Monitoring report 2021-2024

on the occasion of the

study day

"Gold in the North Sea: the importance of marine sand and innovations in terms of monitoring and research"

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1. Introduction

In Belgium, the impact of sand extraction on the marine environment is monitored collaboratively by the Continental Shelf Service of the FPS Economy, the Institute of Natural Sciences, and the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO). Each of these organizations has contributed separately to this report, highlighting key findings and developments from the past three years based on their respective areas of expertise.

2. Monitoring Sand Extraction Activities and Its Impacts on the Seabed: Results, Developments and Innovations from 2020–2024

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2.1. Context

The impact of sand and gravel extraction on the marine environment is monitored by the Continental Shelf Service of the FPS Economy based on the analysis and interpretation of data obtained from the Electronic Monitoring System (EMS), Automatic Identification System (AIS) and Multibeam Echosounder (MBES).

The EMS is a recording system installed on every sand extraction vessel operating in the Belgian part of the North Sea (BPNS). The EMS records data related to the vessel's position and activity (e.g., the status of the dredging pumps). This data enables the monitoring of sand extraction activities and facilitates the estimation of the extracted volume and depth at specific locations.

The AIS was developed in the 1990s to improve navigation safety by enabling the exchange of real-time data, including vessel identity, position, and speed, between vessels and onshore stations. Given the comprehensive information AIS provides, this data is now applied in a large variety of fields (e.g., navigation safety, traffic management, cargo traffic and fishing activity monitoring). By conducting a detailed spatio-temporal analysis of the vessel speed time series, valuable insights into sand extraction activities can be derived, similar to those obtained from EMS data (Figure 1).

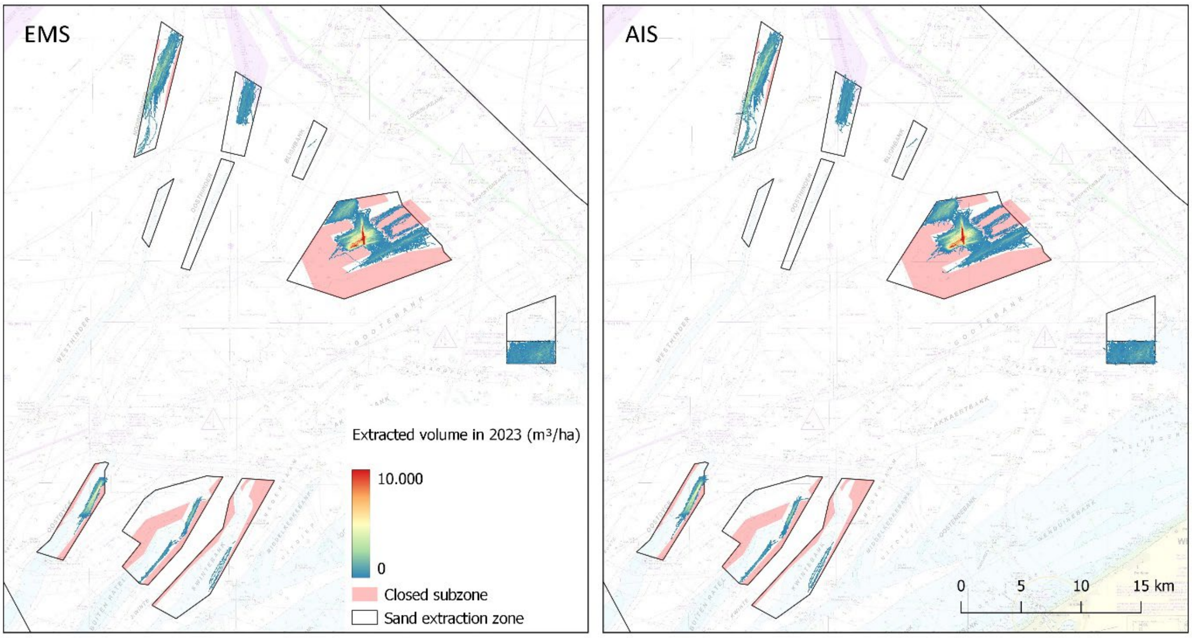

Figure 1. Comparison between the extracted volume for 2023, estimated based on EMS (left) and AIS (right) data.

A MBES is an acoustic instrument that maps bathymetry (seafloor depth) and backscatter strength – BS (proxy for the sediment's characteristics). Using the MBES aboard the RV Belgica, RV Simon Stevin or other vessels, the bathymetry and the BS of a given monitoring zone or reference line is mapped at a given time.

By regularly conducting MBES measurements on the same area, the evolution of bathymetry and the BS can be analysed at that location. The EMS/AIS and MBES data are complementary: MBES data are detailed snapshots and EMS/AIS data provide continuous information about sand extraction in time and space. The EMS/AIS and MBES data allow to (1) analyse the impact of sand and gravel extraction on the seafloor at a local (monitoring zone) and global scale (Decca reference line and BPNS) and (2) verify that the sand extraction activity is within the legally permitted limits.

This contribution is a follow-up and update to the previous reporting:

- Roche, M., Degrendele, K., Vandenreyken, H., Schotte, P., 2017. Multi-time and space scale monitoring of the sand extraction and its impact on the seabed by coupling EMS data and MBES measurements. In: Degrendele, K. and Vandenreyken, H. (Ed.). *Belgian marine sand: a scarce resource?* Study day, 9 June 2017, Hotel Andromeda - Ostend. pp. 5–37.
- Barette, F., Degrendele, K., Roche, M., 2020. Monitoring van de zandwinning en de impact op de zeebodem. In: Vandenreyken, H. (Ed.). *De resultaten van het continue onderzoek uitgevoerd door de Dienst Continentaal Plat, het Instituut voor Landbouw-, Visserij- en Voedingsonderzoek en OD Natuur in de periode 2017-2020: Rapport voor de Raadgevende Commissie*. pp. 4–19.

