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Macrobenthos and morpho-sedimentary recovery dynamics in areas following aggregate extraction cessation

Lucia Lopez Lopez [a,*], Koen Degrendele [b], Marc Roche [b], Florian Barette [b], Vera Van Lancker [c], Nathan Terseleer [c], Annelies De Backer [a]

[a] Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), ILVO Marine Research, Jacobsenstraat 1, 8400 Oostende, Belgium
[b] Federal Public Service Economy, Continental Shelf Service, Boulevard du Roi Albert II, 16, 1000 Brussels, Belgium
[c] Institute of Natural Sciences, Directorate Natural Environment, Vautierstraat 29, B-1000 Brussels, Belgium

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ABSTRACT

Marine sand and gravel extraction alters seabed structure and biodiversity, but recovery dynamics after cessation remain less understood. This study investigates the recovery of macrobenthic communities and morpho-sedimentary characteristics in two areas after cessation of aggregate extraction in a tidal sandbank environment. By combining long-term monitoring data, including multibeam echosounder surveys and grab sampling, we assessed recovery trajectories over up to eight years post-extraction. Our findings highlight that while extraction-induced depressions persist without infill, biological and physical recovery begin almost immediately post-extraction, driven by local sediment reorganization and colonization by opportunistic species. The extent of recovery depends on time elapsed; total benthic abundance, biomass, and species composition deviated strongly from reference conditions at the time of cessation but gradually started to reflect those over time. After eight years, a return to reference conditions is observed. We hypothesize that seabed enrichment with coarse materials through screening during extraction facilitated recovery via the hiding-exposure mechanism. While recovery is evident, we do observe some site-specific variations between the two studied areas influenced by differences in sediment composition, hydrodynamics, and extraction intensity. As such, it is important to recognise that site-specific variability in both environmental conditions and extraction operations may limit transferability to other regions. Moreover, full restoration to pre-extraction conditions may not always be achievable. Instead, new stable ecosystem states, approximating reference conditions, could serve as alternative recovery benchmarks. These findings underscore the importance of adaptive management strategies tailored to the recovery potential of dynamic sandy environments.

1. Introduction

Marine aggregate extraction has become an important industrial activity, driven by the growing demand for raw materials in construction, sand for coastal protection, and more recently for construction in the energy sector (UNEP, 2019, 2022). Annual extraction volumes in the greater North Sea have risen exponentially over the past 50 years, increasing from a few hundred thousand m^3 to tens of millions of m^3 of sand and gravel in recent years (ICES, 2019). As extraction activities intensify, so do concerns regarding their environmental impacts (Torres et al., 2025). The removal of sediment can not only alter the physical structure of the seabed such as bathymetry, morphology and sediment type, but also the benthic ecosystem, including benthic biodiversity, density, biomass and community composition and associated benthic ecosystem functions (Desprez et al., 2022; ICES, 2019). The extent of these near-field changes is related to site-specific characteristics of the seabed, sediment composition, and local hydrodynamics, as well as the resilience and recovery potential of the benthic community (De Backer et al., 2014; Van Lancker et al., 2016). Moreover, recent work showed that the significance of these changes is also dependent on the local geological context and extraction regime (i.e. extraction volume and frequency) (Wyns et al., 2021).

While the immediate effects of sand extraction are well documented, the processes occurring after extraction cessation are less understood. Recovery encompasses both physical and biological dimensions: physical recovery occurs when dredge tracks disappear and initial

* Corresponding author.
E-mail address: lucia.lopezlopez@ilvo.vlaanderen.be (L.L. Lopez).

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morphology regenerates, with sediment composition resembling baseline conditions (Boyd et al., 2004), while biological recovery is achieved when macrobenthic communities return to non-impacted reference levels, characterized by similar species richness, abundance, and biomass (Boyd et al., 2003a, b; Cooper, 2005). Understanding these recovery processes is essential for sustainable marine management and maintaining Good Environmental Status (GES) under frameworks such as the Marine Strategy Framework Directive (MSFD, 2008/56/EC). In relation to the latter, impact of extraction is mostly related to changes in seafloor integrity and hydrographic conditions (Raicevich et al., 2025). A key consideration is whether extraction leads to physical disturbance or physical loss. Compared to loss, disturbance is reversible, activities disturb seabed integrity, but do not lead to a permanent change in benthic broad habitat type (BHT), i.e., mud, sand, mixed or coarse sediments, and when altered, the habitat is able to fully recover to the original BHT within a time span of 12 years. In cases where recovery rates are unknown, but expected to exceed 12 years, this is considered physical loss (Raicevich et al., 2025). To maintain GES, minimization of impacts is critical and human-induced habitat loss should remain equal or below 2 % of the natural extent of a BHT (European Commission, 2024). Some habitats demonstrate resilience through sediment reorganization and biological recolonization, while others may fail to fully restore ecosystem structure and function (Boyd et al., 2004; Cooper, 2013). How morpho-sedimentary changes affect recovery is poorly understood, especially whether local sediment reorganization alone is sufficient for recovery or whether external sediment supply is necessary. This knowledge gap underscores the need for comprehensive studies on post-extraction recovery to inform sustainable management practices and ensure the ecological integrity of marine (eco)systems.

Some studies, mainly in dynamic sandy environments, have shown relatively rapid recovery, especially when seabed changes were minimal (Coates et al., 2015; Krause et al., 2010; van Dalfsen and Essink, 2001). Also in regions dominated by strong currents that govern sediment transport, physical recovery can be relatively fast (Phua et al., 2002). However, aggregate extraction can also impose long-lasting impacts, including persistent morphological depressions, near-total removal of benthic organisms, habitat fragmentation, and prolonged sediment alterations (Ceia et al., 2013). In such cases, both the physical and biological recovery processes are often slow. This is mostly in areas where coarse sediments such as gravel and shells, which are not easily replenished by natural sediment transport, have been removed (Hill et al., 2011; Kenny and Rees, 1994, 1996). Also in deeper waters, where wave action is limited and sediment mobility is low, dredging creates persistent physical changes, such as pits and furrows, which can last for years (Newell et al., 1998). Sand dunes regenerate more slowly as depth increases and natural sediment transport processes becoming less effective in redistributing sediment after dredging (Krabbendam et al., 2022). In contrast, in shallower areas, where wave action and tidal currents are more dynamic, regeneration is more likely to occur, but this process can still take several years (Kint et al., 2023; Krabbendam et al., 2022). Recovery following cessation of extraction can take years or even decades, and even when species richness and abundance return, the community structure and ecological functions often remain fundamentally altered (Barrio Froján et al., 2008; Boyd et al., 2005; Ceia et al., 2013). In general, the recovery literature suggests that faster recovery tends to occur in dynamic, sandy environments with lower extraction intensities, whereas recovery is generally slower in more stable areas with low hydrodynamics or after more intense and repeated disturbances.

Monitoring post-extraction recovery requires a multidisciplinary approach, integrating benthic community assessments and seabed characterization. Benthic monitoring, typically conducted through grab sampling, offers insights into sediment grain size, organic content, and macrobenthic community metrics like density, biomass, and species composition. Multibeam Echosounder (MBES) surveys provide high-resolution data on seabed morphology and sediment redistribution. MBES backscatter strength (BS) is a confirmed proxy for characterizing seabed sediment properties, such as grain size, texture, and roughness (Amiri-Simkooei et al., 2019; Briggs et al., 2005; Chotiros et al., 2023; Costa, 2019), and it has been widely used to classify sediment types, identify seabed habitats, and differentiate sediment textures (Feldens et al., 2018; Ferrini and Flood, 2006). Significant fluctuations in BS time-series reflect changes in sediment properties over time, offering valuable insights into the dynamics of sediment transport and seabed recovery (Kint et al., 2023; Montereale-Gavazzi et al., 2017). Combining grab sampling with MBES data enhances our understanding of recovery processes, particularly in dynamic environments such as tidal sandbanks where sediment and biological interactions are complex.

The Belgian part of the North Sea (BPNS) offers an excellent study area to improve our insights on recovery dynamics because: (1) a number of extraction zones, which were intensively extracted for several years, have been closed since the legally defined extraction depth limit was exceeded; and (2) a legally obliged environmental monitoring program assessing ecosystem impact and seabed integrity is in place (Law of 13 January 1969 and Royal Decree of 23 June 2010 transposing the EU MSFD). The monitoring program includes mapping changes in seabed morphology and composition using MBES bathymetry and BS data, and the analyses of changes in the associated benthic communities. Data are collected on an annual to tri-annual basis in open and closed extraction areas ensuring acquisition of consistent, longer-term data series covering both physical and biological parameters. The current study integrates grab sample and MBES data from two closed extraction zones in the BPNS over a time period covering pre- and post-cessation conditions (two years pre-closure up to 2024) allowing an assessment of the recovery of seabed habitats and macrobenthic communities. The main objective of this study is to investigate how the morpho-sedimentary environment and associated macrobenthic communities evolve over time in these closed extraction zones, and to evaluate whether recovery towards reference conditions is possible. We hypothesized that (1) macrobenthic recovery in dynamic sandy environments occurs within 3–5 years after cessation of extraction, driven by changes in sediment composition and seabed morphology; (2) extraction does not cause irreversible habitat loss, but recovery is likely to occur through local sediment reorganization; (3) after the creation of depressions, seabed bathymetry remains stable, with no significant sediment infill, consistent with observations at other sites such as the Kwintebank extraction area (Degrendele et al., 2010; Krabbendam et al., 2022); and (4) bedform migration rates are anticipated to decline as systems regain equilibrium after disturbance. By addressing these hypotheses, this study provides critical insights into recovery dynamics, informing strategies for sustainable marine management.

2. Materials & methods

2.1. Study sites, natural variability and extraction history

The Belgian Part of the North Sea (BPNS) is located in the southern North Sea and is characterized by sandbanks, designated as habitat type 1110 under the EU Habitat Directive (HD; 92/43/EEC; European Economic Community, 1992). Sand extraction in the BPNS occurs within eleven delineated zones, primarily situated on the crests of offshore sandbanks. These sandbanks belong to the (offshore) circalittoral ‘Sand’ BHT and are dominated by medium to coarse sands (250–500 μm). They are characterized by the *Nephtys cirrosa* and *Hesionura elongata* community, and display rather low overall macrobenthic abundance and biomass and medium diversity (Breine et al., 2018). Extraction is constrained by sediment thickness, which varies between sites depending on geological conditions (TILES Consortium, 2018). The importance of tidally- and wind-driven flows varies across the sand extraction zones, depending on their depth and exposure to the hydrodynamic forces. Semi-diurnal tides predominate that are macrotidal in range (4–5 m). They rotate counter-clockwise, with maximum surface currents (about

1 m/s) observed generally during the flood. Bottom currents exceed the threshold of sand motion (+/− 0.4 m/s; Soulsby, 1997) during both the flood (NE) and ebb (SW) tide. The average tidal ellipse is elongated along a NE-SW axis, rotated some degrees clockwise with the sandbanks' orientation. Sandbanks are covered with large to very-large dunes (sensu Ashley, 1990) with a wavelength of several hundreds of meters, a crest length of several tens of meters and heights varying from 2 m to >6 m. Mostly at the linear parts of the sandbanks, alternating flood and ebb tides induce sand transport from the adjacent throughs towards the crest and play a major role in their maintenance mechanism (Dyer and Huntley, 1999). The vertical growth of the banks is limited by wave and storm action (Housthuys et al., 1994). Frequency of natural sediment disturbance in water depths of 20 m is on average about 5 % on an annual basis considering storms with significant wave heights of >2.5 m and wave periods above 5 s (Beels et al., 2007).

To mitigate the impacts of extraction and support sustainable seabed management, recently new management measures have been implemented, including a volume quota for the industry limiting the extraction of industrial sand in the BPNS to a total cumulative volume of 3 10^6 m^3/year and a depth below seabed limitation (Degrendele et al., 2017, 2021). This depth limitation has been defined in 2021 for each area based on (1) thickness of the upper homogenous sand layer based on geological data from seismic mapping and boreholes (Van Lancker et al., 2019), added with the height of sand dunes; (2) MSFD-compliant variations in bottom shear stress (Van den Eynde, 2017); and (3) wave propagation studies in relation to coastal erosion (Van den Eynde et al., 2019). As such, the depth below seabed limitation has the objective to preserve seabed integrity, limit the impact on hydrodynamic conditions, preserve structure of the sandbanks. Whether or not the vertical limitation boundary has been reached, is evaluated on a yearly basis by integrating high-resolution MBES datasets with extraction data. As a consequence, the vertical limitation enforces a systematic delineation of zones that are closed for sand extraction when the limit is reached, offering a unique opportunity to study recovery dynamics in these closed areas.

