1. Near-field changes in the seabed and associated macrobenthic communities due to marine aggregate extraction on tidal sandbanks: a spatially explicit bio-physical approach considering geological context and extraction regimes

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Abstract

Based on data from Multibeam Echosounders (MBES) and Van Veen grab samples, near-field effects of marine aggregate extraction by trailing suction hopper dredgers in the Belgian part of the North Sea were assessed on a decadal scale. The combined approach allowed to investigate and compare seabed and macrobenthic community characteristics for three extraction areas with similar ecological settings, but with a different geological context and each subjected to a different extraction regime. MBES measurements detected slight alterations of the seabed for areas exposed to a continuous, low extraction regime (monthly average volume = 17 to 83 x 10^3 m^3). However, no significant changes in sediment composition nor the macrobenthic community could be attributed to this low extraction regime. High and continuous extraction in the most intensely extracted area (monthly average volume = 164 x 10^3 m^3) increased surface heterogeneity and created a local depression, hereby exposing clay and gravel from the underlying geological layer. In this area, the highest environmental impact was observed, as the physical changes in the seabed triggered a shift towards a more heterogeneous, transitional macrobenthic community including opportunistic species and species typically associated with muddy sands. Together with the species already present, this resulted in a local increase in macrobenthos density, species richness and biomass. A high but periodic extraction without screening activity on the most offshore located extraction area (monthly average volume = 230 x 10^3 m^3, averaged for those months where extraction took place) led to a redistribution of the medium to fine sand fraction and a winnowing of coarse sediment and shell fragments. The decreased median grain size induced a shift in the macrobenthic community from a typical medium to coarse sand *Hesionura elongata* community towards medium to fine sand representatives of the *Nephtys cirrosa* community, although the overall macrobenthic density and biomass in this extraction area remained stable. Based on these results, we conclude that extraction regime and local geological context are important factors driving the near-field environmental impact of marine aggregate extraction on tidal sandbanks.

1.1. Introduction

Marine aggregate extraction has increased spectacularly over the past 40 years in the North-East Atlantic, from a few hundred thousand m^3 of sand extracted per year in 1970 to tens of millions m^3 in recent years (ICES WGEXT, 2019). Extraction activities have the potential to adversely affect the marine ecosystem (Cooper et al., 2008; Desprez, 2000; Froján et al., 2011; Krause et al., 2010; Waye-Barker et al., 2015). For trailing suction hopper dredgers, the most frequently documented alterations include: sediment removal, disturbance of the seabed by the drag head (Boyd et al., 2004; Phua et al., 2002) and redeposition of material through screening activity and overspill (Cooper et al., 2011a; 2011b; Tillin et al., 2011). These processes can cause (long-lasting) changes in seabed characteristics and bathymetry (Boyd et al., 2004; Desprez, 2000; Mielck et al., 2019; Newell et al., 1998), in sediment composition (Crowe et al., 2016; De Backer et al., 2014a; McCauley et al., 1977; Van Lancker et al., 2010; Van Lancker et al., 2019) and in faunal community composition (Cooper, 2013a; De Backer et al., 2017; De Jong et al., 2015b; Vanaverbeke et al., 2007). The extent of the extraction impact is related to site-specific characteristics of the seabed, sediment composition and local hydrodynamics, next to the resilience and recovery potential of the macrobenthic community (Cooper et al., 2011b; Foden et al., 2009; Whomersley et al., 2010). Extraction intensity and frequency also influence the impact (ICES, 2016), although little is known on their cause-effect relationship with the ecosystem response. An increased understanding of such relationships can lead to mitigation measures and recommendations (eventually embedded in policy instruments) to minimize the environmental impact, which is key for a sustainable management of marine sand extraction activities (Van Lancker et al., 2010).

A major policy driver is Europe’s Marine Strategy Framework Directive (MSFD, 2008/56/EC, European Commission Directive, 2008), aiming for a good environmental status (GES) of marine waters. Eleven GES descriptors are defined, each associated with indicators to be monitored by the Member States. Consequently, each Member State has set-up a six-year cycle monitoring programme. Seabed integrity is the major descriptor to be assessed when it comes to the regulation of marine aggregate extraction. Since physical loss and disturbance are often the precursor of changes in biodiversity, integrated monitoring of both the physical and biological nature of the seabed will provide a more complete view of the situation and is therefore highly recommended.

Whilst GES assessments of the macrobenthos require point sampling (e.g. Rehitha et al., 2017; Seiderer & Newell, 1999; Waye-Barker et al., 2015), cause-effect relationships best rely on a spatially-explicit investigation and characterisation of the seabed. The latter is increasingly done by means of Multibeam Echosounder (MBES) (e.g. Kenny et al., 2003), which allows to study the relief and nature of the seabed by simultaneously acquiring bathymetry and backscatter data at high resolution. The backscatter measures the intensity of the acoustic energy scattered back to the receiving sonar antenna. It depends on the frequency of the acoustic signal used and for a given angle of incidence, the backscatter strength varies with the nature of the seabed: hard, rough bottoms made up of coarse sediments return much more energy than weakly rough, soft bottoms made up of fine sediments. For this reason, over the past two decades, the backscatter has been used more and more as a proxy to characterize the seabed nature and monitoring its evolution makes it possible to evaluate sedimentary changes (Lurton et al., 2015). Embedding MBES technology in monitoring programmes combined with macrobenthos point sampling is the fundament for more thorough GES assessments (Gaida et al., 2020; Lucieer et al., 2018; Mestdagh et al., 2020, Montereale-Gavazzi et al., 2018), ultimately leading to a better extrapolation of point sampling.

Extraction activities in the Belgian part of the North Sea (BPNS) are currently restricted to four concession zones (Royal Decree 19 April 2014). The monitoring of these activities is fourfold: (1) an Electronic Monitoring System (EMS) is installed on all aggregate extraction vessels active in the BPNS and provides information on the location and extraction activity of these vessels (Van den Branden et al., 2014; 2017); (2) regular bathymetric measurements allow to check that the extraction remains within the depth limits authorized by the regulations; (3) the official declarations with respect to extraction activities and volumes are controlled; and (4) the ecosystem impact is assessed through a legally obliged environmental monitoring programme considering seabed integrity (Law of 13 January 1969 and Royal Decree of 23 June 2010 transposing the EU MSFD). The latter includes mapping changes in seabed composition and structure using MBES bathymetry and backscatter data, and the analysis of changes in the soft-sediment associated benthic communities (Belgische Staat 2020; Roche et al., 2017).

The current study integrates data from EMS, MBES, sediment, and macrobenthos samples gathered between 2010 and 2019 at three sand extraction areas (EAs) in the BPNS. The EAs are located on top of three tidal sandbanks and have similar ecological settings and macrobenthic communities, but each of them differs in terms of extraction regime, local geological and morpho-bathymetrical context. This study focuses on direct effects in the near field of extraction. Investigations of indirect and far-field impacts are on-going. See Van Lancker et al. (2020) for a synthesis.

1.2. Study area

From a Habitat Directive perspective, the entire BPNS is considered habitat type 1110, being 'sandbanks slightly covered by seawater at all times' (Degraer et al., 2009). Depending on the location with respect to the coastline and former paleo valleys, the sandbanks have different sediment types, compositions of shell fragments, and gravel and clay, with the latter typically occurring in the troughs in-between the sandbanks (Hademenos et al., 2019; Kint et al., 2021). The offshore Upper Holocene deposits, representative of the present-day hydrodynamic regime, consist mostly of medium sands (250 – 500 µm) with a median grain size (MGS) around 300 – 400 µm (Verfaillie et al., 2006). From a biological perspective, medium sands are mainly inhabited by the *Hesionura elongata* community (average MGS around 350-400 µm), characterised by interstitial species (Breine et al., 2018). Similar ecological settings prevail in terms of temperature, salinity, timing and magnitude of organic matter production (Franco et al., 2008).

1.3. Material & methods

1.3.1. Estimation of extraction intensity

Extraction intensities over the period 2010 - 2019 were estimated in this study based on data derived from the Electronic Monitoring System (EMS); an automatic registration system used for control- and monitoring purposes that is located on each aggregate extraction vessel that is active in the BPNS. The EMS provides detailed, point-based information on the vessel location and pump status (on average every 30 seconds when extracting aggregates), together with an estimation of the extracted volume at that location (Van den Branden et al., 2014; 2017). The latter is calculated in this study as the ratio between the hopper capacity (i.e. the volume of the hopper) and the number of EMS records identified as extraction for a particular extraction trip. The estimation of the extracted volume at each location thus assumes that (1) the total extracted volume during one trip equals the hopper capacity and that (2) the extracted volume at each point-based observation is identical. For a given period, surface and spatial resolution, grids of the extracted volume and depth can be created (e.g. if the extracted volume in a grid cell equals 100 m^3 over an area of 100 m^2, the extracted depth equals 0.01 m), allowing us to properly define targeted acoustic monitoring zones and grab sample locations (see Fig. A1, supplementary figure).

1.3.2. Extraction areas and extraction history

This study focuses on three aggregate extraction areas (EAs) located on top of three tidal sand banks: EA1 on the Thorntonbank, EA2od on the Oostdyck, and EA4c on the Oosthinder sandbanks (Fig. 1). The EMS data revealed that the extraction regime largely differed between the EAs, both in terms of intensity and frequency of extraction (Fig. 2) (Roche et al., 2011b; 2017). EA1 and EA2od were extracted continuously throughout the year, predominantly for industrial purposes. Extraction rates increased since 2010 in both areas, albeit in highly different magnitudes. EA1 became the epicentre of industrial sand extraction in the BPNS in 2015, as yearly extraction rates almost quadrupled from 0.5 x 10^6 m^3 in 2010 to 1.8 x 10^6 m^3 in 2019. EA2od is much less intensively exploited, with yearly extraction rates between 2010 and 2019 not exceeding 0.4 x 10^6 m^3 of sand. The third zone EA4c was mainly exploited for coastal protection purposes and as such the extraction regime here was irregular, characterized by intense extraction events over short time periods (Fig. 2). For EA4c, the activities started in March 2012 and have been irregular throughout the years. In 2014 extraction activity peaked as 2.6 x 10^6 m^3 of sand was removed that year, all within six months (Roche et al., 2017).

Figure 1: Overview map with (a) location of the Belgian exclusive economic zone (EEZ) within the North Sea; (b) the Belgian extraction areas (EAs), monitoring zones (MZs) and extraction intensities (cumulative m³ of sand extracted per hectare from 2010 to 2019); (c, d, e) detail of macrobenthos sampling (indicating REFerence, IMPact and HIGH-IMPact samples) and vertical profile locations, for resp. EA1 Thorntonbank, EA2od Oostdyck and EA4c Oosthinder, plotted on top of the extraction intensity maps.