This report encompasses a triennial overview of the Continental Shelf Service's monitoring activities from 2020 till July 2024. It highlights published results with references, summarizes unpublished findings, and reviews the impact of sand extraction on the BPNS. It also outlines ongoing and completed technical and scientific projects aimed at enhancing the understanding of acoustic tools used to improve the monitoring of sand extraction and its impact on the marine environment. The reference list (section 2.6) presents the key scientific papers, conference contributions, and reports, both published and ongoing, in which the Continental Shelf Service is the primary actor or significant contributor from 2020 to 2024.

2.2. Monitoring Actions

Monitoring of the impact of sand extraction on the seabed has traditionally been based on comparing successive MBES measurements in monitoring zones. The time series consist, on the one hand, of terrain models of monitoring zones, where the local impact in a small area is studied in detail (Figure 2a), and, on the other hand, of a series of measurements along Decca reference lines over the sandbanks, in order to study the impact of sand extraction on the seabed on the long term and over a larger area (Figure 2b). The delineation of the monitoring zones is based on EMS- and AIS-based extracted volumes, thus concentrating on the evolution of the most extracted zones.

The timeline in Figure 3 summarizes all MBES surveys conducted on these monitoring zones and Decca reference lines. The number of monitoring zones has steadily increased in the first two decades of monitoring, due to changes in the spatial distribution of the extraction. The breaks in the time series in 2016 and 2017 are due to the long-term unavailability of the former RV Belgica during this period. After the introduction of the new reference surface in 2021 and the introduction of subzones closed for extraction, the monitoring strategy was adapted on zone 1 (Thorntonbank). Monitoring the existing TBMAB area was less relevant, and a more adaptive strategy was introduced: each year the surveyed area is amended to encompass the changing subzone open for extraction, in order to follow the shift of the extraction hot spot. The discontinuation of the time series on HBMC is due to the shift of the extraction on zone 4 from sector 4c to 4a (see Figure 2a). The Continental Shelf Service focused it's monitoring effort on this area to prepare for the closure of this sector in the course of 2025 due to the establishment of the Princes Elisabeth windfarm. The navigational restrictions of the new RV Belgica (minimal water depth under the keel) resulted in only partially executed surveys along the Decca lines on the Vlaamse Banken (zone 2) and Hinderbanken (zone 4). R2 is only sporadically surveyed due to the limited priority.

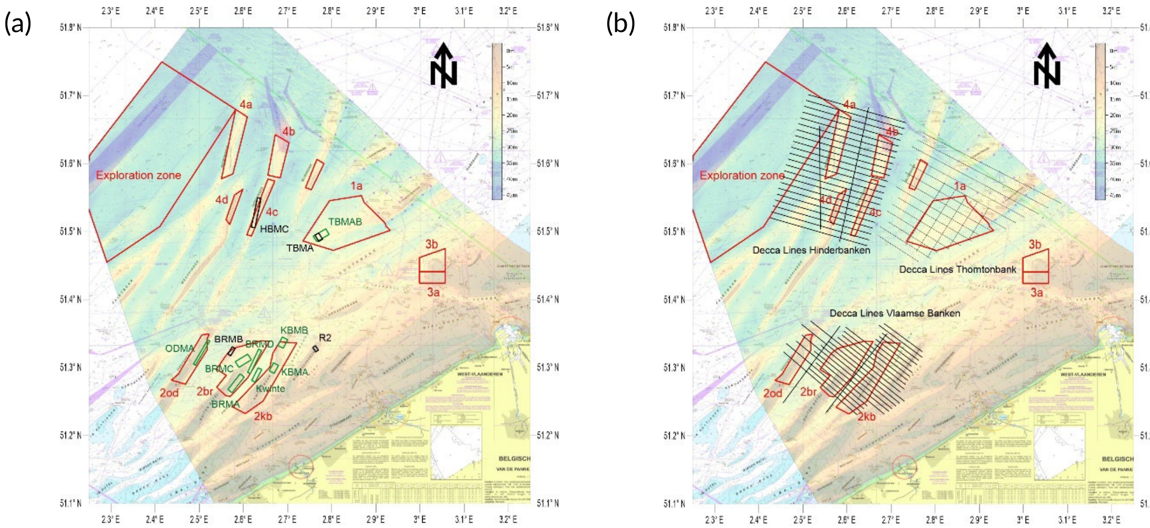

Figure 2. (a) Location of monitoring zones (actively surveyed in green - discontinued in black) and (b) Decca reference lines. Sand extraction control zones in red.

