Structural and functional biological assessment of aggregate dredging intensity on the Belgian part of the North Sea

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Abstract

Marine aggregate dredging in the Belgian part of the North Sea (BPNS) is restricted to four dedicated concession zones. Within these zones, there are areas under different dredging pressure, but with the advantage that these are situated within a similar habitat (cfr. similar sediment characteristics) . As such, this study assessed how different degrees of dredging pressure executed on a similar sandy habitat affect the benthic ecosystem. Possible responses of the macrobenthos on the dredging pressure were evaluated based on both structural (species number, species composition, abundance and biomass) and functional (e.g. bioturbation potential, BTA) characteristics of the benthic ecosystem. The structural changes in benthic characteristics were summarised by the benthic indicator BEQI.

The most obvious impact of dredging on the benthic community was observed in the most intensely used area (high dredging intensity and frequency) with significant changes in the structural benthic characteristics, and a moderate to poor score for the benthic indicator BEQI. For the benthic functional characteristics, no impact of dredging was measured in any of the areas. Furthermore, the heart-urchin (*Echinocardium cordatum*) was observed to be the most sensitive species to dredging, because it reduced substantially in numbers or even disappeared in all impacted areas.

Our results suggest that the current benthic sandy ecosystem of the BPNS is resilient enough to buffer aggregate dredging when performed at low or at high, but infrequent intensities. However, when dredging focuses on a small surface area, and when it is performed at high and frequent intensities, changes in sediments result in clear biological changes.

Introduction

Aggregate dredging in the Belgian part of the North Sea (BPNS) is restricted to four dedicated zones as cited in RD 19 April 2014. Control on the dredging activities is based on two criteria. The first is the control on the actual dredging by means of an Electronic Monitoring System (the black-box) on board the extraction vessels. This is to supervise whether dedicated extraction zones are respected, and whether extracted volumes do not exceed the granted licences. The second implies an assessment of the impact of dredging on the marine environment by regular monitoring (FOD Economie, 2014a&b). Combination of both control measures offers the opportunity to measure the impact of dredging intensity.

Part of the legal monitoring is of biological nature, to assess the impact of dredging on the soft-bottom benthic ecosystem. Many studies have shown that marine aggregate dredging has the potential to change the composition of seabed sediment habitats (e.g. Foden et al., 2009; Le Bot et al., 2010). Since marine macrobenthic communities are strongly related to sediment habitats (Degraer et al., 2008; Vanaverbeke et al., 2011), they are good indicators to measure potential changes in seabed habitats (Van Hoey et al., 2010). For many years, the impact of aggregate dredging on macrobenthos has been assessed using traditional structural metrics such as abundance, number of species, biomass and species composition (e.g. Boyd et al., 2005; Cooper et al., 2007a; De Backer et al., 2014). However, recently marine conservation focuses more on ecosystem functioning, considering the processes of ecosystems and the individual ecosystem components involved in them (Bremner, 2008). Since one may argue that it might be of even greater importance to consider how dredging affects the way ecosystems function rather than how it affects the species that are present. This can be done by looking at changes in functional diversity through biological traits analysis (BTA). Another way of looking at changes in functioning is to measure changes in bioturbation, because this is a key process in marine systems which influences ecosystem function (Meysman et al., 2006). The community bioturbation potential (BPc) can be used as a metric to estimate the potential of a community to bioturbate (Solan et al., 2004).

Black-box data in the past showed that the different extraction areas were dredged with a different regime (intensity and frequency) (Roche et al., 2011), allowing to define areas under different dredging pressure in the BPNS. Furthermore, the entire BPNS is classified as habitat type 1110 (i.e. sandbanks slightly covered by seawater at all times) under the Habitat Directive. Moreover, the areas with actual dredging in the BPNS are situated in similar sedimentary areas i.e. dominated by medium sands (250-500 µm) and with a median grain size around 300-400 µm (Verfaillie et al., 2006). As such the BPNS can be considered an excellent study area to investigate how different degrees of dredging pressure executed on a similar sandy habitat affect the benthic ecosystem. Further, the objective is to compare structural (using traditional metrics and the BEQI indicator) and functional (BTA, BPc) metrics to evaluate the impact of dredging on the benthic assemblage. Besides, European environmental legislation (e.g. Marine Strategy Framework Directive) demands indicator tools to summarise the status of the marine ecosystem, and the impact upon it by human activities. Therefore, an indicator assessment approach (BEQI) is applied to determine the applicability of BEQI in detecting changes caused by the dredging.

The ultimate aim of this study is to be able to determine the best practice in aggregate dredging to minimise the biological impact on sandy benthic ecosystems.

Methods

Study sites and extraction history

This study focuses on four actual aggregate dredging areas within the restricted extraction zones on the Belgian part of the North Sea (BPNS): Buiten Ratel, Oostdyck, Thornthonbank and Oosthinder (Figure 1). All four locations are dominated by medium sands, but are subject to different dredging regimes. Marine aggregate dredging on the BPNS typically occurs on top of the sandbanks (Figure 1).

The Buiten Ratel is currently the most heavily exploited aggregate dredging area on the BPNS. Dredging steadily increased since 2005 from 0.32 x 10^6 m³ to 1.9 x 10^6 m³ in 2011, since then slightly decreasing towards 1.3 x 10^6 m³ in 2013. Especially, the central part of the Buiten Ratel (an area of 2.5 km²) is the most targeted area with yearly extraction volumes around 8 x 10^5 m³ since 2009. The high intensity of extraction resulted into a 6 m deep depression (Degrendele et al., 2014, this volume). More to the south of the extraction 'hotspot' on the Buiten Ratel, extracted volumes are lower, and vary between 7 x 10^4 m³ and 15 x 10^4 m³.

Compared to the other areas, the Oostdyck is the least intensively exploited area, but it has the longest time record of extractions. Yearly volumes since 2003 (start of the black box volume data) are of the same magnitude as in the lower impacted areas of the Buiten Ratel. Extracted volumes varied between 7 x 10^4 m³ in 2007 and 15 x 10^4 m³ in 2013.

The Thorntonbank is increasingly used for aggregate extraction since 2003. Volumes increased tenfold from 0.1 x 10^6 m³ in 2003 to 1 x 10^6 m³ in 2013. The extraction mainly concentrates on the top of the bank and extracted volumes are lower at the edges.

Aggregate dredging on the Oosthinder started only in March 2012. Since then yearly extraction is as high as on the central part of the Buiten Ratel (around 8 x 10^5 m³) but on a larger surface area (approximately 9 km²). Extraction is concentrated to short periods of the year: 4 months intensively dredging with in between periods without dredging (Degrendele et al., 2014, this volume).

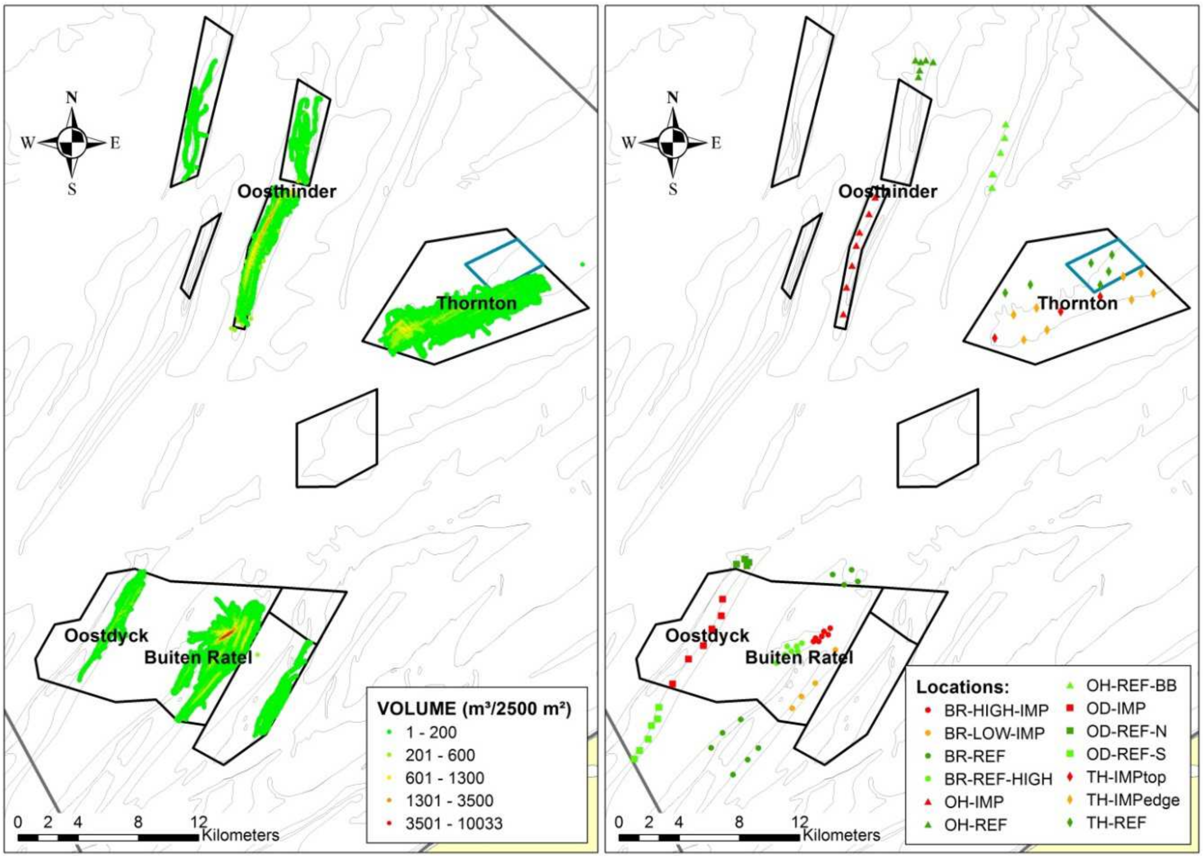

Figure 1: Overview of study sites with black box data extracted volumes in 2013 (left) and sampling locations (right) in the aggregate dredging concession areas on the BPNS. Right panel: sampling locations in the different actual dredging areas, Buiten Ratel (BR, circles), Oostdyck (OD, squares), Thornton (TH, rhombs) and Oosthinder (OH, triangles). Red and yellow symbols indicate impact samples, green symbols indicate reference samples.

Sampling and sample processing

The position of the sampling locations was chosen based on black-box data (a system that keeps track of extraction time and location of the extraction vessels). In all extraction areas, both impact and reference locations were allocated to allow for biological impact assessment (Figure 1). In some areas, a distinction was made between different types of impact samples depending on the dredging pressure, and in reference samples depending on the location of the reference samples. In Table 1 and Figure 1, an overview is given of the different sample groups per area.

In order to avoid any significant seasonal effects in the analyses, all sampling (impact and control) was undertaken at the same time of year. Sampling took place on board the RV Belgica, yearly between 2010 and 2013 in September/October in all extraction areas, except for the Oostdyck in 2012. Furthermore, at the Oosthinder, one extra sampling was done in July 2012 on board the RV Simon Stevin, one month after the first extraction phase had stopped.

Macrobenthos was sampled by means of a Van Veen grab (surface area 0.1 m²), one per location at every sampling occasion. Real-time coordinates of each location were noted. The fauna was sieved alive over a 1-mm sieve, stained with eosin to facilitate further sorting, and preserved in an 8% formaldehyde–seawater solution. All individuals were identified to species level if possible, and counted. For biomass measurements, each species/taxon in every sample was blotted on absorbent paper before being weighed (wet weight) to the nearest 0.00001 g.

A small sediment core (3.6 cm ∅) was taken from each Van Veen sample for granulometric analysis. Grain size fractions up to 1600 µm were analysed using a Malvern Mastersizer 2000G hydro version 5.40 (Malvern, 1999), and determined as volume percentages according to the Wentworth scale. The fraction > 1600 µm was sieved first and as well calculated as volume percentage. The following classes were used: clay/silt (<63 µm), very fine sand (63-125 µm), fine sand (125-250 µm), medium sand (250-500 µm), coarse sand (500-1000 µm), very coarse sand (1000-1600 µm), shells/gravel (> 1600 µm).