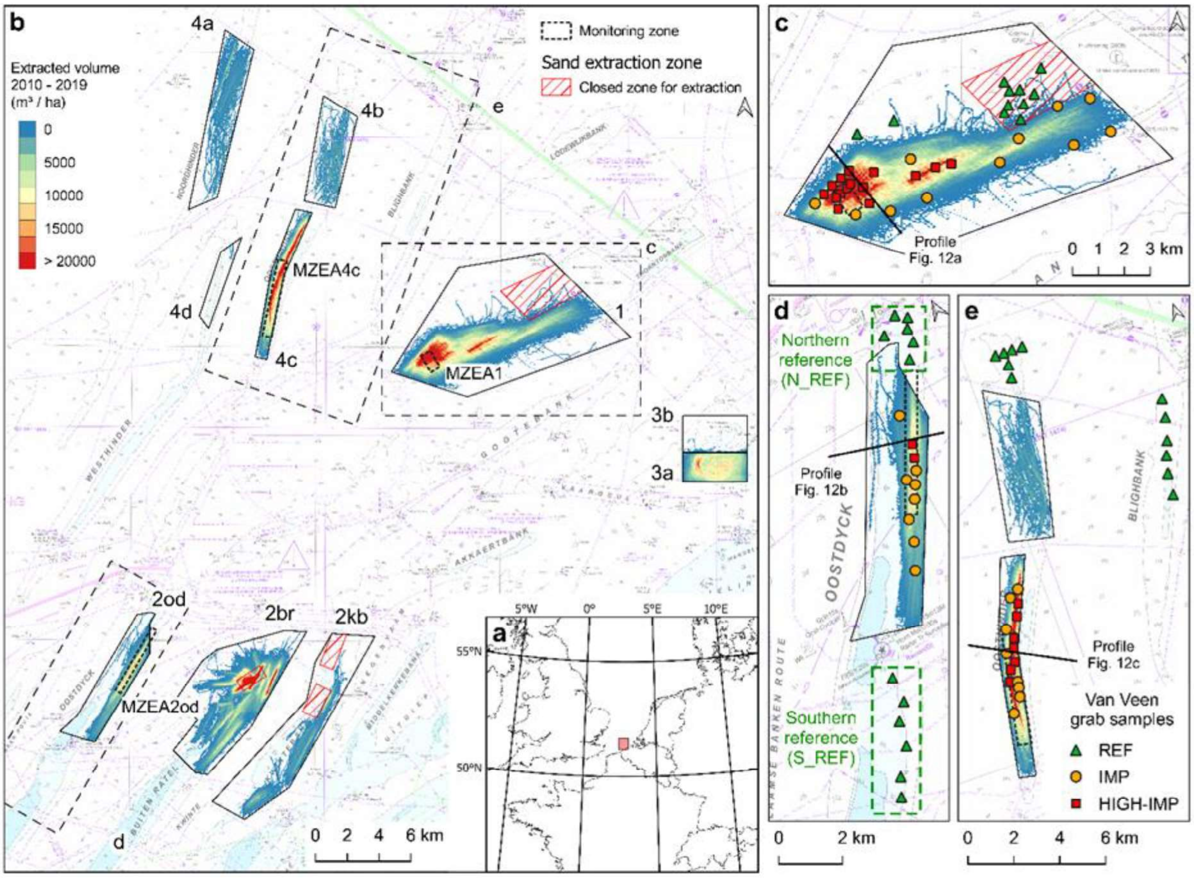
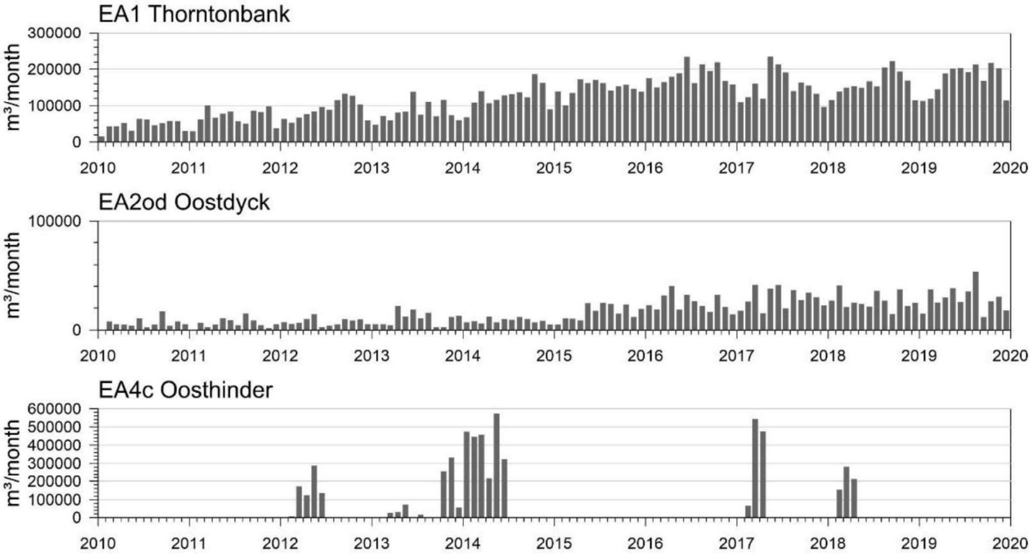


Figure 2: Extraction regimes in the three extraction areas (EA1 Thorntonbank, EA2od Oostdyck and EA4c Oosthinder) illustrated by monthly volumes extracted (m³) between 2010 to 2019.

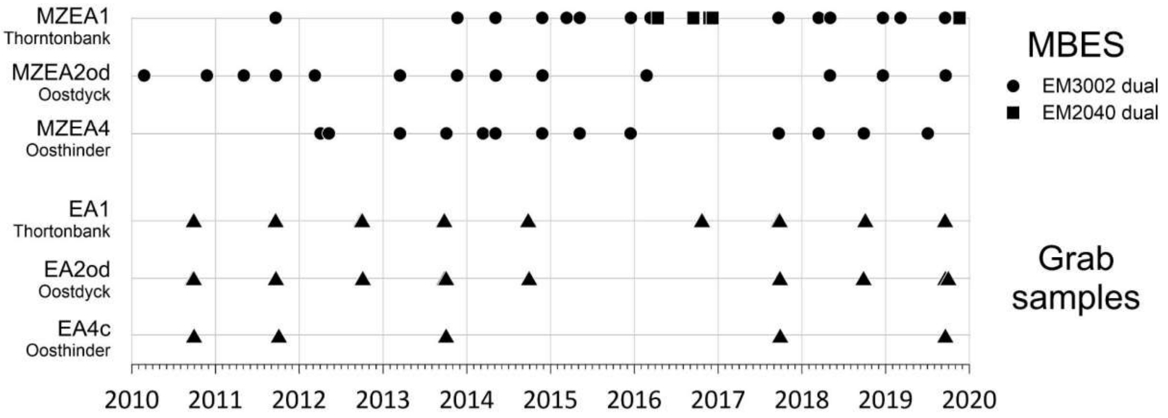


1.3.3. Sampling strategy and data analysis

Multibeam Echosounder (MBES) derived data

For each EA, MBES bathymetric and backscatter measurements were carried out regularly in dedicated monitoring zones (MZs) to control and evaluate the impact of marine aggregate extraction on the seabed integrity. The MZs considered in this study were MZEA1, MZEA2od and MZEA4c (Fig. 1). Three MBES datasets were considered, each acquired with different sensors. In the initial phase of the monitoring program, between 2000 and 2005, a bathymetric and backscatter exploration mapping of the EAs was carried out with a 100 kHz Kongsberg Maritime (KM) EM1002 installed on the RV Belgica (Degrendele et al., 2014; Roche et al., 2011a; 2017). The resulting bathymetric model was used in this study as reference level (time 0) to derive subsequent bathymetric changes based on the other MBES datasets. Simultaneously, MZs were defined and surveyed frequently. From 2009 onwards, bathymetric and backscatter time series have been acquired with a 300 kHz KM EM3002 dual MBES for each MZ at a periodicity of two to three surveys per year. These MBES time series constitute the main dataset to assess the bathymetric, morphological and sedimentary evolution in the MZs (Fig. 3). For MZEA1, additional bathymetric time series have been acquired since 2016 at 300 and 400 kHz with a KM EM2040 dual RX MBES installed on the RV Simon Stevin.

Figure 3: Data time series: Multibeam echosounder (MBES) data acquired on the monitoring zones (MZs) inside the extraction areas (EAs) (See fig. 1 for locations) and grab samples collected within the EAs. Bathymetry was analysed for MBES EM3002 dual and EM2040 dual, backscatter only for MBES EM3002 dual.



Between 2010 - 2019, the MBES KM EM3002 dual was subjected to a rigorous control of the acquisition parameters. The pulse length, which determines the instantaneous insonified area that is critical for the backscatter level calculation (Clarke, 2012), was kept at the same level in order to ensure data comparability. Secondly, the repeatability of the MBES KM EM3002 dual was verified by regular measurements on the nearby Kwintebank reference zone (Deleu & Roche, 2020; Roche et al., 2018). This backscatter time series recorded at 300 kHz produced a homogenous time series, comparable from one survey to another, which may be used as a proxy to detect significant changes in seabed characteristics. Due to the differences in frequency, beam geometry and pulse length, the data obtained with the other MBES systems were not considered in the analysis of temporal variations in the backscatter data in the different MZs. KM EM1002 backscatter data were only considered as a qualitative indicator describing the initial situation of the seabed in each of the EAs and MZs.

The MBES bathymetric dataset follows a standard hydrographic processing workflow using QPS-Qimera® (Version 2.3.1, 2020), which includes tide reduction to Lowest Astronomical Tide (LAT), correction of residual offsets and outlier soundings filtration. For each MZ, the resulting Digital Terrain Models of the successive surveys composed the bathymetric time series. The average depth difference with the reference model (time 0) was considered to assess the overall change in bathymetry and compared with the volume of sand extracted during the same time interval. For each MZ and a given time interval, the average bathymetric variation could be estimated by dividing the EMS-based extracted volume within that MZ and time interval with the area of the MZ considered. Hence, for the same time interval and MZ, the average bathymetric variation derived from the MBES and EMS data was compared. An overall uncertainty of 0.3 m for the RV Belgica KM EM3002 dual MBES bathymetric data was estimated (Roche et al., 2017).

The processing of MBES backscatter used the following approach implemented in Ifremer-SonarScope® (Version 20210107, 2021): for each survey, after suppression of the correction introduced by the manufacturer (*in casu* Kongsberg), the backscatter mean level was estimated from the raw uncompensated backscatter signal corrected for (1) the real time attenuation and (2) the instantaneous insonified area based on the incidence angle measurement provided by the Digital Terrain Model. This processing corresponds to the code A4 B0 C0 D0 E5 F0 of the nomenclature of MBES backscatter processing levels (Lamarche & Lurton, 2018). The incidence angular sector that best discriminated against the different types of sediment is the oblique-incidence sector often forming a plateau within ±[30°- 50°] (APL, 1994; Lamarche et al., 2011). The average backscatter level within the incidence angular sector of ±[30°- 50°] was used as a proxy to derive sediment change over time. To complete this approach with a cartographic visualization of the backscatter time series fluctuation, a grid of the average backscatter levels at the resolution of 10 x 10 m was computed with QPS-FMGT® (Version 7.9.5, 2020) for each survey for each MZ.

Pearson's correlation coefficient (r^2) was used to quantify the level of correlation between data derived from MBES and EMS. The detection and evaluation of time series trends was performed with a Mann-Kendall rank-based test (Rock, 1988).

Grab sample derived data

Van Veen grab samples were taken within each EA to evaluate the impact of extraction on the sediments and their associated macrobenthic communities. This was done on a yearly basis between 2010 and 2019 in September and/or October, to reduce seasonal variation within the samples (Fig. 3). With some exceptions, yearly samples from 15 to 30 different sampling locations were collected for each EA (Table A1, supplementary table). Based on an overview of the extraction intensity mapped for each area, impact locations (subjected to extraction activity) and reference locations (where no extraction has taken place) were allocated for each EA (Fig. 1). The number of locations per EA varied over the years depending on changes in extraction regime or improvements of the sampling design.

Macrobenthos was sampled by means of one Van Veen grab (sampled surface area 0.1 m^2) per location at every sampling event. 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 weighing (blotted wet weight) to the nearest 0.01 mg. All analyses were performed in a NBN EN ISO/IEC 17025 regulated environment, certified for macrobenthos species identification (BELAC T-315 certificate).