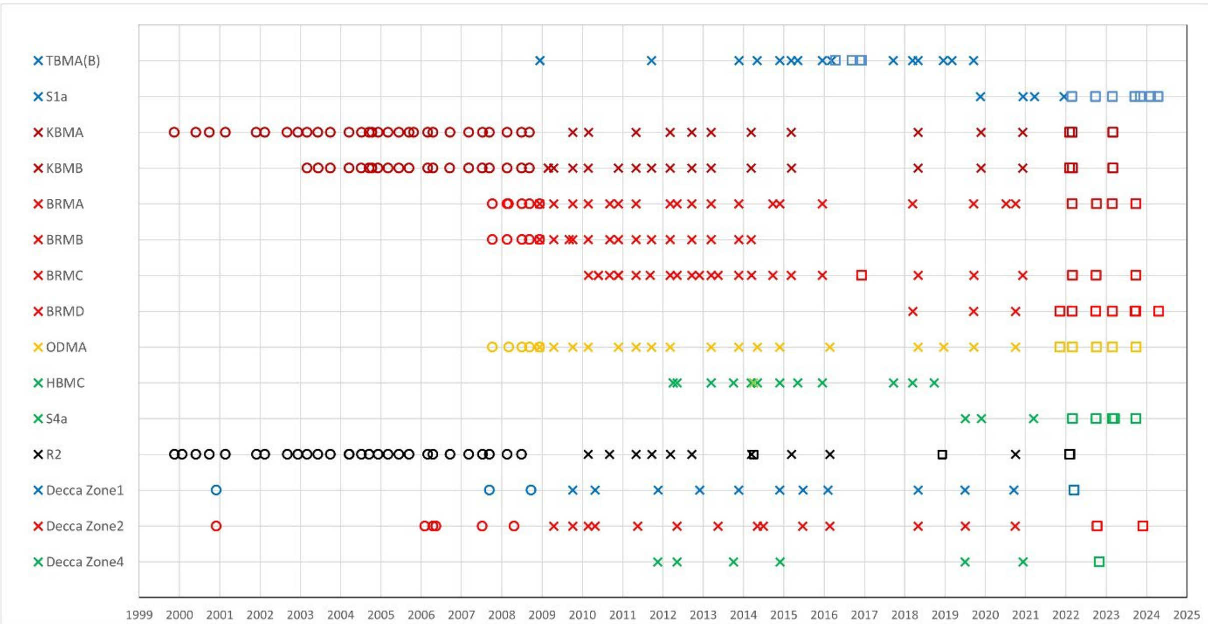

Figure 3. Completed timeline of the different MBES surveys of the monitoring zones and Decca reference lines. Bathymetric and BS data acquired with MBES EM1002 (round) and EM3002 dual (cross) onboard RV Belgica, and EM2040 dual RX (square)onboard RV Belgica, RV Simon Stevin and Geosurveyor XI.

The Decca lines monitoring is presently under consideration. The navigational restrictions for RV Belgica make the surveying very time consuming and makes it impossible to complete the full surveys. The Decca time series is the focus of the ongoing collaboration with ENSTA Bretagne on the minimalization of systematic errors. Pending the outcome of this project, the Decca time series will be re-analysed and the already formulated conclusions re-evaluated.

The Continental Shelf Service is implied in the BANX[1] project, in which the single- and multibeam measurements along Decca lines will play an essential role.

With the objective of assessing the far-field impact of sand extraction in relation to the dispersion of plumes generated during dredging operations, the Continental Shelf Service took the initiative to organise a couple of experiments to study this effect. The goals of these experiments, realised in close collaboration with RBINS and VLIZ (due to their related expertise and the ongoing cooperation inside the closely related project Turbeams[2] funded by BELSPO) are obvious for the Continental Shelf Service: (1) evaluate the usefulness of MBES for the detection and delineation of the sediment plumes generated during the extraction, and (2) evaluate the applicability and accuracy of the sediment dispersion models from RBINS to correctly predict the extent and range of this effect. This would result in an accurate estimation of the range and importance of the impact and establish the MBES as an effective *in situ* validation tool for the sediment dispersion model that will be used in the monitoring of dredging operations.

The experiments took place during two RV Belgica campaigns (November 2022 and March 2023). On both occasions the experiment was repeated twice, resulting in a total of six independent datasets (see summary final experiment on Figure 4). The first analysis and results have been presented on EGU2024 and indicate (1) the usefulness of the EM2040D MBES on board RV Belgica, and (2) the good correlation between the model predictions and MBES and other sensor measurements and water column sampling. Renewed experiments and refinement of the methodology are planned in 2024 and upcoming years. Due to the central role of RBINS in these experiments (model predictions, sensor measurements and water column sampling), and the accomplishment of a methodology for the mayor input (MBES) from the Continental Shelf Service, the lead in this important new aspect in the common monitoring effort by the involved institutes has been passed to RBINS.