Extraction area	Sample groups	Location and description
Buiten Ratel (BR)	HIGH-IMP	Seven impact samples on the central Buiten Ratel, the most impacted dredging area based on the black box data.
	LOW-IMP	Four impact samples on the less impacted area of the Buiten Ratel based on the black box data.
	REF-HIGH	Seven reference samples within the concession area near the high impact area but with no dredging.
	REF	Ten reference samples outside of the concession area both north and south.
Oostdyck (OD)	IMP	Six impact samples in the area under influence of dredging.
	REF-S	Six reference samples on the south-west part of the sandbank.
	REF-N	Four reference samples on the north-east part of the sandbank.
Thorntonbank (TH)	IMPtop	Three impact samples on top of the bank with a higher influence of dredging based on the black-box data.
	IMPedge	Eight impact samples at the edges of the bank with a lower influence of dredging based on the black box data.
	REF	Six reference samples within the concession area but without dredging
Oosthinder (OH)	IMP	Seven impact samples under the influence of dredging since 2012 allocated based on black box data.
	REF	Six reference samples located on the Oosthinder outside of the concession area.
	REF-BB	Five reference samples located on the nearby Bligh Bank.

Table 1: Overview of sample groups in the different extraction areas with indication of the codes used throughout the manuscript.

Data analyses

Table 2 shows an overview of the metrics (structural, functional and benthic indicator) derived from the faunal data (see Sections 0, 0 and 0). These combined with local dredging pressure data provide a profound base for biological impact assessment of aggregate dredging.

	Metric used	No impact if:
Structural	Number of species (No./grab)	at the scale of the 0.1 m² grab, the impact assemblage is as speciose as that of the reference area.
	Number of individuals (No. m^{-2})	total benthic density of the impact assemblage is similar to that of the reference area.
	Biomass (wet weight, g m^{-2})	the biomass of the impact assemblage equals that of the reference area.
	Shannon Wiener diversity (H')	the biodiversity (measured with the metric H') of the impact assemblage is similar to the reference area.
	Assemblage structure	the taxonomic identity and relative abundance of the impact assemblage matches that of the reference area.
Benthic indicator	BEQI (Benthic Ecosystem Quality Index)	the BEQI score of the impact assemblage for the different assessment parameters, is higher than 0.6, which means a comparable benthic habitat condition between impact and reference area.
Functional	Biological traits composition	the numerical composition of the impact assemblage is similar to that of the reference area with respect to life history, behavioural and morphological traits. Implying that the two areas are functionally similar.
	Bioturbation potential (BPc)	the bioturbation potential of the impact assemblage is comparable to that of the reference area.

Table 2: Overview of the biological metrics used throughout the study and how they were interpreted for impact assessment.

Calculating dredging pressure

Different measures of dredging pressure were determined based on the black box data, and the bulk size of the extraction vessel: 1) dredging intensity (total volume extracted in m³ yr^{-1}), 2) total time dredged (in minutes yr^{-1}) and 3) number of days dredged during one year prior to biological sampling. Furthermore, the interval time (in days) between the last time dredging was taking place and the biological sampling was calculated during one year prior to biological sampling. Spearman rank correlations between all measures were calculated in R 3.0.2 (R Core Team 2013) to check the relationships between the different dredging metrics.

To determine dredging pressure at a biological sampling location, real time coordinates of every sampling location were plotted in ArcMap 10. Around each location, a circular 150 m radius buffer was drawn. The shapefile with buffer locations was imported in R 3.0.2 (R Core Team 2013) to calculate dredging pressure at the biological sampling location within the buffer area (surface area 0.07 km²).

The dredging frequency at each sampling location was visualised by plotting daily extracted volumes between 2010 and 2013.

Assemblage structure

Species richness (S) and Shannon Wiener diversity (H') were calculated for every macrobenthos sample using PRIMER v6 (Clarke & Gorley, 2006). For all univariate measures (S, H', macrobenthos density, biomass and median grain size), a two-way Permanova per aggregate dredging area was performed with factors ‘year’ and ‘location’ on an Euclidean distance resemblance matrix to assess the biological impact (Anderson et al., 2008). If significant differences were detected ($p<0.05$), pairwise tests were conducted.

Further, non-parametric Spearman rank correlations between the univariate measures and the dredging pressure measures were calculated using R3.0.2 (R Core Team 2013) to identify which univariate measures were possibly influenced by the aggregate dredging.

Multivariate analyses were carried out to assess the degree of similarity in species composition between impacted and reference areas across the years. The multivariate analyses were performed on a square root transformed species abundance matrix using the Bray–Curtis similarity index, which is most commonly-used and best suitable for biological community analyses (Clarke & Warwick, 2001). To test for differences between the different sample groups (impact – reference) over the years, two-way crossed ANOSIM tests were performed with factors ‘year’ and ‘location’ at the Buiten Ratel, Oostdyck and Thorntonbank, and with factors ‘location’ and ‘Before/After’ at the Hinderbanken. The output of the ANOSIM test presents a global test with both the ANOSIM test statistic R and the p-value for this test. When the global R is significant ($p<0.05$), pairwise tests indicate where the major differences are situated, again with an R statistic and a significance level. The R statistic has a value between 0 (no differences) and 1 (completely different). For pairwise test, the significance level is very dependent on the number of replicates. Clarke & Gorley, 2006) propose that the R value is the most useful criterion to aid interpretation as it is not a function of the number of replicates. ANOSIM R-values >0.5 indicate clear differences between groups with some degree of overlap (Clarke & Gorley, 2006). To determine the species most responsible for discriminating between sample groups, where significant differences existed, the two-way crossed SIMPER procedure (Clarke & Gorley, 2006) was used with the same factors as for the ANOSIM test.

Relationships between the multivariate data cloud and environmental variables (grain size fractions, median grain size and dredging measures) were investigated through DISTLM (Distance-based linear models) analysis using stepwise selection and AICc criterion. Before running the DISTLM analysis, environmental data were normalised and collinearity among variables was examined using Spearman rank correlation coefficients. If a linear dependency between variables was identified ($r > 0.8$) only one of the variables was retained in the analysis.

Benthic Ecosystem Quality Index (BEQI)

The applicability of BEQI in detecting significant changes in the macrobenthic ecosystem due to dredging was tested on abundance, species number, biomass and species composition. BEQI is proposed as a GES (Good Environmental Status) indicator to measure whether the Belgian environmental targets as set within the Marine Strategy Framework Directive (MSFD) are reached (Belgische Staat, 2012).

The benthic indicator BEQI (www.beqi.eu) evaluates the difference in benthic characteristics (density, biomass, number of species and species composition) between two datasets (e.g. reference versus impact) (Van Hoey et al., 2007; Van Hoey et al., 2014). The outcome is scaled between 0 and 1 and divided into five classes: bad [< 0.2], poor [0.2 - 0.4], moderate [0.4 - 0.6], good [0.6 - 0.8] and high [0.8 - 1]. When the BEQI reaches an EQR (Ecological Quality Ratio) value below 0.6, it is suggested that the difference between the two datasets (reference – impact) is higher than what would be expected without human pressure. When this is the case, a detailed analysis of the outcome is advised. In order to perform a proper indicator assessment of a possible impact, the influence of the natural variability in benthic characteristics on the indicator outcome has to be minimised. Therefore, the datasets used for comparison in the assessment design should have the same habitat characteristics (such as sediment type, depth region, etc.), the same time period (season, year) and contain enough samples to obtain a confident assessment (statistical power) (Van Hoey et al., 2013).

The confidence of the BEQI assessment is based on the variability within the data in three classes (good, moderate and poor). Only the indicator outcomes that scored moderate or good were included in the results. Subsequently, an appropriate selection of the control dataset is advised, as different control data samples will have an influence on the final indicator judgment (Van Hoey et al., 2013).

Assemblage functioning

Biological traits analysis (BTA)

BTA is an ecological approach that looks beyond the mere zoological identity of taxa and the species composition of communities by focusing on the form and function of the biota; that is to say ‘what they do’ rather than ‘who they are’. Essentially, BTA uses a series of life history, morphological and behavioural characteristics of species present in assemblages to indicate aspects of their ecological functioning (Bolam, 2013). Changes in the patterns of trait composition within assemblages can be used to indicate the effects of human impacts on ecosystem functioning (Bremner et al., 2006)

The approach used in this study is adopted from Bolam (2014) and Bolam & Eggleton (2014). To estimate assemblage function, ten biological traits were chosen to describe the life history, morphological and behavioural characteristics of the constituent taxa (genus level or above) (Table 3). Each of the traits was subdivided into various categories chosen to encompass the range of possible values of all the taxa. In total, 46 categories were identified (Table 3). Some of the traits referred to measurable characteristics (e.g. size range, longevity) whose categories presented a ‘hierarchical’ organisation. Others (e.g. mobility) were wholly qualitative characteristics whose categories represented discrete classes (Bolam, 2014). Information regarding all traits was needed for all taxa, and was accessed through the traits database of the BENTHIS FP7 project. Information on traits within this FP7 project was collected from a variety of sources (see Bolam, 2014). Since taxa can display multi-faceted behaviour depending upon specific conditions and resources available, traits for each taxon were assessed using a ‘fuzzy coding’ approach (Bolam, 2014 and references herein).

The resulting ‘taxon-by-trait’ matrix was combined with the ‘taxon abundance-by-station’ (Ind. m^{-2}) matrix to create the final ‘station-by-trait’ matrix on which all subsequent trait analyses were based.

The analyses carried out to assess the similarities/differences in traits composition between impact and reference areas were analogous to those performed on the species composition data (see Section 0, ANOSIM and SIMPER procedure).

Trait	**Category**	**Description**
Maximum size	<10	Maximum size (length or height) of adult (mm)
	10-20	
	21-100	
	101-200	
	>200	
Morphology	Soft	External tissue soft and not covered by any form of protective casing
	Tunic	Body covered by a protective outer tissue made up of, for example cellulose, e.g., tunicates
	Exoskeleton	Body covered or encased in either a thin chitinous layer or calcium carbonate shell
Longevity	<18	The maximum lifespan of the adult stage (y)
	1-3	
	3-10	
	>10	
Larval development location	Pelagic Planktotrophic	Larvae feed and grow in the water column
	Pelagic Lecitotrophic	Larvae feed on yolk reserves
	Benthic (direct)	Larval stage missing (eggs develop into juvenile forms) or larvae are limited to the seabed

Egg development location	Asexual/budding	Species can reproduce asexually, either by fragmentation, budding, epitoky. Often this is in addition to some form of sexual reproduction
	Sexual-shed eggs (pelagic)	Eggs are released into the water column
	Sexual-shed eggs (benthic)	Eggs are released onto/into the seabed, either free or maintained on seabed by mucous or other means
	Sexual-brood eggs	Eggs are maintained by adult for protection, either within parental tube or within body cavity
Living habit	Tube-dwelling	Tube may be lined with sand, mucus or calcium carbonate
	Burrow-dwelling	Lives within a permanent or temporary burrow
	Free-living	Not limited to any restrictive structure at any time. Able to move freely within and/or on the sediments
	Crevice/hole/under stones	Adults are typically cryptic, predominantly found inhabiting spaces made available by coarse/rock substrate and/or tubes made by biogenic species or algal holdfasts
	Epi/endo zoic/phytic	Live on other organisms
	Attached to substratum	Attached to larger, stable boulders or rock
Sediment position	Surface	Found on or just above the seabed
	Shallow infauna (0-5 cm)	Species whose bodies are found almost exclusively below sediment surface between 0 and 5 cm sediment depth
	Mid-depth infauna (5-10 cm)	Species whose bodies are partly or exclusively found below sediment surface at a depth generally between 5 and 10 cm
	Deep-infauna (> 10 cm)	Species whose bodies are partly or exclusively found below sediment surface at a depth greater than 10 cm
Feeding mode	Suspension	The removal of particulate food from the water column, generally via filter-feeding
	Surface deposit	Active removal of detrital material from the sediment surface. This class includes species which scrape and/or graze algal matter from surfaces
	Sub-surface deposit	Removal of detrital material from within the sediment matrix
	Scavenger/opportunist	Species which feed upon dead animals
	Predator	Species which actively predate upon animals (including the predation on smaller zooplankton)
Mobility	Sessile	Species in which the adults have no, or very limited, mobility either because they are attached or are limited to a (semi-) permanent tube or burrow
	Swim	Species in which the adults actively swim in the water column (many usually return to the seabed when not feeding)
	Crawl/creep/climb	Capable of some, mostly limited, movement along the sediment surface or rocky substrata
	Burrowers	Infaunal species in which adults are capable of active movement within the sediment
Bioturbation	Diffusive mixing	Vertical and/or horizontal movement of sediment and/or particles
	Surface deposition	Deposition of particles on the sediment surface resulting from e.g. defecation or egestion

		(pseudofaeces) by, for example, filter and surface deposit feeding organisms
	Upward conveyor	Translocation of sediment and/or particles from depth within the sediment to the surface during subsurface deposit feeding or burrow excavation
	Downward conveyor	The subduction of particles from the surface to some depth by feeding or defecation
	None	Do not perform any of the above and/or not considered as contributing to any bioturbative capacity

Table 3: Description of traits and categories used in the biological traits analysis. (after Bolam, 2013 & Bolam, 2014).