Sediment samples used for granulometric analyses were taken with a sediment core (3.6 cm diameter) from each grab sample. The fraction >1600 µm was sieved a priori, followed by the analysis of the <1600 µm fraction by means of a Malvern Mastersizer 2000G hydro version 5.40 (Malvern, 1999). Grain size fractions were determined as volume percentages according to the Wentworth scale: clay to silt (<63 µm), very fine sand (63-125 µm), fine sand (125-250 µm), medium sand (250-500 µm), coarse sand (500-1000 µm) and very coarse sand (1000-1600 µm). The fraction >1600 µm was considered as gravel, since it constituted entirely of shell hash. In addition to the sediment percentage fractions, total median grain size (MGS) was calculated.

Subsequently, the EMS-derived extraction intensity data were used to calculate the local 'sample extraction intensity' for each grab sample. This was done by calculating the amount of sand extracted within a 50 m buffer (i.e. an area of 7800 m^2) around the sample location using the cumulative extracted volume from 2009 up to the sampling date. A second extraction parameter, 'number of days between last extraction activity and time of sampling' (maximum value 366 days) was also derived from these data. Grab samples were further subdivided into three different impact groups based on sample extraction intensity: reference (REF; sample extraction intensity = 0 m^3), impact (IMP; sample extraction intensity

<7000 m^3) and high impact (HIGH-IMP; sample extraction intensity ≥7000 m^3). The threshold of 7000 m^3 sand extracted was objectively determined based on a visual inspection of a graph where sample extraction intensity for all samples and all EAs was plotted against macrobenthic S, N and W, which showed a substantial increase in outliers and between sample variance around 7000 m^3 of sand extracted.

Further analyses were performed per EA. For EA1, we discerned two extraction periods: a low extraction period (LEP; 2010 - 2014) without HIGH-IMP samples and a high extraction period (HEP; 2015 - 2019) including HIGH-IMP samples. EA2od only contained 2 HIGH-IMP samples at the end of the considered time period, therefore only IMP and REF were statistically compared. Additionally, for EA2od a distinction between reference samples taken north (N_REF) and south (S_REF) of the EA was made, to reduce spatial variation within the reference group (Fig 1d). In EA4c, a before-after control-impact (BACI) design was used since sampling started two years prior to the first extraction activities in 2012, introducing an extra time factor 'before' (B; 2010 – 2011) and 'after' extraction (A; 2012 – 2019), besides the factor 'impact group' (REF, IMP, HIGH-IMP).

Three biological univariate measures were calculated for each sample: macrobenthos species richness (S), total density (N, $N.m^{-2}$), and total biomass (W, $gWW.m^{-2}$). Additionally, sediment size class and median grain size (MGS) were also used as univariate parameters. To test for differences in these univariate measures, linear mixed effect regression models (lmer) were performed, with only 'impact group' as fixed effect for EA1 – LEP (2 levels), EA1 – HEP (3 levels) and EA2od (3 levels), while for EA4c 'impact group' (3 levels), 'B/A' (before/after) (2 levels) and their interaction factor were used. 'Year' and 'sampling location' were included in all models as random effects. If needed, the response variable was transformed to meet linear regression model requirements. A type III ANOVA, using the Wald F test with Kenward-Roger approximation of denominator degrees of freedom, was used to test for significance. If significant, differences were situated with Tukey's post hoc analysis test. When linear model assumptions could not be fulfilled, the data were square root transformed and analysed using PERMANOVA (Permutational analysis of variance) based on a Euclidean distance resemblance matrix with factors 'year' (random) (or 'B/A' (fixed) for EA4c) and 'impact group'. If significant differences were detected ($p < 0.05$), pairwise tests were conducted. A complete overview of the specific treatments used on each univariate parameter for each EA and sandbank can be found in supplementary Table A2.

Multivariate analyses were further performed on a square root transformed species-abundance matrix using the Bray – Curtis similarity index, which is most commonly-used and best suited for biological community data (Clarke & Warwick, 2001). To test for significant differences in community composition between the impact groups, PERMANOVA was applied with 'impact group' as fixed factor and 'year' as random factor for EA1 and EA2od, and 'B/A' and 'impact group' as fixed factors for EA4c. When a significant effect was found, pairwise tests were performed to situate the differences within 'impact groups' for EA1 and EA2od or within the interaction term for EA4c. PERMDISP analyses were used to test for significant differences in variance. If the PERMDISP was significant ($p < 0.05$) the PERMANOVA results were interpreted with care. A SIMPER procedure (80% abundance cut-off level) was used to investigate which species contributed most to the differences in community composition. Relationships between the multivariate data cloud and the environmental variables (sediment and extraction parameters) were investigated through DISTLM (Distance-based linear models) analysis using forward selection and AICc criterion, and visualised using a principal coordinate analysis (PCO) plot with vector overlay. This plot is a spatial representation of the similarity between samples based on their macrobenthic communities, and thus allows to have an overview of the differences within and between impact groups. Sediment based parameters (size classes, median grain size) and extraction-based parameters (sample extraction intensity, number of days between last extraction activity and time of sampling) were grouped and DISTLM was performed both on the groups and with the individual parameters. Before running the DISTLM, environmental data were square root transformed and normalised. Collinearity amongst parameters was examined using Spearman rank correlation coefficients. If a linear dependency was detected ($r > 0.8$) only one of the two parameters was kept in the analysis. For all three EAs the 'sample extraction intensity', 'number of days between last extraction activity and time of sampling' and all but one grain size fractions (very fine sand for EA1 and EA2 and clay to silt for EA4c were excluded) were kept in the analyses. Lmer models were performed using R version 4.0.3. For SIMPER, PERMANOVA, PERMDISP analyses and PCO plots we used Primer v7 with PERMANOVA add-on software (Anderson et al., 2008). A significance level of $p = 0.05$ was used in all tests. Throughout the text, averages are always given together with their standard deviation (SD).

Additional datasets

In support of the discussion, some additional datasets have been analysed per EA. They relate to: (1) local geology, based on a subsurface voxel model of the BPNS (Van Lancker et al., 2019); and (2) sediment dynamics based on systematic analyses of all bathymetric monitoring data used in the current paper. More explanation on approaches and methodologies can be found in Hademenos et al. (2019) for (1) and in Terseleer et al. (2016) for (2). For sediment dynamics, only the dune migration rate estimates are presented here, standardized in m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020). The full analyses on sediment dynamics in the BPNS will be published elsewhere.

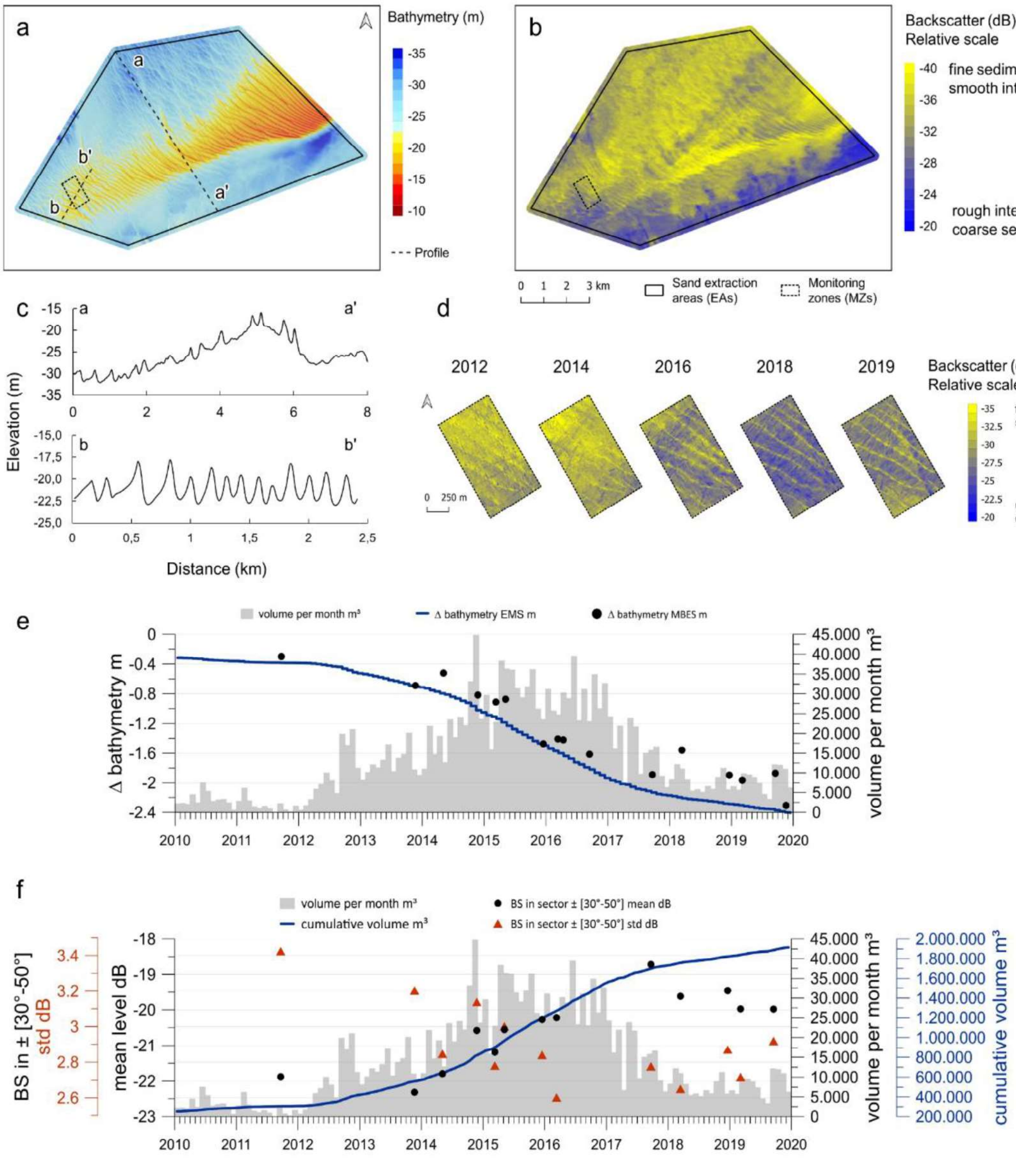
1.4. Results

1.4.1. Thorntonbank – EA1 – MZEA1

From 2010 to 2017, most of the extraction took place in the south-western part of the bank (where MZEA1 has been located). From 2018 onwards, the extraction has moved to the central part of the bank. The top of the Thorntonbank, i.e. where the extraction takes place, shows a relatively flat bathymetry, gently sloping towards the edges with an average depth level of around -22.7 m LAT (Fig. 4a, c). The seabed is shaped by a regular and stable dune pattern, with very large dunes according to the definition given in Ashley (1990), 50 to 300 m wavelength and 1 to 7 m amplitude. Dune migration rate has been estimated at 0.04 m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020).

Figure 4: Bathy-morphology and backscatter synthesis for EA1 and MZEA1 on the Thorntonbank:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2000-2001 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2000-2001 dataset; (c) Cross sections aa' and bb' of the reference bathymetric model; (d) MZEA1 grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (e) MBES Bathymetric and EMS extracted volume time series on MZEA1; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA1.



