Estuarine, Coastal and Shelf Science 146 (2014) 83–94

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Impact on demersal fish of a large-scale and deep sand extraction site with ecosystem-based landscaped sandbars

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ARTICLE INFO

Article history:
Received 2 December 2013
Accepted 26 May 2014
Available online 3 June 2014

Keywords:
infauna
epifauna
sediment
ground fish
sand mining
North Sea

ABSTRACT

For the seaward harbour extension of the Port of Rotterdam in the Netherlands, approximately 220 million m^3 sand was extracted between 2009 and 2013. In order to decrease the surface area of direct impact, the authorities permitted deep sand extraction, down to 20 m below the seabed. Biological and physical impacts of large-scale and deep sand extraction are still being investigated and largely unknown. For this reason, we investigated the colonization of demersal fish in a deep sand extraction site. Two sandbars were artificially created by selective dredging, copying naturally occurring meso-scale bedforms to increase habitat heterogeneity and increasing post-dredging benthic and demersal fish species richness and biomass. Significant differences in demersal fish species assemblages in the sand extraction site were associated with variables such as water depth, median grain size, fraction of very fine sand, biomass of white furrow shell (*Abra alba*) and time after the cessation of sand extraction. Large quantities of undigested crushed white furrow shell fragments were found in all stomachs and intestines of plaice (*Pleuronectes platessa*), indicating that it is an important prey item. One and two years after cessation, a significant 20-fold increase in demersal fish biomass was observed in deep parts of the extraction site. In the troughs of a landscaped sandbar however, a significant drop in biomass down to reference levels and a significant change in species assemblage was observed two years after cessation. The fish assemblage at the crests of the sandbars differed significantly from the troughs with tub gurnard (*Chelidonichthys lucerna*) being a Dufrêne-Legendre indicator species of the crests. This is a first indication of the applicability of landscaping techniques to induce heterogeneity of the seabed although it remains difficult to draw a strong conclusion due the lack of replication in the experiment. A new ecological equilibrium is not reached after 2 years since biotic and abiotic variables are still adapting. To understand the final impact of deep and large-scale sand extraction on demersal fish, we recommend monitoring for a longer period, at least for a period of six years or even longer.

1. Introduction

The demand for marine sand in the Netherlands and worldwide is strongly increasing. In the Netherlands, approximately 24 million m^3 sand is used annually for coastal nourishments and for construction. An increase of annual coastline nourishments of up to 40-85 million m^3 to counteract effects of future sea level rise is expected (Deltacommissie, 2008). For the seaward expansion of the Port of Rotterdam (Maasvlakte 2) approximately 220 million m^3 of sand was extracted between 2009 and 2013 with an average extraction depth of 20 m. In general, only shallow sand extraction down to 2 m below the seabed and beyond the 20 m isobath is allowed in the Netherlands (IDON, 2005; V&W, 2004). For Maasvlakte 2 though, the Dutch government permitted sand extraction deeper than the common 2 m, primarily to reduce the surface area of direct impact.

Fish assemblages at North Sea scale are mainly influenced by bottom water temperature, bottom water salinity, tidal stress and water depth (Callaway et al., 2002; Reiss et al., 2010). Furthermore, fish assemblages are linked to biotic and abiotic habitat characteristics and meso-scale bedforms (Ellis et al., 2011; Sell and Kröncke, 2013). Ellis et al. (2011) found that species richness of infauna, epifauna and fish was larger in the silty troughs of sandbanks off the coast of the UK than on the crests.

Large-scale sand extraction was shown to have a negative impact on fish in the Yellow Sea (Hwang et al., 2013), a decline of more than

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http://dx.doi.org/10.1016/j.ecss.2014.05.029
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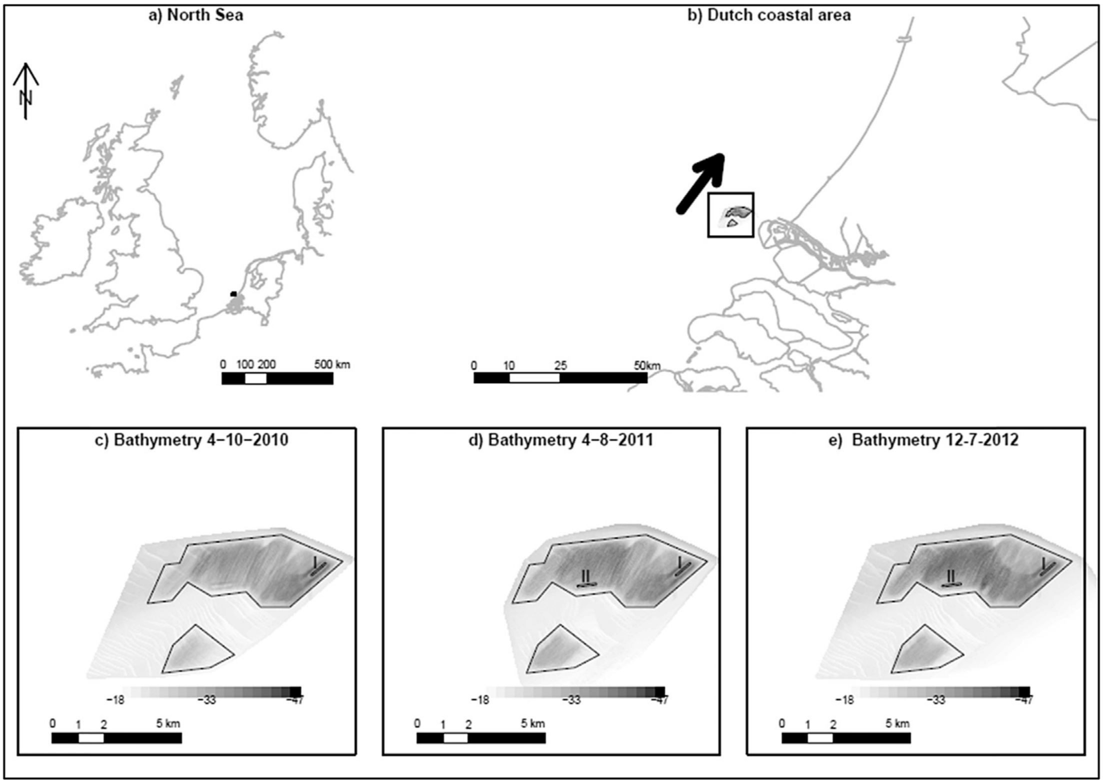

Fig. 1. a) North Sea, b) Dutch coastal area with Maasvlakte 2 sand extraction site and harbour extension in front of the Port of Rotterdam, the arrow denotes the residual tidal current, c) bathymetry of sand extraction site (date 4 October 2010) with one landscaped sandbar parallel to the tidal current (I). d-e) Sand extraction site (dates 4 August 2011 and 12 July 2012) with two landscaped sandbars, one parallel (I) and one oblique to the tidal current (II). Data were derived from bathymetric multibeam surveys of the dredging companies.

70% of the total number of fish and the number of species (Son and Han, 2007) and direct and indirect damages to commercial fisheries were observed (Kim and Grigalunas, 2009). Since the start of aggregate extraction in the Eastern Channel Region, the majority of fish species have shown marked reductions in abundance and draghead entrainment was identified as a possible cause (Drabble, 2012). On the other hand, aggregate extraction may also lead to new habitats and may favour macrozoobenthos and fish (Desprez, 2000).

Ecosystem-based landscaping techniques are not commonly used to reduce the impact of sand extraction. In the UK, gravel-seeding techniques were tested to restore the seabed after gravel extraction (Cooper et al., 2011). In the Maasvlakte 2 sand extraction site, two sandbars were artificially created by selective dredging, copying naturally occurring meso-scale bedforms to increase habitat heterogeneity and thereby possibly increasing post-dredging benthic and demersal fish species richness and biomass (van Dalfsen and Aarninkhof, 2009; van Raalte et al., 2007). In this study, we test the hypothesis that deep and large-scale sand extraction and ecosystem-based landscaping approaches will lead to differences in fish assemblage and we are aiming to answer the following questions:

- Are there significant differences in fish species assemblage between reference area and sand extraction site, and within the extraction site?
- Are there significant temporal differences in fish assemblage, macrozoobenthos and environmental variables during the monitoring campaign?
- Which environmental variables determine the differences?
- Are ecosystem-based landscaping techniques landscaping techniques feasible and effective in influencing fish assemblages?