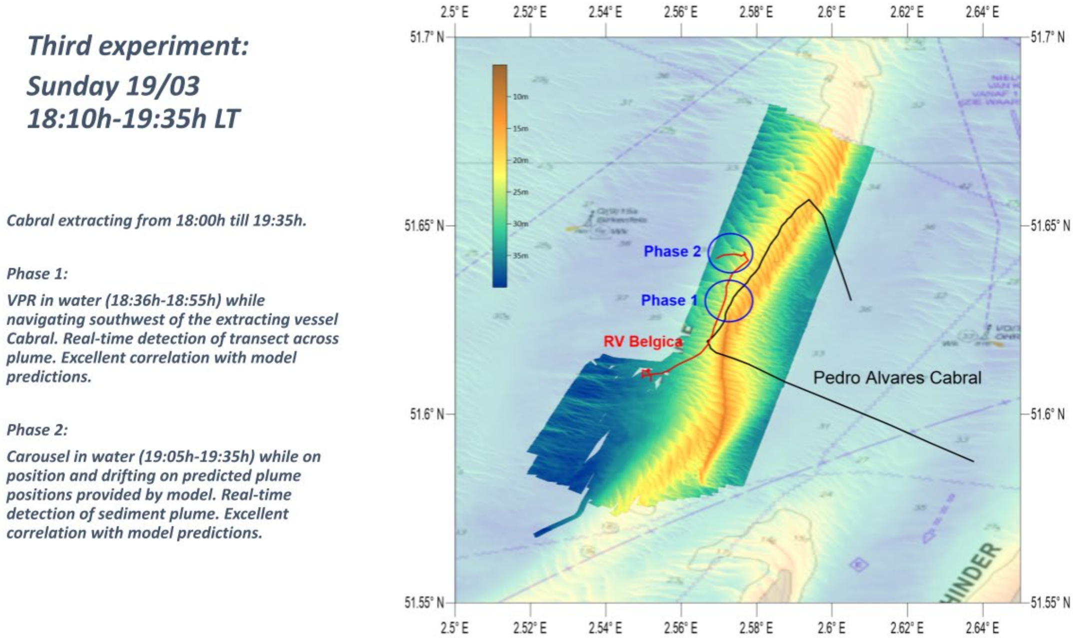

Figure 4. Summary of the course of the third experiment during the March 2023 Belgica campaign.

Regarding the sediment classification based on BS, substantial improvements were made to the scientific methodologies, including data acquisition and processing techniques. Sub-pixel classification techniques of the seabed that account for the gradients in seabed types (i.e., the continuum between for example sand and gravel) were investigated. A key advancement was the implementation of a calibration

[1] https://www.nwo.nl/en/projects/20622

[2] https://www.belspo.be/belspo/NewRV/projects/TURBEAMS_en.pdf

procedure for BS data, which now facilitates the inter-comparison of measurements acquired at comparable frequencies using different MBES systems. This procedure enables the integration of heterogeneous datasets into a continuous-time series, thereby allowing for robust classification based on the modeling of the signal's angular response. BS calibration is a prerequisite for establishing an acoustic sediment classification system based on the angular response of the BS and its modeling. During a three-month sabbatical leave at the Continental Shelf Service, Prof. Dr. Luciano Fonseca from the University of Brasilia investigated in great detail the BS angular response.

To carry out all above-mentioned measurements, the Continental Shelf Service spent a total of 7 days on board the RV Belgica in 2021, 34 days in 2022, 37 days in 2023 and 7 days in 2024. The campaigns with RV Belgica are shared between institutes, so only part of this time on board was spent on effective measurements. Furthermore, a significant part of the measurements was also reserved for calibration and testing. The time on board the RV Simon Stevin (respectively 2, 5, 3 and 3 days in the period 2021–2024) was mostly focused on calibration, ground truthing and testing. Both RBINS – Operational Directorate Natural Environment and VLIZ are acknowledged for the provision of shipboard time and technical support. The crews of both ships (Genavir, Belgian Defence and Vloot) are expressly thanked for their excellent cooperation and their indispensable contribution to obtaining the necessary measurements.

2.3. Methodology

2.3.1. EMS and AIS data

On behalf of the Continental Shelf Service, the EMS-data presented in this report was gathered and processed by the Measurement Service Ostend of RBINS. The AIS-data was gathered and processed by the Continental Shelf Service, using specific tools developed for this purpose.

2.3.2. MBES Acquisition

The MBES measurements took place aboard the research vessels RV Belgica and RV Simon Stevin. Both vessels have the same MBES system for conducting surveys in shallow water on the continental shelf: a Kongsberg EM2040 MKII Dual RX. The system simultaneously records bathymetric and BS data that allow monitoring of the impact of sand extraction on the morphology and composition of the seabed, respectively. The hydrographic quality of the data is ensured by systematic reference measurements on the acoustic reference zone Kwinte. This zone is protected in the ongoing Marine Spatial Plan so that the stability of the seabed cannot be affected by human activities. On both vessels Kongsberg SIS4 or SIS5 were used for acquisition and storage of raw data.

2.3.3. MBES-processing

Bathymetry

The bathymetric data are further processed in the software Qimera after acquisition on board. After a number of operations to achieve correct vertical positioning (depth relative to a fixed reference level - LAT) and filtering out erroneous observations, a detailed terrain model of the seafloor is calculated. These terrain models form the basis of the time series and allow further analysis and evaluation of the impact of sand extraction on the seafloor topography.

Bottom BS

Bottom BS was systematically recorded along with bathymetric data. After correction and calibration, BS provides a reliable indicator of the sediment covering the seabed. Processing was done using Ifremer SonarScope (version 2024-02-24). Monitoring the BS time series involves for each survey: 1) correcting for acoustic absorption; 2) adjusting for the insonified area based on tide-corrected terrain models and real incidence angles; 3) calibrating with a BS correction file from recordings in the Kwinte reference area, allowing data from different sounders to be merged (see 2.3.4); and 4) creating a 1 m × 1 m mosaic, averaging values from the ±[30°, 50°] oblique-incidence sector to extract calibrated BS statistics.

Water Column BS

Water column BS data collected during measurement campaigns aimed at estimating the dispersion of sediment plumes caused by dredging operation are analyzed using Ifremer SonarScope (version 2024-02-24). For each survey, the key steps include: 1) extracting SV values (dB/m^3); 2) interference filtering; 3) generating polar echograms; 4) creating 3D matrix incorporating all data (SV, time, and geographic position); 5) producing longitudinal echograms and 6) performing echo integration of SV values. This comprehensive data processing enables both qualitative and quantitative interpretation of BS data recorded in the water column leading to a 4D mapping of sediment plumes observed during the measurements that allows verification of the plume positions predicted by the dispersion model. Additionally, comparisons are made with data from other acoustic and optical sensors used concurrently, as well as with estimates of particle nature, concentration, and granulometry derived from water samples collected during the measurements.