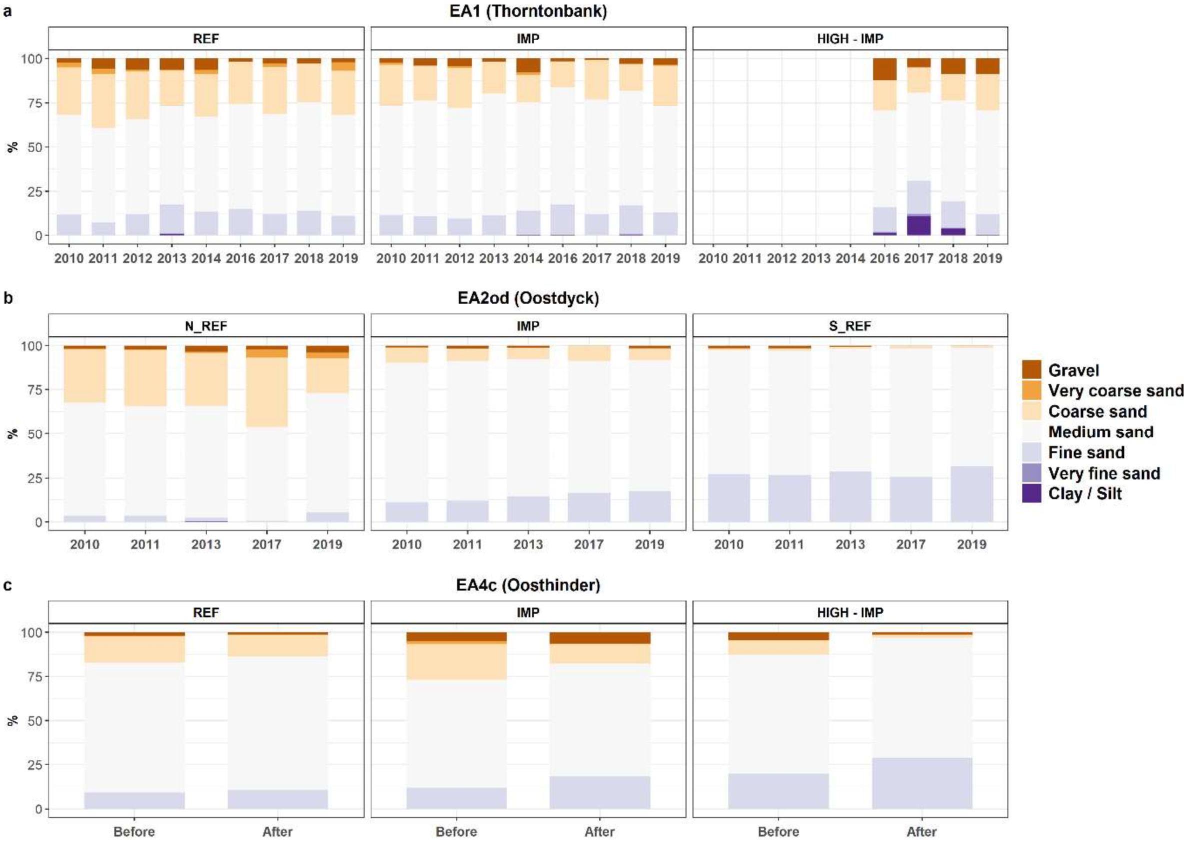
Bathymetry data

The difference in depth between the MBES measurements carried out between 2010 and 2019 and the reference model (MBES data acquired in 2000) in MZEA1 on the Thorntonbank showed a highly significant decreasing trend between 2012 and 2019 (Mann-Kendall test p-value <0.0001). The bathymetric level dropped by 2.4 m on average, but local differences up to 5 m were recorded on the top of the sand dunes. The decrease in bathymetry measured by MBES was strongly correlated with the bathymetric variation deduced from the estimated extracted volumes based on EMS-data ($r^2 = 0.91$, p-value <0.0001) (Fig. 4e). Also for the whole EA1, the bathymetric variation measured by MBES showed a close spatial correlation with extraction intensity (Degrendele et al., 2014; Roche et al., 2011b; Roche et al., 2017).

Backscatter data

In MZEA1 on the Thorntonbank, the average backscatter level in the angular incidence interval ± [30°, 50°] showed a significant positive trend (Mann-Kendall test p-value = 0.0003), ranging from -22 dB in 2014 to -19 dB in 2018 (Fig. 4f). This increase was negatively correlated with the bathymetric decrease deduced from EMS extracted volume data (r^2 = -0.75, p-value <0.001). After 2018, the average backscatter levels stabilized between -19 and -18 dB, linked to a substantial drop and a stabilization around 16 x 10^4 m^3 per month of volumes extracted in MZEA1. As can be seen from the standard deviations, the spatial variation of the backscatter level decreased from 2011 to 2015 (Mann-Kendall test p-value = 0.03) and then stabilized around 2.8 dB from 2016 to 2019 (Fig 4f). The gradual evolution between 2012 and 2019 towards a more reflective seabed is also illustrated by the successive backscatter models (Fig. 4d).

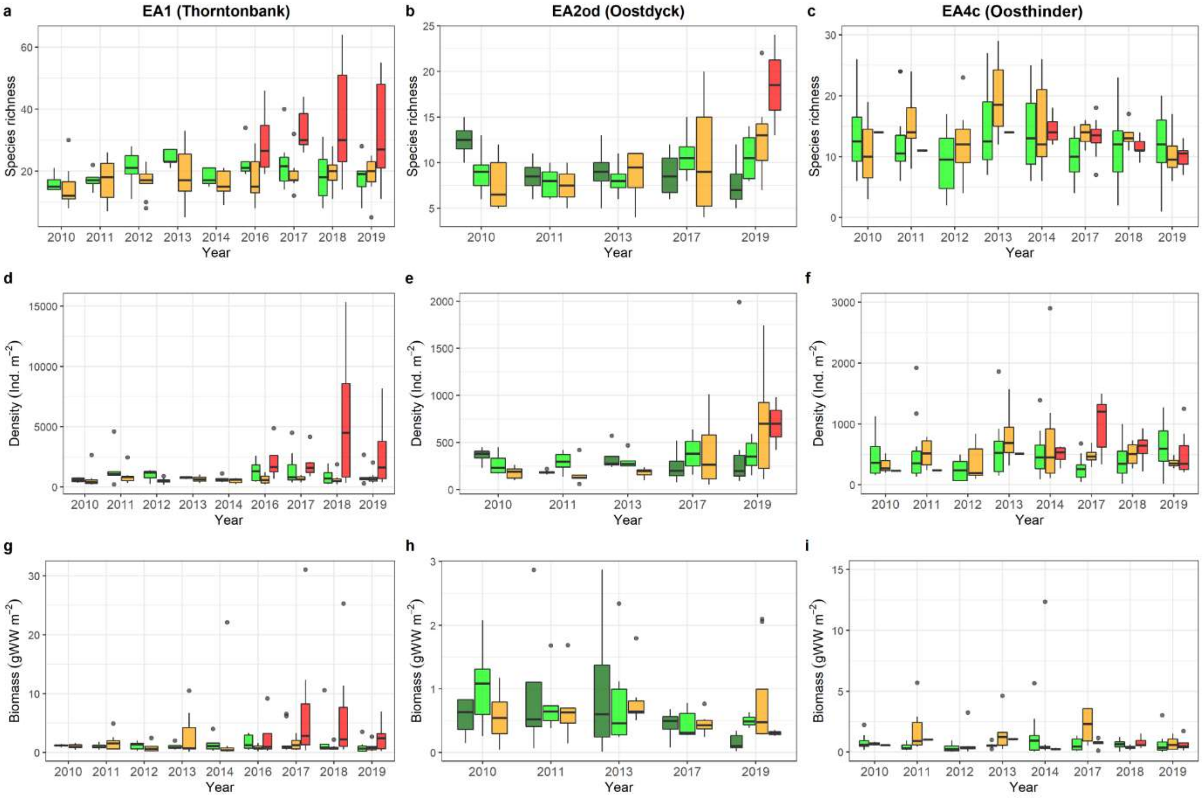
Figure 5: Relative sediment composition (%) for the three EAs for each impact group, i.e. REFerence, IMPact, HIGH-IMPact, N_REF and S_REFerence samples (the latter respectively north and south of the extraction hotspot in EA2od). For EA1 (Thorntonbank) and EA2od (Oostdyck) sampled years are shown, while for EA4c (Oosthinder) 'before' and 'after' extraction periods are shown. Legenda: Gravel >1600 µm, Very coarse sand 1600 - 1000 µm, Coarse sand 1000 - 500 µm, Medium sand 500 - 250 µm, Fine sand 250 - 125 µm, Very fine sand 125 - 63 µm, Clay to silt 63 - 0 µm.



Sediment data

The IMP samples in EA1 on the Thorntonbank had a slightly higher medium sand fraction (average ± SD: 64.04 ± 9.82%) compared to the REF samples (54.37 ± 11.31%) (p_{Anova} = 0.048). Even so, IMP and REF samples did not differ for any of the other sediment classes (p_{Anova} >0.2) during the low extraction period (EA1-LEP) (Fig. 5a). Also during the high extraction period (EA1-HEP), sediment composition did not differ between IMP and REF. However, HIGH-IMP did have significantly higher fractions of gravel (2.69 ± 1.01%) compared to IMP (1.29 ± 0.70%) and REF (1.29 ± 0.90%) (p_{Anova} <0.0001) during this HEP. Also, clay to silt fraction percentages were generally higher for HIGH-IMP locations in EA1, while nearly absent in IMP and REF locations in both LEP and HEP (Fig. 5a). Median grain size (MGS) did not differ significantly between the three impact groups over the whole study period.

Figure 6: Macrobenthos species richness (S), density (N) and biomass (W) per year for the three EAs and for each impact group, i.e. REFerence, IMPact, HIGH-IMPact, N_REF and S_REFerence samples (the latter respectively north and south of the extraction hotspot in EA2od). For EA1 only the high extraction period (HEP, 2016 – 2019) included HIGH-IMP samples.

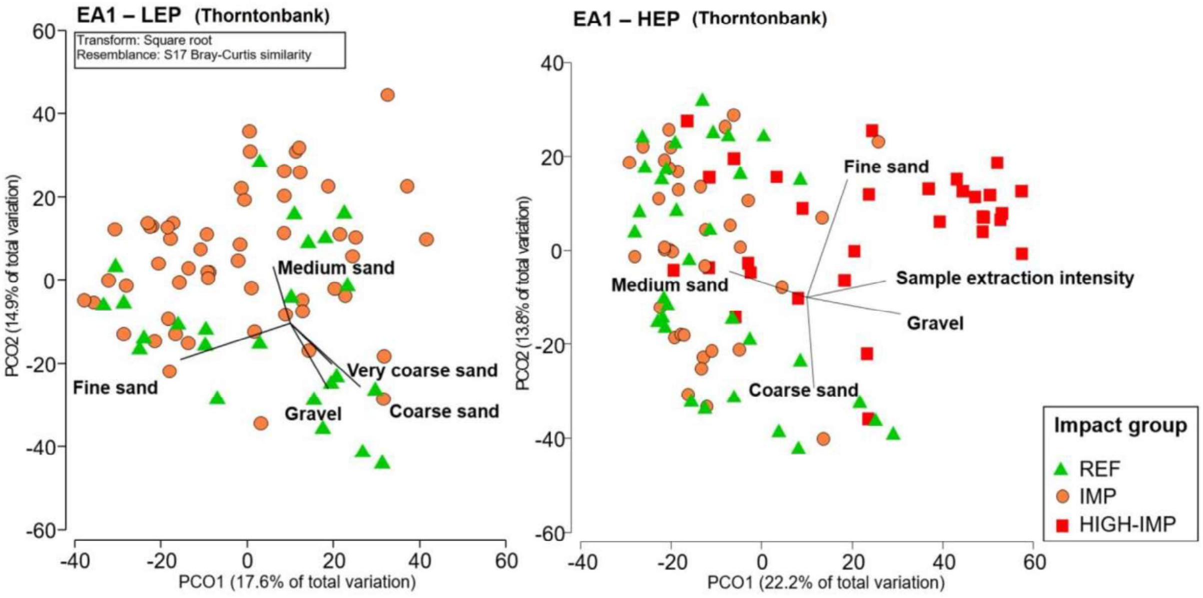


Macrobenthos data

Macrobenthos density (N) and biomass (W) did not differ between impact groups during the LEP in EA1 on the Thorntonbank, but species richness (S) was slightly higher (p_{Anova} = 0.03) in REF compared to IMP samples (Fig. 6a, d, g). Community composition differed significantly between REF and IMP (p_{Perm} = 0.01) (Fig. 7, left) with no significant dispersion between impact groups ($p_{Permdisp}$ = 0.8081). SIMPER revealed that the main dissimilarity was due to higher densities of oligochaetes and *Hesionura elongata* in the REF area. Despite these density differences, IMP and REF are both characterized as *H. elongata* community (Breine et al., 2018). Sediment parameters (size classes and MGS) explained 27.5% of the observed multivariate pattern, while only 2.6% was explained by the extraction parameters (grouped DISTLM marginal test results).