In this study, we focused on two closed extraction subzones, which have been intensively extracted before closure: one on the Buiten Ratel sandbank (BR) and one on the Thorntonbank sandbank (TB) (Fig. 1), respectively in water depths of around –21 m and –24 m Lowest Astronomical Tide (LAT). BR was the primary extraction hotspot in the BPNS from 2008 to 2014, and the area was closed in 2015 because the legal maximum extraction limit of 5 m at that time was reached (Degrendele et al., 2021; Roche et al., 2017). The total cumulative extraction volume at BR reached 3.3 million m^3 during the considered time range. This area, containing the historical extraction hotspot, is located where tidal currents have incised the sandbank head, hence it is characterized by a distinctive morphology. Migration dynamics are both flood- and ebb-dominated and occasionally irregular 3D bedform patterns are observed. Very large dunes dominate the area, with wavelengths ranging from 200 to 400 m and heights between 2.5 and 5.5 m. These bedforms display moderate migration rates (0 to 0.6 m per spring-neap cycle, SN cycle), which are lower than rates observed elsewhere in the BPNS where values can exceed 2 to 3 m/SN cycle (Terseleer et al., 2019; Terseleer et al., 2016). Following the closure at Buiten Ratel, the Thorntonbank became the main extraction area of the BPNS, with high-intensity sand extraction occurring within certain subzones until the maximum extraction depth defined by the depth below seabed limitation was reached. The total cumulative extraction volume at TB amounted 1.57 million m^3, and the area was closed in 2021 (Roche et al., 2017; Wyns et al., 2021). It features well-defined, relatively uniform very large dunes, though smaller in scale compared to BR, with wavelengths approximately 150 m and heights ranging from 2 to 3 m. These bedforms maintain temporal stability with low migration rates, i.e., below 0.2 m/SN cycle. The location is also near the head of the sandbank, and the dunes merely form sand aprons (Caston, 1981) connecting to the sandbank.

Sand extraction on the BPNS is carried out with trailing suction hopper dredgers occurs systematically during industrial sand extraction activities. This practice can have significant local impacts on the seabed. A survey conducted in December 2024 of all active dredging vessels in the BPNS confirmed that screening is systematically applied (100 % of participants) during industrial sand extraction, using sieves with mesh sizes of 8 × 8 mm (56 %) and 10 × 10 mm (44 %). Sediments with a diameter larger than 8 or 10 mm, depending on the sieve, are therefore returned to the seabed.

2.2. Data availability, sampling strategy and data analysis

2.2.1. Grab sample derived data

Van Veen grab samples (surface area 0.1 m^2) were taken for each closed extraction area to evaluate the changes over time in the sediments and their associated benthic fauna. The selected dataset for each area starts two years prior to extraction closure up to 2023, to capture both pre- and post-closure conditions (BR: 2013–2023, TB: 2019–2023) (Fig. 2). Sampling was done on board RV Belgica or RV Simon Stevin on a 1 to 4 year basis and always conducted in autumn (September–October) to reduce seasonal variation within the samples. For each area, impact locations (subjected to extraction at the moment of sampling or in the past) and reference locations (where no extraction took place) were allocated. Reference locations were chosen to represent the broader surrounding environment and were situated outside the direct influence of dredging, providing a baseline for comparison with the impacted areas. The number of sampling locations varied over the years per extraction area depending on logistical challenges or improvements to the sampling design. In total, the dataset consists of 244 sampling events across 56 locations (see Supplementary Table S1; Fig. 1).

Each Van Veen grab sample was sieved on board the research vessel using a 1 mm sieve and preserved in an 8 % formaldehyde-seawater solution stained with eosin to facilitate further sorting. All macrobenthic organisms were identified to the lowest possible taxonomic level, and species wet-weight measurements were obtained after blotting the individuals on absorbent paper (blotted wet weight). Macrobenthos identifications were conducted in an ISO-regulated lab environment (NBN EN ISO/IEC 17025), which holds a BELAC T-315 certificate for macrobenthos analyses. In cases where species-level identification was inconsistent, species were grouped at the next higher taxonomic level.

Sediment samples for granulometric analyses were taken with a sediment core (3.6 cm Ø) from each Van Veen grab. The fraction >1600 μm was sieved a priori, followed by the analysis of the <1600 μm fraction by means of laser diffraction using a Malvern Mastersizer 2000G (hydro version 5.40). 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 above 1600 μm was considered gravel, as it consisted entirely of shell hash. In addition to the sediment percentage fractions, the total median grain size (MGS) was calculated.

For a comprehensive overview and further background information on the data collection procedures for sediment and biological parameters, please refer to Wyns et al. (2021).

2.2.1.1. Statistical analyses

2.2.1.1.1. Univariate analysis on community variables. Four biological univariate measures were calculated for each sample: macrobenthos species richness (S), total density (N, $N.m^{-2}$), total biomass (W, gWW. m^{-2}), and body mass (B/N, gWW.m^{-2}/ $N.m^{-2}$). For W, the common heart urchin, *Echinocardium cordatum*, was excluded from the species list, because it introduces too high variability in the dataset (related to its presence/absence) due to its very high biomass compared to other species.

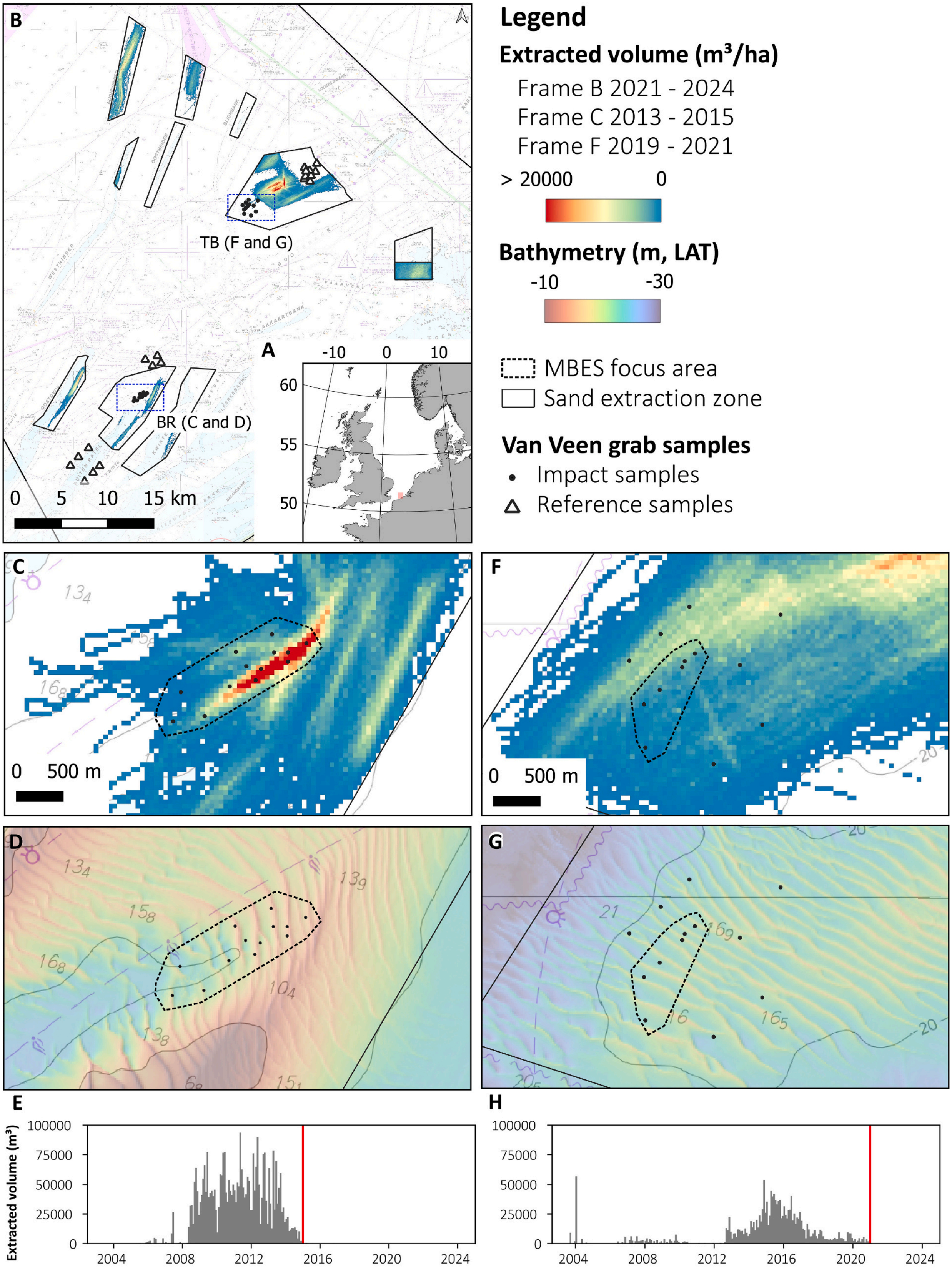

Fig. 1. (A) Overview map of the Belgian exclusive economic zone (EEZ) within the North Sea; (B) Map of the two study areas, Buiten Ratel (BR) and Thorntonbank (TB), highlighting reference samples (triangles), impact samples (dots), sand extraction zones, and MBES focus areas. Extraction intensity for Buiten Ratel (C) and Thorntonbank (F). Bathymetry of Buiten Ratel (D) and Thorntonbank (G), showing seabed morphology and MBES focus areas. Historical sand extraction regimes within the Buiten Ratel (E) and Thorntonbank (H) MBES focus area.

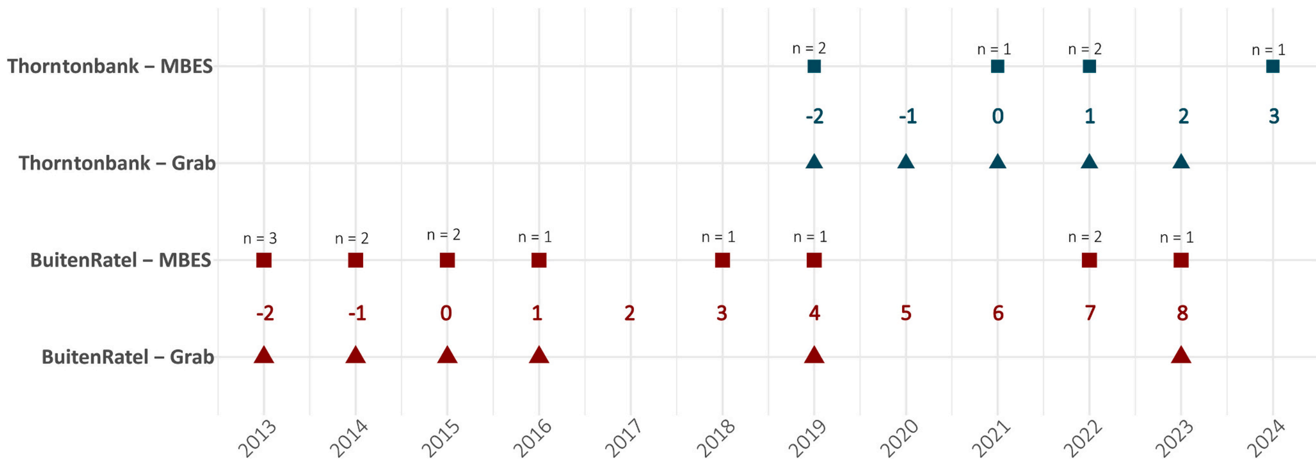

Fig. 2. Data time series: Multibeam echosounder (MBES) data and grab samples collected on the study areas. The numbers on the plot represent the number of years since the cessation of extraction for each subarea. The values of (n) represent the number of MBES surveys conducted in a given year.