► For more information: 2.5. Reference list / Water column backscatter knowledge and measurement of sediment plumes.

2.3.4. Hydrographic Quality Assessment and BS Calibration

The Kwinte reference area (KRA) established in the Marine Spatial Plan 2020–2026 (Art. 19, § 3), is a key resource for public and private actors conducting MBES measurements to assess the hydrographic quality of bathymetric data and BS measurement consistency. Since 2023, this zone also allows BS calibration across various acquisition frequencies. The Flemish Hydrography team of the Maritime and Coastal Services Agency, in collaboration with the Continental Shelf Service, oversees promoting the use of the zone, analysing and managing related data and sharing the derived information. Regular measurements of KRA with the various MBES used by the Continental Shelf Service have been carried out since 2009.

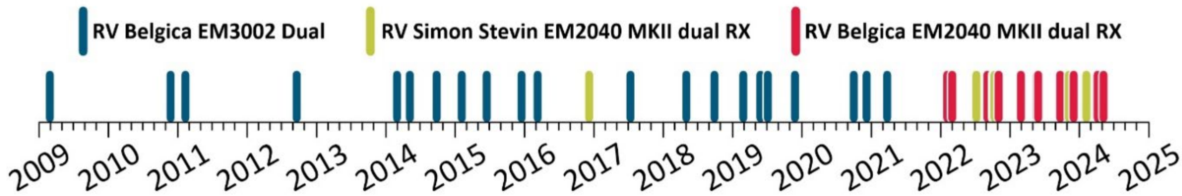

Figure 5. Kwinte reference area 300 kHz MBES times series registered by the Continental Shelf Service.

For each survey, the bathymetric data are compared against the reference model of the KRA, which is constructed and regularly updated by the Flemish Hydrography team of the Maritime and Coastal Services Agency using data from the latest MBES technology and real-time kinematic (RTK) corrections, guaranteeing precise positional and depth accuracy. For Z values, the soundings collected with the EM3002 dual system from the former RV Belgica meet Special Order quality standards as defined by the International Hydrographic Organization's (IHO) S44 standards. Even better, surveys done with the EM2040 MKII dual RX systems on the RV Simon Stevin and the new RV Belgica exceed this standard, achieving Exclusive Order quality.

Since 2009, regular surveys have consistently demonstrated the stability of the mean BS level in the KRA, characterized by a uniform layer of sandy gravel. This acoustic consistency makes the area ideal for assessing the repeatability of BS data, which is crucial for using it as a sediment proxy for monitoring the impact of sand extraction on the seabed.

In May 2023, in collaboration with Ifremer (France), absolute BS measurements were conducted using a calibrated Single Beam Echosounder across frequencies ranging from 50 to 400 kHz, covering the full range of incidence angles. The calibrated angular BS responses from these measurements serve as unique references, enabling post-calibration of any MBES based on its own data from the KRA. Once calibrated, data from different MBES systems operating at similar frequencies can be directly compared. This approach allows the Continental Shelf Service to integrate data collected since 2009 from various MBES systems into a single, consistent time series.

BS time series collected in the KRA with the RV Belgica EM2040 MKII dual RX MBES have revealed a strong dependence of BS levels on seawater temperature, showing variations of up to 4 dB for temperature changes of 10 °C. This temperature dependence, confirmed by Kongsberg Discovery's measurements in test-tank facilities, is complex, influenced by both frequency and steering angle and potentially caused by changes in transducer sensitivity, fluctuations in the acoustic properties of the antenna coating and transducers coupling variation. This variability introduces a new challenge for BS calibration. To address this, a protocol has been established, involving systematic measurements of the KRA at the start of each campaign.

► For more information: 2.5. Reference list / c. MBES quality control, bottom backscatter knowledge and calibration.

2.4. Results

a. Monitoring of ongoing extraction

Between 2019 and 2023, a significant part of the sand extraction occurred at the Thorntonbank (sector 1a; Figure 6 and 7), which is currently the primary hotspot for sand extraction aimed at industrial purposes. With the implementation of the new reference level in 2021, extraction activities progressively shifted eastward as the western part of Thorntonbank was closed. Sand extraction in sector 2 has slowed considerably, focusing mainly on the Oostdyck (2od) and Buiten Ratel (2br) areas, with minimal activity on the Kwintebank (2 kb). This contrasts sharply with the 2000s, when a very large part of the extracted sand was coming from the sectors of zone 2. In sector 3, sand extraction accounts for approximately one-third of the annual total and has shown a decreasing trend in recent years. Sector 4, predominantly used for coastal defense purposes, has seen concentrated extraction in the northernmost Noordhinder (4a) and Oosthinder (4b) sectors.