2. Methods

2.1. Study area

The Maasvlakte 2 sand extraction site is situated in front of the Port of Rotterdam, the Netherlands, outside the 20 m depth contour (Fig. 1). The sand extraction site is 2 km long, 6 km wide with an average extraction depth of 20 m at an initial water depth of approximately 20 m below average sea level. Approximately 220 million m^3 sand was extracted between 2009 and 2013, of which 170 million m^3 in the first two years (Borst and Vellinga, 2012).

Two sandbars were created in the extraction site to investigate the applicability of ecosystem-based landscaping in sand extraction projects (Figs. 1 and 2). One sandbar (I), parallel to the tidal current, was left behind in the seabed in spring 2010. This parallel sandbar has a length of 700 m, a width at the crest of 70 m and slopes of 140 m length (Fig. 2). The crest of the sandbar is located at a water depth of 30 m and the troughs are more than 40 m deep. In 2011, the second sandbar (II) was completed with an orientation oblique to the tidal current. 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 sand extraction site. The volume of each sandbar is approximately 1.25 million m^3 with slopes of 1:7–1:10.

During our surveys in 2011 and 2012, two trailer suction hopper dredgers were active in the centre of the sand extraction site, extracting approximately 2 million m^3 marine sand per week. The

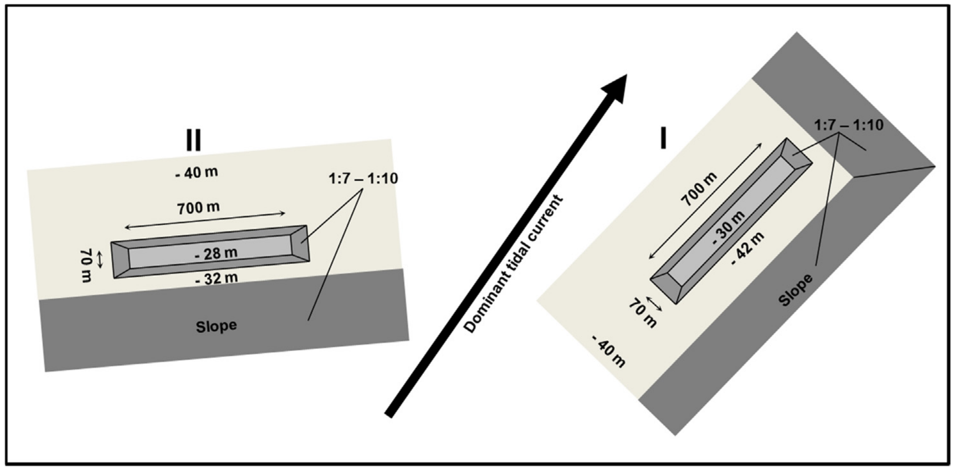

Fig. 2. Schematic representation of the ecosystem-based landscaped sandbars, left: sandbar II, oblique to the tidal current and right: sandbar I, parallel to the tidal current.

water depth increased from 33 m to approximately 40 m (Fig. 1) but the areas near the landscaped sandbars remained un-dredged after completion.

2.2. Fishing methods

A commercial fishing vessel was used, the Jan Maria, GO 29, with a length of 23 m, less than 300 horsepower and equipped with a standard commercial 4.5 m beam trawl. The beam trawl was equipped with four tickler chains, five flip-up ropes and diamond mesh size of 80 mm, which was applied at 4 knots fishing speed. The ship GPS-system logged the position of the sampling locations and water depth was determined with the ship's depth sounder. The maximum haul distance was one nautical mile in the reference area. Shorter hauls were planned within the sand extraction site; at the landscaped sandbars, hauls of approximately 700 m length were applied. Some of the hauls ended before the planned end-coordinates because of difficulties with fishing inside the sand extraction site due to large changes in seabed topography and sediment composition. In surrounding reference areas, fishing direction was generally perpendicular to the direction of naturally occurring seabed patters to ensure heterogeneous sampling of crests and troughs of sand waves. In the sand extraction site, fishing direction was generally parallel to the seabed structures to enable comparisons between the different locations. We sampled in the reference area, at the slope of the sand extraction site, two locations in the deep parts of the extraction site i.e. the south-east and north-west, in the troughs and at the crests of the sandbars (Fig. 3, Table 1).

Table 1
Sub locations and the number of fish samples.

Year	Reference	Slope	Crests	Troughs	Deep (SE)	Deep (NW)	Total
2010	4	–	1	2	1	1	9
2011	7	4	3	3	1	2	20
2012	4	2	3	4	2	2	17

The fish surveys were conducted on 14 July 2010, 27–29 July 2011 and 13–15 June 2012. In 2010, four reference fish samples and five sand extraction site samples were collected (Table 1, Fig. 2). In 2011, seven samples were collected in the reference area and thirteen samples in the extraction site. In 2012, for samples were collected in the reference area and thirteen in the extraction site.

Fish were sorted and length frequency distribution 'to the cm below' was determined. Abundance of fish was calculated by dividing the number of fish by the fishing surface area and expressed as number of fish per hectare (length of haul $\times$4.5 m $\times$ number of nets). Species richness of a haul (number of species haul^{-1}) was determined and published length–weight relationships (Coull et al., 1988; Robinson et al., 2010) were used to calculate the weight of fish (WW biomass, kg ha^{-1}). The average length of a fish species was calculated by dividing the sum of all multiplied size classes and their abundances with the total abundance.

In 2012, stomach and intestine contents of on average 10 specimens of plaice (*Pleuronectes platessa*), dab (*Limanda limanda*), and shorthorn sculpin (*Myoxocephalus scorpius*) were taken from

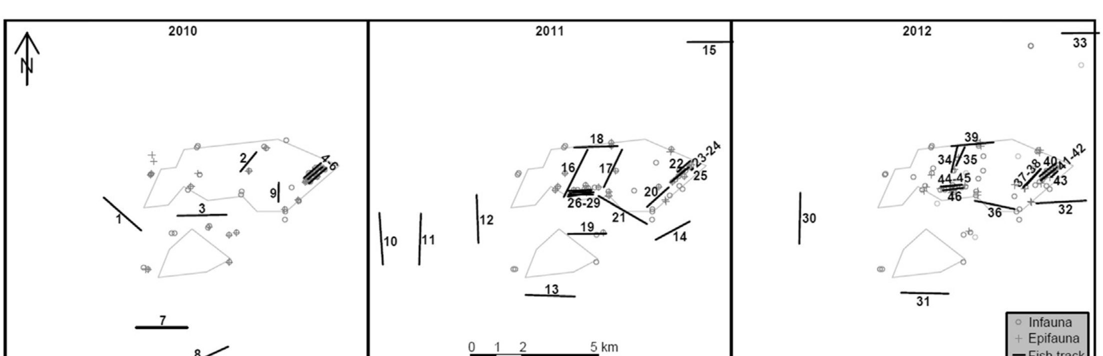

Fig. 3. Sand extraction site and reference area, fish hauls (in black) and infaunal and larger fauna samples in grey for 2010, 2011 and 2012. Sandbars were not drawn but are indicated with fish hauls.

the south-eastern deep part and troughs to obtain a rapid indication of fish diets.

2.3. Macrozoobenthos and sediment

The closest macrozoobenthos and sediment samples locations were selected to link with the fish hauls (Fig. 3). A boxcorer was used to sample macrobenthic infauna (>1 mm) and sediment, carried out by the Monitor Taskforce of the Royal Netherlands Institute for Sea Research (NIOZ) on 29–30 June 2010, 2–5 May 2011 and 23–25 April 2012. The boxcorer surface area was 0.0774 m^2 with a maximum penetration depth of 30 cm (Perdon and Kaag, 2006; Craeymeersch and Escaravage, 2010). Infaunal ash-free dry weight biomass (g AFDW m^{-2}) was analysed by means of loss on ignition (2 days at 80 °C followed by 2 h at 520 °C).