Post-extraction changes over time in univariate variables were assessed using a general linear mixed-effect model (GLMM) for each extraction area separately with 'time' (levels different per focus area, see below), 'impact' (levels: IMP and REF) and their interaction as fixed factors and 'station' as a random factor. Time was expressed as years relative to the stop of the extraction, which ranged from −2 to 8 for Buiten Ratel (2013−2023) and − 2 to 2 for Thorntonbank (2019–2023). To assess density, abundance of individuals (ind.0.1 m^{-2}) was used as the response variable in the negative binomial model, as this distribution was more suitable for count data that exhibited overdispersion, making a Poisson distribution inappropriate. For biomass and B/N, a gamma distribution with a log link was chosen to stabilize the variance due to the constant coefficient of variation. For richness, a Gaussian distribution was applied. Model assumptions were visually inspected by using the DHARMa package (Hartig, 2022).

Statistical significance was set at $p < 0.05$; p-values between 0.05 and 0.1 were considered marginally significant and were interpreted cautiously and consistently throughout the manuscript.

2.2.1.1.2. Multivariate analysis on community composition. To test for the evolution in benthic species composition over time following cessation of sand extraction, a two-way PERMANOVA was performed on a fourth-root transformed species-abundance matrix using Bray-Curtis similarity index. "Impact" and "Time" and their interaction were considered fixed factors, while 'Station' was included as a random factor. When significant effects were detected, pairwise tests were used to explore specific differences within Impact and Time. Additionally, PERMDISP analyses were carried out to test for differences in dispersion, with PERMANOVA results interpreted cautiously if PERMDISP was significant ($p < 0.05$).

To further investigate community-level changes over time, Principal Coordinate Analysis (PCoA) was applied to the Bray–Curtis similarity matrix of benthic abundance data. This allowed us to visualize shifts in community structure, highlighting changes in species composition across both impact and reference zones over different years. A vector overlay (Pearson correlation) was used to visualize the relationship between the multivariate data cloud and sediment parameters. For sediment fractions, only those with correlations below 0.7 were included, ensuring that only non-collinear variables were represented. Similarly, vector overlay of species abundance (multiple correlation $r >$ 0.3) showed species best explaining the observed multivariate pattern. Following the PCoA, a similarity percentage breakdown (SIMPER) analysis (70 % cut-off level) was conducted to identify the species contributing most to the dissimilarity between impact and reference locations across different years.

The combination of univariate GLMMs and multivariate analyses (PERMANOVA, PCoA) allows for a more robust detection of ecological changes. While univariate metrics aggregate community responses into a single summary (e.g., abundance, biomass, richness), multivariate methods capture shifts in species composition and turnover that may not be reflected in univariate analyses, especially when overall totals remain stable.

The univariate analyses and PCoA plots were conducted in R Studio using the R software (v4.2.3; R Core Team, 2023), and for SIMPER, PERMANOVA and PERMDISP analyses we used Primer v7. The significance level was set at 0.05 for all analyses.

2.2.2. Multibeam Echosounder (MBES) raw data and derived information

The monitoring strategy for assessing the morpho-sedimentary impact of sand extraction primarily focusses on regular and repetitive MBES surveys conducted in the most extracted areas on the BPNS. These regular surveys have led to extensive time series, enabling the analysis of the evolution of these areas over extended periods. In recent years, several of these monitored areas were closed for extraction, but regular surveys continued, facilitating post-extraction recovery analysis. For this study, we selected two closed MBES focus areas on BR and TB (Fig. 1) and the dataset selected for each area starts two years prior to extraction closure up to 2024, similarly as for the grab samples, to capture, both pre- and post-closure conditions (BR: 2013–2023, TB: 2019–2024). Sometimes multiple surveys per year were undertaken (Fig. 2).

MBES measurements were carried out aboard the research vessels RV Belgica and RV Simon Stevin. Until its decommissioning in 2021, the RV Belgica was equipped with a Kongsberg Discovery EM3002 dual MBES. Its successor, commissioned in 2022 and bearing the same name, is equipped with a Kongsberg Discovery EM2040–04 MKII dual RXMBES, identical to the system installed aboard the RV Simon Stevin. The use of similar acoustic equipment, acquisition software (Kongsberg SIS), and a well-documented raw data format ensures consistent and reliable data processing over the entire time series.

2.2.2.1. Bathymetry and derived morphodynamics. The MBES bathymetric dataset follows a standard hydrographic processing workflow using QPS-Qimera®, which includes tide reduction to Lowest Astronomical Tide (LAT), correction of residual offsets through calibration and outlier soundings filtration. Based on the processed individual depths, a digital terrain model (DTM) of each survey is constructed with a resolution of 1x1m. An overall vertical uncertainty of 0.3 m for the RV Belgica KM EM3002 dual MBES bathymetric data was estimated (Roche et al., 2017), and the continuous calibration with both EM2040 MBES's confirms the validity of this broad value. For each selected area, the resulting DTMs from successive surveys form the backbone of the bathymetric time series analyses. The DTMs are reduced and constricted to the boundaries of the defined monitoring areas, enabling the comparison between models and calculated statistical parameters, such as mean, median, standard deviation, minimum and maximum. The morphology of the areas is globally summarized in the mean slope value calculated at a resolution of 1x1m, representing small-scale variations in seabed heterogeneity.

To quantitatively assess the impact of marine aggregate extraction and its subsequent cessation on seabed morphology and dynamics over time, a systematic morphodynamic analysis was implemented using bathymetric profiles from designated focus areas (Fig. 1). The analysis relies on an automated procedure (Terseleer et al., 2019) that processes time series of multibeam echosounder (MBES) measurements, enabling the standardized extraction of key morphodynamic parameters such as bedform heights and migration rates. The methodology begins with separating two components of bathymetric profiles: the stable sandbank body and the superimposed dynamic bedforms. This conceptual separation is based on the geomorphometric concept of the "osculatory surface" (Debese et al., 2018) which tangentially intersects the sandbank at dune feet, effectively differentiating between the dynamic dune-covered upper section and the stable internal part of the sandbank. In our approach, this separation is achieved through wavelet analysis of detrended bathymetric profiles. The method adaptively identifies the main bedforms by implementing a moving window technique, where the window width is calibrated to the dominant wavelengths observed across the profile. Within each window segment, the algorithm identifies bedform troughs by selecting the deepest bathymetric minima. The connection of these troughs creates a boundary similar to the osculatory surface, effectively isolating the mobile upper part of the seabed while avoiding interference from the sandbank's long-wavelength signal in subsequent analyses. Once the troughs are identified and the dynamic upper part of the profiles is isolated, morphological parameters are computed directly from the bathymetric data. These parameters include bedform height (the vertical distance from the base, defined by neighbouring troughs, to the highest point or crest between these troughs) and wavelength (the horizontal distance between successive troughs).

The horizontal shift of bedforms is quantified through cross-correlation analysis between successive profiles, treating them as univariate time series. The spatial lag corresponding to maximum correlation indicates the migration distance between surveys, following an approach similar to that of (McElroy and Mohrig, 2009).

This automated method allows for the rapid, objective, and systematic extraction of morphodynamic parameters (here, bedforms heights and migration rates) at high spatial and temporal resolutions, providing a robust foundation for monitoring seabed evolution, particularly in the context of before-and-after analyses of extraction activities.

2.2.2.2. Bottom BS. All MBES data were recorded at 300 kHz with medium pulse lengths, allowing for BS intercomparison following calibration. BS data processing was performed with Ifremer's SonarScope software (release 2024-02-24) using a systematic procedure: (1) correction for acoustic absorption; (2) adjustment for insonified area based on digital bathymetric models and actual incidence angles; (3) calibration using a reference BS correction file from the Kwinte Reference Area (KRA; Deleu and Roche, 2020) following the method described by Eleftherakis et al. (2018). The BS calibration minimizes the influence of seawater temperature on BS levels, facilitating the comparison of BS levels obtained across different seasons and enabling the integration of data from various MBES systems (Roche et al., 2024) and (4) generation of a BS grid at a resolution of 1 m × 1 m, considering only the incidence angle sector between ±[30°–50°], which optimally distinguishes sediment types (APL, 1994; Lamarche et al., 2011). The average backscatter level within this angular sector was used as a proxy for detecting sedimentary changes over time. The repeatability of BS data has been regularly assessed at the KRA (Roche et al., 2018). The Mann-Kendall test was used to assess significant trends in backscatter (BS) levels over time and to evaluate the correlation between BS levels and sediment evolution.

3. Results

3.1. Buiten Ratel

3.1.1. Sediment and macrobenthic changes at the wider area

3.1.1.1. Sediment. The IMP locations underwent sediment fining, characterized by a reduction in coarse sediment fractions and an increase in medium sand, along with a decline in median grain size (MGS) (Fig. 3A). The gravel fraction (>1600 μm) decreased from 14 ± 18 % (average ± SD) in year −2 to 3 ± 3 % by year 8, while the medium sand fraction (250–500 μm) increased from 40 ± 11 % in years −2 to 0 to 52 ± 9 % by year 4 and remained steady at 51 ± 4 % by year 8. The MGS, which was 517 ± 249 μm during extraction (year −2), progressively decreased to 373 ± 86 μm by year 8, becoming similar to the MGS of the REF locations (350 ± 71 μm). In contrast, the REF locations remained stable, with minimal changes in sediment fractions and MGS (Fig. 3A).

3.1.1.2. Species richness, abundance and biomass. The interaction 'Time x Impact' was significant for macrobenthos abundance, biomass and the B/N ratio (Table 1). However, pairwise tests did not reveal significant differences between IMP and REF over time (except for abundance in year 1, $p = 0.03$), probably because of high variability within IMP samples. Both biomass and abundance were higher in IMP locations during (year −2 and − 1) and immediately following extraction (year 0 and year 1 only for abundance) (Fig. 3B; Supplementary Tables S2,S3; Fig. S1,S2). While in year 4 and 8, abundance and biomass of IMP locations closely resembled reference values. Pairwise tests did, however, show significant differences between years for IMP samples. A clear decrease in both abundance and biomass was observed immediately post-extraction (Fig. 3B) and this was significant between year 0 and years 4 and 8 for abundance (resp. $p = 0.0343$ and $p = 0.0005$), and marginally significant between year 0 and 8 for biomass ($p = 0.0558$) (Supplementary Tables S2,S3; Fig. S1,S2).

In contrast to abundance and biomass, the B/N ratio in IMP was lower than in REF locations, and this was particularly significant in year −1 and year 1 (pairwise tests, resp. $p = 0.0004$ and $p = 0.030$). Within the IMP locations, a significant increase in the B/N ratio was observed post-extraction with years 4 and 8 differing significantly from years −2 to 1 (Supplementary Tables S4; Fig. S3). In contrast, the interaction 'Time x Impact' was not significant for species richness, that was only affected by the 'Impact' factor ($p = 0.002$). S showed stable trends across impact groups, with slightly higher richness in the impact locations but decreasing after cessation.

3.1.1.3. Community structure. Community composition was significantly affected by 'Time' (Pseudo-F = 3.78, $p = 0.0001$), 'Year' (Pseudo-F = 6.92, p = 0.0001), and their interaction 'Time x Impact' (Pseudo-F = 2.31, $p_{perm} = 0.0001$). During extraction (years −2 and − 1) and right after cessation of extraction activities (years 0 and 1), impact and reference differed significantly from each other (pairwise tests, all $p_{perm} < 0.05$, Supplementary Table S5). By 4 and 8 years post-cessation, IMP did not differ significantly in community composition from REF (resp. t-value = 1.16, $p_{perm} = 0.184$ and t-value = 1.01, $p_{perm} = 0.4544$). The PCoA plot corroborated these results, showing a consistent position over time of REF samples, while IMP samples were separated during extraction and progressively moved towards the REF samples with time, overlapping them in years 4 and 8 (Fig. 3C). Very coarse sand and gravel highly correlated with IMP samples during extraction (year −2 and − 1), and very fine sand with IMP samples right after cessation of extraction