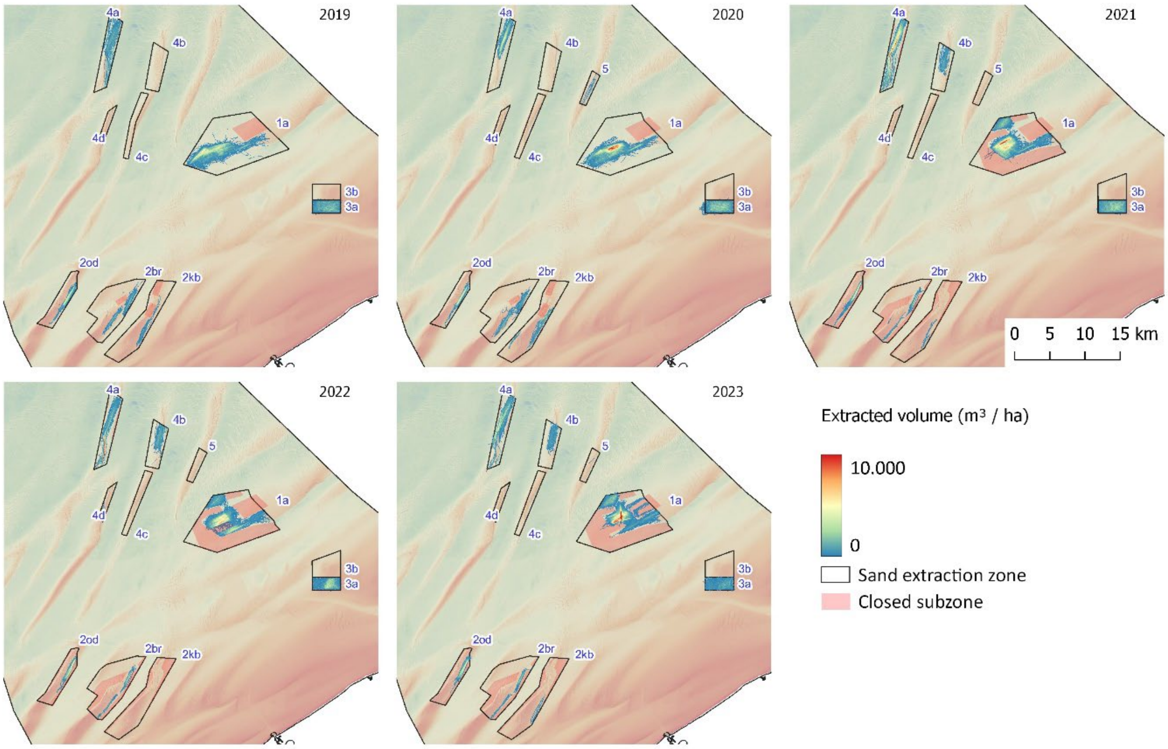

Figure 6. Detailed mapping of the extracted volume for the period 2019 – 2023 based on EMS and AIS- data. A yearly update of this figure is available on our web page3.

[3] https://economie.fgov.be/en/themes/enterprises/specific-sectors/offshore-sand-and-gravel/monitoring-sand-and-gravel

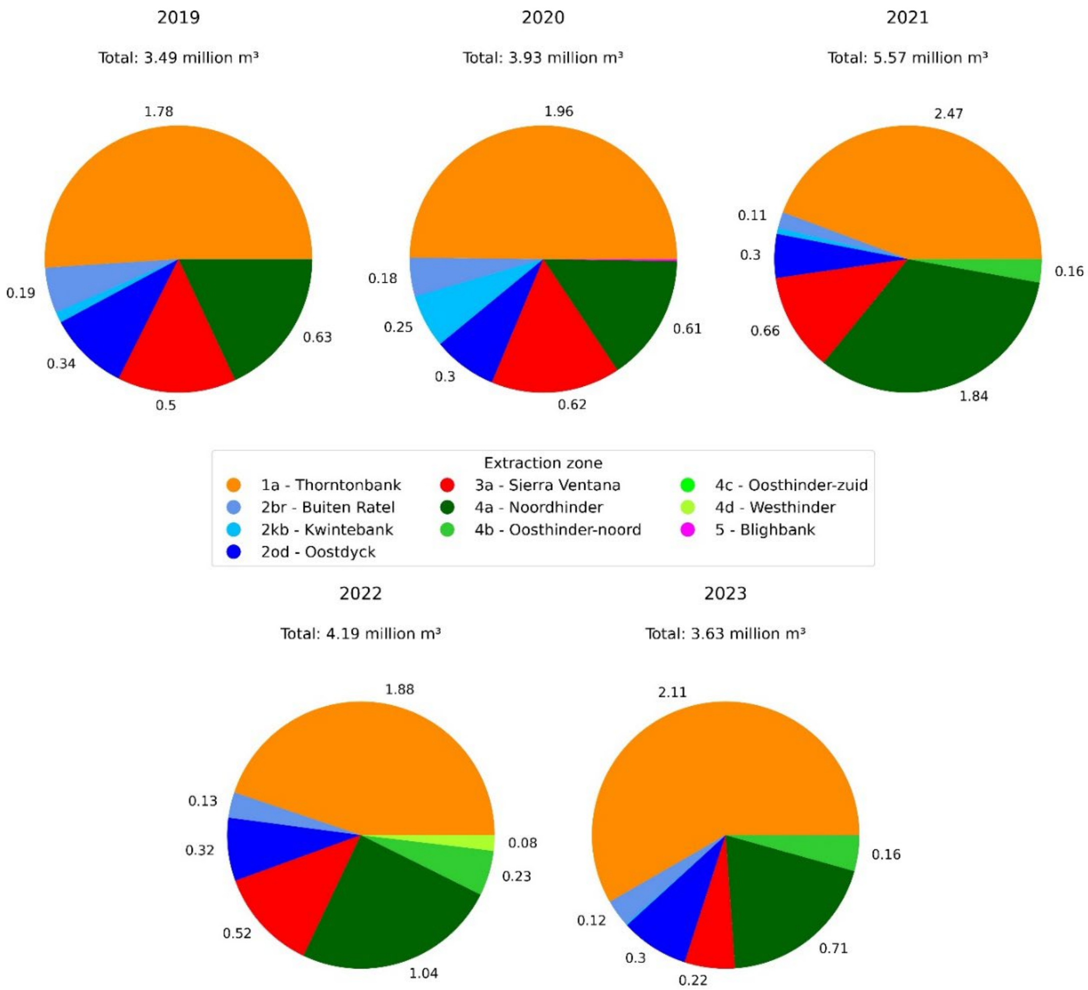

Figure 7. Yearly extracted volume (in million m³) within each sector based on information from the sand extraction declaration. A yearly update of this figure is available on our web page4.