A bottom sledge was used to sample larger macrobenthic fauna (0.5–10 cm), executed by the Institute for Marine Resources & Ecosystem Studies (IMARES Wageningen UR) on 7–8 July 2010, 14–15 June 2011 and 6–7 June 2012. The sledge was equipped with a 5 mm mesh cage. On average, 15 m^2 was sampled during each sledge haul (~150 m length, 10 cm width and a maximum penetration depth of ~10 cm). Wet weight of larger fauna was directly measured (g WW m^{-2}).

Samples from the upper 5 cm were collected from untreated boxcorer samples and kept frozen until analysis. Sediment samples were freeze dried, homogenised and analysed with a Malvern Mastersizer 2000 particle size analyser. Percentile sediment grain size (D_{10}, D_{50}, D_{90}) and sediment grain size distribution among the different classes; clay (<4 μm), silt (4–63 μm), mud (<63 μm), very fine sand (63 μm-125 μm), fine sand (125 μm-250 μm), medium sand (250 μm-500 μm) and coarse sand (>500 μm) were measured as percentage of total volume. Sediment organic matter (SOM) was analysed in 2012 by means of loss on ignition as percentage of sediment mass (freeze-dried sediment samples were placed for 2 h at 520 °C).

2.4. Time after the cessation of sand extraction and fishing activity

Areas surrounding the extraction site are labelled as reference area (Ref), T_{recent} denotes sampling directly after sand extraction and for 1 and 2 year after the cessation, T_1 and T_2 are used. Fishing activity in- and outside the sand extraction site was derived from Vessel Monitoring through Satellite (VMS) data for the years of the fish survey (2010, 2011 and 2012).

2.5. Statistics

Significance of differences in fish species composition between location and time after sand extraction was tested using analysis of homogeneity by the Betadisper function of the package 'vegan' followed by permutation test and Tukey's HSD test posteriori multi-comparison tests of the package 'stats'. We applied Dufrêne-Legendre Indicator species analysis using the indval function of the package 'labdsv' to determine indicator species of sub locations. The analysis is based on the product of relative frequency and relative average abundance of a fish species for a certain sub location (Dufrêne and Legendre, 1997). After checking of normality and homogeneity of univariate variables (Shapiro–Wilk, Levene's Test and diagnostic residuals plot) the parametric two-way ANOVA with interaction of variables followed by Tukey's HSD test was used. When the normality and homogeneity assumptions were violated, the non-parametric Kruskal–Wallis one-way multi-comparison tests of the package 'pgirmess' was used to determine significant differences between locations. We applied Non-Metric Dimensional Scaling (nMDS) using the metaMDS function in the package 'vegan', based on Bray–Curtis dissimilarities of fish abundance data, to visualize differences in fish assemblages in the extraction site and reference area (Oksanen, 2013). Environmental variables were linearly fit onto the ordination using the envfit function in the package 'vegan' (999 permutations). We used the ordisurf function to plot a smooth surface onto the ordination in the case of non-linear relationships. When Spearman rank correlation coefficients between a set of variables exceeded 0.9 one of the variables was dropped (Zuur et al., 2007). We used the mantel.correlog function in the package 'vegan' to check for autocorrelation between the ecological distance matrix and geographic distance matrix (Borcard and Legendre, 2012). For all analyses we used R: A Language and Environment for Statistical Computing, version 3.0.1 (R Core Team, 2013).

3. Results

3.1. Species assemblage, indicator species and biomass

In total, 32 fish species were identified. Fish assemblages in the reference area were dominated by dab (*Limanda limanda*), plaice (*Pleuronectes platessa*), scaldfish (*Arnoglossus laterna*), common sole (*Solea solea*), shorthorn sculpin (*Myoxocephalus scorpius*) and solenette (*Buglossidium luteum*). On average, 20.9 ± 12.2 kg WW ha^{-1} of fish and 13.1 ± 1.7 fish species $haul^{-1}$ were caught (Table 2). Species assemblage and biomass at the slope of the extraction site were not significant different from the reference area (Tables 4 and 5). Plaice, dab, scaldfish, shorthorn sculpin and solenette were most abundant and on average 20.2 ± 6.7 kg WW ha^{-1} and 14.2 ± 1.9 species $haul^{-1}$ were caught. Turbot (*Psetta maxima*) and brill (*Scophthalmus rhombus*) were Dufrêne-Legendre indicator species for the slope of the extraction site due to a higher relative frequency and average abundance compared to the other sub locations (Table 3).

At the crests of the sandbars, plaice, dab, sole, shorthorn sculpin and hooknose (*Agonus cataphractus*) were most abundant and on average, 93.8 ± 47.1 kg WW ha^{-1} and 11.4 ± 2.1 species $haul^{-1}$ were caught. Tub gurnard (*Chelidonichthys lucerna*) is a Dufrêne-Legendre indicator species of the crests of the sandbars (average 4.4 ind. ha^{-1}). Species assemblage at the crest of the oblique sandbar (T_1) significantly differed from the assemblage of the reference areas in 2012 (Table 4). Biomass at the crests showed a nearly 4.5-fold increase compared to the reference area (Table 2) and was significantly different for the comparisons between crests (T_1 and T_2) and reference area (Table 5).

Plaice, dab, european flounder (*Platichthys flesus*), sole and hooknose dominated the troughs of the sandbars. On average, 164.6 ± 205.1 kg WW ha^{-1} and 10.2 ± 2.5 fish species $haul^{-1}$ were caught (Table 2). The highest biomass values were found for fish sample 44 and 45 (Fig. 3) in the trough of the oblique sandbar (T_1), respectively 522.1 and 484.0 kg WW ha^{-1} (Fig. 4). This is a significant 23-fold increase in biomass values compared to the reference area in 2012. Increased biomass of white furrow shell (*Abra alba*) was not detected in the accompanying infaunal sample but in a sample from the trough west of the sandbar, total infaunal biomass reached 61.9 g AFDW m^{-2} with 24.9 g AFDW *A. alba* m^{-2}.

In 2012, species assemblage in the south-eastern deep area significantly differed from the troughs two years after cessation of sand extraction whereas in 2011 and in troughs 1 year after cessation significant differences were absent (Tables 4 and 5). This difference is also clearly visible in the nMDS ordination (Fig. 6) as T_2 samples from the trough ended up in the left region surrounded by reference and deep north-western samples (T_{recent}). Furthermore, fish biomass values in the troughs of the parallel sandbar (31.4 kg WW ha^{-1}, Table 2) differed significantly from the locations

Table 2
Total biomass, total species richness, top ten species abundance (number of fish per hectare) with standard deviation (sd) and environmental and biological variables at reference locations for 2010–2012 and at the sub locations in the sand extraction area for recent sand extraction (T_{recent}) and 1 (T_1) and 2 year after sand extraction (T_2).