During EA1-HEP on the other hand, N, S and W strongly differed between impact groups (resp. p_{Anova} <0.0001; p_{Anova} <0.0001; p_{Anova} <0.001), with significantly higher and more variable values for HIGH-IMP (S = 32.6 ± 13.8; N = 3257.4 ± 3537.9 ind.m^{-2}; W = 5.1 ± 7.3 g.m^{-2}) compared to IMP (S = 17.3 ± 6.0; N = 650.7 ± 420.5 ind.m^{-2}; W = 1.5 ± 2.6 g.m^{-2}) or REF (S = 19.9 ± 6.2; N = 1041.4 ± 897.9 ind.m^{-2}; W = 1.5 ± 1.8 g.m^{-2}), where IMP and REF did not differ significantly ($p_{Post\ hoc}$ >0.05 for N, S and W) (Fig. 6 a,d,g). Community composition differed significantly between impact groups (p_{Perm} = 0.007) with slightly significant differences in dispersion ($p_{Permdisp}$ = 0.0156) due to a higher dispersion in HIGH-IMP (Fig 7, right panel). Pairwise tests showed that the HIGH-IMP community structure differed significantly from IMP (pairwise p_{Perm} = 0.0271) and REF (pairwise p_{Perm} = 0.0272), which did not differ significantly from one another (pairwise p_{Perm} = 0.1). SIMPER analysis revealed IMP and REF were still *H. elongata* community according to Breine et al. (2018), while HIGH-IMP differed due to the presence of muddy sand species as *Kurtiella bidentata*, *Lanice conchilega*, *Abludomelita obtusata* and opportunists as *Poecilochaetus serpens*, *Echinocyamus pusillus*, *Spiophanes bombyx* and juvenile *Ophiuroidea*. *Hesionura elongata* community representatives were still present in HIGH-IMP samples, albeit in lower densities. During the HEP, 12.6% of multivariate sample variation could be attributed to extraction, and 31% to sediment parameters (grouped DISTLM marginal test results).

Figure 7: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA1 on the Thorntonbank, with indication of the three impact groups (REF, IMP, HIGH-IMP). Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset. Left: low extraction period (LEP, 2010 - 2014), right: high extraction period (HEP, 2015-2019).



1.4.2. Oostdyck – EA2od – MZEA2od

In EA2od, most of the sand extraction took place on the gently sloping eastern flank of the Oostdyck sandbank, i.e. inside MZEA2od, which has a mean depth of -14.9 m LAT (Fig. 8a, b). The dune morphology in MZEA2od showed a pattern of very large dunes with a wavelength of 150 m, an amplitude around 2 m and a well-marked SW-directed asymmetry, corresponding to a predominance of the ebb-tidal currents. This pronounced asymmetry corroborates the high dune migration rates in this area, which may exceed 1 m per Spring-Neap tidal cycle (Van Lancker et al., 2020).

Bathymetry data

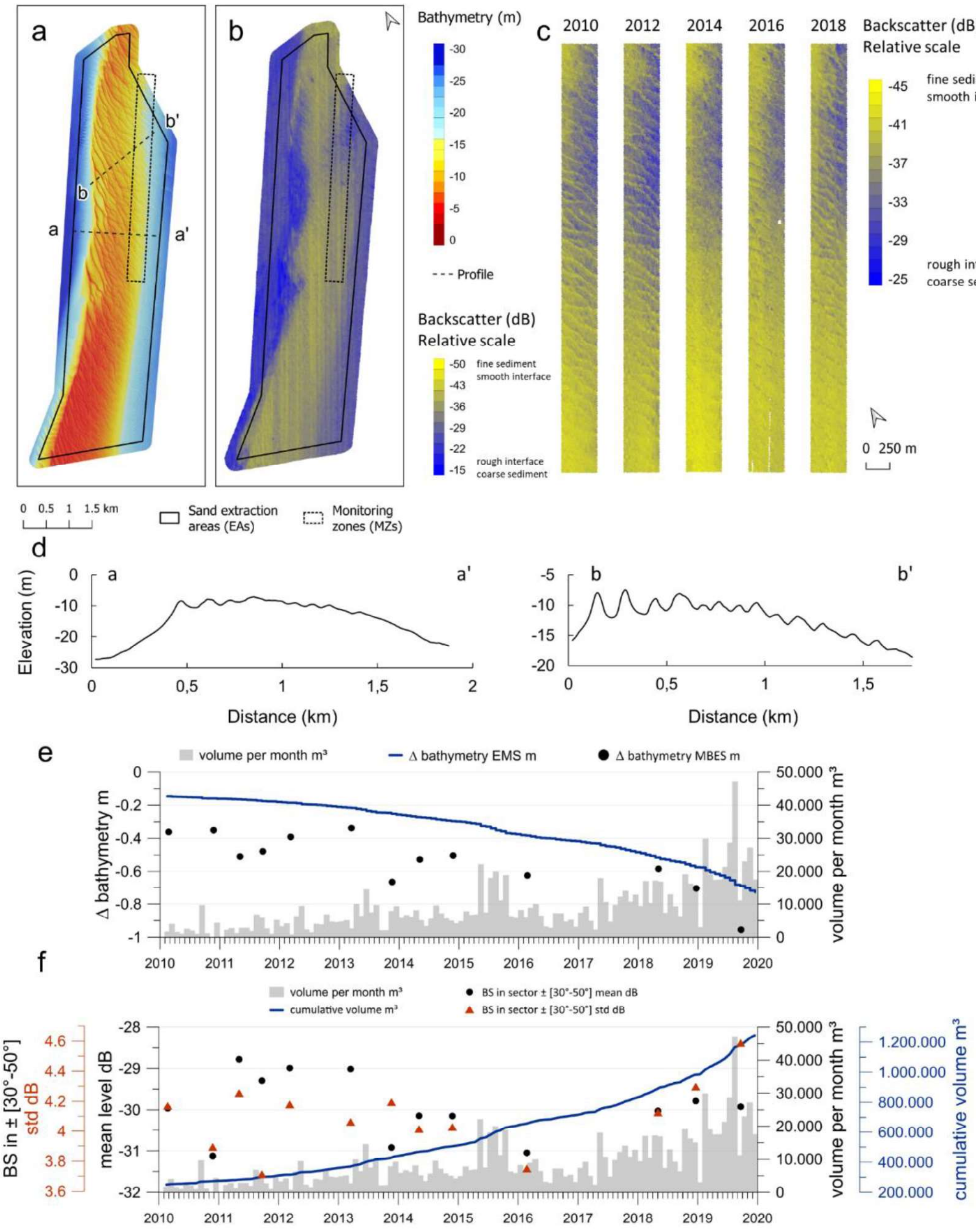
The mean bathymetric variation measured by MBES was relatively well correlated ($r^2 = 0.73$, p-value = 0.0002) with the bathymetric variation estimated from the extracted volumes based on the EMS-data (Fig. 8e). The bathymetric data recorded between 2010 and 2019 showed a significant negative trend with an average final deepening of almost 1 m. On most of the measurements, a vertical bias of on average 0.25 m was observed between the MBES and EMS data. This bias probably results from a combination of systematic errors, an underestimation of the volumes extracted in the EMS data on the MZEA2od, and/or a bias on the bathymetric reference model and the subsequent bathymetric data from the MBES.

Backscatter data

MZEA2od on the Oostdyck showed intermediate to moderately high backscatter levels, suggesting a fine to medium sand sediment cover. The average levels and standard deviations fluctuated around average values of -30 dB ± 4 dB, without a clear significant trend (Fig. 8f) nor a correlation with the extracted volumes values derived from EMS data. The successive models of the backscatter (Fig. 8c) confirmed the lack of a clear trend.

Figure 8: Bathy-morphology and backscatter synthesis for EA2od and MZEA2od on the Oostdyck:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2003 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2003 dataset; (c) MZEA2od grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (d) Cross sections aa' and bb' of the reference bathymetric model; (e) MBES Bathymetric and EMS extracted volume time series on MZEA2od; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA2od.



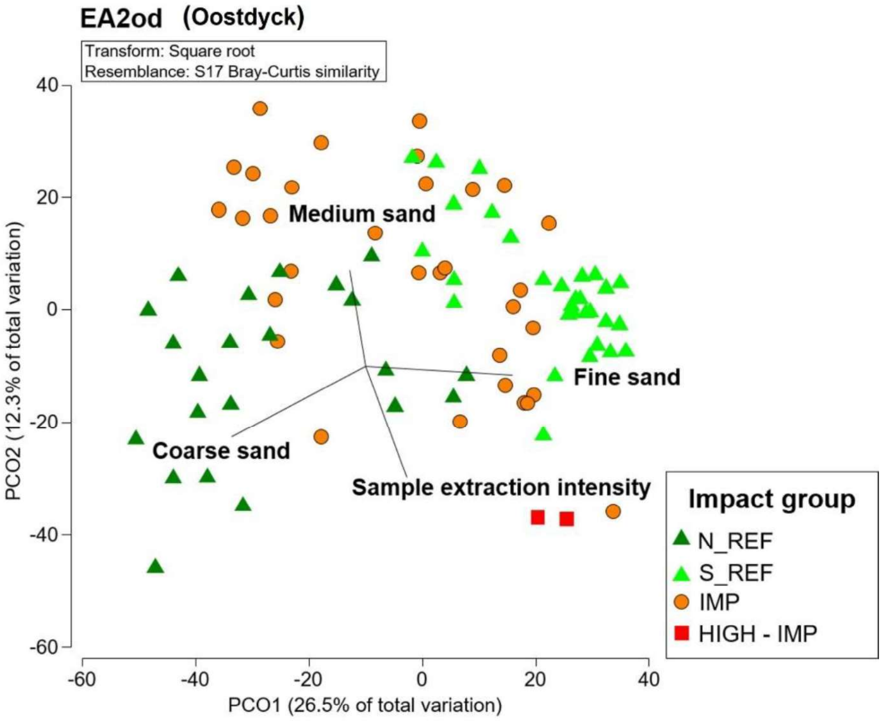
Sediment data

Medium sand was the dominant sediment fraction for all impact groups and did not differ significantly between impact groups, i.e. the impact samples *vs*. the reference zones north and south of the EA2od. On the other hand, median grain size (MGS) significantly differed between N_REF, S_REF and IMP, with all impact groups significantly different from each other (pairwise $p_{Perm} < 0.0091$). A decrease in average MGS from north (N_REF, avg. MGS = 452 ± 116 µm) to south (S_REF, avg. MGS = 311 ± 12 µm) was observed with an intermediate average MGS (343 ± 18 µm) in IMP, indicating that the Oostdyck sandbank in EA2od was still characterized by a natural gradient in sediment grain size over the ridge of the bank (De Backer et al., 2014b). Fine sand significantly increased from N_REF (3.21 ± 3.39%) over IMP (14.62 ± 7.61%) to S_REF (27.85 ± 5.33%), while coarse sand (N_REF = 29.31 ± 14.39%; IMP = 7.09 ± 3.77%; S_REF = 1.37 ± 0.77%) and gravel decreased from north to south (Fig. 5b).

