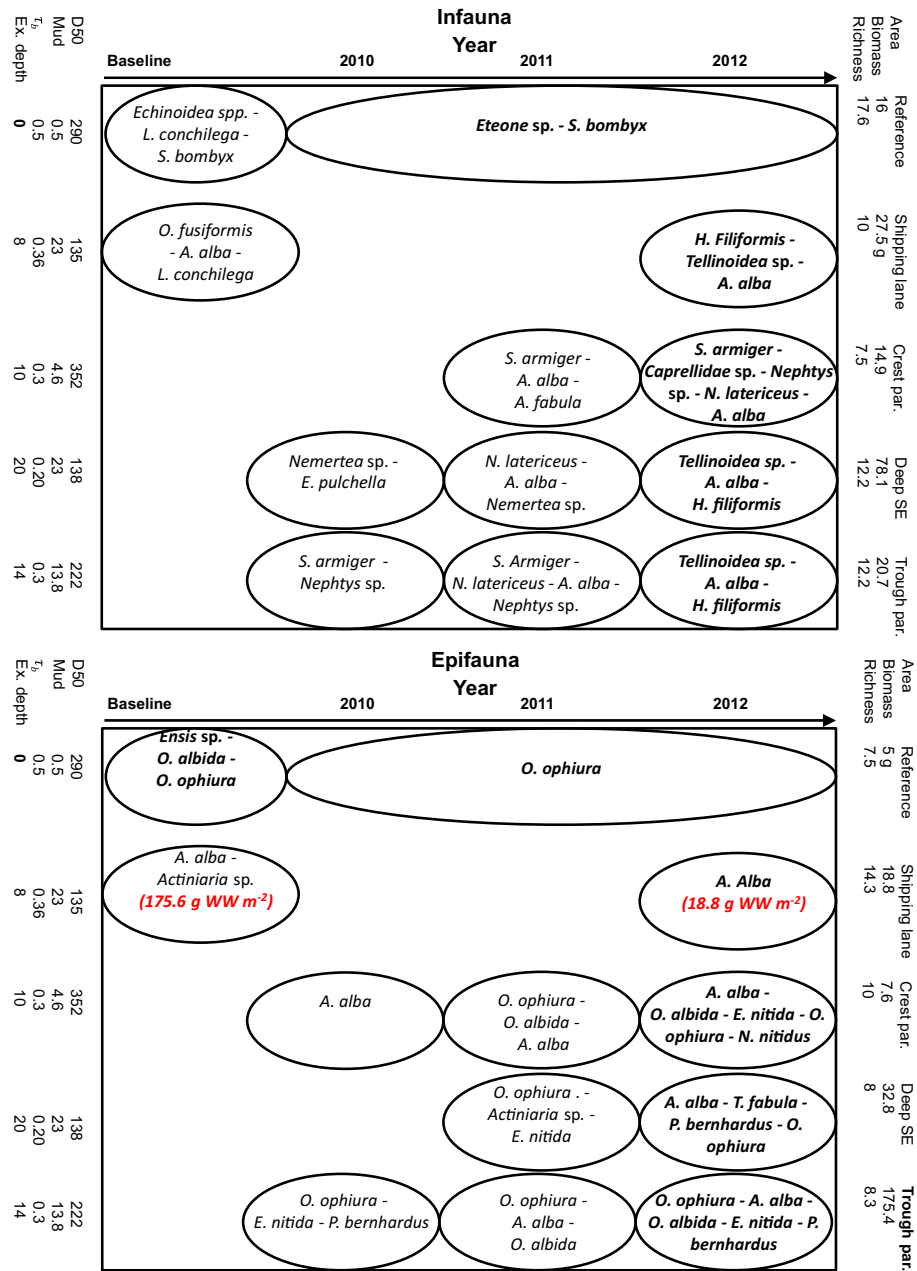


Fig. 16. Summary of infaunal and epifaunal species composition and biomass in relation to D<sub>50</sub>, mud content, mean near-bed shear stress ( $\tau_b$ ) and excavation depth.

The samples collected at the shipping lane area are characterised by more species compared to the samples from the troughs and south-eastern deep parts which are dominated by *Abra alba* (Fig. 15). The samples from the crest grouped in the middle of the ordination and harboured Tellinids such as *Tellina fabula* and *Abra prismatica* which are commonly found in less fine sediments (Degraer et al., 2006). Samples from the reference locations grouped in the right part of the ordination and are dominated by *Ophiura ophiura* and *Spisula subtruncata*.