The follow-up of the impact on the actively extracted areas has two goals: (1) review and refine the conclusions of the ongoing research based on the continuous mapping of the defined monitoring zones. (2) yearly evaluate the available volume of sand for extraction. If the reference surface is reached, the limits of the closed areas inside the control zones are adjusted.

For zone 1 (Thorntonbank) the introduction of the reference surface in 2021 had a major impact on the extraction locations. The consecutive closure of large parts of the zone forced the yearly relocation of the extraction hot spot in the area (see Figure 8) This forced the Continental Shelf Service to change its monitoring strategy on the Thorntonbank and start a new dynamic phase in the MBES monitoring. This became possible by the introduction of AIS, allowing a near real-time cartography of the extraction activities.

The focus on TBMA (and TBMAB – see below) was abandoned, and the monitoring effort from the Continental Shelf Service was increased to be able to map the entire open area on the Thorntonbank, thus allowing the accurate evaluation of the available volume on control zone 1. In Figure 3 the TBMA(B) monitoring series is replaced by a more intensified global S1a monitoring series.

[4] https://economie.fgov.be/en/themes/enterprises/specific-sectors/offshore-sand-and-gravel/monitoring-sand-and-gravel

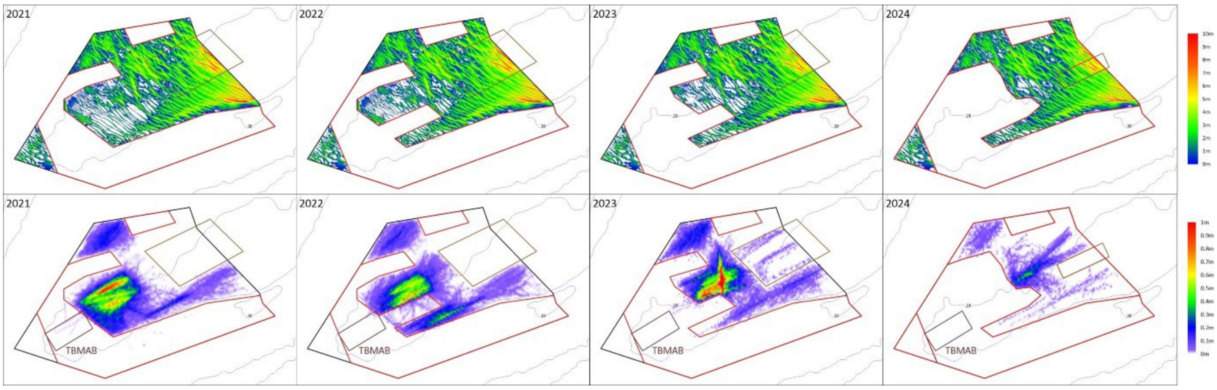

Figure 8. (a) Thickness of the available sand layer (m) in zone 1 in the period 2021–2024 – white = reference surface reached. (b) Extracted depth (m) in zone 1 in the period 2021–2024– white = no extraction. In red the areas that are closed for extraction due to the yearly evaluation. In brown the reference area and the monitoring area TBMAB.

The impact of the extraction until 2020 on the TBMA monitoring area was studied intensively and reported in Wyns et al., 2021. The evolution after the closure for extraction in 2021 is discussed below.

The monitoring series in zone 2 (Vlaamse Banken) are less impacted by the introduction of the reference surface, which closed large areas on the lower flanks of the three sandbanks (Kwintebank, Buiten Ratel and Oostdyck; see Figure 9a). These closed zones mainly covered non extracted areas and thus did not lead to a relocation of the extraction activities. Although the hotspots didn't shift and the monitoring zones that cover them (see Figure 9b) remain appropriate, the extraction is still focused on the edges of the "open" areas and is closely monitored.

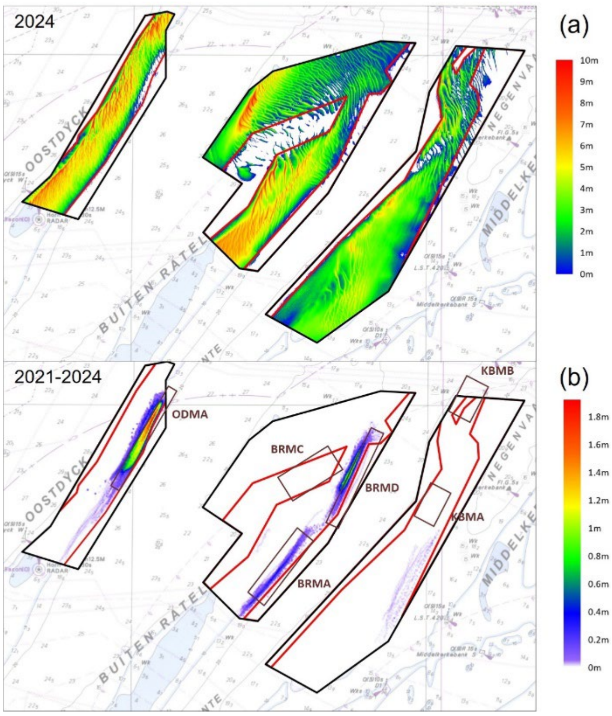

Figure 9. (a) Thickness of the available sand layer (m) in zone 2 in 2024 – white = reference surface reached. (b) Total extracted depth (m) in zone 2 over the period 2021–2024 – white = no extraction. In red the areas that are closed for extraction due to the yearly evaluation. In brown the relevant monitoring areas.