Macrobenthos data

Macrobenthos species diversity, density nor biomass were affected by the impact group parameter in EA2od of the Oostdyck ($p_{Anova} > 0.2$) (Fig. 6b, e, h). However, the macrobenthic community composition differed significantly between all impact groups (pairwise test $p_{Perm} < 0.0143$) (Fig. 9), and also the amount of dispersion differed significantly for the impact groups ($p_{Permdisp} = 0.0001$), with highest dispersion found in IMP. SIMPER results matched the observed sediment gradient with N_REF containing typical coarser sand interstitial species as *H. elongata* and *Protodriloides spp.* characteristic for the *H. elongata* community, whereas S_REF displayed a medium to fine sand *N. cirrosa* community, with *Bathyporeia elegans* and high densities of *Nephtys cirrosa* as characteristic species. The IMP community composition was a transition between both, with typical *N. cirrosa* community species, but also a higher density of *H. elongata* and a lower density of *B. elegans* compared to S_REF. Two stations were classified as HIGH-IMP (in 2019) and these clustered a bit apart on the PCO plot, mainly due to the abundant presence of juvenile *Urothoe brevicornis*, *B. elegans* and *Nephtys spp*. The sample extraction intensity vector seemed to correlate with their community composition (Fig. 9).

Figure 9: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA2od on the Oostdyck with indication of the three impact groups (N_REF, S_REF, IMP, HIGH-IMP). Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset.

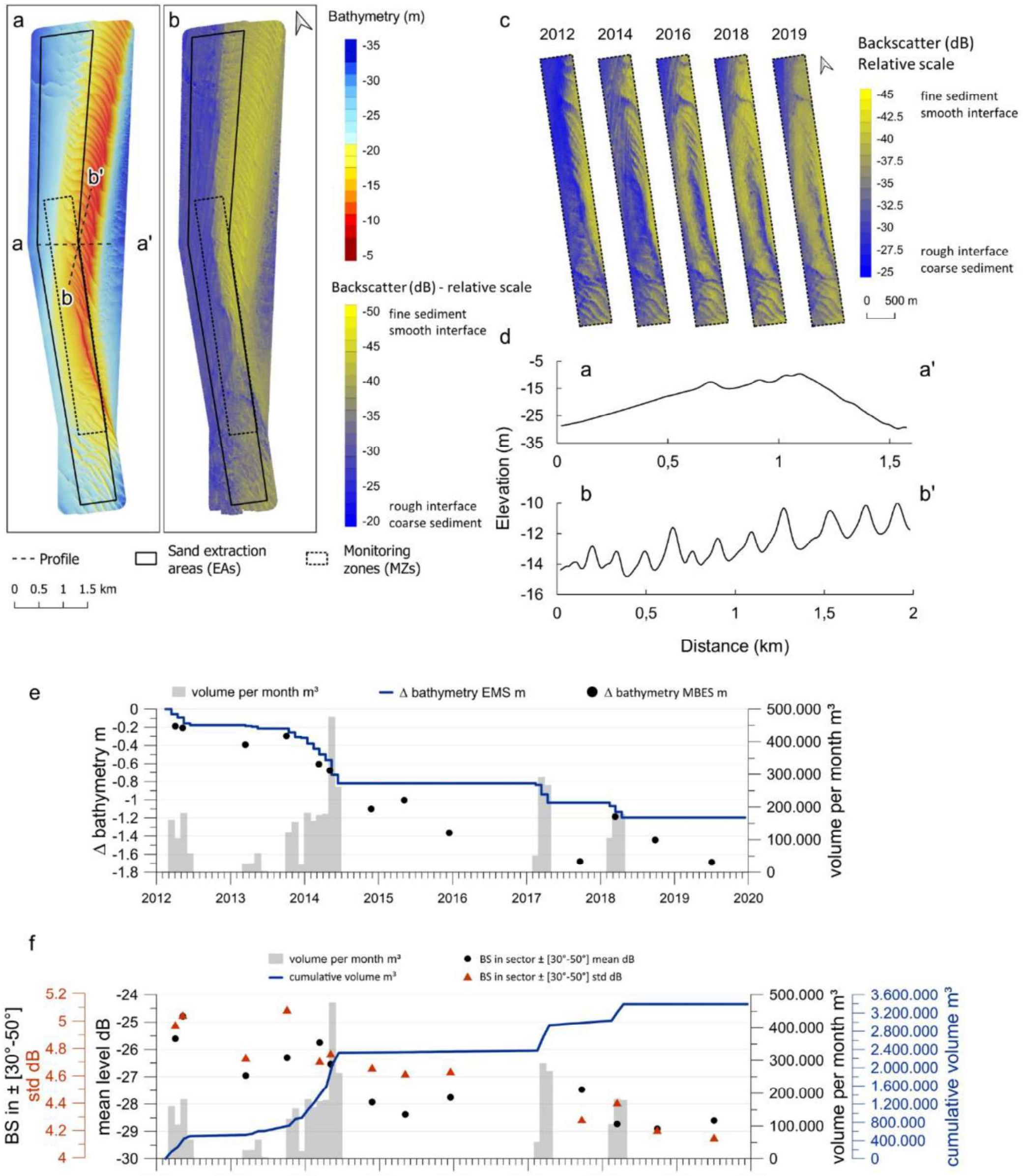


1.4.3. Oosthinder – EA4c – MZEA4c

Located in the southern part of the Oosthinder sandbank, EA4c essentially covers the less steep western flank of the bank parallel to its main ridge. The extraction was spread out over the entire length of EA4c in parallel with the crest of the bank, with a mean depth of -17.5 m LAT in MZEA4c. Very large dunes with a wavelength of 120 to 260 m and amplitudes ranging from 2 to 7 m characterize the morphology of EA4c. The median dune migration rate was estimated at 0.25 m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020).

Figure 10: Bathy-morphology and backscatter synthesis for EA4c and MZEA4c on the Oosthinder:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2004-2005 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2004-2005 dataset; (c) MZEA4c grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (d) Cross sections aa' and bb' of the reference bathymetric model; (e) MBES Bathymetric and EMS extracted volume time series on MZEA4c; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA4c.



Bathymetry data

The temporal evolution of the extracted volumes estimated from the EMS data in MZEA4c on the Oosthinder showed intense extraction phases between March and June 2012, from October 2013 to June 2014, in March-April 2017, and between February and April 2018, each time followed by longer periods of no extraction (Fig. 10e). The average MBES bathymetry in MZEA4c showed a highly significant decrease (Mann-Kendall test p-value <0.0001) in the order of 2 m from 2012 to 2019 (Fig. 10e). An acceleration of the bathymetric lowering was observed each time after a period of intense extraction. A highly significant correlation ($r^2 = 0.91$ p-value <0.0001) was measured between the mean bathymetric change derived from MBES data and the trend estimated from EMS data.

Backscatter data

The average backscatter level showed a highly significant (Mann-Kendall test p-value = 0.0006) regular negative trend (Fig. 10f). The first measurements taken in early 2012 showed average levels around -25 dB, while in 2015 the average level dropped to around -28 dB, and this negative trend continued through 2019 with average backscatter levels reaching -29 dB. The correlation between the average backscatter level and the bathymetric change deduced from the extracted volumes based on EMS data was highly significant ($r^2 = 0.79$, p-value = 0.0002). The backscatter standard deviation also decreased towards 2019, and followed the same significant decreasing trend as the average level. The successive backscatter maps in MZEA4c on the Oosthinder (Fig. 10c) revealed a gradual disappearance of the zone with high backscatter levels on the western flank of the bank. In the March 2014 backscatter image, the dredging traces of the drag head underlined by weaker lower-level backscatter lineaments were unambiguously identifiable. After the most intense extraction phase in spring 2014, the highly reflective zone on the western flank had practically disappeared, revealing a bathy-morphology with acoustic properties similar to the ones covering the top zone of the bank.

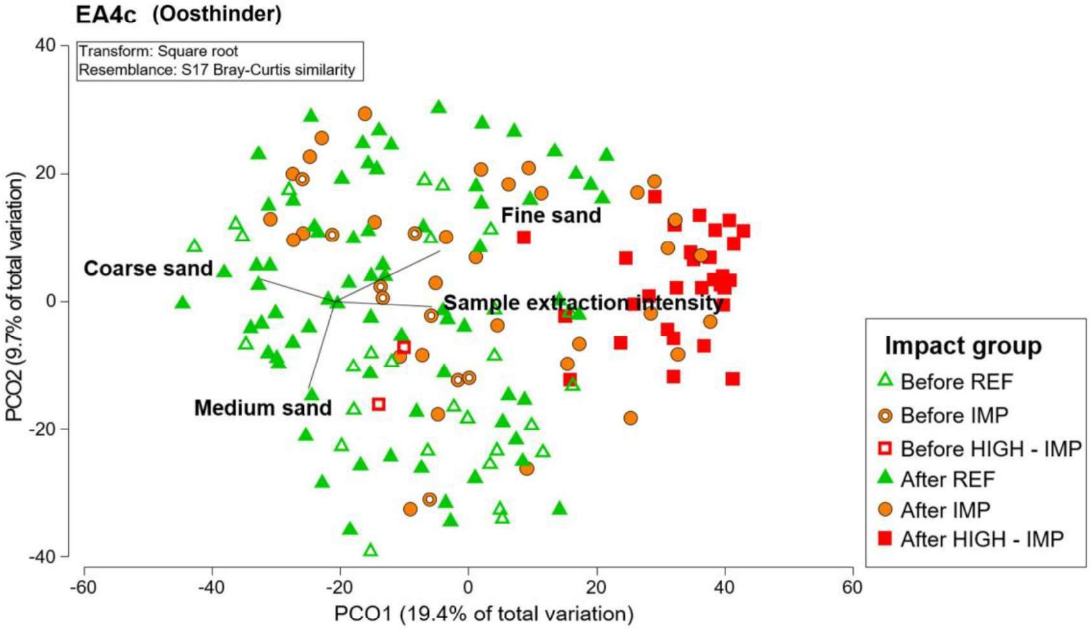
Sediment data

Sediment data in EA4c on the Oosthinder revealed a significant interaction (Before/After extraction x impact group) for median grain size ($p_{Anova} = 0.005$), caused by a decrease in average MGS in HIGH-IMP locations after the start of extraction (B: 341.1 ± 0.4 µm and A: 312.1 ± 18.5 µm). This was mainly due to a significantly larger fine sand fraction in HIGH-IMP (28.09 ± 6.30%) compared to IMP (18.31 ± 6.84%) ($p_{Post\ hoc} = 0.005$) and REF (10.62 ± 5.17%) ($p_{Post\ hoc} <0.0001$), and a lower coarse sand fraction in HIGH-IMP (2.13 ± 2.18%) compared to IMP (11.17 ± 10.29%) ($p_{Post\ hoc} = 0.0967$) and REF (12.76 ± 6.64) ($p_{Post\ hoc} = 0.0067$) in the period after extraction started (Fig. 5c). Medium sand was not significantly affected by the extraction activities in the 'After' period. In the 'Before' period, neither median grain size nor the fine, medium and coarse sand fractions did differ significantly between REF, IMP and HIGH-IMP groups.