Bioturbation potential

Bioturbation is the biogenic modification of sediments through particle reworking and burrow ventilation, and a key mediator of many biogeochemical processes in marine systems which in turn have important effects on ecosystem function and structure (Meysman et al., 2006). The bioturbation potential (BPc) is a metric used as a proxy for bioturbation (Solan et al., 2004; Queiros et al., 2013). Furthermore, it is one of the benthic measures incorporated as a GES indicator in the Belgian environmental targets for the MSFD (Belgische Staat, 2012).

BPc is a metric which combines abundance and biomass data with information about life traits of individual species or taxonomic groups. This information describes modes of sediment reworking (R*i*) and mobility (M*i*) of taxa, two traits known to regulate biological sediment mixing, a key component of bioturbation (Queiros et al., 2013 and references herein). The standardised functional classification table as presented in Queiros et al., 2013) was used to assign our taxa to a certain sediment reworking and mobility mode. This allowed us to calculate the BPc for each sample according to the following formula:

$$\mathrm{BPc} = \sum_{i=1}^{n} \sqrt{\frac{Bi}{Ai}} \times Ai \times Mi \times Ri$$

B*i* and A*i* are the biomass and abundance of species/taxon *i* in a sample.

To test for differences in BPc between impact and reference areas, a two-way Permanova with factors ‘year’ and ‘location’ was performed on an Euclidean distance resemblance matrix (Anderson et al., 2008). If significant differences were detected ($p<0.05$), pairwise tests were conducted.

Results

Dredging impact at the different sampling locations

Dredging impact was calculated for all biological sampling stations at the different extraction areas. There was a high correlation between the different dredging parameters calculated across all areas. Correlation between the extracted volume and both the total time dredged and the number of days dredged was highly significant with Spearman r-values of resp. 0.93 ($p<0.0001$) and 0.935 ($p<0.0001$) (Figure 2). Similarly, correlation between total time dredged and number of days dredged had a very high significant Spearman r of 0.999 ($p<0.0001$) (Figure 2). A negative significant correlation existed between these three dredging parameters and the interval between last day dredged and biological sampling time with a Spearman r of approximately -0.7.

Because of these high correlations between the different parameters, we chose to continue with extracted volume in our analysis, together with the dredging interval.

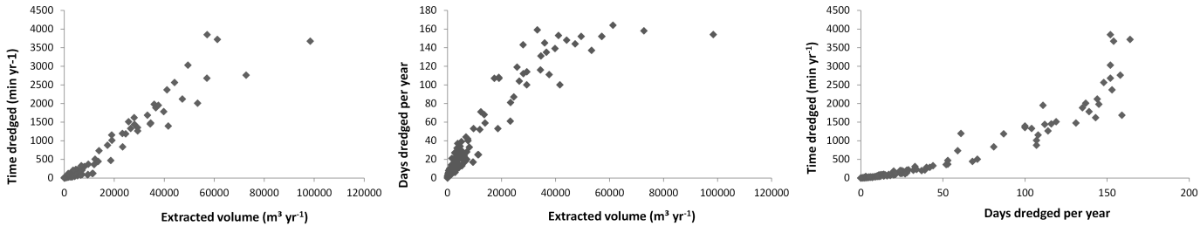

Figure 2: Correlations between the dredging parameters extracted volume (m³), time dredged (min) and days dregded.

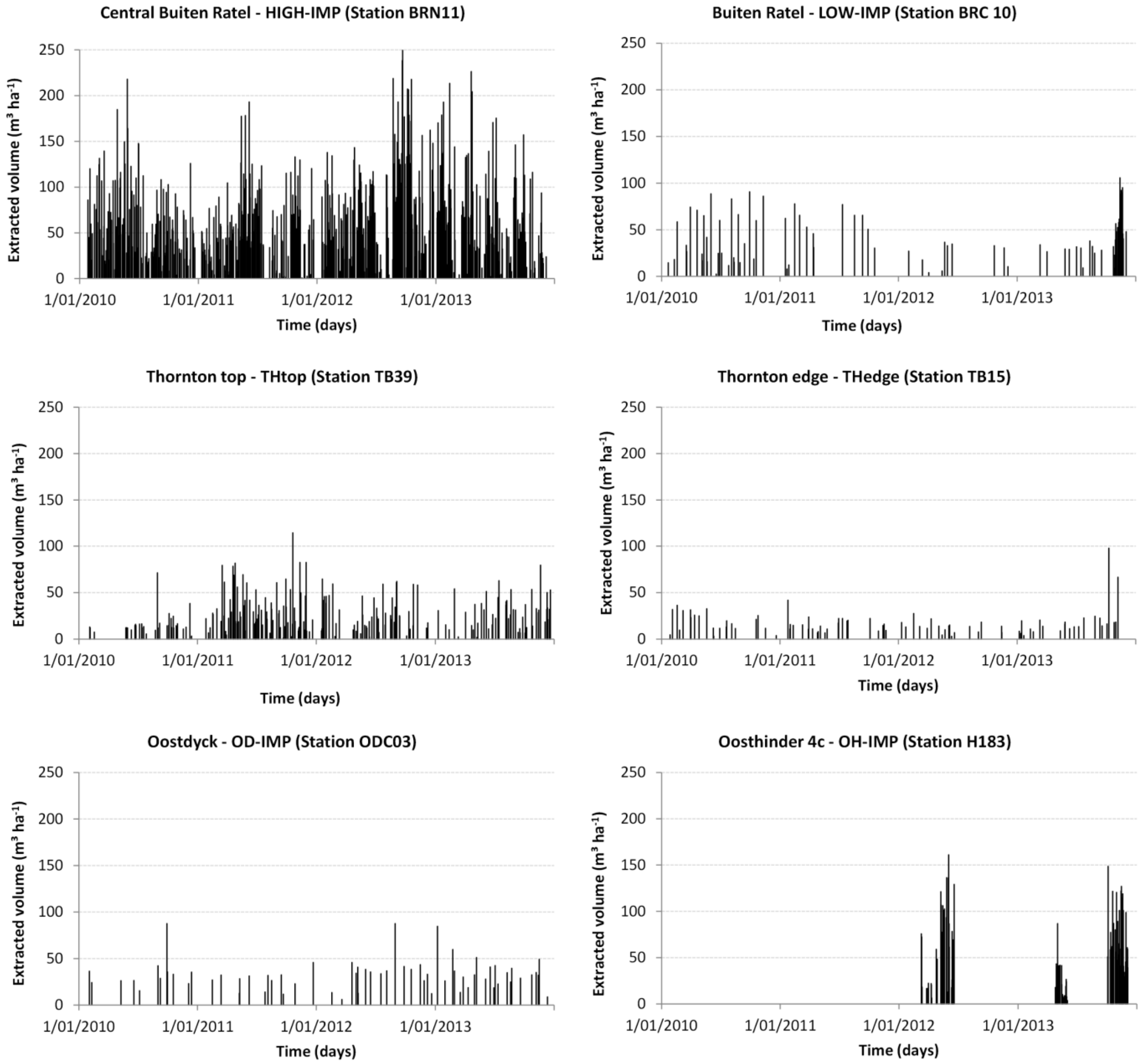

Figure 3: Daily extracted volumes (m^3 ha^{-1}) during the period January 2010 - December 2013 at a biological sampling location (buffer of 150 m around the station, 0.07 km² surface area) for the different extraction areas. The visualised biological sampling location (between brackets) is representative for all biological stations and dredging activities occurring in this particular area of the extraction zone.

Extraction volumes at our sampling locations are highest at the central part of the Buiten Ratel (HIGH-IMP) with maximum daily volumes reaching over 280 m^3 ha^{-1}. Dredging frequency is very high on the central Buiten Ratel with regular dredging activity during the entire year (Figure 3). A sampling location is on average dredged 112 days per year at an average daily extraction volume of 54 m^3 ha^{-1}. At the south of the 'extraction hotspot' on the Buiten Ratel (LOW-IMP) both dredging volume and frequency are much lower. On average, a sampling location is dredged 21 days per year at an average extraction volume of 34 m^3 ha^{-1}. At the end of 2013, extraction frequency is however increasing (Figure 3). Extraction activity at the Thorntonbank is highest at the top with on average 42 days per year extraction activity at the biological sampling location, while at the edge of the bank extraction is low, taking place at on average 10 days per year (Figure 3). Average daily volumes are resp. 24 m^3 and 15 m^3 ha^{-1}. At the Oostdyck, extraction activity is low with on average 11 days dredging per year at an average volume of 33 m^3 ha^{-1}. At zone 4c on the Oosthinder, extraction activity is high and frequent but only in certain periods of the year (Figure 3). Average extraction volume around the biological sampling location is 58 m^3 ha^{-1}. The number of dredging days per year varied between 6 and 50 days (Figure 3) with on average 20 days of dredging per year around the biological sampling locations.

Buiten Ratel

Sediment characteristics

Median grain size was significantly different between the different location groups (pseudo-F=18.297, p=0.0001) with higher median grain size in the HIGH-IMP (avg. 423 µm) and REF-HIGH group (avg. 540 µm) compared to the LOW-IMP (avg. 277 µm) and REF group (avg. 317 µm) (Figure 4 left). Dominant sediment fractions in the HIGH-IMP and REF-HIGH group were medium sand (250-500 µm, resp. avg. 40% and 33%) and coarse sand (500-1000 µm, avg. resp. 24% and 32%), while the dominant sediment fractions in the LOW-IMP and REF group were the fine sand (125-250 µm, avg. resp. 38% and 31%) and medium sand fraction (avg. resp. 58% and 53%) (Figure 4 right).

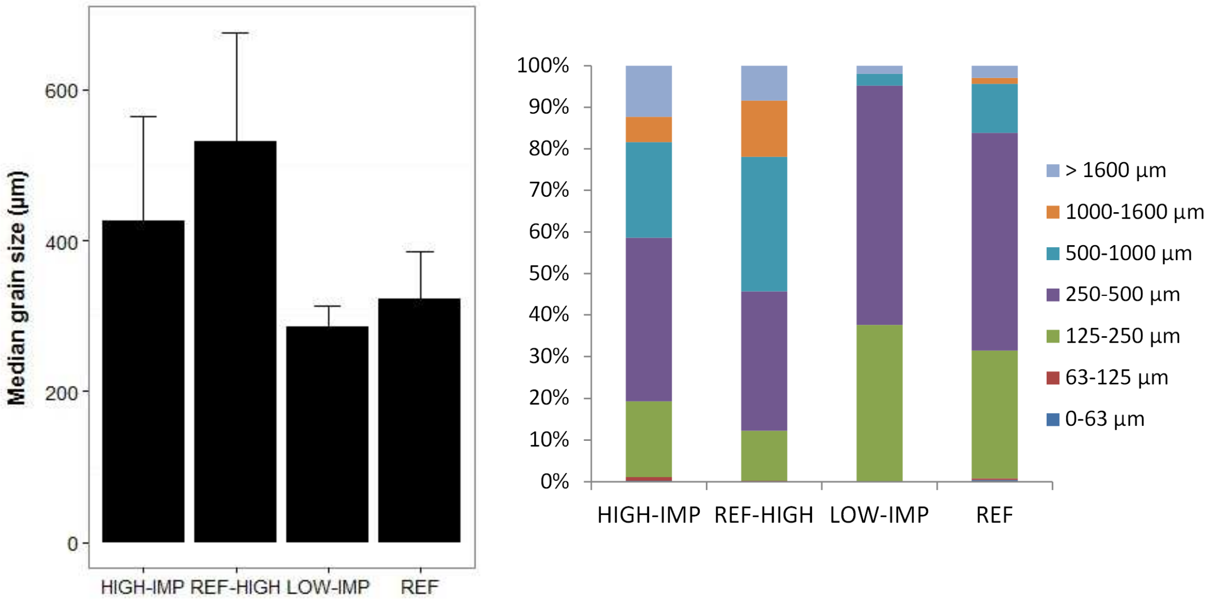

Figure 4: Average median grain size (µm)(left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Buiten Ratel.