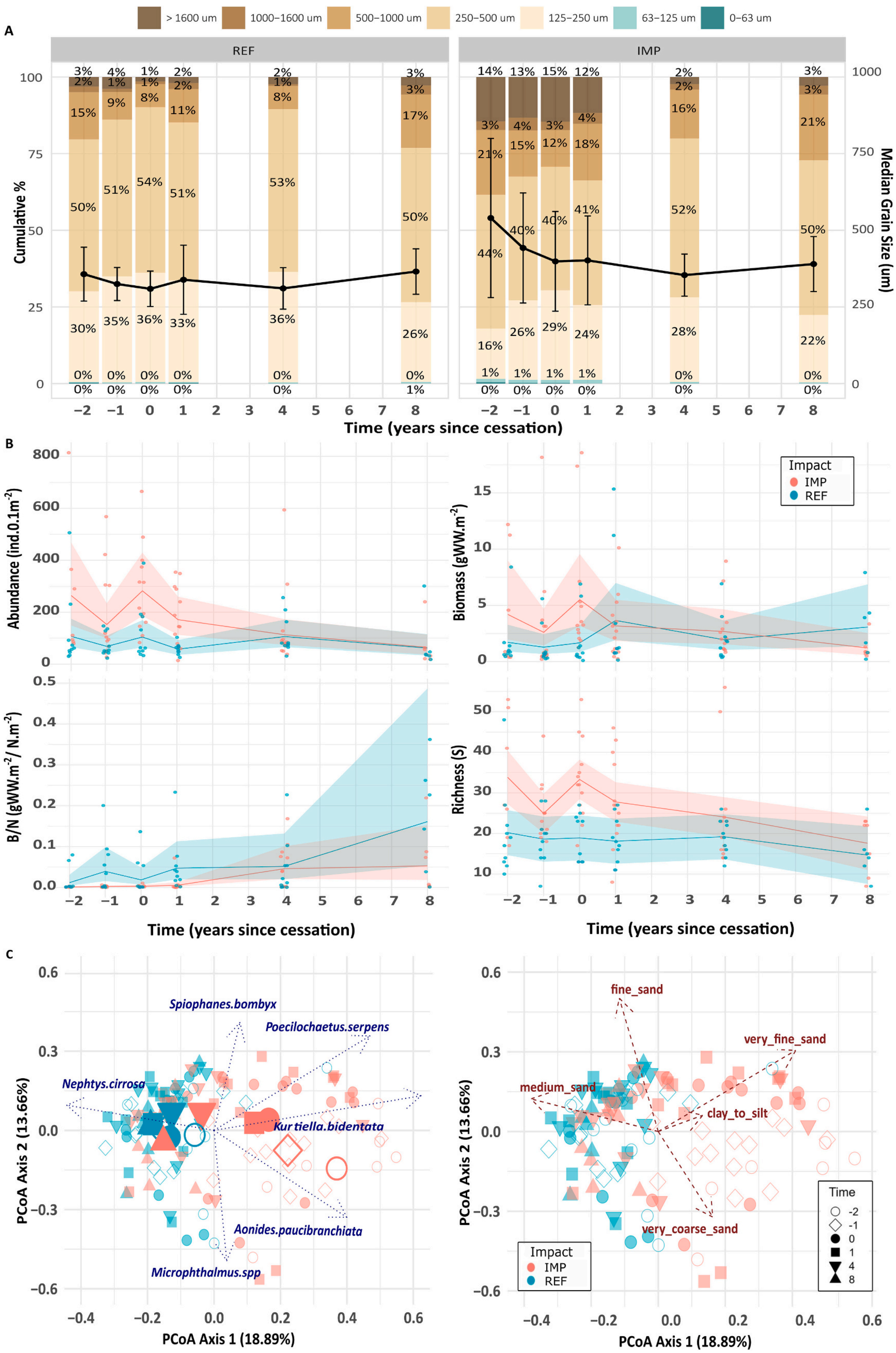

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Fig. 3. A. Relative sediment composition (%) over time since cessation of sand extraction in reference (REF) and impacted (IMP) locations at the Buiten Ratel. Grain size fractions include gravel (>1600 μm), very coarse sand (1000–1600 μm), coarse sand (500–1000 μm), medium sand (250–500 μm), fine sand (125–250 μm), very fine sand (63–125 μm) and clay/silt (<63 μm), shown as stacked bar plots. Median grain size (μm) is plotted on the secondary y-axis. B. Temporal trends in macrobenthic community metrics at the Buiten Ratel: Abundance (ind. 0.1 m^{-2}), Biomass (gWW.m^{-2}), B/N ratio (Biomass per individual), and Species Richness (n° of species). Shaded areas represent 95 % confidence intervals around the mean values for reference (REF) and impact (IMP) across years. C. Principal Coordinates Analysis (PCoA) plots based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data on the Buiten Ratel with indication of impact group (REF, IMP) in colour and time as years since extraction cessation in different symbol shapes. On the left PCoA plot, centroids per impact-time group are plotted on top as bigger symbols. Overlay vectors indicate direction and degree of correlation (length of vector) in which the species (blue vectors) and sediment fractions (red vectors) fit the multivariate data cloud. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results of Generalized Linear Mixed Models (GLMM) for the Buiten Ratel sandbank assessing the effects of Impact, Time, and their interaction (Impact: Time) on the response variables of macrobenthic community metrics (Abundance, Biomass, Biomass-to-Density Ratio (B/N), and Species Richness.

Response: abundance	Chisq	Df	Pr(>Chisq)
(Intercept)	355.2962	1	< 2e−16 ***
Impact	5.6269	1	0.01769*
Time	8.6016	5	0.12605
Impact:Time	11.0513	5	0.05037.
Response: Biomass	**Chisq**	**Df**	**Pr(>Chisq)**
(Intercept)	2.6720	1	0.10213
Impact	3.1378	1	0.07650.
Time	7.2264	5	0.20434
Impact:Time	13.0256	5	0.02314*
Response: B/N	**Chisq**	**Df**	**Pr(>Chisq)**
(Intercept)	82.030	1	< 2.2e-16 ***
Impact	10.547	1	0.001164 *
Time	15.728	5	0.007666 **
Impact:Time	13.274	5	0.020942 *
Response: Richness	**Chisq**	**Df**	**Pr(>Chisq)**
(Intercept)	483.8514	1	< 2e-16 ***
Impact	9.9825	1	0.00158 **
Time	1.5023	5	0.91280
Impact:Time	3.8137	5	0.57654

Chisq represents the chi-squared statistic, Df denotes degrees of freedom, and Pr (>Chisq) indicates the *p*-value. Significant effects are marked with ($p < 0.1$), * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$). Significant variables are indicated in bold.

Table 2
Species contributing most to the similarity within the impact and reference zones across different years at Buiten Ratel, as identified by SIMPER analysis (70 % abundance cut-off level). Percentage contributions (% of total similarity) are listed for the top five species in each category.

Time	IMPACT	Contrib. %	REFERENCE	Contrib. %
-2	*Eumida sanguinea*	8.15	*Nephtys cirrosa*	19.17
	Anthozoa spp	7.39	*Magelona jonhstoni*	13.29
	Ophiura juv	6.77	*Spiophanes bombyx*	13.20
	Ophelia juv	5.23	*Urothoe brevicornis*	6.38
	Kurtiella bidentata	4.59	*Nephtys juv*	5.68
−1	*Kurtiella bidentata*	13.46	*Nephtys juv*	17.19
	Anthozoa spp.	13.01	*Nephtys cirrosa*	14.39
	Nephtys juv	8.59	*Bathyporeia elegans*	13.31
	Aonides paucibranchiata	5.14	*Bathyporeia juv*	10.89
	Spiophanes bombyx	5.08	*Spiophanes bombyx*	5.28
0	*Spiophanes bombyx*	11.65	*Nephtys cirrosa*	16.72
	Nephtys cirrosa	8.66	*Nephtys juv*	12.04
	Spio spp	8.18	*Bathyporeia elegans*	10.48
	Nephtys juv	6.46	*Urothoe brevicornis*	7.38
	Poecilochaetus serpens	5.02	*Magelona johnstoni*	6.01
1	*Spiophanes bombyx*	12.68	*Nephtys cirrosa*	17.11
	Nephtys juv	10.55	*Nephtys juv*	14.57
	Nephtys cirrosa	6.16	*Urothoe juv*	11.34
	Urothoe brevicornis	5.19	*Urothoe brevicornis*	8.89
	Ophiura juv	4.00	*Bathyporeia elegans*	8.07
4	*Spiophanes bombyx*	15.87	*Nephtys juv*	15.73
	Nephtys juv	15.86	*Nephtys cirrosa*	13.67
	Nephtys cirrosa	13.58	*Spiophanes bombyx*	13.12
	Urothoe juv	7.27	*Urotohe juv*	8.19
	Urothoe brevicornis	5.66	*Phoronida spp*	6.63
8	*Nephtys cirrosa*	21.81	*Nephtys juv*	24.59
	Nephtys juv	19.50	*Nephtys cirrosa*	22.84
	Spiophanes bombyx	12.10	*Spiophanes bombyx*	11.75
	Megaluropus agilis	8.12	*Echinocardium cordatum*	10.92
	Urothoe brevicornis	7.42	*Bathyporeia juv*	6.61

(year 0 and 1), while medium sand correlated most with REF samples and IMP samples 4 and 8 years post-extraction (Fig. 3C). SIMPER analyses revealed that REF samples contained typical medium sand species like *Nephtys cirrosa* and *Urothoe brevicornis* characteristic of the *N. cirrosa* community. IMP samples contained species typical for muddy sands like *Kurtiella bidentata* during extraction, shifting towards species characteristic of fine to medium sands post-closure (years 0 and 1), with opportunist species like *Poecilochaetus serpens* and juvenile *Ophiura*, as well as increased abundance of *Spiophanes bombyx* and *Nephtys cirrosa*. Four years post-closure, the community resembled the *N. cirrosa* community characteristic of medium sands, which remained stable up to 8 years after closure of the area (Fig. 3C, Table 2).

3.1.2. Morpho-sedimentary changes in the closed focus area

3.1.2.1. Bathymetric and morphodynamic evolution. Two years prior to closure for extraction of the BR area, the mean bathymetry dropped by 0.4 m, while slope values remained stable at an average of 4.4° (Fig. 4A). This period coincides with the final phase of high extraction activity, resulting in the removal of approximately 0.45 m of sediment across the focus area. The cross-sectional profiles (Fig. 4D) and the extraction phase DTM (Fig. 4B) reveal numerous furrows, culminating in the formation of a depression in the southeast. After the last extraction year and thus the area's closure, bathymetry remained stable. Slope values (Fig. 4A) decreased by nearly 2° during the closure period (year −1 to year 1), coinciding with the gradual diminishing of the deep furrows (Fig. 4D). The recovery phase DTM (Fig. 4B) and later profiles (Fig. 4D) indicate that these furrows have completely disappeared, with a stable mean bathymetry of 22.6 m and a slope varying around 3° (Fig. 4A). Although the dune height (Fig. 4C) varies across the area, the general trend during the recovery phase is stable. Only on the northernmost profile, next to the depression, a decrease of >50 cm was observed during and directly after the extraction phase (year −2 to year 1). Migration rates (Fig. 4C) show consistently higher rates during active extraction (0.2–0.8 m/SN cycle), reduced when extraction volumes decreased and stabilize around lower values (0.1–0.2 m/SN cycle) after cessation.