Macrobenthos data

Period B/A, impact group or their interaction factor did not significantly affect macrobenthos S, N, or W ($p_{Anova} >0.05$) (Fig. 6c, f, i). Nonetheless, community composition was significantly affected by the interaction factor 'B/A x impact group'. Before extraction took place, impact groups did not significantly differ from each other ($p_{Perm} >0.05$), while after the start of extraction, impact groups strongly differed in community composition ($p_{Perm} = 0.0001$) (Fig. 11). Dispersion also differed significantly ($p_{Permdisp} = 0.0001$) between impact groups as REF and IMP had a higher dispersion compared to HIGH-IMP after the start of extraction, partly because only few HIGH-IMP samples were available before extraction (Fig. 11). SIMPER results revealed that in the 'Before' period, all impact groups could be classified as *H. elongata* community, whilst for the 'After' period, the REF group still represented the *H. elongata* community, but IMP shifted towards the *N. cirrosa* community and HIGH-IMP clearly resembled the *N. cirrosa* community according to the classification given in Breine et al. (2018). This community shift in both IMP and HIGH-IMP is characterized by decreased densities of *Ophelia borealis* and interstitial species such as *H. elongata*, and increased densities and biomass of species like *N. cirrosa*, *Urothoe brevicornis*, *B. elegans* and *Magelona johnstoni* (SIMPER results). Grouped DISTLM attributed 13.9% of the observed multivariate pattern to extraction parameters, and 23.1% to sediment parameters (marginal test results).

Figure 11: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA4c on the Oosthinder, with indication of the three impact groups (REF, IMP, HIGH-IMP), and whether the sample was taken 'before' or 'after' (B/A) the start of extraction activities. Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset.



1.5. Discussion

The first Royal Decree regulating marine aggregate extraction in Belgian waters dates from 1974. In the period 1976-1986 around 6 x 10^6 m^3 of sand was extracted (De Moor and Lanckneus, 1992). At the time, it was believed that the natural maintenance mechanism of sandbanks would counterbalance the extraction, though already in the period 1987-1994, when cumulatively 4.5 to 5 x 10^6 m^3 of sand was extracted in the top zone of one sandbank alone, it was concluded that the extraction had surpassed the recovery potential (De Moor, 2004). Van Lancker et al. (2010) synthesized the findings of the subsequent period during which the creation of extraction-induced depressions was evidenced and the impact these had on the hydrodynamics, morphology, sedimentology and biology.

Our results now indicate that extraction regime and local geological context are important factors driving the direct environmental impact of marine aggregate extraction in subtidal sandbank ecosystems. Table 2 summarizes the differences in extraction regime and the observed effects for each extraction area (EA). The observed seabed changes were not consistent for the three sandbanks and their respective EAs, with both fining and coarsening trends observed. The most drastic impact was observed when a high and continuous extraction regime coincided with a varying nature in local geological layers and sediment types. The macrobenthic community response always matched changes in the seabed and especially changes in sediment characteristics, highlighting once more the strong association between both as has been noted by other studies (Cooper, 2013b; Creutzberg et al., 1984; Snelgrove & Butman, 1995; Van Hoey et al., 2004).

In the following paragraphs, we discuss the relevance of considering the local geological context in environmental impact assessments, and the consequences that bathy-morphological and sedimentary changes may have on the biological (macrobenthic) responses, considering differences in exposure to low continuous, high continuous and high irregular extraction regimes. We conclude with some recommendations concerning the environmental impact monitoring in relation to marine aggregate extraction and seabed integrity.

Table 1: Summary of the different conditions in each sandbank, extraction regime and observed changes in relation to marine aggregate extraction in each EA (EA1 Thorntonbank, EA2od Oostdyck, EA4c Oosthinder). Mean backscatter level estimated in angular range ± [30°-50°].

*Legenda: Increase (+); Decrease (-); No change (=), with Intensity of change from Moderate (1 symbol) over Strong to Very Strong (3 symbols). Sections marked with an * are based on the MBES monitoring zones MZEA1, MZEA2od and MZEA4c within the respective EAs. **LEP and HEP refer to the Low (2010 – 2014) and High (2015 – 2019) extraction periods for EA1.*

Extraction area			**EA1 (Thorntonbank)**		**EA2od (Oostdyck)**	**EA4c (Oosthinder)**
			LEP**	**HEP****		
Dune characteristics *	Wavelength (range & *median*; m)		50–300 *(130)*		50–220 *(130)*	120–260 *(200)*
	Amplitude (range & *median*; m)		1-7 *(4)*		0,5-4 *(2)*	2-7 *(2.5)*
	Dune migration rate (avg. m per Spring-Neap tidal cycle)		0.04		0.75	0.25
Extraction regime	Avg. depth of extraction area (m LAT)		-22		-12	-15
	Monthly average volume (m^3) (only months when extraction took place considered)		83 x 10^3	164 x 10^3	17 x 10^3	230 x 10^3
	Yearly average volume (m^3) (idem)		996 x 10^3	1969 x 10^3	197 x 10^3	1150 x 10^3
	Frequency of extraction		continuous	continuous	continuous	periodic
Effects of marine aggregate extraction	Bathy-morphological evolution*	Mean depth	+	+++	+	++
		Mean backscatter level	+	++	=	---
	Sediment characteristics	Median grain size	=	=	=	--
		Coarse fractions	=	++ Gravel	=	- Coarse sand
		Fine fractions	=	+ Clay to silt	=	+++ Fine sand
	Macrobenthos	Species richness	=	+++	=	=
		Density	=	+++	=	=
		Biomass	=	+++	=	=
		Species community	No effect on community structure	Attraction of muddy sand species and opportunistic species	No effect of extraction; Natural sediment gradient determines species community	Transition from coarse sand community to medium sand community

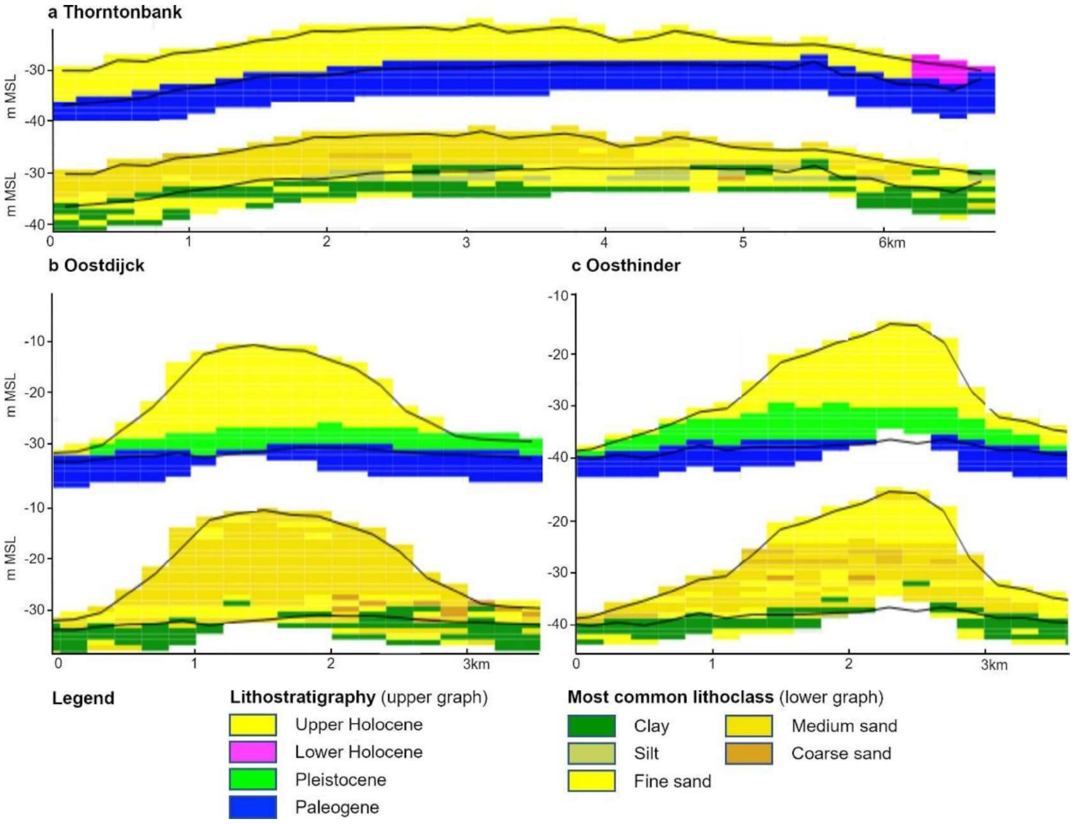
1.5.2. Local geology of the EAs

Figure 12 provides an overview of the differences in local geology for the three EAs. For the entire Belgian part of the North Sea, four main litho-stratigraphic units can be differentiated, each with different sediment characteristics (so-called lithoclasses). From old to young these units are: (1) Paleogene, composed mainly of stiff clay with local gravel occurrences; (2) Pleistocene, varying in sand composition, shell fragments and silt/clay percentages; (3) Lower Holocene, also highly varying in sediment composition; and (4) Upper Holocene, mostly representative of the present-day hydrodynamic regime, with a more uniform sediment composition (Hademenos et al., 2019; Van Lancker et al., 2019).

The southwestern part of EA1 has a relatively thin Upper Holocene cover (Fig. 12a). The high extraction rates make EA1 on the Thorntonbank prone to depletion of this thin top layer. Moreover, sediments are more heterogeneous in nature near the Paleogene/Quaternary transition, and depletion of surface sediments may locally result in the surfacing of Paleogene clay together with increased gravel and shell occurrences. EA2od (Oostdyck) and EA4c (Oosthinder) have similar sequences of Paleogene, Pleistocene and Upper Holocene sediments, but the Holocene cover of EA2od is more extensive homogeneous compared to EA4c (Fig. 12b, c). At EA4c, extraction took place at the lower flanks of the sandbank, where Pleistocene medium sands outcrop. Compared to the other EAs, the top zone of EA4c is composed predominantly of sands with a lower grain size, i.e. fine to medium sands.

Figure 12: Vertical profile sections presenting the local geology for the three EAs (see Fig. 1. for location of the different cross sections): (a) south-western extremity of the Thorntonbank EA1; (b) north-eastern part of Oostdijck EA2od, and (c) south-west part of Oosthinder sandbank EA4c (c). The upper figures show the litho-stratigraphic units, the lower figures the main lithoclasses (sediment types).

Figures extracted from TILES Consortium (2018), http://www.bmdc.be/tiles-dss/#). The subsurface models are represented by voxels of 200 x 200 x 1 m. MSL: Mean Sea Level.



1.5.3. Effects of continuous but low extraction

In areas exposed to continuous, low extraction intensities, such as EA1 (Thorntonbank) during the low extraction period (LEP, 2010 - 2014) or EA2od (Oostdyck), only limited changes in sediment composition and macrobenthic community were observed, which were rather similar to changes that may be expected from natural variations. The low extraction intensities, continuous migration of the underwater sand dunes (Boyd et al., 2004; Van Lancker et al., 2020) and the resilient nature of the macrobenthos (Boyd et al., 2004) are probably the main reasons why biological responses were not directly evoked. This is also evidenced by the absence of a significant trend in the mean backscatter level in MZEA2od. The latter may be attributed to continuous dune migration as well as to the homogeneous Upper Holocene sand cover in that area, but also to reduced screening activities during extraction.