Assemblage structure

Macrobenthic density and biomass were significantly affected by the factor ‘location’ (resp. pseudo-F=6.29, p=0.0026 and pseudo-F=5.75, p=0.0024) but not by ‘year’ or the interaction effect. Pairwise comparisons revealed significantly higher densities at the HIGH-IMP stations compared to the LOW-IMP and REF stations but density at the HIGH-IMP stations was not significantly different from the REF-HIGH stations (Figure 5). For biomass, however, HIGH-IMP stations showed a significantly lower biomass compared to the REF stations (Figure 5). LOW-IMP stations did not differ in density or biomass from the REF stations. Species richness was significantly affected by the factors ‘location’ (pseudo-F=12.81, p=0.0001) and ‘year’ (pseudo-F=4.54, p=0.007) but not by the interaction effect. Species richness was significantly higher at the HIGH-IMP stations compared to REF, LOW-IMP and REF-HIGH stations (Figure 5). REF and LOW-IMP stations showed no difference in species richness. For Shannon-Wiener diversity (H’) only the ‘location’ factor was significantly influenced (pseudo-F=5.39, p=0.0027) with both HIGH-IMP and LOW-IMP stations having a significantly higher H’ than REF stations (pairwise comparison resp. p=0.0003 and p=0.024).

Dredging intensity was significantly positive correlated with species richness (Spearman r=0.41, p<0.0001), density (Spearman r=0.2, p=0.017) and H’ (Spearman r=0.46, p<0.0001). While it was slightly negative correlated with biomass (Spearman r=-0.21, p=0.013).

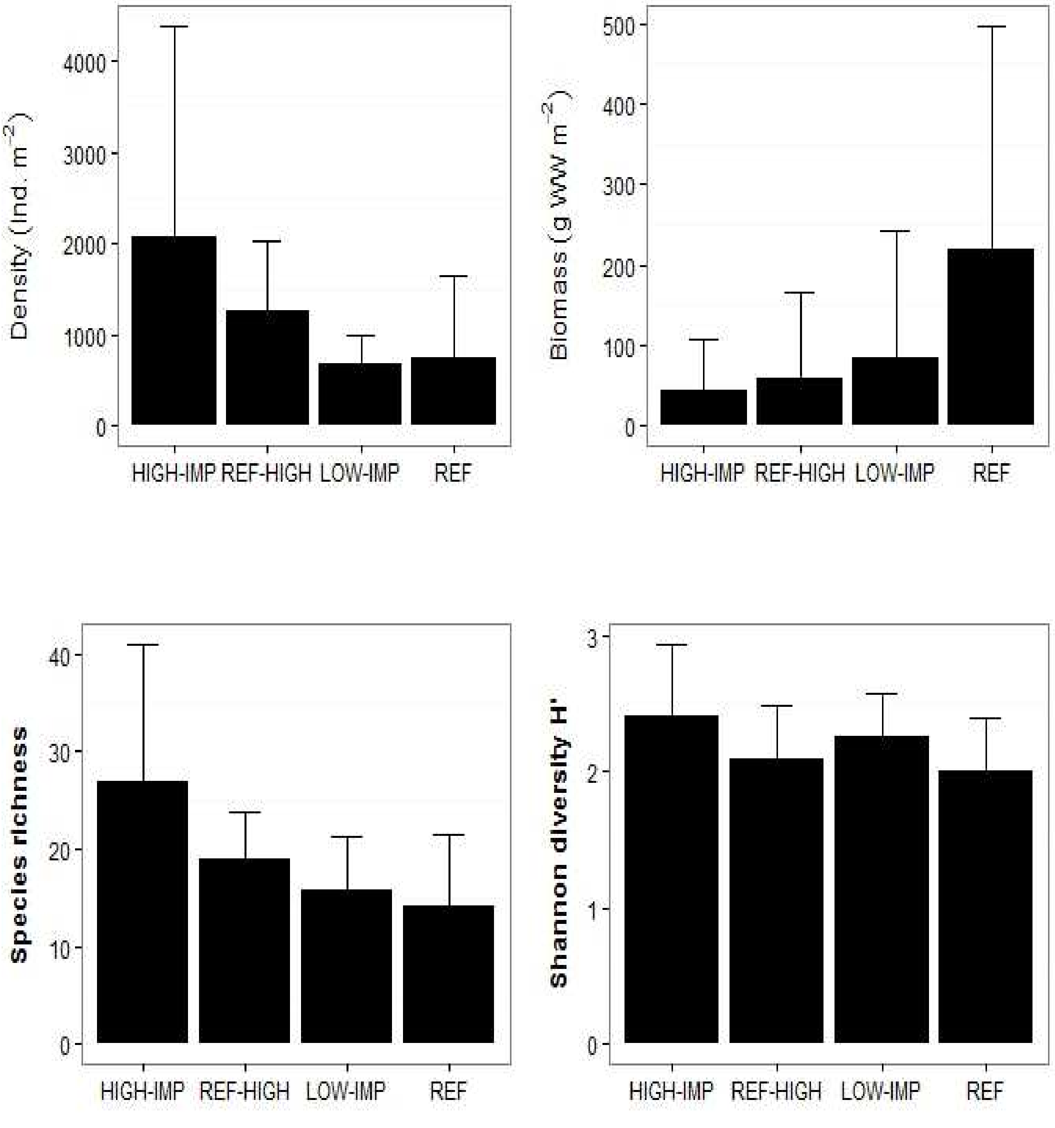

Figure 5: Univariate parameters density, biomass, species richness and Shannon diversity for the different sample groups at the Buiten Ratel.

The multivariate community composition was significantly affected by the factor ‘location’ across all years (Anosim R=0.423, p=0.0001). Pairwise tests showed that differences were significant between all groups, except between the REF and LOW-IMP group. Differences in community composition were largest between HIGH-IMP and REF (R=0.623), and least different between HIGH-IMP and REF-HIGH (R=0.364) (Table 4 and Figure 6).

The shifts in community composition were confirmed by SIMPER (impact across all years). *Nephtys cirrosa*, *Magelona johnstoni*, *Bathyporeia elegans* and *Urothoe brevicornis* belonged to the 5 most important species with respect to within-group similarity in both the LOW-IMP and REF group. All are typical for clean medium sands. While in the HIGH-IMP group, except for *Urothoe brevicornis*, different species belonged to the top 5 with respect to contributing most to the within-group similarity. Species contributing most to within-group similarity for the HIGH-IMP group were *Lanice conchilega*, *Spio* sp, *Nototropis swammerdamei* and *Eumida sanguinea*. These species were not listed or had a limited contribution (*Spio* sp.) to the within-group similarity of the REF-HIGH group, where *Hesionura elongata*, Oligochaeta sp. and *Nephtys cirrosa* were the 3 species contributing most to within-group similarity. The species for the HIGH-IMP group showed a mixture of species characteristic for medium sands and muddy sands, probably attracted by the increased presence of fine sediments caused by the overflow during dredging. Species in the REF-HIGH samples were more interstitial species, and other species characteristic for coarser sediments e.g. *Ophelia borealis*.

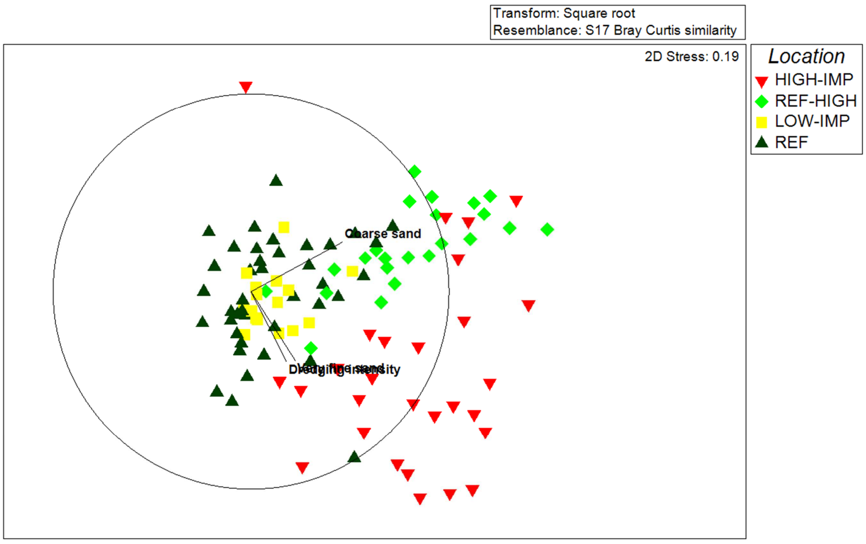

Figure 6: MDS plot based on species abundance data of the Buiten Ratel with indication of the different sample groups.

The environmental variables explaining together 24 % of the multivariate community composition were: dredging intensity (7%), the coarse sand fraction (14%) and the very fine sand fraction (3%). All increased towards the HIGH-IMP samples (Figure 6).

BUITEN RATEL	HIGH-IMP	REF-HIGH	LOW-IMP	REF
HIGH-IMP		**0.364**	**0.469**	**0.623**
REF-HIGH	0.049		**0.619**	**0.467**
LOW-IMP	0.099	**0.239**		-0.171
REF	**0.268**	**0.268**	-0.139	

Table 4: Pairwise ANOSIM R-values between the different sample groups. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

BEQI

The BEQI scores for the HIGH-IMP area indicated that there was an impact of dredging on the benthic ecosystem, especially on species composition, density and biomass (Table 5). Densities were higher than expected as based on the variability within the reference locations (Figure 5). Biomass scored bad in comparison with the REF area. This is partly caused by the nearly absence of *Echinocardium cordatum* in the HIGH-IMP area. But even without this species, biomasses in the highly impacted area were much lower than within the REF area. Species composition scored moderate compared with the REF-HIGH area which is in accordance with the multivariate analyses. However, the good status when using the REF area contradicts the MDS plot and the SIMPER analysis. This is probably caused by the high variability within both the HIGH-IMP and the REF area, which causes the indicator not to pick up the signal of change in community composition. Number of species scored high because more species were present in the HIGH-IMP area compared to both reference areas.

For the LOW-IMP area, except for biomass, the status for the different parameters is high, and the overall status is good. The moderate status for biomass was the result of less or smaller *Echinocardium cordatum* in the LOW-IMP area compared to the REF area. The lower dredging intensity in this area of the Buiten Ratel had thus no or a very limited impact on the benthic ecosystem, according to the BEQI indicator.

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Central Buiten Ratel (HIGH-IMP)	REF-HIGH	**0.49**	**1**	**0.388**	0.607	**0.621**
Central Buiten Ratel (HIGH-IMP)	REF	**0.61**	**1**	**0.185**	**0.181**	**0.494**
Buiten Ratel flank (LOW-IMP)	REF	**0.807**	**0.83**	0.825	0.535	**0.749**

Table 5: BEQI scores for the parameters similarity, species number (S), density and biomass, and the overall BEQI score for the area. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status; orange: poor status; red: bad status.

Assemblage functioning

Traits composition

The different location groups were more closely grouped when based on traits composition compared to species composition (Figure 7). Nevertheless, the trait composition of the benthic community was significantly affected by the factor ‘location’ across all years (ANOSIM R=0.158, p=0.001), but the lower R-value indicates the greater similarity in traits composition compared to species composition. Pairwise tests between the ‘location’ groups revealed significant differences in trait composition between the REF samples on the one hand, and the HIGH and REF-HIGH samples on the other hand, and between the LOW-IMP samples and the REF-HIGH samples but the R-values are very low indicating a large overlap in traits composition between these groups (Table 4). No significant differences were detected between the REF and LOW-IMP samples, and also differences between HIGH and REF-HIGH samples were not significant.

When looking at SIMPER results, trait composition with respect to within-group similarity is highly similar between the different groups which was in accordance with the observed low Anosim R-values. ‘Planktotrophic’ and ‘free living’, respectively from traits Larval type and Living habit are in all impact groups amongst the five most important traits with respect to within-group similarity. The small differences between the sample groups result mainly from differences in contribution% with respect to the within-group similarity or from differences in average abundance of the traits between the sample groups.