3.1.2.2. Backscatter and sediment evolution. In the BR focus area, the BS average in the incident angular interval of ±[30°-50°] presents a clear downward trend from year −2 to year 5 after closure, decreasing from −12 dB to −17 dB, then stabilizing between −16 dB and − 17 dB until the latest measurements taken in 2024, 9 years after closure (Fig. 5A;

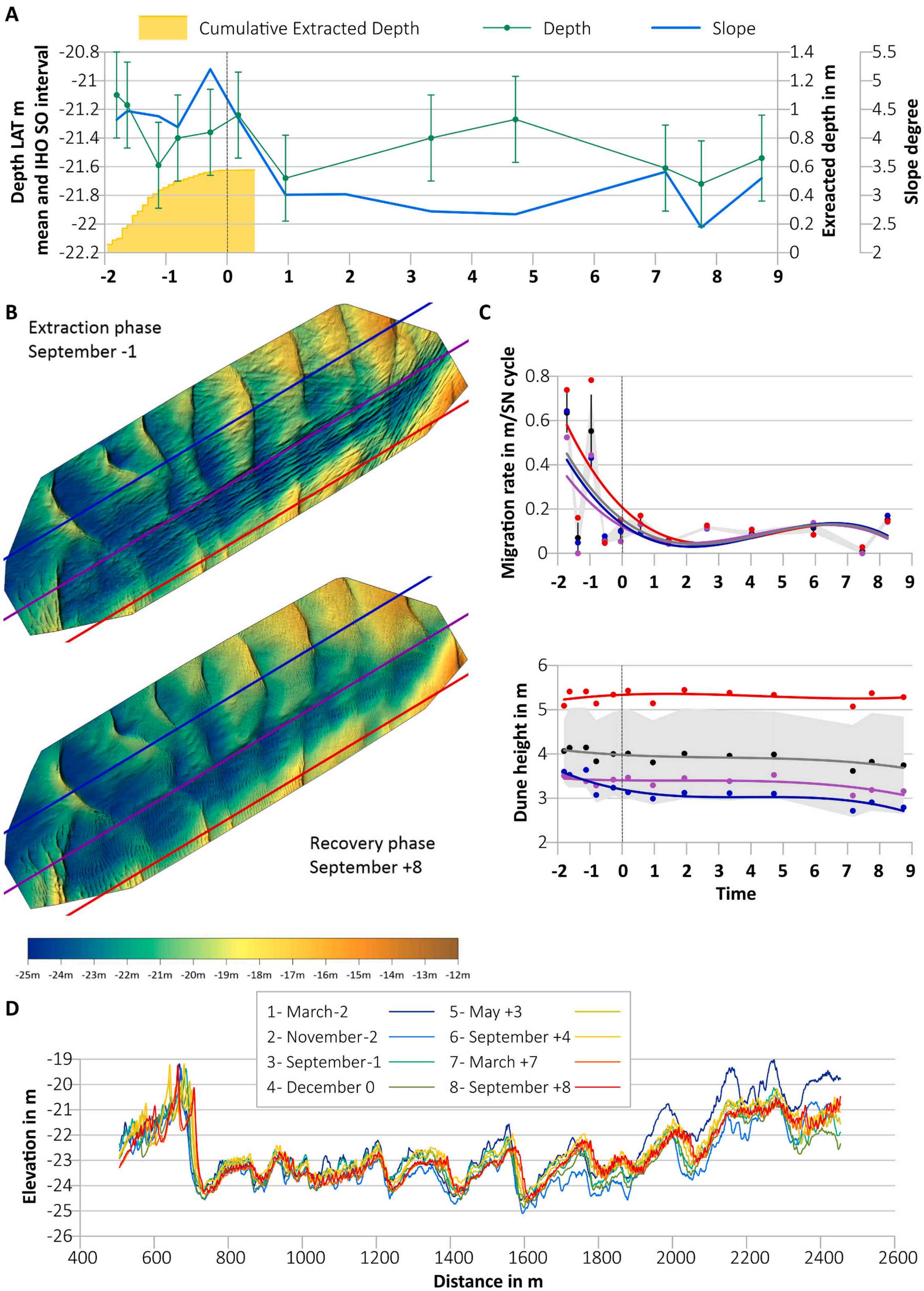

Fig. 4. Detailed bathymetric and morphodynamic evolution of the Buiten Ratel focus area. A. Mean bathymetry (green), slope (blue) and cumulative extracted depth (yellow, calculated by dividing the cumulative monthly extracted volume by the surface area) over time. B. Bathymetric models (1x1m) representing the two main phases, with indication of profile locations. C. Migration rate per spring-neap cycle and mean height over bathymetric profiles. Colours represent different profiles indicated in B. Points show individual measurements. The black points and line show the overall trend across all profiles with its 95 % confidence interval (grey shading). D. Bathymetric profile across the central profile indicated in B. Colours represent successive surveys over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

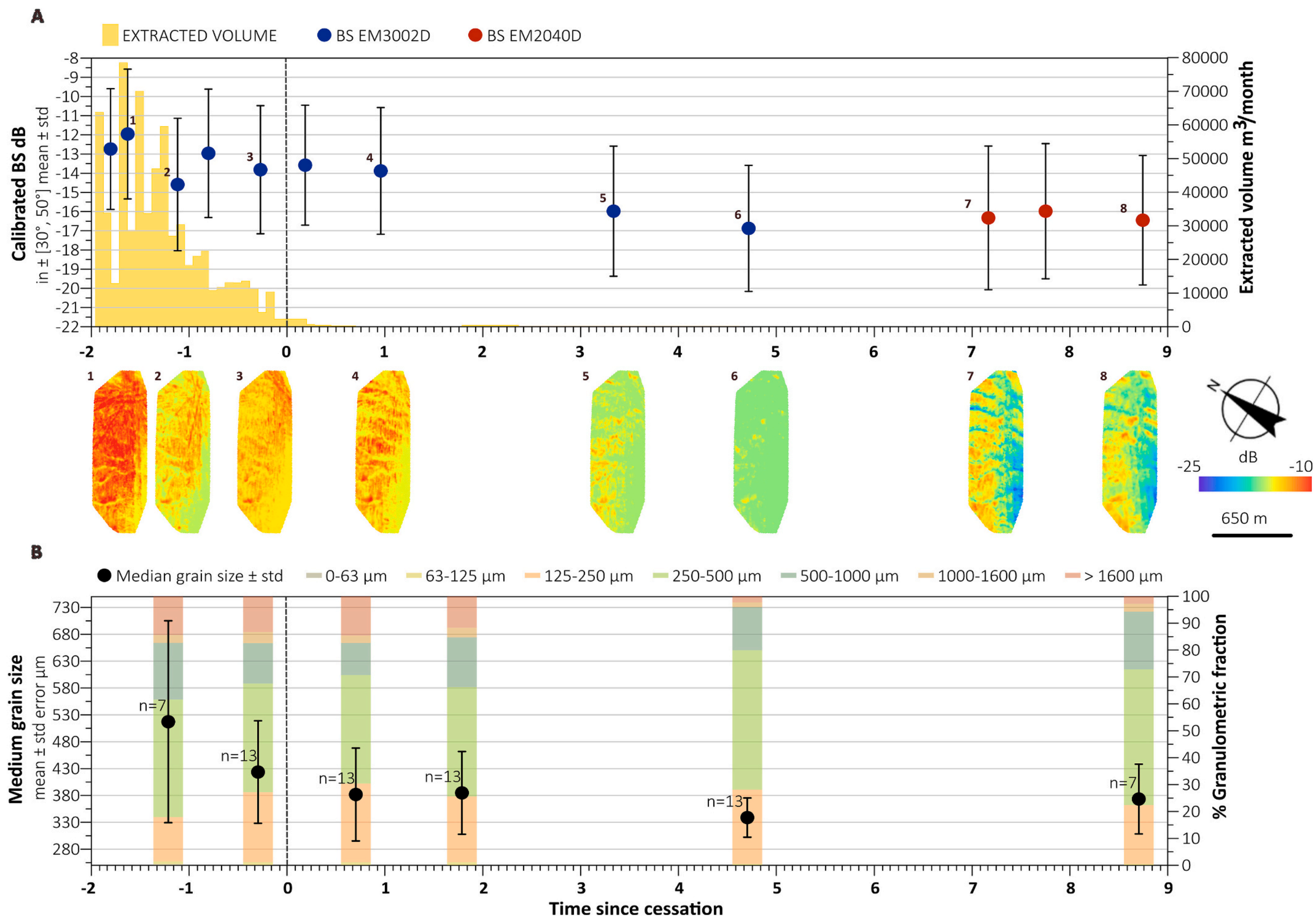

Fig. 5. Overview of extraction, bathymetric and sedimentological evolution of the Buiten Ratel focus area. A. Temporal trends in calibrated backscatter strength (BS, dB) from two echosounder systems (BS EM3002D in blue; BS EM2040D in red) and monthly extracted sediment volumes (yellow bars). BS data are shown as mean ± standard deviation for each time point relative to cessation (years since cessation). Backscatter maps illustrate spatial variations across the study area for selected time points. B. Median grain size (black points, mean ± standard deviation) and granulometric composition (% of sediment fractions) over time. The horizontal stacked bars represent the proportional contribution of granulometric fractions (colours) to the sediment composition. Sample sizes (n) for median grain size analyses are indicated for each time point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5B). Over the whole time series, the highly significant decline of BS levels (Mann-Kendall test *p*-value = 0.0016) is clearly linked to the extraction. The relatively high BS values from −12 dB to −14 dB observed from 2 years before closure up to the year after closure (years −2 to 1) reflect a high seabed rugosity with a surficial concentration of strong acoustic scatterers (shells and shell fragments and gravels). Once extraction ceased, BS levels gradually decreased and stabilized between −16 dB and − 17 dB, suggesting a sediment fining and the re-establishment of characteristics closer to the pre-dredging conditions. In the BR focus area, the evolution of BS correlates very well with the evolution of the sediment (Fig. 5C). Logically, as the acoustic wave interacts with sediment at a scale close to its wavelength (5 mm at 300 kHz), the BS shows a highly significant correlation with the % of particle size >1600 μm (Pearson's $r = 0.98$, p < < 0.01).

3.2. Thorntonbank

3.2.1. Sediment and macrobenthic changes at the wider area

3.2.1.1. Sediment. Although median grain size (MGS) was similar between the impact and reference locations during extraction (in year −2, IMP: 386 ± 55 μm, REF: 402 ± 144 μm), impact locations exhibited higher gravel content (8.8 ± 4.5 %) and lower medium sand fractions (56 ± 7 %) compared to the reference locations (resp. 2 ± 1 % and 62 ± 9 %). Following cessation of extraction, MGS in the impact zone decreased from 386 ± 55 μm in year −2 to 269 ± 78 μm in year 2. This shift was driven by an increase in finer sediment fractions (<250 μm): fine sand (28 ± 4 % in year 2), very fine sand (3 ± 5 % in year 2), and clay-to-silt (from 0.4 ± 1 % to 9 ± 15 %). Concurrently, gravel and coarse sediment fractions decreased, reflecting the transition towards finer sediments in the impact zone post-cessation (Fig. 6A).

3.2.1.2. Species richness, abundance and biomass. The interaction between ‘Time’ and ‘Impact’ was not significant for any of the response variables (all $p > 0.05$), suggesting that the changes over time in all variables were consistent across impact groups (Table 3). However, the main effect of ‘Impact’ was significant ($p < 0.05$) for all variables, with significantly higher values in impact locations for abundance, biomass, and richness, but a significantly lower B/N ratio compared to reference locations (Fig. 6B).

3.2.1.3. Community structure. Community composition was significantly influenced by ‘Time’ (Pseudo-F = 3.1484, $p = 0.0001$), ‘Impact’ (Pseudo-F = 5.2676, p = 0.0001), and their interaction ‘Time x Impact’ (Pseudo-F = 1.5983, $p = 0.004$), with notable differences between impact and reference locations across all years, during and after extraction activities (pairwise tests, all p < 0.05, Supplementary Table S6). The PCoA plot corroborated these results, showing a clear