#### 4. Discussion

##### 4.1. Macrozoobenthos in the Maasvlakte 2 borrow pit

Two years after sand extraction, macrozoobenthic species composition and biomass differed between the reference area and the deepest parts of the borrow pits. White furrow shell (*Abra alba*)

became the most abundant species in the borrow pit. Macrozoobenthic biomass significantly increased fivefold in the deepest areas 2 years after the cessation of sand extraction. Species richness in the deepest areas is slightly lower than in reference areas. In the reference area, macrozoobenthos consists of a broad array of organisms such as worms, brittlestars, sea urchins and shellfish. For shallow sand extraction, recovery time was 4–6 years with species assemblage, species richness and biomass returning to pre-dredged status (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001; Boyd et al., 2005).

##### 4.2. Macrozoobenthos in the Euromaasgeul shipping lane

The conditions in the Euromaasgeul shipping lane area are similar to the large-scale and deep borrow pit, both in biotic and abiotic characteristics and may give insight in the long-term development of macrozoobenthos in heavily impacted dredged

areas. Species composition in the shipping lane area changed considerably between 2006–2008 and 2012. The most abundant infaunal species of 2006–2008 were: *Owenia fusiformis*, *A. alba* and *Lanice conchilega* (de Jong et al., in press). In 2012, infauna was dominated by *Heteromastus filiformis*, *Tellinoidea* and *A. alba*. *L. conchilega* and *O. fusiformis* were not found in the entire research area in 2012. In 2006 and 2008, also strong differences in abundance of *Lanice conchilega* and *Owenia fusiformis* were detected which may be related to variation in winter temperature (de Jong et al., in press). Infaunal species richness in the shipping lane in 2006, 2008 and 2012 was higher than in the reference areas. Comparing species richness in 2012 in the shipping lane with baseline data research is not possible due to the decrease in sampled surface. In 2012, species richness in the shipping lane (10 species per boxcore) is higher than in the reference areas (7.4 species per boxcore) and infauna appears to be more diverse. Infaunal biomass reached the highest levels in 2012, 27.5 compared to 6.4 and 9.9 g AFDW m<sup>-2</sup> in 2006 and 2008. Epifauna in the shipping lane in 2012 was dominated by *A. alba* dominated in contrast to the more diverse species composition in 2006 and 2008 (*A. alba*, anemones, *Ophiura albida*, *Venerupis senegalensis* and *Nassarius reticulatus*). Biomass and species richness decreased considerably in 2012, which may be a sign of disturbance from the surrounding shipping lane with some minor maintenance dredging (in the period between boxcore sampling 23–25 April and bottom dredge sampling 5–7 June 2012). There is a possibility that instead of maintenance dredging differences in water depth were levelled by moving crests from ripples and small sand waves in the troughs.

#### 4.3. Natural deep seafloor crater

30 years after the formation of a deep natural seafloor crater, infaunal species composition and biomass still differed strongly from the surrounding area (Thatje et al., 1999). Maximum infaunal (fresh weight) biomass inside the crater was 487 g WW m<sup>-2</sup> due to the frequent occurrence of the sea potato (*Echinocardium cordatum*), which accounted for about 82% of the total biomass. *Amphiura filiformis* and *Ophiura* sp. fluctuated between and within years and *A. alba* was detected but not dominant in terms of abundance or biomass. In the borrow pit, a maximum epifaunal biomass value of 601.4 g WW m<sup>-2</sup> was detected in the trough of the parallel sandbar, mainly due to high wet weight values of *Ophiura ophiura* (483.7 g WW m<sup>-2</sup>), *Ophiura albida* (46.3 g WW m<sup>-2</sup>) and *A. alba* (44.9 g WW m<sup>-2</sup>). The very fragile *E. cordatum*, however, is severely damaged in the epifaunal sampling procedure with the bottom sledge and gets uncountable so biomass values may be underestimated. In the deep SE, *E. cordatum* accounted for 11.8% and *A. alba* for 67.2% of the total infaunal AFDW biomass (collected with the boxcore). In the trough of the oblique sandbar, *E. cordatum* accounted for 50.2% and *A. alba* for 28.3%. In the trough of the parallel sand bar, no *E. cordatum* was present and *A. alba* accounted for 70.0%. In the shipping lane, *E. cordatum* accounted for 61.1% and *A. alba* for 19.3% of the total biomass. Biomass of infaunal macrozoobenthos in the crater, shipping lane and troughs of the oblique sandbar is dominated by *E. cordatum*, whereas being absent through of the parallel sandbar.