	2010		2011		2012		Average	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Reference area								
Water depth (m)	18.8	1.7	21.7	2.8	26.5	5.2	22.2	4.3
D50 (μm)	267.6	20.6	290.3	42.0	307.5	55.3	288.8	41.6
Very fine sand (%)	0.6	0.3	0.2	0.2	0.1	0.1	0.3	03
SOM (%)	–	–	–	–	0.8	0.1	0.8	0.1
Mud (%)	0.9	0.4	0.1	0.2	0.0	0.0	0.3	0.5
A. alba (g AFDW m^{-2})	0.3	0.3	0.0	0.0	0.0	0.0	0.1	0.0
O. ophiura (g WW m^{-2})	2.3	2.1	3.4	0.9	1.8	0.0	2.7	1.4
Biomass (kg ha^{-1})	17.8	6.2	20.0	13.3	25.7	15.8	20.9	12.2
Species richness ($haul^{-1}$)	12.0	1.8	14.0	1.6	12.8	1.0	13.1	1.7
Limanda limanda	57.4	30.1	100.3	79.8	171.4	123.1	107.8	89.9
Pleuronectes platessa	102.7	59.6	89.0	107.7	54.2	23.3	83.4	78.8
Arnoglossus laterna	12.1	6.59	24.4	13.9	10.0	4.5	17.3	12.0
Solea solea	24.3	26.9	11.3	8.0	5.5	1.9	13.2	15.4
Buglossidium luteum	4.2	3.4	18.8	21.5	3.4	3.4	10.8	16.3
Agonus cataphractus	7.3	6.7	11.9	21.3	4.9	0.3	8.8	14.6
Myoxocephalus scorpius	2.8	2.0	10.7	4.1	5.9	4.0	7.4	4.9
Platichthys flesus	9.9	6.5	2.9	3.1	4.4	4.1	5.2	5.1
Chelidonichthys lucerna	1.4	1.0	4.4	2.2	3.2	0.8	3.3	2.0
Pomatoschistus sp.	10.8	19.3	0.0	0.0	0.1	0.3	2.9	10.2
Slope of the extraction site								
Water depth (m)	–	–	23.5	4.4	27.5	0.0	24.8	4.0
D50 (μm)	–	–	280.3	47.5	314.2	73.0	291.6	52.2
Very fine sand (%)	–	–	0.7	0.1	0.7	0.6	0.7	0.3
SOM (%)	–	–	–	–	0.9	0.1	0.9	0.1
Mud (%)	–	–	0.1	0.1	2.1	3.0	0.7	1.7
A. alba (g m^{-2})	–	–	0.0	0.0	0.0	0.0	0.0	0.0
O. ophiura (g WW m^{-2})	–	–	0.7	0.5	1.2	0.5	0.9	0.5
Biomass (kg ha^{-1})	–	–	17.9	5.6	24.8	8.1	20.2	6.7
Species richness ($haul^{-1}$)	–	–	14.5	2.1	13.5	2.1	14.2	1.9
Pleuronectes platessa	–	–	126	104.5	96.1	64.2	116.0	87.3
Limanda limanda	–	–	69.6	2.8	145.9	53.4	95	46.1
Arnoglossus laterna	–	–	16.6	5.4	12.1	5.7	15.1	5.4
Myoxocephalus scorpius	–	–	12.8	9.8	15.8	0.4	13.8	7.8
Buglossidium luteum	–	–	11.9	7.5	7.3	4.6	10.4	6.6
Solea solea	–	–	8.5	2.9	7.4	1.8	8.1	2.5
Agonus cataphractus	–	–	7.5	6.4	7.0	2.3	7.4	5.1
Scophthalmus rhombus	–	–	7.4	8.2	1.6	0.6	5.5	7.0
Psetta maxima	–	–	7.7	8.2	0.6	0.0	5.4	7.3
Platichthys flesus	–	–	3.1	2.5	6.9	6.0	4.4	3.9
Crests of sandbars								
Water depth (m)	29.0	4.2	29.5	1.8	31.5	1.4	29.9	2.4
D50 (μm)	240.8	106.8	270.4	25.7	303.8	16.0	271.5	53.1
Very fine sand (%)	11.9	15.0	5.6	0.2	6.1	1.0	7.5	6.8
SOM (%)	–	–	–	–	2.0	0.9	2.0	0.9
Mud (%)	1.7	1.6	7.1	7.5	6.6	0.8	5.4	5.1
A. alba (g AFDW m^{-2})	1.5	2.1	0.2	0.2	0.0	0.0	0.5	1.1
O. ophiura (g WW m^{-2})	0.4	0.2	2.0	0.4	1.2	0.0	1.3	0.7
Biomass (kg ha^{-1})	45.6	21.5	119.3	42.4	103.6	50	93.8	47.1
Species richness ($haul^{-1}$)	11.5	0.7	12	3	10.5	2.1	11.4	2.1
Pleuronectes platessa	272.9	251.4	706.6	348.0	534.1	321.2	533.4	325.1
Limanda limanda	215.4	31.3	477.6	298.1	191.6	49.3	321.0	227.5
Solea solea	48.1	24.5	188.1	202.5	51.1	38.5	109.0	139.7
Myoxocephalus scorpius	58.2	61.6	82.4	58.5	43.4	27.6	64.4	47.2
Agonus cataphractus	19.9	0.8	113.7	153.5	1.4	2.0	54.8	104.6
Platichthys flesus	5.8	2.0	31.6	10.3	37.1	34.6	25.8	20.7
Buglossidium luteum	28.4	31.8	24.8	19.9	0.6	0.9	18.9	21.4
Arnoglossus laterna	23.8	21.2	20.0	12.9	2.0	1.1	15.9	15.0
Merlangius merlangus	5.9	8.3	30.5	31.1	1.3	0.1	15.1	23.3
Trisopterus luscus	33.0	42.5	0.0	0.0	0.0	0.0	9.4	23.7
Troughs of sandbars								
Water depth (m)	35.7	9.3	37.4	3.7	40.0	0.7	37.4	5.4
D50 (μm)	296.1	77.2	232.7	62.9	133.9	2.3	231.9	83.2
Very fine sand (%)	2.1	1.6	10.6	11.5	25.9	0.4	11.2	11.7
SOM	–	–	–	–	6.0	0.6	3.3	3.0
Mud	0.3	0.3	2.3	1.0	18.0	2.8	5.1	7.5
A. alba (g AFDW m^{-2})	0.0	0.0	0.1	0.1	20.6	1.6	4.6	9.1
O. ophiura (g WW m^{-2})	0.4	0.4	3.5	1.3	242.2	341.5	55.5	160.6
Biomass (kg ha^{-1})	20.8	7.2	339.1	197.1	31.4	26.9	164.6	205.1
Species richness ($haul^{-1}$)	9.7	1.5	11.0	2.4	9.5	4.9	10.2	2.5
Pleuronectes platessa	69.7	103.6	1780.2	504.8	133.6	152.8	844.1	943.6

(*continued on next page*)

Table 2 (*continued*)