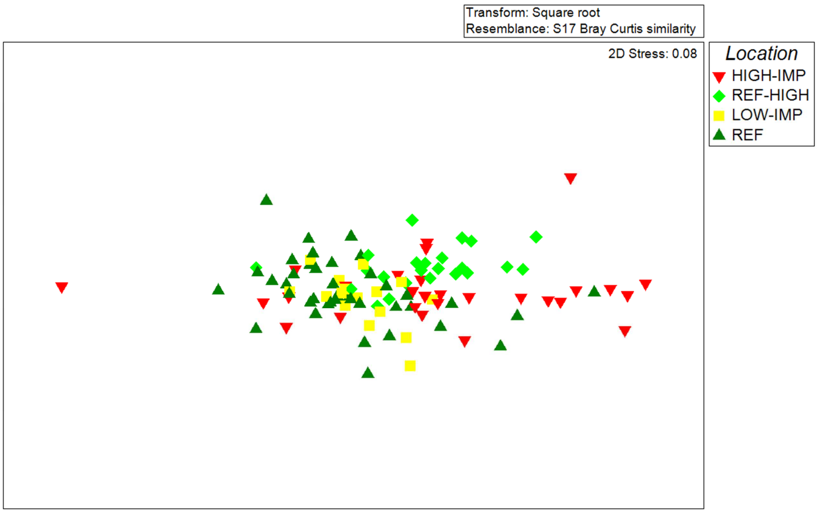

Figure 7:MDS plot based on traits abundance data of the Buiten Ratel with indication of the different sample groups.

BPc

Bioturbation potential of the macrobenthic community was not significantly affected by any of the factors 'location', 'year' or the interaction factor (Figure 8). Spearman correlation showed as well no significant correlation between BPc and dredging intensity. However, a slightly negative significant correlation was detected with median grain size (Spearman r=-0.27, p=0.0012). Thus, with a lower median grain size, a higher BPc might be expected.

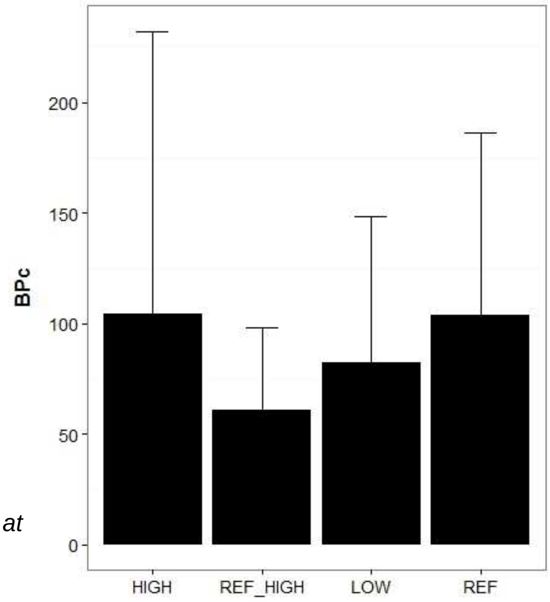

Figure 8: Average BPc for the different sample groups at the Buiten Ratel.

Oostdyck

Sediment characteristics

Median grain size was significantly affected by the factor 'location' (Pseudo-F=33.51, p=0.0001), not by 'year' or the interaction factor. Pairwise tests showed that median grain size differed significantly between all groups. We observed a decrease in median grain size from north to south, indicating a natural gradient in sediment grain size over the bank: the reference samples in the north of the Oostdyck were the coarsest with an average median grain size of 431 µm, the impact samples had an average median grain size of 346 µm, and the reference samples in the south of the Oostdyck had an average median of 310 µm (Figure 9). The dominant grain size fraction was the medium sand (250-500 µm) in all three sample groups: 64% in REF-N, 79% in IMP and 70% in REF-S. In REF-N, the coarse sand (500-1000 µm) was with average 31% the second biggest fraction, while for REF-S, the fine sand (125-250 µm) with on average 27% was the second biggest fraction. In the IMP samples, fine sand (avg. 12%) and coarse sand (avg. 7%) were the second and third most important fractions (Figure 9).

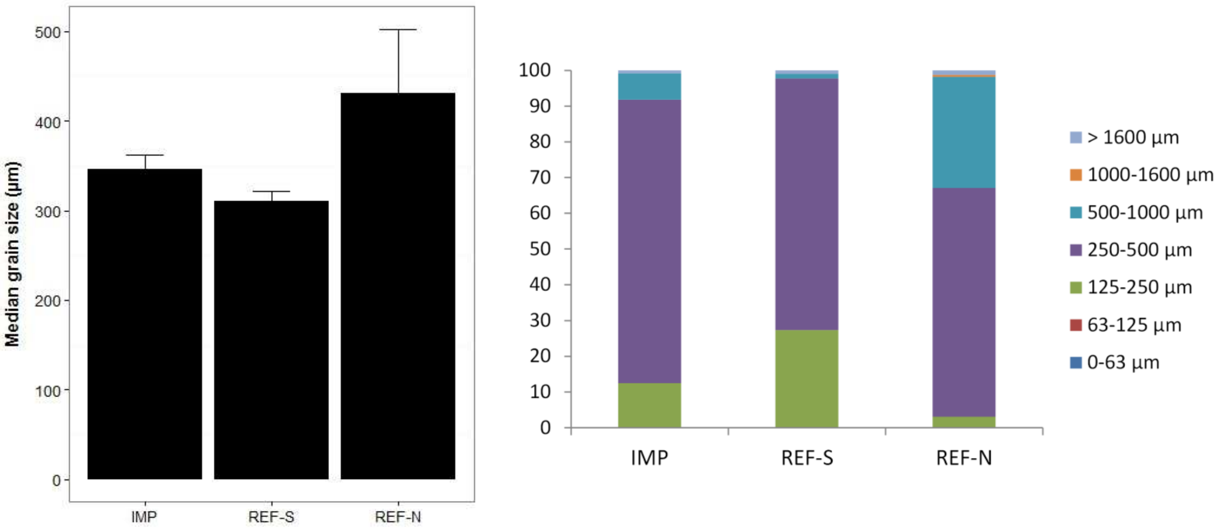

Figure 9: Average median grain size (µm) (left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Oostdyck.

Assemblage structure

Macrobenthic densities were significantly affected by the factor ‘location’ (pseudo-F=7.86, p=0.0015), but not by ‘year’ or the interaction factor. Macrobenthic densities were significantly lower in the impact area compared to both reference areas REF-N and REF-S (Figure 10). Shannon-Wiener diversity H’ was significantly affected by the factor ‘location’ (pseudo-F=3.48, p=0.04) with a significantly higher H’ in the REF-N samples compared to the REF-S samples (Figure 10). No significant differences were observed between the IMP and the reference samples. The other univariate parameters, biomass and species richness were not affected by the factors ‘location’, ‘year’ or the interaction factor.

A small, negative but significant correlation was detected between both species richness and Shannon-Wiener diversity, and the dredging intensity (resp. Spearman r=-0.29, p=0.014 and r=-0.25, p=0.042). With density, a bigger significant negative correlation with dredging intensity was observed (Spearman r=-0.38, p=0.0012) which might indicate that, although dredging intensity is low at the Oostdyck, it may negatively impact species densities.

Multivariate community composition was significantly influenced by the factor ‘location’ across all years (Anosim R=0.535, p=0.0001). Significant differences were detected between communities at the impact locations (IMP), and communities at both reference locations (REF-S, R= 0.42 and REF-N, R=0.402). But communities were even more different between both reference locations (REF-N and REF-S, R=0.824) (Table 6). The multivariate community pattern visualises the sediment gradient over the Oostdyck sandbank with coarser sediments in the north, gradually changing to finer sediments towards the south (Figure 11).

Oostdyck	**IMP**	**REF-SOUTH**	**REF-NORTH**
IMP		**0.42**	**0.402**
REF-SOUTH	**0.23**		**0.824**
REF-NORTH	0.122	**0.499**	

Table 6: Pairwise ANOSIM R-values between the different sample groups. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

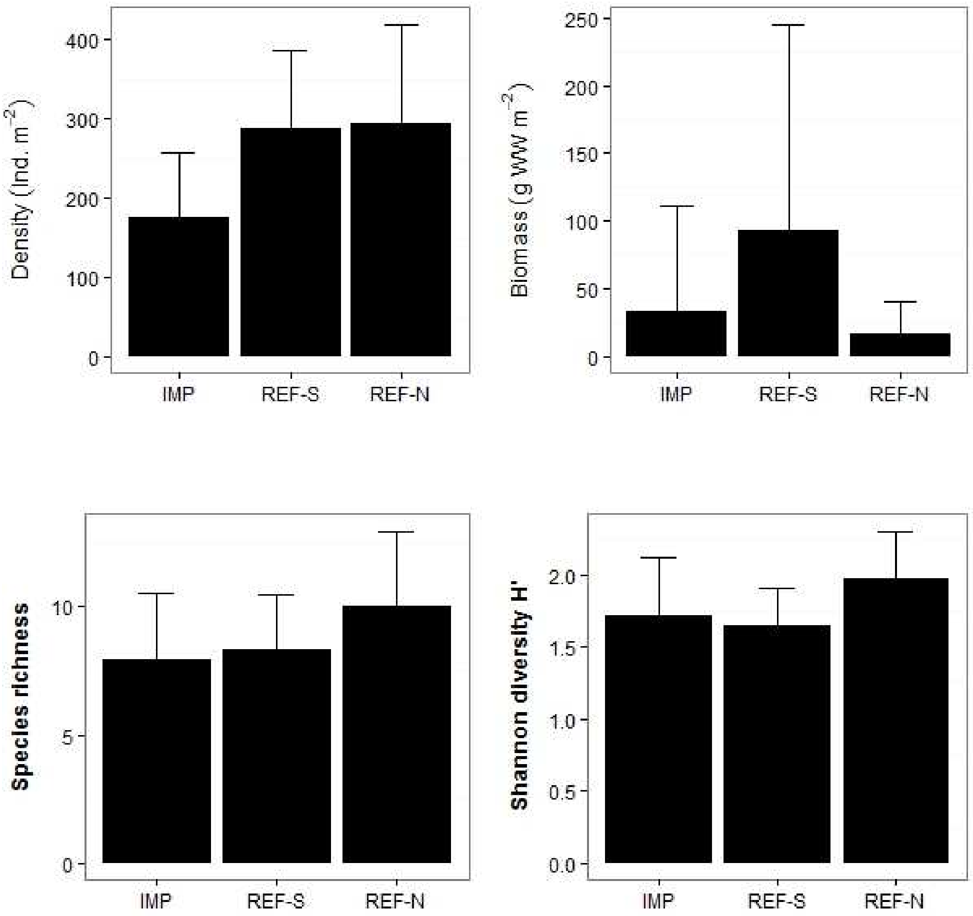

Figure 10: Univariate parameters density, biomass, species richness and Shannon diversity for the different impact and reference groups at the Oostdyck.

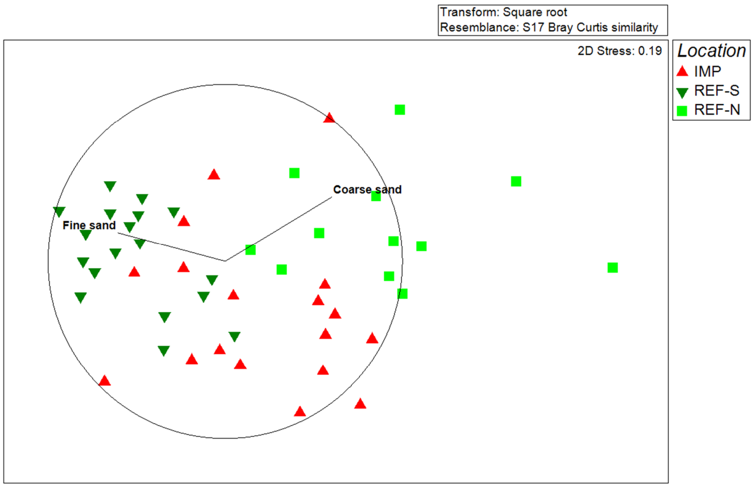

Figure 11: MDS plot of species abundance data of the Oostdyck with indication of the different sample groups.

The shift in community composition was confirmed by SIMPER (impact across all years). *Nephtys cirrosa* was in both the IMP as both reference communities (REF-S and REF-N) an important contributor to within-group similarity. Other species contributing most to the within-group similarity for the REF-SOUTH community, e.g. *Bathyporeia elegans* and *Echinocardium cordatum*, were typical for medium sands. The IMP community reflected the gradient from coarser to finer sediments in its species composition by a mixture of medium and coarser sand species such as resp. *Bathyporeia elegans* and *Ophelia borealis*. While in the REF-N community, interstitial species typical for coarse sands *Hesionura elongata* and *Protodriloides chaetifer* contributed most to within-group similarity.

The observed multivariate pattern based on species composition was best explained by the fine sand (24%) and the coarse sand fraction (8%), together explaining 32% of the observed variation (Figure 11). The dredging had no significant impact on the species composition.