Although the extraction intensity is low, direct bathy-morphological effects of continuous extraction are clearly visible: the average bathymetric deviation of -0,8 m in MZEA2od has not been refilled by the migrating dunes, which means that the natural processes cannot compensate for the extracted sand volumes. Deepening may cause local alterations in physical processes (e.g. erosion and sedimentation rates or changes in bed shear stress), which in turn structure the macrobenthic (De Jong et al., 2015a) but also meiobenthic communities (Vanaverbeke et al., 2007). However, no clear environmental responses were observed in EA2od nor EA1-LEP. Most likely, the continuous extraction only caused a gradual physical abrasion of homogeneous sediments. Macrobenthic communities in high energetic sandy areas are expected to have a lower sensitivity to extraction or bathymetric changes (Cooper et al., 2011b; Foden et al., 2009). In conclusion, limited changes in the soft sediment associated macrobenthic communities are expected (at least in the BPNS where extraction takes place on top of the sand banks) when extraction intensity is low to intermediate.

1.5.4. Effects of continuous and periodic high extraction

In areas exposed to continuous (EA1-HEP from 2015 onwards) or periodic (EA4c) high extraction intensities, the aggregate extraction activities clearly altered the bathy-morphology and the associated macrobenthic community. However, different responses were observed, mainly related to local variations in sandbank geology and differences in extraction practices (screening versus non-screening).

The continuous aggregate extraction of 20 x 10^3 to 40 x 10^3 m^3 per month over the period 2015 - 2018 in MZEA1 on the Thorntonbank created a local depression with an average bathymetric difference of 2.4 m compared to the reference level , with local differences up to 5 m. Formation of local depressions have been observed earlier as well for the BPNS e.g. on the Kwintebank (Degrendele et al. 2010). The continuous high excavation on the Thorntonbank most probably removed the Upper Holocene medium sands, exposing the older geological layers, which consist of muddy and gravelly sediments (Van Lancker et al., 2019). The gravel fraction significantly increased in the HIGH-IMP samples, but also the silt to clay fraction increased for samples taken during the high extraction period (HEP) in the centre of the EA1 depression. Additionally, processes such as screening and overflow also contributed to the increase of both fractions. When screened, the larger sediment fractions fall more or less directly to the seabed, within a 300 – 600 m range from the point of discharge (Cooper, 2013a; Newell et al., 1998; Poiner & Kennedy, 1984). As a result of overflow, fine fractions can disperse up to several kilometres depending on local hydrodynamics (Van Lancker & Baeye, 2015). As such, overflow not only contributes to the local fine particle enrichment, but also down current of the extraction activity (Le Bot et al., 2010; Robinson et al., 2005). Changes in seabed characteristics are also evidenced by an increase in the average backscatter level through time. This may be explained by an increase in seabed roughness due to the mechanical impact of the dredge head and the local concentration of the coarse sand fraction and shells due to screening during the HEP. Furthermore, the seabed surface inside a depression is often subjected to a lower bed shear stress compared to the natural surface (De Jong et al., 2016). These local slower bottom currents can reduce the degree of sand transport and allow mud to settle (Mielck et al., 2019), which corroborates our finding of increased fine sediments near the extraction hot spot in EA1.

Also, the macrobenthic community showed a clear biological response to the high and continuous aggregate extraction activity. In the EA1 depression, all biological parameters (species richness, densities and biomass) strongly increased. The density and numbers of typical *H. elongata* community representatives slightly reduced, while *Spiophanes bombyx* densities increased. The latter is a typical r-strategist often found in unstable habitats such as extraction areas (Ager, 2005; Coates et al., 2015; De Backer et al., 2017). The increased fine sediments further attracted species typical for fine to muddy sediments, such as *Abludomelita obtusata*, *Kurtiella bidentata* and the reef builder *Lanice conchilega*. Furthermore, opportunistic species such as juvenile *Ophiuroidea* and *Echinocyamus pusillus*, also colonised the area, likely due to an increased availability of organic matter (De Jong et al., 2015a). An observation very similar to the latter has been described by Bonne et al. (2010) concerning the 5m deep excavation depression on the Kwintebank. Several studies showed that extraction activities can increase the organic matter content through release, resuspension and settlement of organic matter and fine sediments in relation to drag head disturbance (Cooper et al., 2011a; Newell et al., 1998; Snelgrove & Butman, 1995). Secondly, extraction-induced trawl marks increase the patchiness and heterogeneity of the seabed surface area (Boyd et al., 2004; Cooper, 2013b; Phua et al., 2002). In MZEA1 this is reflected by the increased mean backscatter levels, increased between-sample variance of grab samples and significantly higher species richness, density and biomass values of the associated macrobenthic communities. An enhanced macrobenthos production due to extraction has been reported before (De Backer et al., 2014b; De Jong et al., 2015b; Gubbay, 2003; Newell et al., 1998). De Backer et al. (2014b) found similar physical and ecological responses to extraction for another extraction zone in the BPNS, located on the Buiten Ratel, a sandbank east of the Oostdyck (see Fig. 1). Both the increase in fine sediments and organic matter, which attracts opportunists, and the increased seabed surface heterogeneity, which provides more niches to colonise, likely contributed to the observed enhancement in macrobenthos species richness, density and biomass.

In contrast to EA1, EA4c is subjected to periods of very high extraction intensities alternated with longer periods without extraction. For EA4c, a gradual change in sediment composition was observed, without abrupt shifts as seen in EA1 during the HEP. The Upper Holocene cover on the Oosthinder EA4c is thicker, and also the estimated dune migration rates were higher than for EA1 (Van Lancker et al., 2020). The coarse sediment fractions in EA4c mainly comprised fragmented shells, which have been gradually removed from the area through extraction, as the vessels usually do not screen when dredging for beach nourishment purposes. This may have caused the gradual decrease of the backscatter level from ca. -25 dB in 2012 to ca. -29 dB in 2017 in the western part of MZEA4c, although the change in backscatter may also reflect a redistribution of the predominantly occurring fine sands in the top zone of the sandbank.

As a response to this sediment transition, the macrobenthic community shifted from a medium to coarse sand *H. elongata* community towards a typical medium to fine sand *N. cirrosa* community in the high impact (HIGH-IMP) samples. In contrast to EA1, the densities of opportunistic species did not increase in EA4c, and species richness, densities and biomass of the local macrobenthic community remained constant. This response is very similar to what Vanaverbeke et al. (2007) observed for meiobenthic communities after long-term intensive extraction on the Kwintebank, where diversity parameters also were not altered, while community composition responded to changes in sediment characteristics with more small-sized species after disturbance. Although the settlement of fine sediments due to extraction is normally associated with a local influx of organic matter, it seems that the easy resuspendable material seems less prone to settle in EA4c compared to EA1. Likely, the local hydrodynamics and high dune dynamics in EA4c evoked a faster resuspension of organic matter, in contrast to the situation in EA1, where the extraction depression acts as a fine sediment trap due to local conditions of reduced bed shear stress.

1.5.5. Recommendations for monitoring seabed integrity

Specific environmental and biological responses to sand extraction are highlighted when comparing EAs of highly similar ecological settings located on tidal sandbanks. These responses depend on both the geological context and the extraction regime. High extraction regimes can lead to depletion of the Upper Holocene aggregate resource layer, as such exposing older geological layers with different sediment characteristics. This may lead to physical loss of the upper sediment habitat, which may lead to drastic changes in the main macrobenthic community parameters. Up until now, this might be seen as a rather local effect of aggregate extraction (e.g. in EA1 and EA4c). However, this will become a more frequent threat with increasing allocations of EAs, especially in regions with a relatively thin Quaternary cover like the BPNS. This implies that in order for extraction to be sustainable from an ecological point of view, it is critical that the physical seabed integrity is maintained in order to prevent changes in biological communities or to at least enable recovery towards original communities. It is not possible to determine a maximum sustainable exploitation rate in this context, since this will depend on the capacity and production rate of the dredging vessel and on the extraction practice as well. In-depth knowledge on geological layers does enable us to determine a maximum depth limit for extraction in order to maintain seabed integrity. To enforce accounting for this depth limit, the Belgian regulators on aggregate extraction provide, since 2021, a maximum extraction limit or reference surface (FPS Economy, 2021). It is based on resource thickness and sediment characteristics criteria extracted from a newly built Quaternary geological knowledge base (Van Lancker et al., 2019), and further fine-tuned with criteria related to minimizing changes in bottom shear stress (Van den Eynde 2017). Previously, extraction was limited to 5 m below initial bathymetric surface for all extraction areas, possibly leading to exposure of older geological layers as shown in this study. With the new extraction surface, major changes in seabed integrity and hydrographic conditions should be prevented. Provided that a regular monitoring of environmental and biological responses is maintained, a more sustainable exploitation of the aggregate resources is envisaged.

Besides analysing the physical characteristics of the EA, an ecological assessment of the area is crucial, as this allows to identify sensitive communities and important habitats that need to be conserved (Van Lancker et al., 2010). The biological impact assessments in this study focused on active extraction areas, where we accounted for progressive impacts over multiple years by using cumulative extraction intensities over the study period, thereby excluding a potential recovery factor in the analyses. A degree of recovery is very likely present and should be accounted for in future ecological impact assessments. Moreover, as in other traditional ecological impact assessment studies (e.g. De Backer et al., 2014a; Rehitha et al., 2017; Seiderer & Newell, 1999; Waye-Barker et al., 2015), we compared macrobenthic community parameters for the EAs with those from nearby reference areas. Changes in the macrobenthic community structure have proven to be a reliable indicator when analysing the ecological status of a certain site (Dauer, 1993). However, more recent publications revealed that structural impact and recovery trajectories of benthic communities do not always match their functional counterparts (Bolam et al., 2016; Hussin et al., 2012). Physical changes of the habitat, whether naturally or induced by human activities, may change the biological community structure and the functional traits expressed by the community, thereby affecting ecosystem functioning and its services (Toussaint et al., 2021). In general, structurally diverse communities express more functional traits compared to structurally poor communities (Hillebrand & Matthiessen, 2009; Reiss et al., 2009; Snelgrove et al., 2014), but the strength and direction of this relationship is highly variable (Lam-Gordillo et al., 2020). From an ecosystem management perspective, it is necessary to improve our understanding of how the quality and quantity of ecosystem services provided by coastal marine ecosystems may change in relation to potential disturbances (Hillman et al., 2020; Snelgrove et al., 2014). Therefore, gathering empirical information on the impact of aggregate extraction on the functional diversity and benthic ecosystem functioning is the way forward.

This study presented a spatially explicit and integrated bio-physical approach by combining Multibeam echosounder (MBES) and Van Veen grab (sediment and macrobenthos) data. The integration allowed us to substantiate our findings and to present a more holistic impact assessment of marine aggregate extraction. Still, both datasets were acquired during different monitoring campaigns, implying potential spatio-temporal lag effects and a suboptimal sampling design. In tidal-dominated sandbank ecosystems, multi-scale morphological surface patterns prevail, ranging from sand ripples to entire sandbanks, resulting in nested levels of habitat heterogeneity (Mestdagh et al., 2020). Such patterns have seldom been accounted for in past ecological assessments, even though a high degree of heterogeneity in macrobenthos samples has often been described (e.g. De Backer et al., 2014b; De Jong et al., 2015b; Gubbay, 2003; Newell et al., 1998; this study; Phua et al., 2002). Therefore, combining MBES measurements with physical and biological sampling from the start of the monitoring, allows for a better selection of grab sample locations whilst considering the spatial heterogeneity of the seabed (cfr. Amiri-Simkooei et al., 2019; Haris et al., 2012; Mestdagh et al., 2020; Montereale-Gavazzi et al., 2019).

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