	2010		2011		2012		Average	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
Limanda limanda	47.7	52.5	567.5	448.4	72.7	62.2	284.3	385.8
Solea solea	23.7	14.6	373.6	510.1	33.3	33.5	181.3	362
Platichthys flesus	18.1	16.4	182.7	161.5	9	0.9	89.2	133.1
Agonus cataphractus	105.3	60.8	114	116.9	4.2	5.9	86.7	90.9
Myoxocephalus scorpius	26.8	24	122.2	84.0	8.3	11.8	65.1	76.1
Merlangius merlangus	8.2	10.2	36	39.5	4.2	5.9	19.7	29.3
Buglossidium luteum	15.4	18.1	21.6	27.1	4.4	1.7	15.7	20.2
Arnoglossus laterna	9	10.7	23.3	28.4	2.1	2.9	13.8	20.5
Callionymus lyra	6.9	12	7.9	9.4	0.0	0.0	5.8	8.9
Deep (SE)								
Water depth (m)	38.0	–	33.5	–	38.5	0.7	37.1	2.5
D50 (μm)	338.3	–	233.7	–	126.9	–	206.5	101.3
Very fine sand (%)	0.0	–	14.9	–	26.0	–	16.8	12.3
SOM (%)	–	–	–	–	3.9	–	3.9	–
Mud (%)	0.0	0.0	3.6	0.0	23.3	–	12.5	12.5
A. alba (g AFDW m^{-2})	0.0	–	1.4	–	97.4	–	49.1	55.8
O. ophiura (g WW m^{-2})	0.0	–	4.8	–	2.4	0.0	2.4	2.0
Biomass (kg ha^{-1})	5.5	–	413.9	–	409.5	25.7	309.6	203.3
Species richness ($haul^{-1}$)	7.0	–	15.0	–	8.5	0.7	9.8	3.6
Pleuronectes platessa	4.5	–	3520.1	–	1771.4	295	1766.9	1445.3
Solea solea	9.1	–	607.1	–	211.2	78.7	259.7	254.6
Platichthys flesus	2.3	–	330.8	–	299.3	77.6	232.9	160.8
Limanda limanda	18.1	–	653.8	–	48.9	22.0	192.4	308.2
Myoxocephalus scorpius	5.7	–	110.9	–	70.5	5.5	64.4	43.7
Buglossidium luteum	0.0	–	68.1	–	5.9	1.1	20.0	32.2
Agonus cataphractus	6.8	–	38.9	–	0.0	0.0	11.4	18.6
Arnoglossus laterna	0.0	–	7.8	–	3.3	4.7	3.6	4.2
Trisopterus luscus	0.0	–	13.6	–	0.0	0.0	3.4	6.8
Merlangius merlangus	3.4	–	3.9	–	0.6	0.9	2.1	1.8
Deep (NW)								
Water depth (m)	28.0	–	36.5	2.1	35.3	0.4	34.3	3.7
D50 (μm)	130.9	–	483.7	139.5	308.3	–	343	163.1
Very fine sand (%)	25.4	–	2.0	1.7	8.3	–	9.2	9.6
SOM (%)	–	–	–	–	2.0	–	–	–
Mud (%)	23.8	–	0.4	0.3	8.2	–	8.2	9.5
A. alba (g AFDW m^{-2})	14.0	–	1.5	1.1	0.0	–	3.1	6.1
O. ophiura (g WW m^{-2})	1.6	–	0.1	0.2	1.3	0	0.9	0.7
Biomass (kg ha^{-1})	28.6	–	26.4	30.6	23.6	3.2	25.7	15.5
Species richness ($haul^{-1}$)	8.0	–	11.0	2.8	7.5	2.1	9.0	2.5
Pleuronectes platessa	181.2	–	386.4	508.7	41.4	3.7	207.3	307.7
Limanda limanda	54.4	–	123.6	135.5	128.5	84.1	111.7	86
Myoxocephalus scorpius	9.1	–	7.8	5.0	34.3	10.1	18.7	15.4
Solea solea	9.1	–	10.7	14.3	13.2	10.9	11.4	9.2
Agonus cataphractus	4.5	–	6.4	9.0	9.7	1.9	7.3	5.1
Platichthys flesus	11.3	–	3.4	4.7	4.5	2.5	5.4	4.3
Buglossidium luteum	0.0	–	8.2	9.3	5.2	7.4	5.4	6.8
Arnoglossus laterna	0.0	–	6.6	7.8	4.2	5.9	4.3	5.6
Merlangius merlangus	6.8	–	0.9	0.6	3.1	4.4	3.0	3.3
Pomatoschistus minutus	0.0	–	3.4	4.7	0.0	0.0	1.3	3.0

sampled one year after cessation, which harboured 175.1 and 413.9 kg WW ha^{-1}. The accompanying bottom sledge samples of the fish samples from the troughs of the parallel sandbar was characterised by a very high biomass of serpent star *Ophiura ophiura* (242.2 g WW m^{-2}).

The most dominant species in the south-eastern deep area of the sand extraction site were plaice, sole, European flounder, dab and shorthorn sculpin. European flounder and plaice are Dufrêne-Legendre indicator species (Table 3). In 2011, 2012, fish biomass significantly increased 20-fold and reached 413.9 and 409.5 kg WW ha^{-1} and 15 and 8.5 fish species were caught (Table 2, Fig. 4).

Demersal fish biomass in south-eastern deep area remained in 2012 almost as high as in 2011 but the abundance of plaice decreased from 3520.1 in 2011 to 1771.4 ind. ha^{-1} in 2012. In 2012,

Table 3
Dufrêne-Legendre Indicator species.

Species	Location	Indval	*P* value
European flounder (*Platichthys flesus*)	Deep (SE)	0.6	**
Plaice (*Pleuronectes platessa*)	Deep (SE)	0.5	*
Turbot (*Psetta maxima*)	Slope	0.6	***
Brill (*Scophthalmus rhombus*)	Slope	0.5	**
Tub gurnard (*Chelidonichthys lucerna*)	Crest	0.3	*

(***) $0.001 < p < 0.01$, (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (.).

Table 4
Results of analysis of homogeneity (betadisper) of multivariate distance of species composition, followed by permutation and post-hoc pairwise comparisons between locations (Tukey's HSD test).

Comparison	*p*-value
Reference (2012) : crests (T_1)	*
Reference (2012) : troughs (T_1)	*
Reference (2012) : troughs (T_2)	*
Reference (2012) : deep south-eastern (T_2)	**
Slope (2012) : troughs (T_2)	**
Crest (T_2): troughs (T_2)	**
Crest (T_2): deep south-eastern (T_2)	*
Trough (T_2): deep south-eastern (T_2)	**

(***) $0.001 < p < 0.01$, (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (.).

Table 5
Tukey's HSD pairwise comparison of log transformed demersal fish biomass among locations with adjusted *p*-values. R: Reference, Sl: Slope, Cr: Crests, Tr: Troughs, SE: South-eastern deep area and NW: North-western deep area. Ref: Reference, 0: Recent sand extraction, 1 and 2: 1 − year after the cessation of sand extraction.

	Ref	SL_0	Cr_0	Tr_0	SE_0	NW_0	Sl_1	Cr_1	Tr_1	SE_1	NW_1	Sl_2	Cr_2	Tr_2	SE_2
Ref	–	ns	Ns	ns	ns	ns	ns	*	***	**	ns	ns	*	ns	***
SL_0		–	ns	ns	ns	ns	ns	ns	**	*	ns	ns	ns	ns	**
Cr_0			–	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Tr_0				–	ns	ns	ns	.	**	**	ns	ns	ns	ns	**
SE_0					–	ns	ns	**	**	*	ns	ns	*	ns	***
NW_0						–	ns	*	***	**	ns	ns	.	ns	***
SL_1							–	ns	***	**	ns	ns	ns	ns	***
Cr_1								–	ns	ns	ns	*	ns	ns	ns
Tr_1									–	ns	*	**	ns	**	ns
SE_1										–	ns	*	ns	*	ns
NW_1											–	ns	ns	ns	*
SL_2												–	ns	ns	**
Cr_2													–	ns	ns
Tr_2														–	**
SE_2															–

(***) $0.001 < p < 0.01$, (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (.).

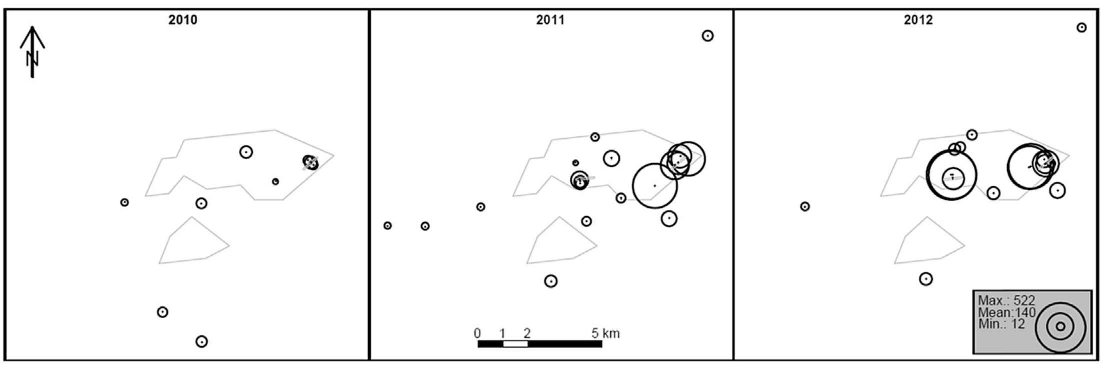

Fig. 4. Demersal fish biomass in- and outside the sand extraction site in 2010, 2011 and 2012. Values are proportional to the radius of the circles in the bubble plot with maximum values converted to bubbles with 1000 m radius. The highest biomass value was found in 2012 at the trough of the oblique sandbar (522 kg WW ha^{-1}).