BEQI

The final BEQI score indicated that the impact of the dredging on the Oostdyck was within acceptable limits (> 0.6), since the benthic ecosystem scored overall ‘good’ independent of the reference area used (Table 7). Thus, the observed variation in the impact area was overall within the boundaries of the variability within the reference area.

Since the natural variability in sediments was high in the area, using only one reference area as control resulted in moderate scores for all parameters except for species number (Table 7). This shows the importance of the use of relevant reference areas.

The moderate score for density was detected regardless of the reference area used. This suggests that the dredging impacted the macrobenthic densities. Because densities in the impact area were lower than expected based on the variability occurring in both reference area (Table 7 and Figure 10).

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Oostdyck	REF-SOUTH	**0.597**	**1**	**0.427**	0.499	**0.631**
Oostdyck	REF-NORTH	**0.563**	**1**	**0.473**	0.511	**0.628**
Oostdyck	REF-SOUTH & -NORTH	**0.677**	**0.846**	**0.434**	0.726	**0.671**

Table 7: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the area (Oostdyck). Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status.

Assemblage functioning

Traits composition

The trait composition of the benthic community was significantly affected by the factor ‘location’ across all years (Anosim R=0.267, p=0.001). The R-value is considerably smaller compared to the R-value based on the species composition matrix, indicating a bigger overlap in traits composition between the different sample groups (Figure 12). Pairwise tests revealed that REF-S differed significantly from both IMP (R=0.23) and REF-N (R=0.499) in trait composition.

SIMPER showed that the traits contributing to the within-group similarity are very similar for the different sample groups and dissimilarity percentages between sample groups are rather small (≤ 25%). ‘Free-living’, ‘diffusive mixing’ and ‘shallow infauna’, respectively from traits Living habit, Bioturbation and Sediment position, were the most important traits in terms of within-group similarity for all three sample groups. Significant differences are mainly based on differences in abundance of the traits between the different sample groups.

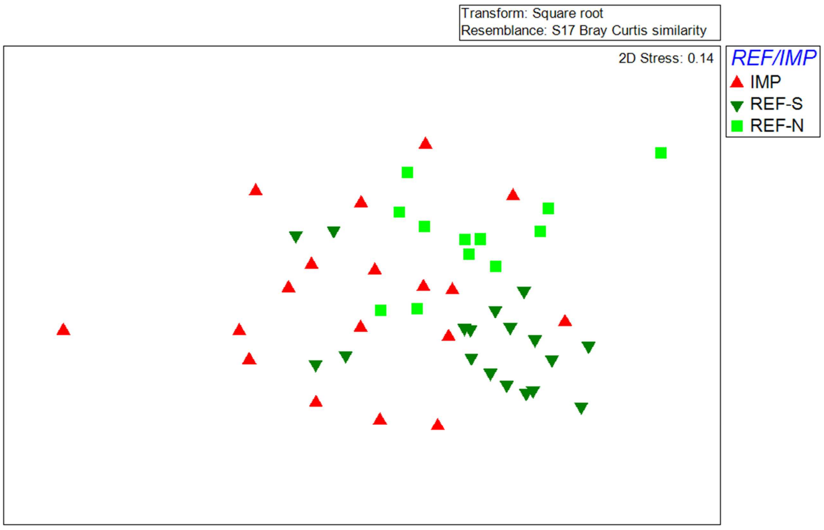

Figure 12: MDS plot based on traits abundance data of the Oostdyck with indication of the different sample groups.

BPc

Bioturbation potential was significantly affected by the factor ‘location’ (Pseudo-F=5.35, p=0.0065), not by the factor ‘year’ or the interaction factor. The bioturbation potential was noticeably higher in the REF-S group compared to both the REF-N and IMP group (Figure 13). The higher BPc in the REF-S samples is due to the occurrence of *Echinocardium cordatum* in these samples, which is an important bioturbator and not or less present in the other sample groups.

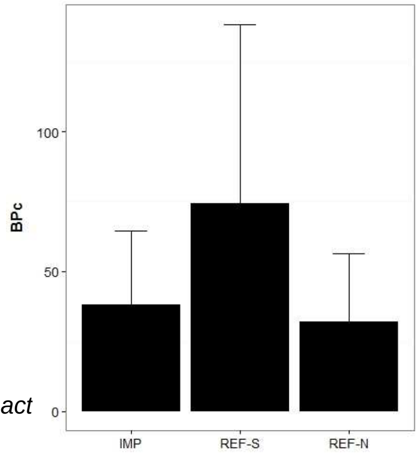

Figure 13: Bioturbation potential for the different impact and reference groups at the Oostdyck.

Thorntonbank

Sediment characteristics

Median grain size is not significantly different between the different sample groups with an average median grain size around 400 µm (Figure 14). The dominant grain size fraction is the medium sand fraction (250 – 500 µm) which constitutes around 60% of the different fractions, followed by the very coarse sand fraction (1000 – 1600 µm) which amounts approximately 20% (Figure 14).

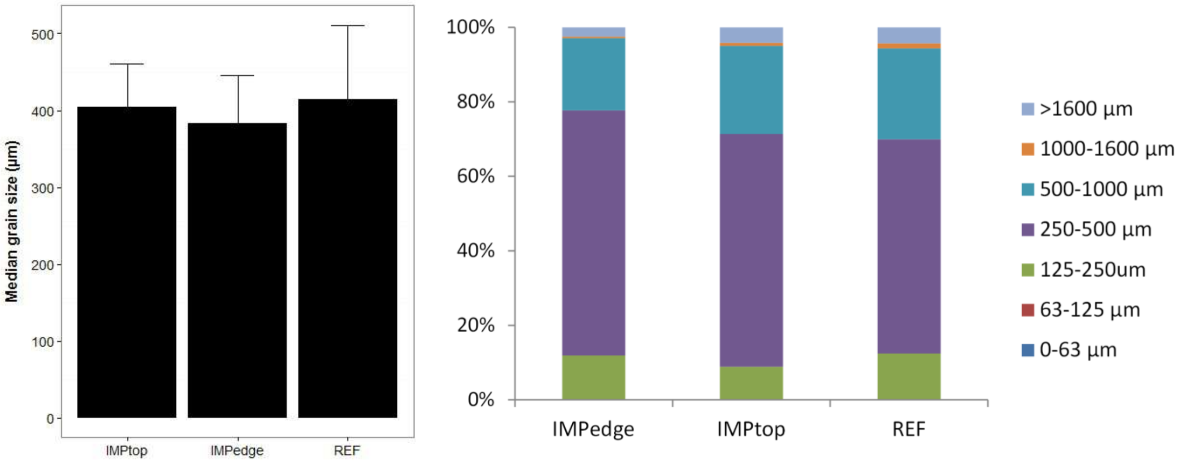

Figure 14: Average median grain size (µm)(left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Thorntonbank.

Assemblage structure

None of the univariate parameters (density, biomass, species richness and Shannon diversity) were significantly affected by the factor 'location', nor by the interaction factor. This despite the observed lower average biomass (caused by the absence of *E. cordatum*) in the most heavily impacted stations on the top of the Thornton bank (Figure 15). The only significant effect detected within the factor 'year' was for the Shannon-Wiener diversity, but this was both in the impact samples as in the reference samples.

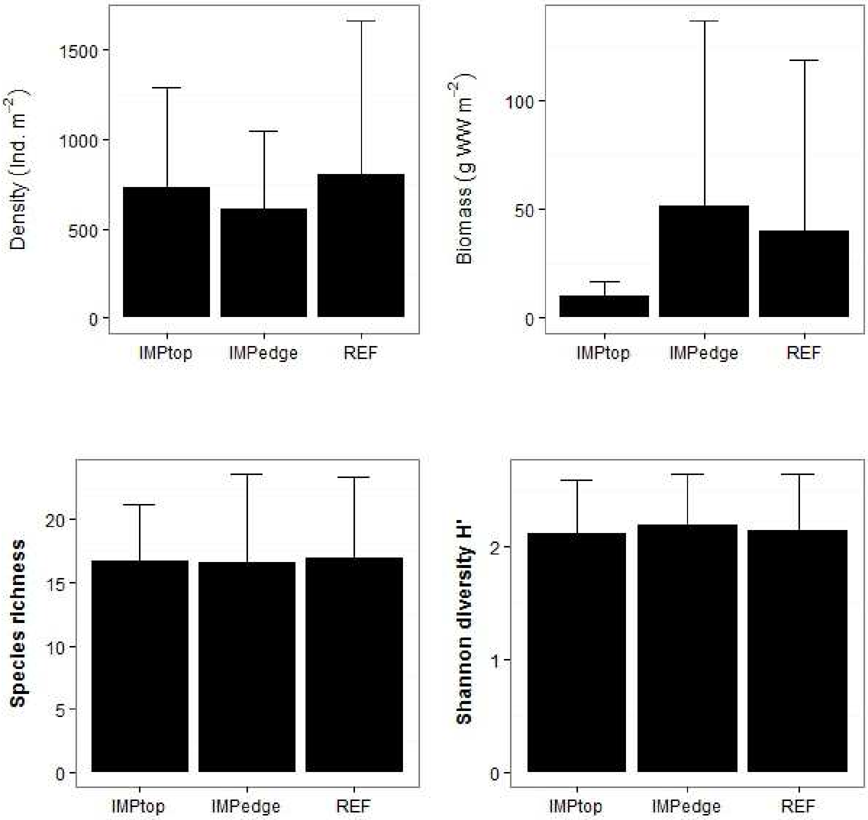

Figure 15: Univariate parameters density, biomass, species richness and Shannon-Wiener diversity for the different sample groups at the Thorntonbank.

No significant correlations were observed between the univariate parameters and dredging intensity, except for biomass. Biomass was slightly negative correlated with dredging intensity (Spearman r=-0.2, p=0.04).

Multivariate community composition was very similar between both impact groups and the reference group (two way crossed ANOSIM R=0.034, p=0.26) (Figure 16). So, the benthic community composition was not influenced by the dredging. The interannual variation was significant, but was very small with an overall R of 0.1.

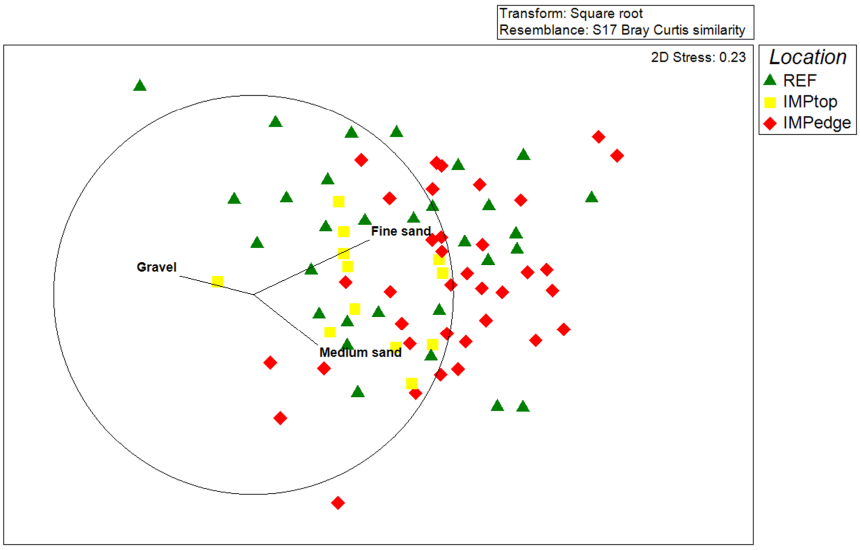

Figure 16: MDS plot of species abundance data of the Thorntonbank with indication of sample groups.

The species listed as contributing most to within-group similarity were very similar for the different groups. *Nephtys cirrosa*, *Spio* sp. and *Hesionura elongata* were among the most important common species in all sample groups.

The observed multivariate pattern was best explained by the sediment. In total 18% of the observed variation was explained by fine sand (10%), medium sand (5.5%) and the gravel fraction (>1600 µm, 2.5%) (Figure 16). Dredging intensity did not affect the species community at the Thortonbank.

BEQI

The BEQI indicator scored overall good for both the more impacted top area and the lower impacted edge area. Only for biomass, the Thorntonbank top area scored moderate, since the biomass in the impacted area was lower than expected of the variability within the reference area. For all other parameters, scores ranged from good to high for both the top and the edge area.

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Thornton top (MODERATE impact)	REF	**0.703**	**0.657**	0.834	0.562	**0.689**
Thornton edge (LOW impact)	REF	**0.664**	**0.95**	**0.693**	0.76	**0.767**

Table 8: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the impact areas at the Thorntonbank. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status.