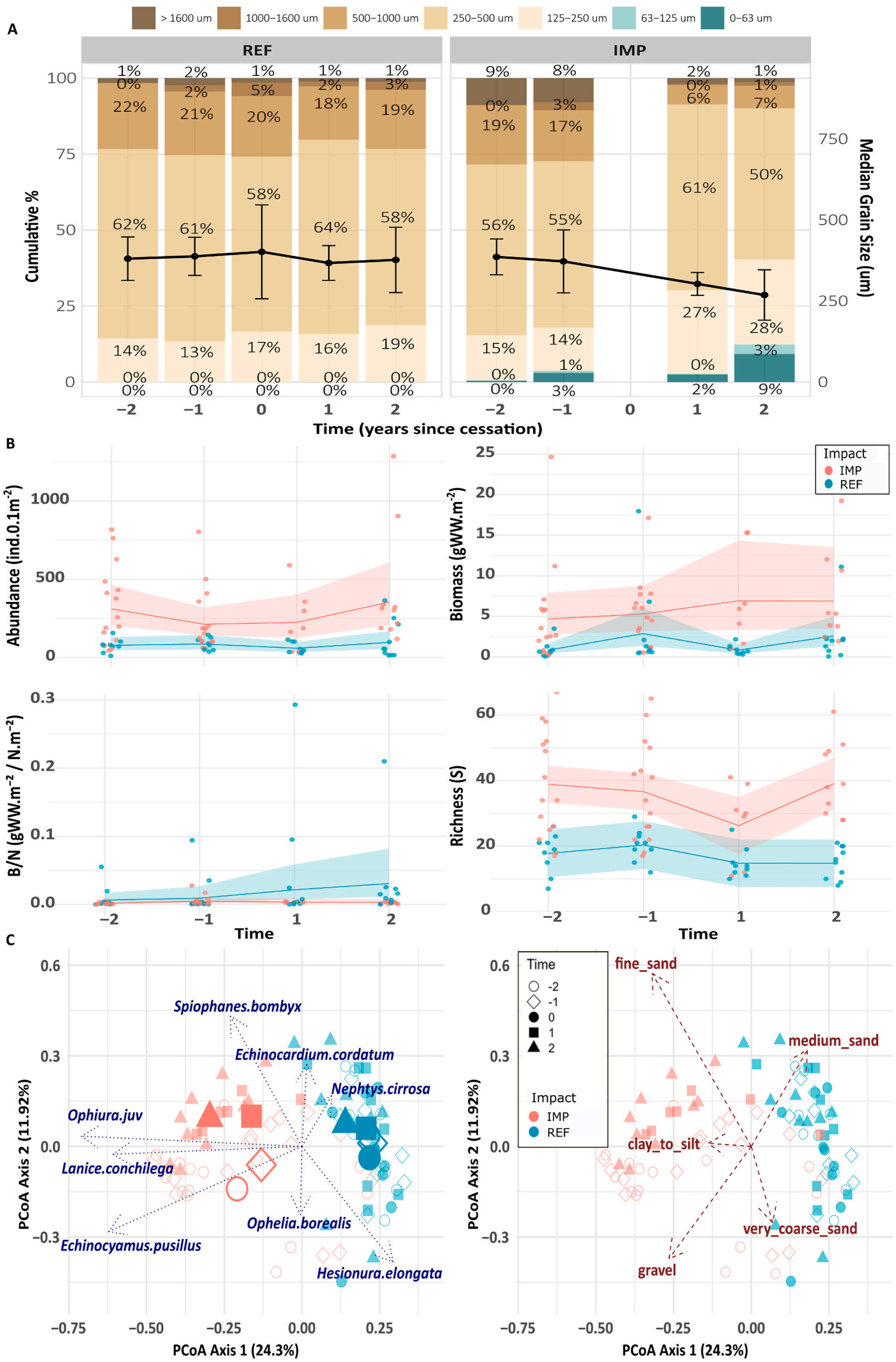

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Fig. 6. Thorntonbank results. A. Relative sediment composition (%) over time since cessation of sand extraction in reference (REF) and impacted (IMP) locations at the Thorntonbank. A. Relative sediment composition (%) over time since cessation of sand extraction in reference (REF) and impacted (IMP) zones. Grain size fractions include gravel, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, and clay/silt, shown as a stacked bar plot. Median grain size (μm) is plotted on the secondary y-axis. B. Temporal trends in macrobenthic community metrics at the Thorntonbank: Abundance (ind./0.1 m2), Biomass (gWW.m^{-2}), B/N ratio (Biomass per individual), and Species Richness (n° of species). Shaded areas represent 95 % confidence intervals around the mean values for reference (REF) and impact (IMP) across years. C. Principal Coordinates Analysis (PCoA) plots based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data on the Thorntonbank with indication of impact group (REF, IMP) in colour and time as years since extraction cessation in different symbol shapes. On the left PCoA plot, centroids per impact-time group are plotted on top as bigger symbols. Overlay vectors indicate direction and degree of correlation (length of vector) in which the species (blue vectors) and sediment fractions (red vectors) fit the multivariate data cloud. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Results of Generalized Linear Mixed Models (GLMM) assessing the effects of Impact, Time, and their interaction (Impact) on the response variables of macrobenthic community metrics (Abundance, Biomass, Biomass-to-Abundance Ratio (B/N), and Species Richness for TB.

Response: Abundance	Chisq	Df	Pr(>Chisq)
(Intercept)	204.6113	1	< 2.2e-16 ***
Impact	0.0017	1	3.039e-05 ***
Time	17.6749	3	0.5069
Impact:Time	16.2832	3	0.6756
Response: Biomass	Chisq	Df	Pr(>Chisq)
(Intercept)	0.2929	1	0.5883651
Impact	14.8628	1	0.0001156***
Time	13.6888	3	0.0033608**
Impact:Time	5.8500	3	0.1191387
Response: B/N	Chisq	Df	Pr(>Chisq)
(Intercept)	113.6650	1	< 2e-16 ***
Impact	5.8209	1	0.01584*
Time	8.8209	3	0.03730*
Impact:Time	3.8743	3	0.27536
Response: Richness	Chisq	Df	Pr(>Chisq)
(Intercept)	23.8113	1	1.063e-06***
Impact	20.9749	1	4.653e-06***
Time	1.9061	3	0.5921
Impact:Time	4.0558	3	0.2555

Chisq represents the chi-squared statistic, Df denotes degrees of freedom, and Pr (>Chisq) indicates the *p*-value. Significant effects are marked with * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$). Significant variables are indicated in bold.

Table 4
Species contributing most to the similarity within the impact and reference areas across different years in TB, as identified by SIMPER analysis. Percent contributions (% of total similarity) are listed for the top five species in each category.

Time	IMPACT	Contrib. %	REF	Contrib. %
-2	*Glycera juv*	7.53	*Hesionura elongata*	15.47
	Echinocyamus pusillus	7.17	*Nephtys juv*	14.72
	Nephtys juv	6.84	*Nephtys cirrosa*	11.08
	Ophiura juv	6.49	*Spiophanes bombyx*	8.01
	Spiophanes bombyx	6.11	*Spio spp*	7.50
-1	*Ophiura juv*	9.90	*Nephtys juv*	13.86
	Nephtys cirrosa	7.47	*Nephtys cirrosa*	13.54
	Echinocyamus pusillus	6.60	*Bathyporeia elegans*	13.29
	Nephtys juv	5.84	*Hesionura elongata*	9.38
	Eumida sanguinea	4.93	*Diogenes pugilator*	6.49
0			*Nephtys juv*	21.08
			Nephtys cirrosa	16.76
			Spio spp	10.56
			Spiophanes bombyx	8.81
			Bathyporeia juv	8.66
1	*Nephtys juv*	13.51	*Nephtys juv*	26.01
	Spiophanes bombyx	11.95	*Nephtys cirrosa*	23.03
	Lanice conchilega	9.21	*Spiophanes bombyx*	8.17
	Ophiura juv	7.47	*Phoronida spp*	7.06
	Urothoe brevicornis	7.10	*Echinocardium cordatum*	6.98
2	*Spiophanes bombyx*	6.91	*Nephtys juv*	27.52
	Ophiura juv	6.51	*Nephtys cirrosa*	13.86
	Echinocyamus pusillus	6.22	*Spiophanes bombyx*	11.06
	Phoronida spp	6.16	*Phoronida spp*	10.49
	Lanice juv	6.05	*Thia scutellata*	7.62

temporal shift of the IMP communities, which initially clustered with gravel/shell associated sediments when extraction was ongoing (years −2 and − 1), but shifted towards associations with finer sediments such as muddy sand after the cessation (years 1 and 2), contrasting with the relatively stable community structure in REF, which consistently aligned with medium sands (Fig. 6C). SIMPER analysis revealed distinct species changes over time: when the extraction was ongoing, the IMP samples were initially dominated by *Glycera juv, Echinocyamus pusillus,* and *Nephtys* spp. After closure the IMP samples shifted towards *Nephtys juv, Spiophanes bombyx*, and *Lanice conchilega*. In contrast, REF consistently showed high abundances of *Nephtys juv* and *Nephtys cirrosa* throughout the study period, species characteristic for medium sand (Table 4).

3.2.2. Morpho-sedimentary changes in the closed focus area

For the Thorntonbank sub-zone, the MBES time series spans from March 2019 to February 2024. The initial two surveys were conducted during extraction, though at a low level. Activities ceased at the end of 2020, and the subsequent four surveys, from −2 to 2, captured the seabed conditions immediately following extraction. The available sediment analysis is aligned with this timeline.

3.2.2.1. Bathymetric and morphodynamic evolution. The MBES time series (Fig. 7A) showed a decrease in mean bathymetry from year −2 to year 0, while the average slope value sharply dropped after the end of extraction (from 3.65° to 1.44°). This coincided with the end of the extraction period, resulting in the removal of an average of 0.18 m of sediment across the area. The central profile across the area (Fig. 7D) showed a sharp drop between the first two years and the subsequent ones. After the closure, bathymetry and slope remained stable, at approximately 24.2 m and 1.4°, respectively (Fig. 7A). This is confirmed by the central profile (Fig. 7D), where the last four surveys reveal only local variance. The final DTM from year 3 showed that the furrows, which were abundant before the end of extraction, are now less apparent.

Mean dune heights (Fig. 7C) range between 2 and 3 m, with similar temporal patterns across profiles. The easternmost profile exhibits the highest values (~2.6–3.0 m) and showed a steady decrease before cessation, followed by a gradual increase starting about one year after cessation. The other profiles displayed lower heights (~2.5 m and ~ 2.1 m, respectively) but follow the same trend, with a gradual increase from year 1 onwards. Notably, the westernmost profile, located in the most extracted area, showed the steepest increase after cessation. By the end of the observation period, all profiles appear more convergent, suggesting evolution towards original, pre-extraction heights. Migration rates (Fig. 7C) remained low and relatively stable overall, with values mostly below 0.1 m/SN cycle. Some consistent temporal variability was visible, with a potential decrease before cessation followed by an increase afterward, but the overall migration rates indicated limited

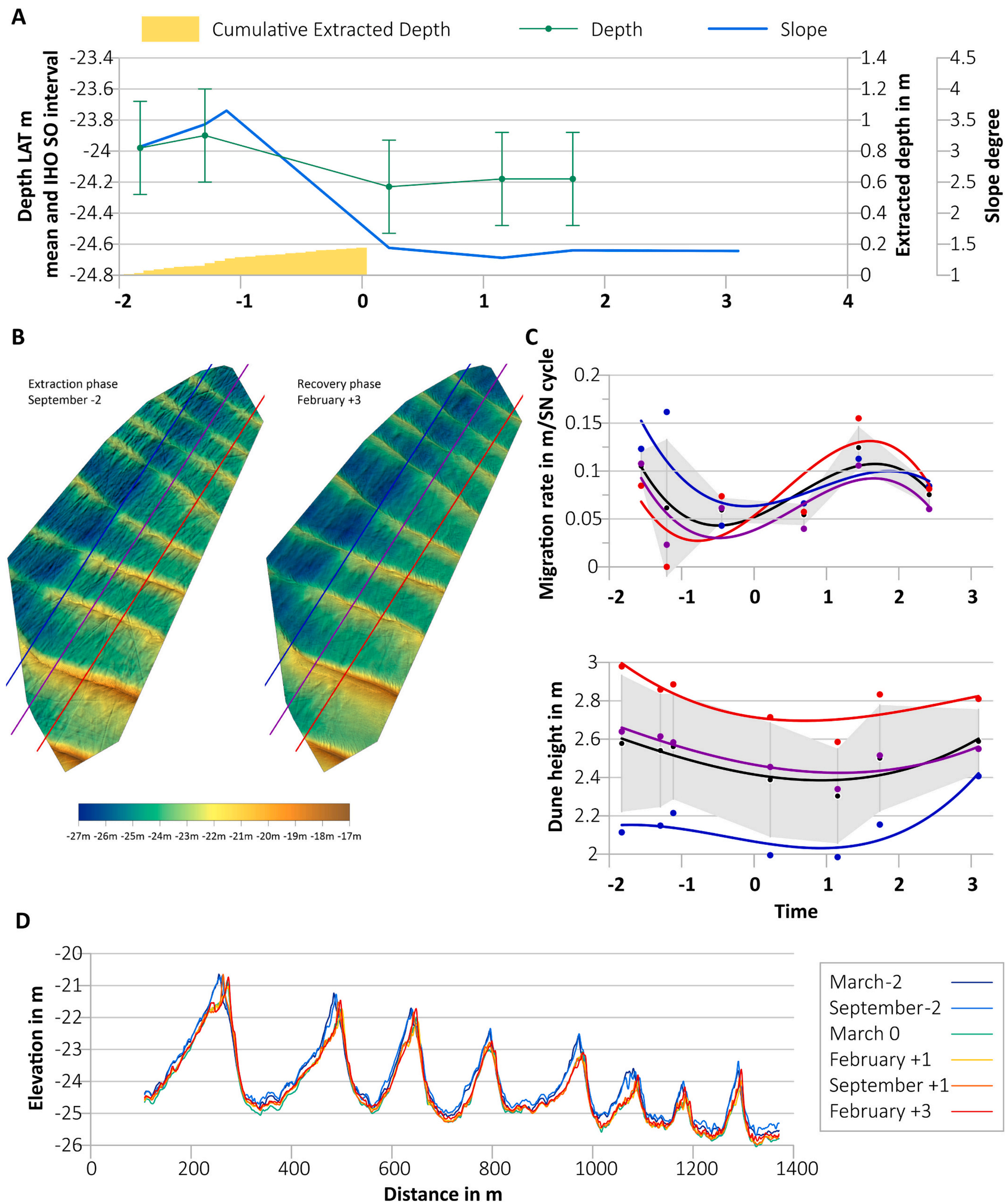

Fig. 7. Detailed bathymetric and morphodynamic evolution of the Thorntonbank area. A. Mean bathymetry green), slope (blue) and cumulative extracted depth (yellow, calculated by dividing the cumulative monthly extracted volume by the surface area) over time. B. Bathymetric models (1x1m) representing the two main phases, with indication of profile locations. C. Mean height over bathymetric profiles and migration rate per spring-neap cycle. Colours represent different profiles indicated in B. Points show individual measurements. The black points and line show the overall trend across all profiles with its 95 % confidence interval (grey shading). D. Bathymetric profile across the central profile indicated in B. Colours represent successive surveys over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variations around low values.