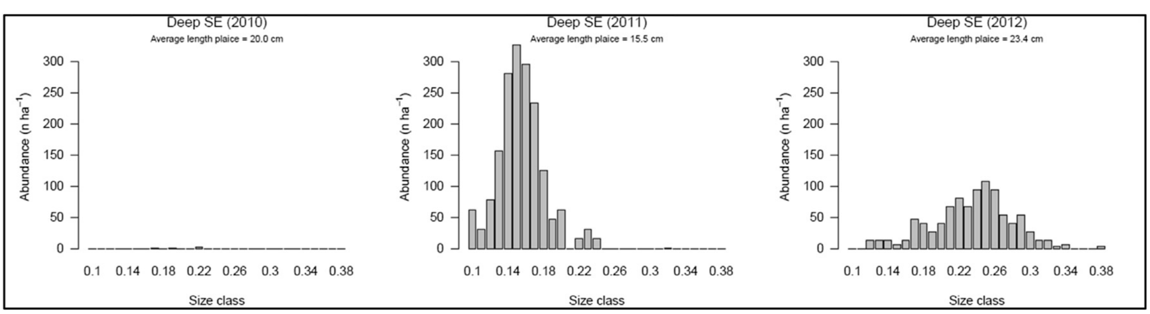

Fig. 5. Length abundance distribution of plaice in the south-eastern deep area of the sand extraction site for 2010, 2011 and 2012 ($T_{0,1 \text{ and } 2}$).

the length of plaice was larger than in 2011, 23.4 cm instead of 15.5 cm, which compensated for the lower observed abundance in 2011 (Table 2, Fig. 5). A similar trend was found in the troughs; in 2012, the average length of plaice was 20.8 cm instead of 15.4 cm in 2011. The average length of plaice in the reference area in 2010, 2011 and 2012 was 17.82, 15.29 and 17.11 cm, which means that the deep areas of the extraction site attracted larger plaice specimen. The length of plaice in the reference area in 2011 was the smallest of the three years, which may explain the smaller length of plaice in the deep areas in 2011. No differences in length of the other dominant fish species were observed.

Biomass in the north-western deep area remained relatively low but just above the reference level, 25.7 ± 15.5 kg WW ha^{-1}. Species richness is significantly lower in the north-western deep area, 9 species $haul^{-1}$ compared 13.1 species $haul^{-1}$ in the reference area, (Tukey's HSD, $p < 0.05$). The most dominant species were plaice, dab, shorthorn sculpin, sole and hooknose.

3.2. nMDS ordination and associated variables

Fish assemblage and environmental dissimilarities revealed a significant association (Mantel: $p < 0.01$, $r = 0.2181$). Percentage coarse sand was dropped from the analysis because of collinearity with D50, percentage medium and fine sand and mud content were dropped because of collinearity with very fine sand. Mantel correlograms analysis showed that autocorrelation was below significance level. All nMDS ordinations had stress values below 0.07, which means an outstanding goodness of fit. For the 2010–2012

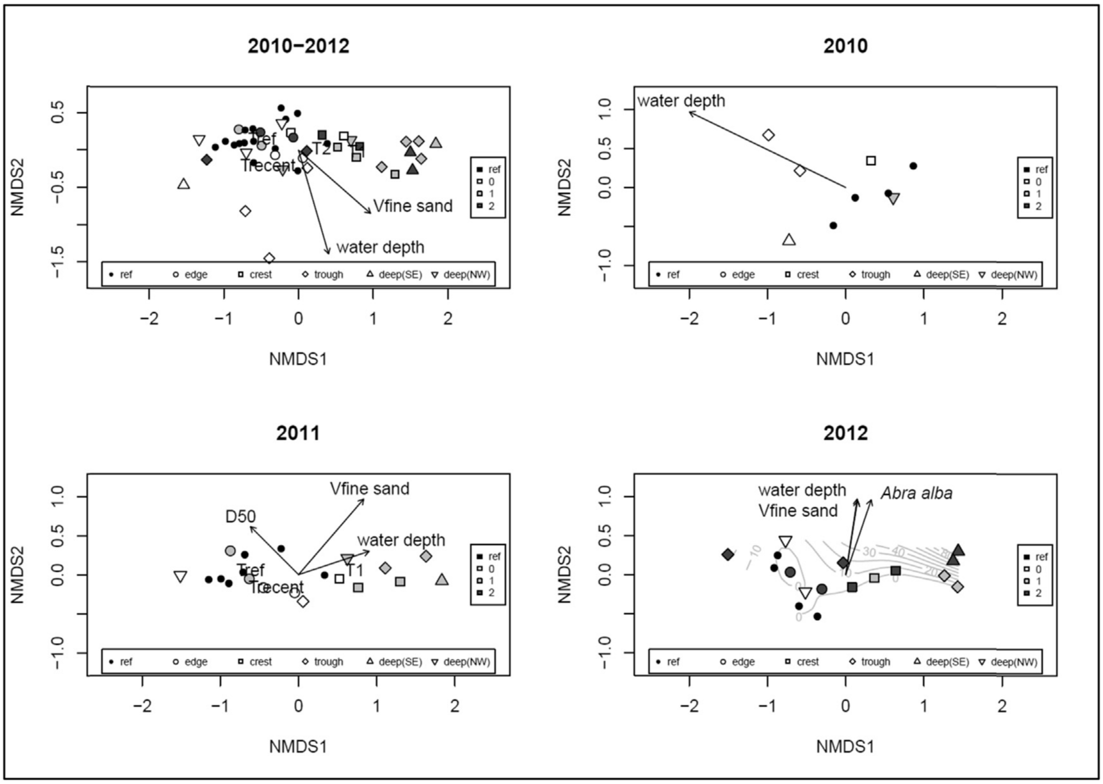

Fig. 6. nMDS ordination with sites and significant associations with variables. Continuous variables are depicted with arrows and categorical variable time after the cessation, only with text (Tref: reference in black, T_{recent} in white, T_1 in light grey and T_2: dark grey. Sub locations are denoted with symbols, reference as black bullets, slope of the reference area as open large circles, crests of sandbars as squares, trough of sandbars as diamonds, deep (SE) as point-up triangles and deep (NW) as point-down triangles. In 2012, the significant association of the ordination and infaunal white furrow shell biomass is denoted with an arrow and surface plot to show the non-linearity. Stress of all ordinations was below 0.07.

survey periods, the ordination showed a significant association with time after the cessation of sand extraction and water depth (Fig. 6 and Table 6). Median grain size D50 (μm), the fraction very fine sand and infaunal white furrow shell biomass was just above the significance level.

In 2010, only water depth showed a significant association with the ordination. In 2011, the very fine sand fraction, time after the cessation of sand extraction, water depth and D50 showed significant associations with the ordination. In 2012, infaunal white furrow shell biomass, water depth and the fraction very fine sand showed a strong association with the ordination. The association of the ordination with time after the cessation of sand extraction was just above the significance level. No significant associations were found for total epifaunal biomass and specific species sampled with the bottom sledge, e.g. scavenging brittlestars (*Ophiura* sp.) and predatory flying crab (*Liocarcinus* sp.).

3.3. Stomach and intestine contents

Stomach and intestine content of plaice was dominated by undigested crushed white furrow shell remains, dab stomachs end guts were filled with remains of brittle stars (*Ophiura* sp.) and shorthorn sculpin stomachs were filled with whole swimming crabs (*Liocarcinus* sp.).

3.4. Colonization of infaunal macrozoobenthos and sedimentary evolution

We observed significant changes in fish assemblage in the sand extraction site, which showed a strong association with sediment composition and white furrow shell biomass. For the fraction of very fine sand significant differences were found between location and time after sand extraction (Kruskal–Wallis chi-squared = 27.7, df = 5, all $p < 0.001$). In 2011, a significant difference was found between reference and troughs. In 2012, the fraction very fines significantly differed between reference area and the south-eastern deep area. In general, the fraction very fines decreased at the crests of the sandbars and increased in the troughs and deep areas of the extraction site. D50 at the crests of the parallel sandbar increased from 165 μm in 2010 to 304 μm in 2012 and very fine sand fraction

Table 6
Multiple regression of environmental variables and nMDS scores for two axis ordination, r^2 is the squared Spearman's rank correlation coefficient and p-value.