Assemblage function

Traits composition

The trait composition of the benthic community was not affected by the factor ‘location’ (Anosim R=0.028, p=0.26), and very little affected by the factor ‘year’ (R=0.103, p=0.002). Thus, both impact groups and the reference group were functionally similar (Figure 17).

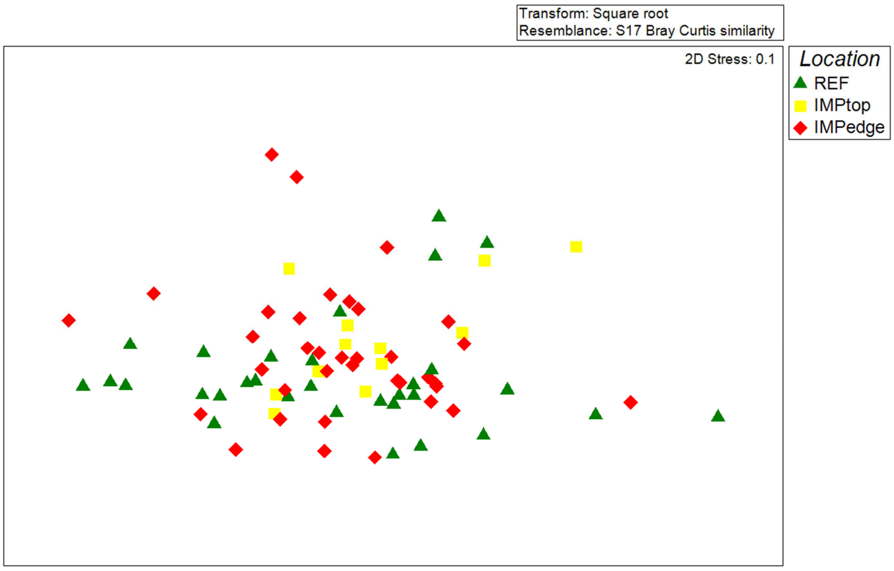

Figure 17: MDS plot of the traits abundance cdata of the Thorntonbank with indication of the different sample groups.

BPc

The bioturbation potential did not differ significantly between the different sample groups, nor between the different sampling years. Although, the bioturbation potential is on average a bit lower at the most impacted top area (42 ± SD 24) compared to the lower impacted edge area (55 ± SD 38) and the reference area (62 ± SD 46) (Figure 18). Furthermore, the BPc was slightly negative correlated with the dredging intensity (Spearman r=-0.21, p=0.04). Again, this is caused by the nearly absence of *Echinocardium cordatum* in the IMP top group.

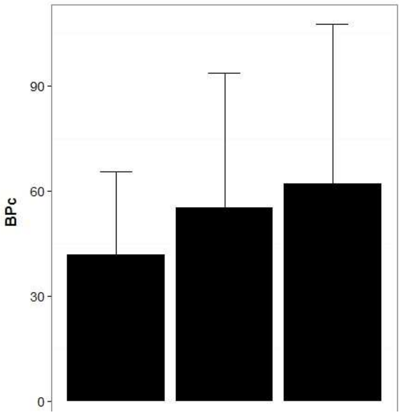

Figure 18: Bioturbation potential for the different impact and reference groups at the Thorntonbank.

Oosthinder

Sediment characteristics

Across all years, median grain size was significantly smaller for the REF-BB group (+/- 350 µm) compared to the IMP and REF group (resp. +/- 370 µm and +/-380 µm). The factor ‘year’ or the interaction factor did not significantly affect the median grain size (Figure 19). In all three groups, medium sand was the dominant grain size fraction over the years (IMP=62%, REF=74% and REF_BB=76%), followed by 16% coarse sand in both the IMP and REF group, and by fine sand (125-250 µm) in REF-BB (12%) (Figure 19).

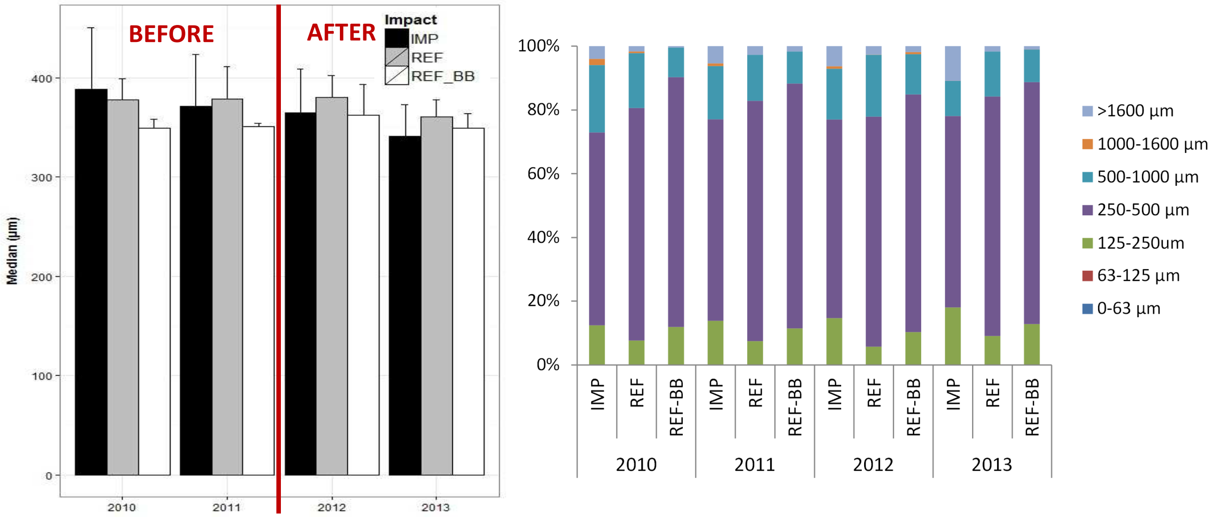

Figure 19: Average median grain size (µm) (left) and average volume percentages of the different sediment fractions (right) for sample groups during the period 2010-2013 with indication before/after dredging.

Assemblage structure

None of the univariate measures was significantly affected by the interaction factor ‘location x year’. Thus the dredging, which started in March 2012, had not a measurable impact on macrobenthic density, biomass, species richness and Shannon-Wiener diversity. However, biomass in the impact area was consistently lower after dredging started compared to both reference areas. The only significant effect detected was a lower species richness in the REF-BB group compared to both the IMP and REF group throughout the entire sampling period (2010-2013) (Figure 20). Further, no significant changes between years or sample groups were detected for any of the univariate measures.

None of the univariate parameters were significantly correlated with dredging intensity indicating again that dredging did not affect the structural metrics of the benthic community. Small significant positive correlations were observed between median grain size on the one hand and species number and density on the other hand (resp. Spearman r = 0.21, p=0.012 and r=0.22, p=0.008), which is in accordance with the observed lower species numbers and densities in REF-BB samples compared to IMP and REF samples.

Multivariate community composition was overall significantly different between the different sample groups but with a low overall R-value (ANOSIM R=0.245, p=0.001). Pairwise tests showed that most sample groups differed significantly but R-values were very small indicating a large degree of overlap (Table 9, Figure 21). The only significant changes in community composition were observed between the REF-BB in the period before dredging, and both IMP, REF and REF-BB after dredging (R≥0.45) (Table 9). All other pairwise tests between groups showed no large changes in community composition over time (very small R-values) indicating that the dredging did not influence community composition of the dredging area on the Oosthinder at present.

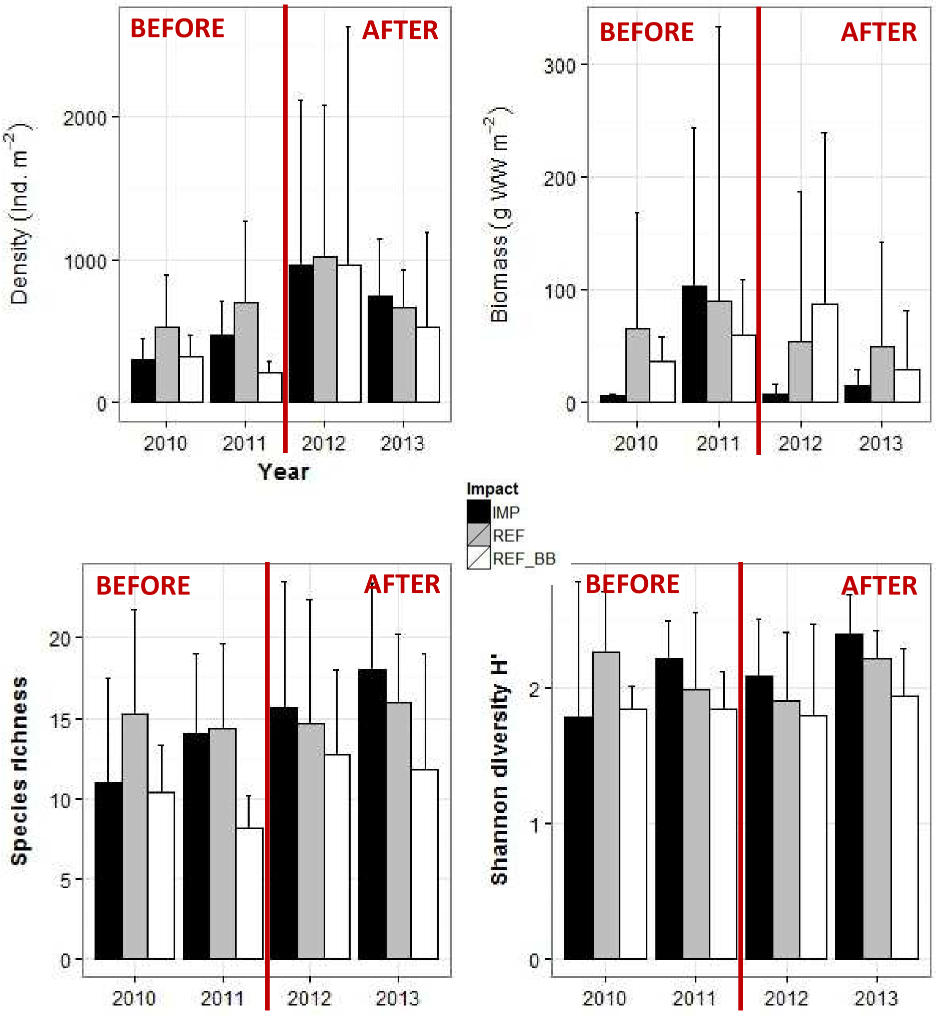

Figure 20: Univariate parameters density, biomass, species richness and Shannon diversity for the impact and both reference groups before dredging started (2010-2011) and after dredging started (2012-2013) at the Oosthinder.

OOSTHINDER	**IMP Before**	**IMP After**	**REF Before**	**REF After**	**REF-BB Before**	**REF-BB After**
IMP-Before		0.127	**0.114**	**0.201**	**0.342**	**0.281**
IMP-After	0.022		**0.231**	**0.175**	**0.511**	**0347**
REF-Before	-0.014	0.004		**0.085**	**0.304**	**0.091**
REF-After	0.075	0.018	0.025		**0.452**	**0.072**
REF-BB-Before	**0.126**	**0.263**	**0.216**	**0.299**		**0.474**
REF-BB-After	0.005	**0.086**	0.019	0.041	0.068	

Table 9: Pairwise ANOSIM R-values between the different sample groups both before and after the start of dredging. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

SIMPER showed that the differences in the REF-BB group were caused by the absence of Fabriciidae (different from REF after dredging and REF-BB after dredging), and the high abundance of *Echinocardium cordatum* (absent in IMP after dredging). In general, the community present in all groups resembled the *Ophelia borealis* community as defined by Van Hoey et al. (2004).

Sediment characteristics determined the observed multivariate species composition, and the pattern was not affected by the impact of dredging. In total only 14% of the observed variance in species community is explained by the grain size fractions medium sand (7%), fine sand (5%) and very fine sand (2%) (Figure 21).