3.2.2.2. Backscatter and sediment evolution. In the TB focus area, BS levels showed a gradual decrease, from −13 to −14 dB at the end of the extraction phase (year 0) to −17 dB four years after extraction ceased (Fig. 8A). This highly significant trend in BS (Mann-Kendall test, *p*-value << 0.01) is correlated with sediment evolution towards finer grain sizes, with the median grain size decreasing from 346 to 270 μm in the focus area and an almost complete disappearance of the fraction >1600 μm (Fig. 8B).

4. Discussion

This study integrates both biological (macrobenthos) and physical (bathymetrical, morphological, and sedimentological) data to provide comprehensive insights in recovery processes following sand extraction. Our findings highlight that while extraction-induced depressions persist without infill, clear signs of both biological and physical recovery begin almost immediately after cessation of extraction. The extent of recovery, however, depends on the time elapsed. Fig. 9 summarizes the main observed changes over time for the different studied variables.

4.1. Local morpho-sedimentary reorganization drives recovery dynamics in tidal sandbank environments

Prior to extraction cessation, both sites exhibited high seabed heterogeneity with mixed sediments, persistent deep furrows and altered morphological features, which are known phenomena (e.g., Le Bot et al., 2010). In both zones, the coarse material fraction (> 1600 μm) and the finest fractions (< 125 μm) increased during extraction due to on-site rejection of unwanted coarser sediment (i.e. on-site sediment screening) and overflow of fines, along with the exposure of older geological layers. These physical changes resulted in a shift in the macrobenthos towards a more heterogeneous community, favouring opportunistic species and those typically associated with muddy sands (De Backer et al., 2014; Wyns et al., 2021).

After extraction cessation, the extraction-induced depressions in both zones persisted without sediment infill, corroborating earlier studies in the area (Bellec et al., 2010; Degrendele et al., 2010). This contrasts with observations from other regions (e.g., Gonçalves et al., 2014; Mielck et al., 2019; Witbaard and Craeymeersch, 2023), where depressions tend to fill. In our case, no such infill occurred, likely due to the high-energy sandbank environment, and depressions rather

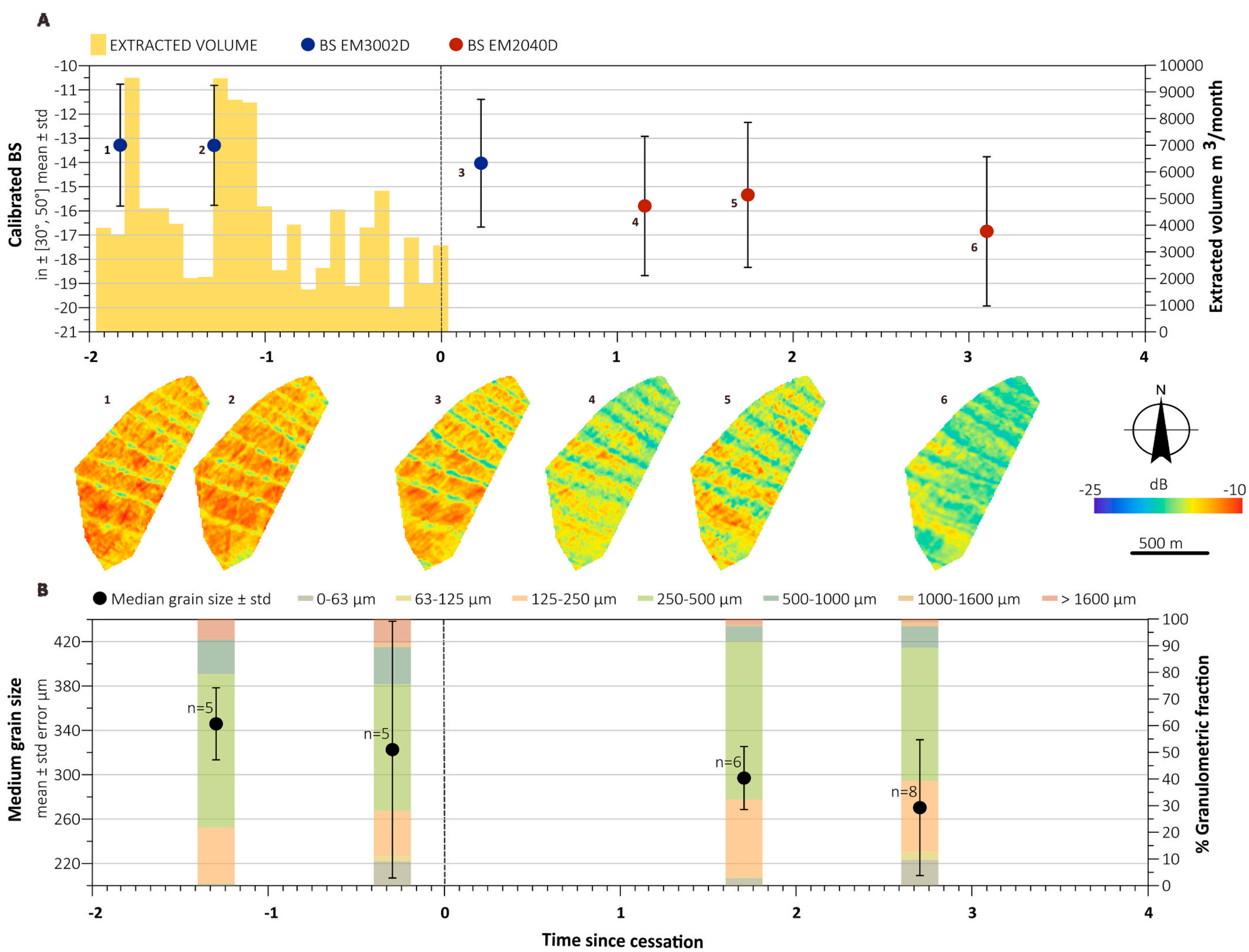

Fig. 8. Overview of extraction, bathymetric and sedimentological evolution of the Thorntonbank area. A. Temporal trends in calibrated backscatter strength (BS, dB) from two echosounder systems (BS EM3002D in blue; BS EM2040D in red) and monthly extracted sediment volumes (yellow bars). BS data are shown as mean ± standard deviation for each time point relative to cessation (years since cessation). Backscatter maps illustrate spatial variations across the study area for selected time points. B. Median grain size (black points, mean ± standard deviation) and granulometric composition (% of sediment fractions) over time. The horizontal stacked bars represent the proportional contribution of granulometric fractions (colours) to the sediment composition. Sample sizes (n) for median grain size analyses are indicated for each time point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

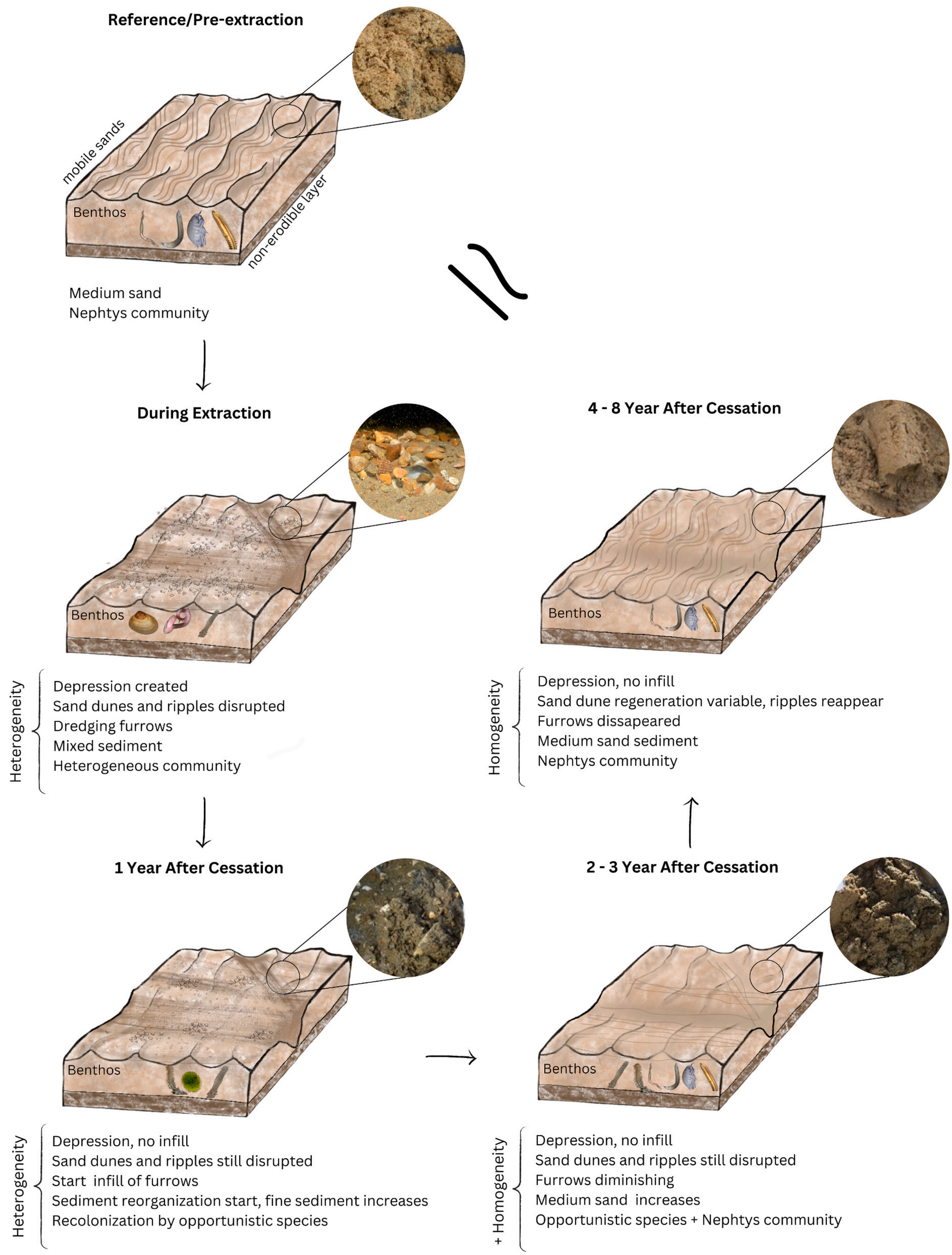

Fig. 9. Schematic representation of recovery processes following cessation of sand extraction over multiple years based on grab sample and MBES time series based on our results in tidal sandbanks. The term Mixed sediment follows the definition of Folk, indicating the presence of sand, coarse material, shells, and some mud enrichment. The on-site screening of the fraction >8 or 10 mm carried out during the extraction phase explains the enrichment in shells and shell fragments. Over time, sediment reorganization leads to increasing homogeneity, with fine sediments being trapped in troughs and coarser grains accumulating on crests and slopes. Between 4 and 8 years post-extraction, sand dune regeneration becomes variable, and ripples begin to reappear, depending on sediment availability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

channelizing currents (Garel, 2010). However, within these depressions, local sediment reorganization led to a gradual transition towards a more homogeneous seabed, particularly at Buiten Ratel, which had been closed the longest (8 years). Infilling and collapse of the furrows occurred primarily within the first year after cessation at Buiten Ratel and at Thorntonbank, already in the year before cessation because of reduced extraction effort (similar to observations in Uścinowicz et al., 2014 and Le Bot et al., 2010). Over time, the furrows continued to diminish, disappearing entirely after three years. Furrow filling occurs when sufficient sandy material is available, as observed in studies by Van den Eynde et al. (2010) and Degrendele et al. (2010), where natural sediment transport facilitates the gradual infill of furrows. A more homogeneous seabed is also evidenced by the gradual decrease in BS values indicating sediment fining and especially a drop in coarse material (> 1600 μm), leading to a lower seabed heterogeneity. At Buiten Ratel, a shift from mixed sediments towards medium sand occurred reflecting reference conditions after 4 to 8 years. Also at Thorntonbank, evidence of a sediment shift is observed already two years post-cessation, but it is still too early to reflect reference conditions.