Variable and period	r^2 linear	p-value
2010–2012		
Time after the cessation	0.36	***
Water depth	0.27	***
Very fine sand (vol %)	0.21	*
Abra alba (infaunal)	0.13	·
D50	0.13	·
2010		
Water depth	0.66	*
D50	0.56	·
2011		
Very fine sand	0.58	***
Time after the cessation	0.40	*
Water depth	0.32	*
D50	0.27	*
2012		
Abra alba (infaunal)	0.42	*
Water depth	0.40	*
Very fine sand (vol %)	0.38	*
Time after the cessation	0.41	.

(***) $0.001 < p < 0.01$, (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (·).

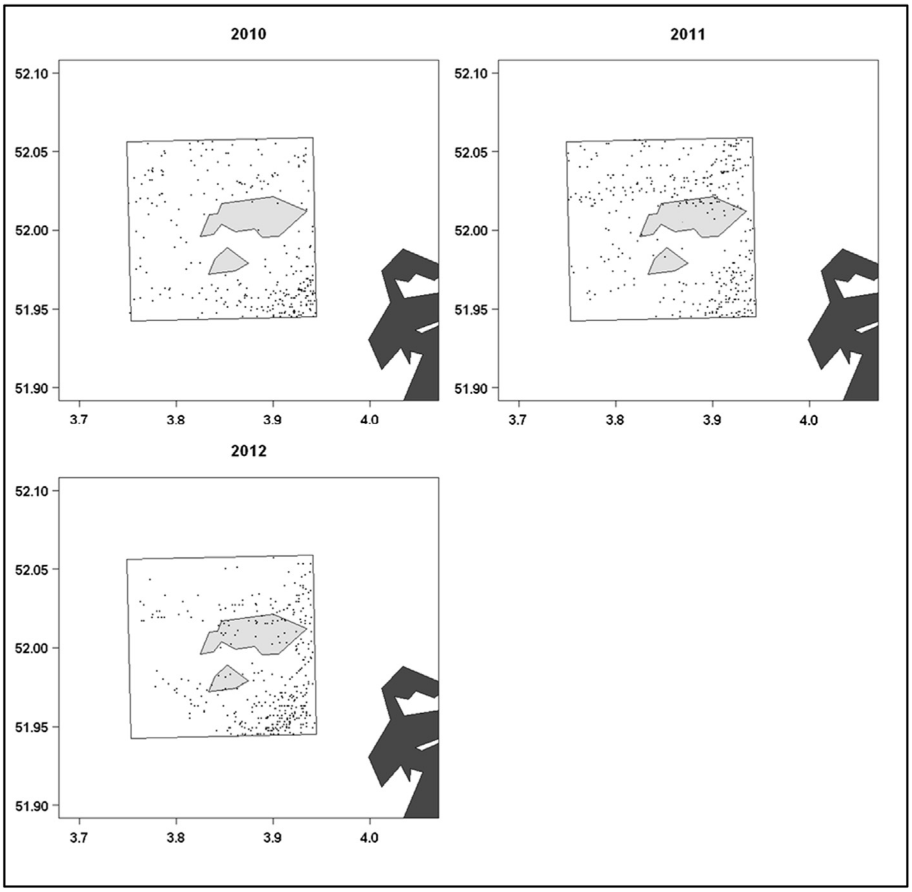

Fig. 7. Fishing activity, in 2010–2012 derived from Vessel Monitoring through Satellite (VMS) data of all seabed disturbing fish gears Beam Trawl (>300 and <300 hp.), Bottom Otter Trawl, Bottom Pair Trawl and Fly Shooting Seine. Area in dark grey is the Maasvlakte I area, area in light grey is the northern and smaller southern sand extraction site.

decreased from 22.5% in 2010 to 6.1% in 2012. We observed the opposite for the sediment in the trough of parallel sandbar, D50 decreased from 321.8 to 133.9 μm.

Significant differences were found in white furrow shell (*Abra alba*) biomass, between locations and year (2011: Kruskal–Wallis chi-squared = 15.7729, df = 5, $p < 0.01$ and 2012: Kruskal–Wallis chi-squared = 12.25, df = 5, $p < 0.05$). In 2011, biomass of white furrow shell was significantly higher at the crests of the sandbars compared to the reference areas. White furrow shell is virtually absent in reference areas and the slope of the extraction site. After 2 years, white furrow shell biomass increased to 20.6 and 97.4 g m^{-2} AFDW for respectively the troughs of sandbars and the south-eastern deep area.

3.5. Fishing activity

Based on Vessel Monitoring through Satellite (VMS) data (Hintzen et al., 2013) seabed disturbing fishing activity in the sand extraction site was virtually absent in 2010 (Fig. 7). In 2011, fishing activity mainly occurred in the northern area of the northern sand extraction site. In 2012, fishing activity in the sand extraction site exceeded the fishing activity level of the reference area. Furthermore, fishing activity in 2012 almost equalled the fishing activity level before sand extraction (Steenbergen and Machiels, 2013).

4. Discussion

Fish biomass significantly increased 20-fold in the south-eastern deep area of the Maasvlakte 2 sand extraction site and 5-fold on the crests of the landscaped sandbars compared to the reference areas and recently extracted areas. This increased biomass is associated with a significant increase in biomass of infaunal white furrow shell (*Abra alba*). In the north-western deep area biomass values remained relatively low but just above the reference level, 25.7 ± 15.5 kg WW ha^{-1} probably due to ongoing sand extraction activities and the absence of the increase in white furrow shell biomass.

The highest species richness, 14.2 species $haul^{-1}$, was found at slope the of the extraction site with turbot (*Psetta maxima*) and brill (*Scophthalmus rhombus*) being indicator species. These species are at a length of 20 cm known to forage on mobile prey while severely relying on eyesight (De Groot, 1971; Western, 1971; Beyst et al., 1999; Vinagre et al., 2011). Instead of foraging in more turbid circumstances, the edge of the extraction site may be more suitable while still favouring from increased fish biomass in the surroundings. Species richness in the sand extraction site is lower compared to the reference area. Inside the extraction site, on average, 10.5 species per haul were found compared to 13.1 species $haul^{-1}$ in reference areas. The lowest species richness was found in the north-western deep area, 9.0 species $haul^{-1}$ probably again due to continuing sand extraction. Comparisons of species richness between reference area and locations in the sand extraction site are potentially biased due to differences in sampled surface area.

Based on a study in an extraction site in France, Desprez (2000) stated that sand extraction on the long term might create new habitats such as the presence of boulders and higher heterogeneity of sediment and favour an increase in the richness of benthic fauna and fish. A qualitative analysis of fish assemblage was however lacking. In line with our results, large-scale sand extraction in the Yellow Sea and the resulting bottom disturbance was shown to have a more pronounced negative impact on fish species richness, a decline of more than 70% of the total number of fish and the number of species was observed (Son and Han, 2007).

In the Eastern Channel Region, the majority of fish species have shown marked reductions in abundance since the start of aggregate extraction and draghead entrainment was identified as a possible cause (Drabble, 2012). Next to differences in biomass and species richness, significant differences in fish species assemblage between reference area and extraction site were found. Dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*) were the most abundant species in the reference area whereas in the sand extraction site plaice was more abundant. This difference is again possibly due to the increase in white furrow shell biomass, which may be a more preferred prey item of plaice. In a smaller sand extraction site on the Belgium Continental Shelf with shallow sand extraction dab was also more abundant than plaice (Maertens, 1988) although a clear change in fish distribution was not observed possibly due to continuous sand extraction or less pronounced differences in bathymetry and sediment characteristics. Epibenthos in the Belgium extraction site was dominated by the predatory common starfish *Asterias rubens* and the scavenging serpent star *Ophiura ophiura*.

The fish assemblage differed significantly between crests and troughs of the sandbars and tub gurnard (*Chelidonichthys lucerna*) is an indicator species of the crests which may be induced by differences in macrozoobenthic assemblage. The difference in fish assemblage is a first indication of the applicability of landscaping techniques to induce heterogeneity of the seabed although it remains difficult to draw a strong conclusion due the lack of replication of the experiment. Comparable differences in species assemblage also occur on the crests of natural sandbanks, early-life history stages of the lesser weever (*Echiichthys vipera*) were found to be more abundant compared to the troughs (Ellis et al., 2011).