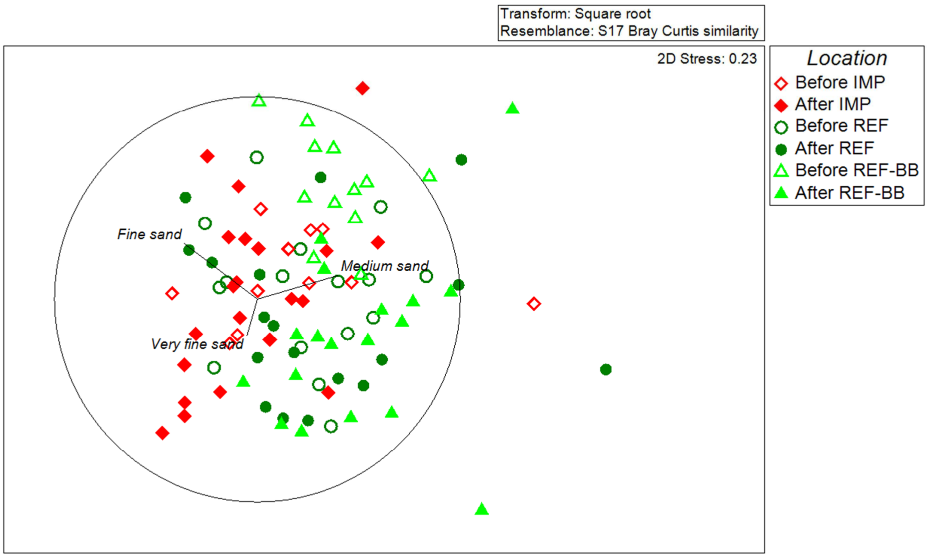

Figure 21: MDS plot of species abundance data of the Oosthinder with indication of sample groups before and after the start of dredging.

BEQI

The BEQI scored overall ‘good’ for the Oosthinder impact area independent of the reference samples used. The reference samples on the Oosthinder (REF) were most alike with the impact samples (IMP), and scored for all parameters good to high (Table 10).

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Oosthinder (Before impact)	REF	**0.72**	**0.822**	**0.644**	n.r.	**0.794**
Oosthinder (After impact)	REF	**0.616**	**1**	**0.979**	n.r.	**0.799**
Oosthinder (Before impact)	REF_BB	**0.757**	**0.968**	**0.776**	0.482	**0.746**
Oosthinder (After impact)	REF_BB	**0.595**	**1**	0.901	0.293	**0.697**

Table 10: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the impact area at the Oosthinder. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. (N.r). not reliable: insufficient power to detect changes. Blue: high status; green: good status; yellow: moderate status; orange: poor status.

Sediments in the Bligh Bank reference area (REF-BB) were finer, which gave even before dredging started, a moderate score for biomass caused by a lower abundance of the sea-urchin *E. cordatum* on the Oosthinder. After dredging started the score for biomass was poor, and moderate for similarity both due to the complete absence of *E. cordatum* in the impacted area (Table 10).

Assemblage function

Traits composition

Trait composition of the macrobenthic community was very similar between the different groups (ANOSIM R=0.076, p=0.005). All of the pairwise tests were not significant or had very low R-values, indicating a large degree of overlap in traits composition (Table 9, Figure 21). Thus trait composition was not affected by dredging at the Oosthinder area.

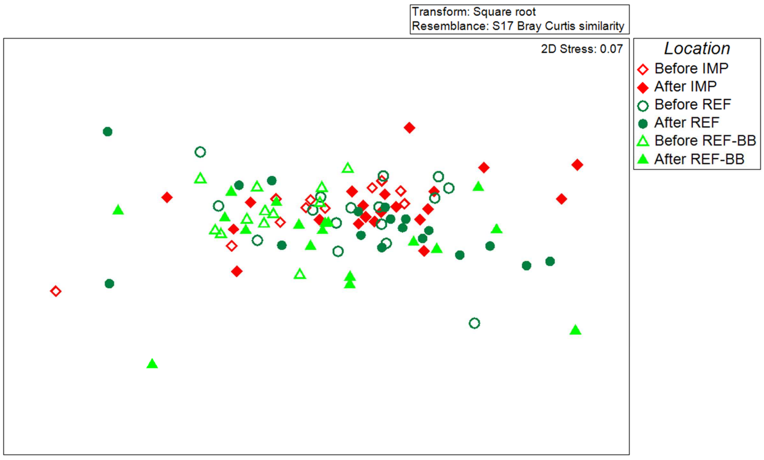

Figure 22: MDS plot of the trait abundance data of the Oosthinder with indication of samples groups before and after the start of dredging.

BPc

No significant changes were detected in bioturbation potential for the factors 'location', 'year' or the interaction factor (Figure 23). Consequently, dredging did thus not affect the bioturbation potential of the benthic community. We did however observe a small negative significant correlation between BPc and median grain size (Spearman r=-0.2, p=0.017).

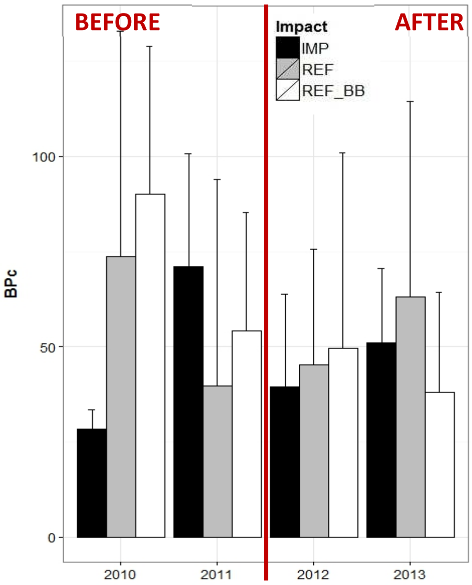

Figure 23: Average bioturbation potential for the impact and reference groups during the period 2010-2013 at the Oosthinder and Bligh Bank with indication before/after dredging.

Discussion and conclusions

A real measurable biological impact of aggregate dredging on the BPNS was only detected at the central Buiten Ratel, the most intensively used dredging area in terms of extracted volumes, and frequent presence of dredging vessels. Clear changes in species composition, density and biomass were observed. Resulting in more and different species at higher densities but at a lower biomass in the intensively impacted area. The current results are similar to previous monitoring results in this area

(De Backer et al., 2011; De Backer et al., 2014). So despite the continuous intensive dredging in the area, no collapse in species numbers and densities was observed. The dredging at the central Buiten Ratel has changed the sediment composition in such that on the one hand the sediment became coarser (more shell gravel and cobbles due to reject chute), but on the other hand there was an increased input of very fine sand as well (due to the overspill). This created a heterogenic habitat preferred by both species characteristic for very fine sand and coarser sediments The community established in the highly dredged area up to March 2011, a heterogenic, dynamic, transitional community, continued to exist until October 2013. This community was characterised as a mixture of muddy sand (*Abra alba*) and coarse sand (*Ophelia borealis*) species (De Backer et al., 2014).

Although differences in structural metrics were detected at the central Buiten Ratel, macrobenthic ecosystem functioning measured by means of BTA and bioturbation potential did not differ between the high impact and reference areas at the Buiten Ratel. Based on those two functional measures, no impact of dredging on ecosystem functioning was detected. So it appears that structural metrics are more sensitive to pick up changes in macrobenthic assemblages. Similar results were observed in other impact studies where functional recovery after impact was much faster than structural recovery (Cooper et al., 2008; Bolam, 2014). In the other studied aggregate dredging areas (Oostdyck, Thornton and Oosthinder), functional differences between sample groups, were as well less pronounced (lower Anosim R-values) in BTA compared to traditional multivariate species analysis. This indicates that although different species are present, they exert similar functions in the ecosystem, resulting in a largely similar basic ecosystem functioning. This is what one could expect intuitively, since all areas have very similar coarse permeable sandy sediments, where similar ecosystem processes are expected to occur.

Besides the observed dredging impact at the central Buiten Ratel, other signs of dredging impact on the BPNS were recorded on the Oostdyck, where densities in the impact area were reduced compared to the reference samples. Although, dredging impact on the Oostdyck is low, the continuous impact of dredging since more than 10 years, has its consequences on macrobenthic densities. However, species numbers and species composition remained stable compared to reference areas. Moreover, in most areas (Buiten Ratel LOW-IMP & HIGH-IMP, Thornton top and Oosthinder), macrobenthic biomass is negatively affected by dredging. In general, biomass is largely influenced by the presence/absence of the sea-urchin *E. cordatum*. This species is known to be sensitive to aggregate dredging (Newell et al., 1998). Even at low intensities, dredging caused *Echinocardium* to disappear or decrease in numbers, and this caused a substantial decrease in overall biomass. Furthermore, dredging in certain areas (e.g. central Buiten Ratel) influenced overall biomass as well causing older, long-living species to disappear, and inducing a higher recruitment of juvenile/young individuals, as such reducing overall biomass. A decrease in biomass is negative for the secondary production in the ecosystem, and potentially limits the food potential of the ecosystem for higher trophic levels such as epibenthos and demersal fishes.

The BEQI indicator was capable to pick up changes caused by dredging. In general, results obtained by the BEQI indicator matched perfectly the results obtained by statistically testing the univariate structural metrics and the multivariate species composition. The only case were BEQI underperformed was on species composition at the highly impacted area of the central Buiten Ratel. Because within-group variation in both the impact and the reference samples was high, differences in species composition were not detected. Since, a high within-group variation is characteristic for impact samples, it is necessary to interpret results with much caution. However, the BEQI is very useful as a quick and summarising assessment tool to detect potential dredging impact, and can thus be used in future biological impact assessment. The choice of relevant control data is imperative for reliable interpretation of the BEQI results, but this should be the case for all types of analyses in impact assessment.

A potential drawback of this study is the lack of pre-impact samples for most aggregate dredging areas on the BPNS, except for the Oosthinder. As such no real BACI- design (Before/After – Control/ Impact) is used but only a CI-design (Control /Impact). However, we tried to cope as well as possible with this pitfall by allocating suitable reference samples at similar depth profiles and within similar physical conditions for every impact area. Therefore, we are quite confident that all conclusions regarding biological effects of dredging activities based on the current CI-design are reliable. The only area which might need relocation of the reference samples is the Oostdyck to take better into account the natural gradient in sediment composition in this area.

The observed results showing such a limited biological effect of aggregate dredging are intuitively unexpected. Because most studies investigating the impact of aggregate dredging record substantial negative effects on macrobenthic assemblages (e.g. van Dalfsen & Essink, 2001; Cooper et al., 2007). The reason of the limited observed effects in our study might be twofold. First, the BPNS is an area with very high natural physical disturbances. Cooper et al. (2011) showed that the faunal sensitivity to aggregate extraction depends on the natural physical disturbance in the area, with benthic assemblages being less sensitive in areas with a high natural disturbance. Secondly, we could question whether our reference samples are really pristine samples. Fisheries on the BPNS are virtually everywhere (Vandendriessche et al., 2013; Pecceu et al., 2014), and the pressure of other human impacts (e.g. dredge disposal, offshore wind farms, shipping,…) is so high that one could wonder whether it is possible to allocate a real pristine reference area. As a consequence, we have to recognize that, even though reference samples are allocated carefully to minimise natural sources of variation, they will have been influenced by human pressure(s), and might therefore reveal a depleted macrobenthic assemblage. Because of both of the above reasons, most macrobenthic species in the BPNS are expected to be able to cope with, and to be very resilient against a certain degree of human pressure. In this respect, impacted areas are expected to be recolonised very fast by resilient and opportunistic species, even when impact is ongoing. This could explain why in most areas where the impact is relatively low, no impact was measured. On top of all this, sediments in most areas are rather uniformly dominated by medium sands, and although dredging is taking place, sediment composition has hardly changed because of the high uniformity in sediments. Only when dredging pressure is really high, and depressions are being formed like on the Buiten Ratel, sediment composition could change because other sediment layers become exposed and because of the reject chutes. As long as changes in sediment composition do not occur, no changes in macrobenthic species composition and ecosystem functioning should be expected.

To conclude, our results indicate that as long as the aggregate dredging occurs at low intensities (Oostdyck, Thorntonbank, southern central Buiten Ratel) or at high, but infrequent intensities (Oosthinder), the current sandy benthic ecosystem of the BPNS seems resilient enough to buffer the biological impact of dredging both structurally and functionally. Based on this study, no estimates can be made on the length of the period needed in between two major dredging events to allow the benthic community to buffer the impact. Therefore a more targeted monitoring should be designed. On the other hand, when the dredging pressure is high and focussed on a small surface area, that is frequently visited and dredged in high volumes, changes in sediments result in biological changes as is now visible at the Buiten Ratel. Similar observations were made in the past at the high impacted areas of the Kwintebank (De Backer et al., 2011).

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Quality assurance

All analyses were performed in a NBN EN ISO/IEC 17025 regulated environment. ILVO is certified for macrobenthos species identification with NBN EN ISO/IEC 17025 (BELAC T-315 certificate).

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