#### 4.4. Ecological landscaping

Infaunal species composition at the crest of the parallel sandbar differed significantly from the deep SE and NW, whereas the trough of the parallel sandbar was not significantly different. The crest of the parallel is characterised by the highest species richness, high epifaunal species richness, a higher abundance of bean-like tellin (*Tellina fabula*) and the sediment is becoming coarser in time. The species composition of epifauna inside the extraction site and

shipping lane area differed significantly from the edge of the extraction site and the reference area. Epifaunal composition at the crest of the oblique sandbar differed significantly from the shipping lane area with a higher abundance of bean-like tellin (*Tellina fabula*). This is an indication of the feasibility and effectivity of ecological landscaping. One sample on the crest of the oblique sand bar with a biomass value of 129.08 g AFDW m<sup>-2</sup> was dominated by white piddock (*Barnea candida*) which both feed on littoral fossilised peat and wood fragments. The presence of this species rich and productive assemblage is however coincidental and not the result of landscaping. Little information was found regarding the characteristics of this assemblage, longevity presumably depends on the stock of peat and wood fragments (Budd, 2008).

#### 4.5. Sedimentation rate and backfilling in the Maasvlakte 2 borrow pit

Between 2010 and 2011, we only observed small differences in water depth but between 2011 and 2012 sedimentation rate in the troughs of the parallel sandbar increased considerably in the southern trough. In the deep SE area 0.18 m y<sup>-1</sup> of sediment settled whereas on the crest of the parallel sandbar 0.27 m y<sup>-1</sup> settled.

A highly similar sedimentation rate was found inside a natural seafloor crater, sedimentation rates of 0.50 m yr<sup>-1</sup> were encountered and mud content increased from 5% to 40% (Thatje et al., 1999). In a morphological model analysis, a sedimentation rate of 5 m non-cohesive sediment in the first 10 year is predicted in the SE area of the borrow pit (Klein and van den Boomgaard, 2013; Stolk, 2014). The PUTMOR study, however, revealed that 20,000 m<sup>3</sup> of fines settled in one year which equals 0.03 m yr<sup>-1</sup> (Boers, 2005).

Backfilling of Maasvlakte 2 borrow pit may take decades or longer, Klein and van den Boomgaard (2013) predict sedimentation of 5 m sediment in 30 years. The morphological study revealed a higher sedimentation rate in the southern parts of the borrow pit due to the asymmetry of the tide. After 30 years, water depth in the north-western part of the northern borrow pit will be around 40 m. The observation of the decrease in median grain size and increase in mud values in the borrow pit may be originating from the exclusion area transported as sediment load. When sand from the exclusion area is entering the borrow pit, smaller sediment particles are mobilised first (suspended load), followed by sediment particles with increasing grain size (bed load). The large observed spatial and temporal differences in sedimentation rate in the borrow pit may be originating from a combination of effects. During storms, settled particles may resuspend, redistribute and settle again during more calm situations. Under influence of the Coriolis effect, a higher sedimentation rate may be expected in eastern direction of the borrow pit. The discrepancy between the modelled sedimentation rate and observed elevated sedimentation rates in the troughs of the parallel sandbar may be because only non-cohesive sediment is taken into account.

#### 4.6. Organic matter enrichment and species richness in the Maasvlakte 2 borrow pit

Hyland et al. (2005) suggested that risks of reduced infaunal species richness from organic loading and other associated stressors in sediments should be relatively low at total organic carbon (TOC) concentrations less than about 10 mg g<sup>-1</sup>, high at concentrations larger than 35 mg g<sup>-1</sup>, and intermediate at concentrations in between. Total organic carbon (TOC) was measured with a CHN analyser and some samples as organic matter content by mass loss on ignition (MLOI), these values were reduced by a factor of 3 to convert to TOC and correct for the overestimation of organic carbon associated with the MLOI methodology (Leong and Tanner,



1999). In 2012, SOM contents were in the range of decreasing species richness. In the deep SE part and at the top of the oblique sandbar values were 9.6% (TOC: 32 mg g<sup>-1</sup>) and 9.8% (TOC: 33 mg g<sup>-1</sup>) respectively. Our GAM analysis however revealed no decrease in infaunal species richness in the region 10–35 mg g<sup>-1</sup>; species richness is best explained by D<sub>50</sub> and water depth. A similar response between species richness with D<sub>50</sub> and water depth was found for the baseline data (de Jong et al., in press). Epifaunal species richness in the borrow pit only correlated with time after cessation of sand extraction. In the baseline study, epifaunal species richness showed a negative correlation with mean bed shear stress and peaked at a value of 0.4 N m<sup>-2</sup>, peaked at a water depth of 20 m, at 200 µm and at a maximum shear stress of 2.25 N m<sup>-2</sup>. Infaunal biomass peaked at 200 µm.