Several environmental variables may be responsible for the differences in fish species assemblage. In general, fishing activity may also play a role but, in 2012, activity in the extraction site was almost equal to the reference area (Steenbergen and Machiels, 2013). Therefore, differences in fish assemblage and biomass between dredged and non-dredged areas are not induced by differences in fishing intensity. In 2010, only water depth showed a significant association with the ordination. In 2011, the very fine sand fraction, time after the cessation of sand extraction, water depth and D50 showed significant associations with the ordination. In 2012, infaunal white furrow shell biomass, water depth and the fraction very fine sand showed a strong association with the ordination. In 2011, observed differences in the ordination were not yet associated with infaunal white furrow shell biomass, possibly due to the gap between the two sampling activities. Macrozoobenthos sampling occurred at the end of June 2010, the start of May 2011 and at the end of April 2012 while fishing occurred mid-July 2010, at the end of July 2011 and mid-June 2012.

Sell and Kröncke (2013) concluded that fish assemblages on the Dogger Bank (North Sea) were linked to both biotic and abiotic habitat characteristics, abundance of specific fish species could be linked with individual in- and epifauna species. In the Western Baltic, white furrow shell comprised 24% of the diet of plaice (Arntz and Finger, 1981; Rainer, 1985) and a comparison of present-day diet and the diet of plaice at the beginning of the 20th century suggested that the preponderance of polychaetes has increased and that of bivalves decreased (Rijnsdorp and Vingerhoed, 2001). White furrow shell is a deposit feeding bivalve and tends to prefer fine-grained sediments with a median grain size between 50 and 250 μm and a mud content of 10–50% (Degraer et al., 2006). An increase of Tellinid shellfish (e.g. white furrow shell), plaice and common sole was found at deposition areas around aggregation sites in France (Desprez and Lafite, 2012). We found that stomach and intestines of plaice were mainly filled with undigested remains of white furrow shell. Stomach content analysis of the other fish species also revealed specific preference of prey items but this is not confirmed by our statistical analysis. Prey items of dab were dominated by brittle stars (*Ophiura* sp.), a similar preference was also found by other researchers (Hinz et al., 2005). All shorthorn sculpin stomachs contained swimming crabs (*Liocarcinus* sp.) and this preference was also found in other studies (Western, 1971; Link and Almeida, 2002).

Time after the cessation of sand extraction is an important variable. Directly after sand extraction, fish biomass values are similar to the reference area. Fish biomass values increased in 2011 and 2012. White furrow shell biomass is showing the same pattern, median grain size in the extraction site is decreasing and the fraction of very fines in the sediment is rising. For shallow sand extraction in the North Sea, recovery time of benthic assemblages is estimated to be six years (van Dalfsen et al., 2000; van Dalfsen and Essink, 2001; Boyd et al., 2005).

A study in a deep temporary sand extraction site with 6.5 million m^3 sand extracted, an initial water depth of 23 m and extraction depth between 5 and 12 m revealed a sedimentation rate of 3 cm per year (Boers, 2005). Thatje et al. (1999) found a continuous sedimentation rate of around 50 cm per year inside a 700 m wide and 48 m deep natural seafloor crater 20 miles off the coast of Germany with an initial water depth of 34 m. Mud content inside the crater increased from 5% in 1963 up to 40% in 1995 and the benthic community was characterized as an urchin – brittle star association (*Echinocardium cordatum* and *Amphiura Filiformis*). Considering these sedimentation rates, backfilling of the Maasvlakte 2 sand extraction site may take decades or longer, resulting in a prolonged and more pronounced effect on macrozoobenthos and fish assemblages in the area.

The increase in length of plaice in the troughs and south-eastern deep area (T_2) may be the result of a residing cohort within the extraction site, plaice with body size 16 cm is 1.5 years old and with body size 22 cm is 2.5 years old (Bolle et al., 2004). The increase in length of plaice may also be related to prey-size preferences of juvenile plaice. In one year specimens of *Abra alba* reach lengths of 12–14 mm, in two years 13–16 mm and maximum length of 20–25 mm (Holtmann et al., 1996). All sediment parameters remained in the same range except SOM values, which was on average 3.9% in the south-eastern deep area and 6.0% in the troughs of the parallel sandbar. However, the statistical analysis revealed no significant association of the ordination in 2012 with SOM. Dissolved oxygen (DO) levels are influenced by factors such as; SOM, water depth, temperature and water circulation (Eldridge and Roelke, 2011). The increase in length may also be induced by avoidance of the south-eastern deep area by smaller plaice, which are more sensitive to reduced DO levels (Miller et al., 1995; Rabalais et al., 2001; Gray et al., 2002). DO levels may even be more reduced in the troughs resulting from the specific bathymetry and greater water depth, which may have led to the significant decrease in biomass values from the 23-fold increase in 2011 down to reference level and significant change in species assemblage in 2012. Fish biomass was found to be significantly correlated with oxygen concentration and a reduction in fish biomass was observed when oxygen concentration in the bottom water dropped below 3 mg l^{-1} (Petersen and Pihl, 1995). Next to the difference in SOM and possible differences in DO levels, differences in macrozoobenthic assemblage were also present. The accompanying bottom sledge samples of the fish samples from the troughs of the parallel sandbar were characterised by very high biomass values of serpent star *Ophiura ophiura* (242.2 g WW m^{-2}).

4.1. Limitations of present study and recommendations

Studying the distribution of demersal fish for two years is not sufficient to understand the final impact of deep and large-scale sand extraction on demersal fish. Conclusions on sedimentary evolution are based on a relatively small sample size and short monitoring period. More sediment samples from the 2010–2012 surveys will be analysed in future work. On-going sedimentation and a rise of mud content up to 40% can be expected (Thatje et al., 1999). The highest encountered mud content in the second Maasvlakte extraction site was 23.3% in the south-eastern deep part in 2012. Fish surveys were conducted mid-July 2010, at the end of July 2011 and mid-June 2012 while the oxygen concentration reached a minimum at the end of the summer and a maximum in May (Boers, 2005). The occurrence of temporal hypoxia and possible detrimental effects on fish and macrozoobenthos cannot be excluded with our data.

We recommend monitoring of demersal fish and macrozoobenthic assemblage and accompanied sediment variables for a longer period, at least for a period of six years, i.e. the estimated recovery time of shallow sand extraction. Six years of monitoring may be even insufficient because of larger differences resulted from the large-scale and deep sand extraction.

5. Conclusions

An increase of annual coastline nourishments up to 40-85 million m^3 per year is expected for counteracting effects of future sea level rise. For the seaward harbour extension of Maasvlakte 2, the Dutch government permitted deep and large-scale sand extraction to reduce the surface area of impact. It is questionable if the seabed of the Maasvlakte 2 extraction site will return to its original state within decades. We showed that deep sand extraction leads to significant differences in fish biomass between the deep extraction site and the surrounding reference. Our findings indicate that ecosystem-based landscaping techniques are feasible and effective in influencing fish assemblages. These findings have to be included in future design and permitting procedures of large-scale sand extraction projects.

Acknowledgements

We are grateful to the dredging companies Royal Boskalis Westminster N.V. and Van Oord for the fast realisation of the landscaped sandbars and the supply of bathymetric data. We thank the Port of Rotterdam for increasing our dataset by adding samples collected during the environmental impact assessment measurements in 2012. Many thanks to the fish survey team and the crew of GO29 for conducting the fish sampling and to Niels Hintzen for the VMS data. We also want to thank Building with Nature, the user group committee and anonymous reviewers for the useful comments. This study is part of Building with Nature innovation program and funded from several sources, including the Subsidieregeling Innovatieketen Water (SIW, Staatscourant nrs. 953 and 17009), the Dutch Ministry of Transport, Public Works and Water Management and partner contributions of the participants to the Foundation EcoShape. The study received cofunding from the European Fund for Regional Development EFRO and the Municipality of Dordrecht.

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