Furthermore, smaller-scale morphological features, such as sand ripples, started reappearing within the depression at Buiten Ratel three years after closure, but the amplitude of the larger sand dunes did not change significantly, aligning with the observations of Krabbendam et al. (2022). In contrast, the smaller dunes at Thorntonbank returned to pre-extraction relative height after only two years. This suggests that sand dune recovery rates may differ between the two areas, possibly due to variations in local sediment availability and dynamics. Sediment redistribution may occur during extraction itself, as described by Terseleer et al. (2016, 2019), where erosion at crests and deposition in troughs or nearby extraction pit influenced seabed morphology. However, the extent to which these processes contribute to post-extraction recovery remains uncertain. The balance between sediment deposition and erosion is crucial for sandbank regeneration (Nnafie et al., 2020; van Veelen et al., 2024). If the human disturbance led to excessive erosion, recovery may be hindered, whereas areas with greater sediment availability may experience faster rebuilding over time (Uścinowicz et al., 2014; Van Lancker et al., 2010). Factors such as sediment properties (e.g., grain size, homogeneity), current velocities, and the broader topographic setting may favour sand dune recovery at Thorntonbank, which has a more uniform large-dune system compared to the more complex Buiten Ratel area, with sandbanks and morphological irregularities. Differences in extraction volumes may also influence recovery, as deeper depressions from higher extraction volumes could lead to prolonged recovery times due to a greater sediment deficit. Further research is needed to assess which physical mechanisms drive the observed differences in recovery trajectories.

We hypothesized that macrobenthic recovery in the tidal sandbank environments would occur within 3–5 years after cessation of extraction, driven by changes in sediment composition and seabed characteristics. Our results confirmed the hypothesis that cessation of extraction leads to a shift in macrobenthic communities, with Buiten Ratel progressing towards a *Nephtys cirrosa*-dominated assemblage by year 4, similar to reference conditions. This transition coincided with the gradual increase of the medium sand fraction for which the *N. cirrosa* community is characteristic. Macrobenthic abundance and biomass initially peaked, but later declined, which aligns with *Nephtys* community properties, typically having lower abundance and biomass (Breine et al., 2018). Moreover, the B/N ratio increased with time after cessation, indicating fewer but larger individuals. Similar results were observed in Area 408 (UK), where the B/N ratio in the abandoned area aligned with reference values (Newell et al., 2002). In Thorntonbank, similar early-stage shifts in benthic community composition were observed. However, after two years, no significant changes were detected in abundance and biomass, making it uncertain whether these parameters will eventually return to reference conditions. This highlights the importance of assessing both univariate and multivariate parameters, as they capture different aspects of ecological recovery. In both areas, the shift is initiated by opportunistic species (e.g., *Spiophanes bombyx, Poecilochaetus serpens*) abundantly colonizing the area following extraction. These species are able to take advantage of the dredged and sometimes unstable sediments, a process widely observed in disturbed seabed habitats, including those affected by dredging, trawling, and natural sediment shifts (Kenny and Rees, 1994, 1996; Kenny et al., 1998; Desprez, 2000; van Dalfsen et al., 2000; van Dalfsen and Essink, 2001; Newell et al., 1998; Bolam and Rees, 2003).

Our findings suggest that macrofaunal recovery in dynamic, tidal sandbank systems occurs relatively quickly, with the benthos returning to the reference community after 4 years when the sediment is reflecting reference conditions. However, when depressions are infilled with muddy sediments like in Thatje et al. (1999), de Jong et al. (2016), Mielck et al. (2019), and Witbaard et al. (2023), the benthic community does not return to the sandy reference conditions. Moreover, while our study found that biomass and abundance became similar to reference conditions over time (4–8 years), other studies have reported persistent deviation in these recovery times. For example, at a sand/gravel site off the southeast coast of England, biomass and abundance remained lower than in reference areas even four years after extraction ceased (Boyd et al., 2003a, b; Boyd et al., 2005). Similarly, Desprez (2000) reported that biomass and densities at a sand extraction site in France were still lower two years post-extraction. A recent study showed that in these areas benthic recovery takes up to 15 years (McIlwaine et al., 2025).

This variability in recovery rates observed across different extraction areas can be attributed to differences in sediment availability and characteristics, hydrodynamic conditions, and biological resilience. Unlike gravelly areas, where sediments do not easily return to reference conditions and benthic communities are highly vulnerable to disturbances (Ceia et al., 2013; De Backer et al., 2014; de Jong et al., 2016), macrotidal sandbank environments like our study area are more resilient to disturbance. This may promote natural sediment reorganization and facilitate faster recovery. Additionally, the resident fauna in these environments is naturally adapted to frequent disturbances, enhancing their resilience and enabling quicker recolonization post-extraction. Previous research has shown that benthic communities in dynamic sandy habitats exhibit higher recovery potential compared to those in more stable, coarse sediment environments (Dernie et al., 2003; Desprez et al., 2022; Degraer et al., 2010; Foden et al., 2009; Hill et al., 2011).

4.2. On-site screening of coarse material may accelerate recovery by enhancing sediment retention and redistribution

From the above, it is obvious that in both areas, similar recovery processes are at play, starting immediately after cessation of extraction and leading to an increased sediment homogenization and habitat type that resembles reference conditions (see also Fig. 9). This most probably is caused by local sediment reorganization which is potentially accelerated by the coarse material deposited through on-site screening during the extraction process. The effect of sediment screening on recovery has received less attention in previous studies, yet we suggest it could play a critical role in determining how quick physical recovery can occur. For instance, the selective removal of coarse/gravel materials and redeposition of sandy material during extraction in gravelly areas alters the capacity of natural processes to replenish these areas, leading to long-lasting changes in seabed composition (Hill et al., 2011). In contrast, in dynamic sandy environments where sediment screening enriches the sandy seabed with coarse material, we hypothesize that this process can facilitate recovery once extraction ceases.

Finer sediments are more easily transported and redistributed by natural processes, while coarser materials, such as gravel and shells, are less mobile and, once removed, will naturally not be replaced. Sediment screening during extraction is critical in this respect. In areas where extraction targets coarse material (e.g. gravel in UK) and screening selectively redeposits sands, recovery is significantly delayed due to the inability of natural processes to replenish the coarse material, leading to long-term alterations in seabed composition (Barrio Frojan et al., 2011; Hitchcock and Bell, 2004). Conversely, in the BR and TB areas, where sand is the target resource, the systematic screening of coarse material (>8 or 10 mm) carried out during extraction operations (pers. comm. with industry) has led to the enrichment of the seabed surface with shells and pebbles. Once extraction ceases, the presence of this coarse material, through the hiding-exposure mechanism, contributes to the accumulation of fine sediments in certain areas such as troughs while allowing coarser grains to dominate in others like crests or stoss slopes (Damveld et al., 2020; McCarron et al., 2019). This dynamic interplay facilitates the spatial redistribution and sorting of sediments across various bedforms. According to this mechanism, the enrichment of coarse material due to screening during the extraction phase in the studied areas may facilitate a local physical recovery of the seafloor. This process is somewhat analogous to induced restoration methods in former extraction sites that involve gravel or shell dispersion (Cooper et al., 2011).

The lack of comparison with a cessation area that did not undergo screening limits our ability to confirm whether recovery of the studied sandbanks would have been slower without screening. This limitation highlights the importance of including such control areas (i.e., impacted areas without screening) in future studies to better understand the role of coarse material deposition in recovery dynamics of tidal sandbank habitats. Furthermore, the observed mechanism is also dependent on local hydrodynamics and depth (Harris, 2014). In areas with deep waters or limited sediment mobility, natural recovery of seabed structure and sediment composition is by definition a slower process and it is unknown whether the hide-exposure mechanism could potentially accelerate recovery in such areas. Extraction with on-site screening must therefore always consider factors such as water depth, tidal current velocity and sediment composition to better predict recovery outcomes (Hill et al., 2011).

4.3. Effective sand extraction management in the BPNS prevents habitat loss

Our findings provide important insights into how sand extraction can remain compliant with EU Directives, particularly the EIA (Environmental Impact Assessment), Habitats Directive, and the MSFD. The current management strategies in place in the BPNS (i.e. total volume quotas for the industry and depth below seabed limitation, see 2.1) effectively mitigate disturbance, with no permanent habitat loss observed in the extracted areas, indicating that well-designed management frameworks can promote recovery.

The observed recovery underscores the importance of allowing time for recovery. Buiten Ratel, with its 8-year post-closure recovery period, exemplifies that sand extraction causes disturbance rather than irreversible habitat loss (ICES, 2019; Raicevich et al., 2025). Despite its intense historical extraction, the area demonstrates resilience, with significant signs of recovery in morpho-sedimentary characteristics and benthic community. In comparison, Thorntonbank illustrates early trends of recovery within a 2-year period, reflecting initial sediment stabilization and macrobenthic transition. However, the limited timeframe highlights that full recovery has yet to be achieved. The results emphasize that adaptive management built on and informed by a well-designed monitoring program is key to ensure long-term recovery without compromising ecosystem resilience (Schmitt et al., 2023).

The multidisciplinary monitoring approach, integrating seabed characterization and benthic community assessments, has been effective in assessing recovery and evaluating management practices. Ongoing and consistent monitoring efforts, aligned with the MSFD targets for "Good Environmental Status" (GES) (Belgische Staat, 2025), enable accurate assessments of recovery trajectories as shown in this study. Monitoring tools like MBES (multibeam echosounders) and grab sampling provide robust data on morpho-sedimentary and benthic changes, facilitating informed decision-making (Van Lancker et al., 2024), and providing essential insights for adaptive management and conservation strategies.

Overall, the recovery trajectories in both areas indicate that, under current management policies and extraction volumes, disturbed sandy habitats in the BPNS can recover within 12 years, aligning with EU regulations that define recovery as a return to reference conditions (Raicevich et al., 2025). This highlights the need to differentiate between habitat 'disturbance' and 'loss,' as ecosystems can regain stability when recovery is supported through effective management. The Belgian approach, integrating implementation of extraction depth below seabed limitations, total volume quota for the industry, close cooperation with the industry and multidisciplinary continuous monitoring supporting micromanagement at extraction site level, appears successful in preventing direct habitat loss, critical for maintaining Good Environmental Status, as required by the MSFD and EU Biodiversity Strategy (Belgische Staat, 2025).

5. Conclusion

This study provides new insights into the recovery dynamics of macrobenthic communities and morphosedimentary characteristics following sand extraction on tidal sandbank environments. While large-scale bathymetric depressions persist without natural infill, smaller-scale recovery processes occur gradually. At Buiten Ratel, both physical and biological recovery evolve over 4 to 8 years, with sediment homogenization and a shift in benthic communities towards reference conditions. Small-scale ripples reform, suggesting sediment deposition, though larger sand dunes remain lower than pre-extraction levels. At Thorntonbank, recovery is not yet evident after 3 years, but initial trends such as sediment fining and homogenization indicate a similar trajectory, warranting extended monitoring to assess long-term evolution. Recovery appears to be driven by local sediment reorganization rather than external sediment supply, with on-site screening practices potentially accelerating the process through the hiding-exposure mechanism. Further research should examine long-term recovery across diverse sedimentary environments and extraction regimes to refine management strategies. Our findings highlight the importance of adaptive management supported by multidisciplinary monitoring in balancing resource extraction with ecosystem resilience, particularly in evaluating Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD).

CRediT authorship contribution statement

Lucia Lopez Lopez: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Koen Degrendele:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Marc Roche:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Florian Barette:** Writing – review & editing, Visualization, Methodology, Data curation. **Vera Van Lancker:** Writing – review & editing, Supervision, Conceptualization. **Nathan Terseleer:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Annelies De Backer:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118184.

Data availability

Data will be made available on request.

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