#### 4.7. Epifauna shifting from *A. alba* to *Ophiura* spp. in the trough of the parallel sandbar

Epifauna in the SE trough of the parallel sandbar strongly differed in species composition and biomass compared to other deep parts with a dominance of *Ophiura ophiura*, *Ophiura albida* and some *A. alba* and a biomass value of 601.4 g WW m<sup>-2</sup> instead of epifauna dominated by *A. alba* and an average biomass of 32.8 g WW m<sup>-2</sup>. Unfortunately, boxcore sampling failed in the SE trough of the parallel sandbar presumably due to a thick layer of semi-fluid muddy layer on top of the sediment. The overabundance of ophiuroids may be related to factors such as sedimentation rate or increase in sediment organic matter, biological activity, water depth and changes in water circulation. These factors may also lower dissolved oxygen (DO) levels (Eldridge and Roelke, 2011).

#### 4.8. Limitations of present study and recommendations

To increase infaunal sample size in 2012, subsampling of the samples was applied. Due to smaller sample volumes, species richness may be biased. Regarding biomass and species composition, large deviations are not likely. Our conclusion are based on short-term results and continuing research is recommend to get insight in medium- or long-term results. Sedimentation rate and oxygen concentration were not modelled in our hydrodynamic model because first model improvements were needed regarding appropriate nesting. The horizontal grid size for the Maasvlakte 2 extraction site was decreased from approximately 100 by 100 m in the first assessment to 45 m by 38 m in the improved model. The smaller grid enabled determining differences in bed shear stress and near bed salinity around the landscaped sandbars. For the present Maasvlakte 2 borrow pit we recommend ongoing monitoring including sedimentation rate and oxygen measurements since significant changes occurred in the deepest parts of the borrow pit. For future deep and large-scale borrow pits it is recommended to model oxygen concentration and sedimentation rates of cohesive and non-cohesive material in the environmental impact assessments of future borrow pits. In our study, macrozoobenthos was analysed with a boxcorer and bottom sledge. The advantage of a boxcorer is the combination of infauna and sediment sampling. Collecting information about the occurrence of *Ensis* spp. is only possible with the bottom sledge due to their escape behaviour. On the other hand, the fragile *Echinocardium cordatum* is severely damaged in the epifaunal sampling procedure with the bottom sledge and gets undistinguishable. Numerous studies are based on data derived with a boxcorer whereas studies based on bottom sledge samples are scarce. Furthermore, although we found the same amount of in- and epifaunal assemblages, more variation was determined with the boxcorer, which was also observed by Stronkhorst et al. (2003). To safeguard a full coverage

of data, a combination of boxcore and bottom sledge data is recommended.

## 5. Conclusion

This is the first report on the short-term impact on macrozoobenthos in a deep and large-scale borrow pit. Contrary to shallow sand extraction, macrozoobenthic biomass significantly increased fivefold in the deepest areas 2 years after the cessation of sand extraction. Furthermore, species composition changed significantly and white furrow shell (*Abra alba*) became the most abundant species. Macrozoobenthic species composition and biomass correlates with time after cessation of sand extraction, sediment and hydrographical characteristics. Next to changes in macrozoobenthos, sediment characteristics also significantly changed in the deepest parts. Ecosystem-based landscaped sand bars were found to be effective in significantly influencing sediment characteristics and macrozoobenthic assemblage. Significant changes in epifauna occurred in deepest parts in 2012 and coincided with the highest sedimentation rate. In the case of shallow sand extraction in the Netherlands, macrozoobenthos returns to pre-dredged conditions within 4–6 years. Combining the results of macrozoobenthic species composition in the borrow pit, shipping lane area and natural deep seafloor crater with sedimentation rate and backfilling time leads to the conclusion that benthos is presumably not returning to pre-dredged conditions within decades. We recommend continuing monitoring including sedimentation rate and oxygen measurements since significant changes occurred in the deepest parts of the borrow pit.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.marpolbul.2015.06.002>.

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