The evolution of the monitoring zones BRMA, BRMD and ODMA (Figure 10) reflect the different extraction regimes: most of the extraction is focused on the Oostdyck, where the higher extraction volumes since 2019 translate in a downward evolution of the bathymetry. As illustrated in Figure 9a, this results in the depletion of the available volume on the northern part of the eastern flank of the sandbank, which in return will be taken into account during the yearly evaluation. The extraction on the Buiten Ratel areas is much lower, resulting in stable bathymetry and BS levels for zone BRMA (very limited extraction) and a slow continuation of the negative trend for BRMD (limited extraction) and stable BS levels. In addition to these recent results, the impact of the extraction until 2020 on the ODMA monitoring area was studied intensively and discussed in Wyns et al., 2021.

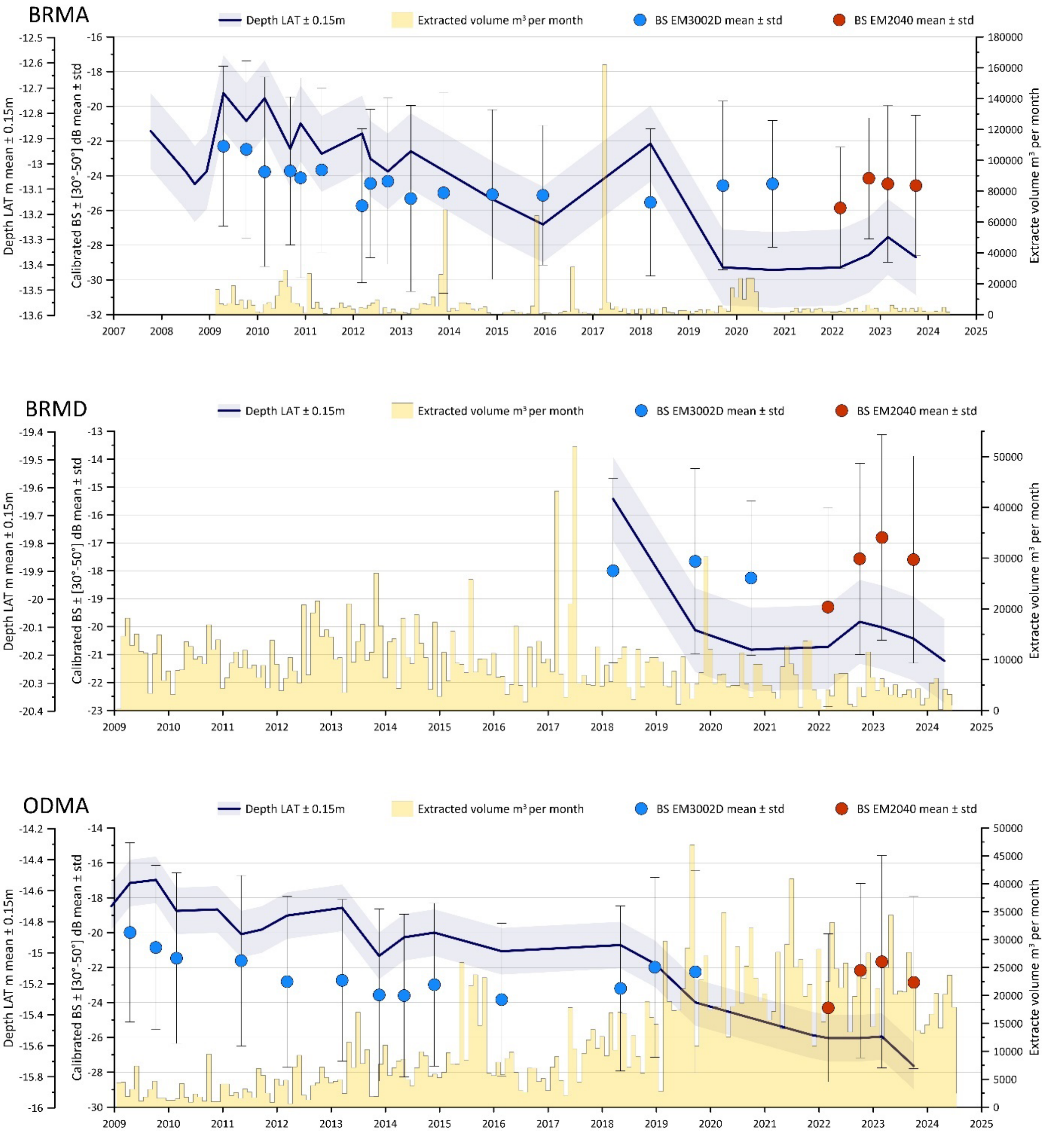

Figure 10. Monthly extracted volume (yellow bars), mean bathymetric depth (purple line) and mean BS values (blue and red points) for monitoring areas BRMA, BRMD and ODMA, based on the successive MBES bathymetric and BS models until 2024.

The yearly analysis of the available volume in zone 3a (Figure 11) shows that the extraction is limited to the upper sand layer, and that for a large part of zone 3a, the volume is still abundant. Subsequently no monitoring zone was defined, and considering the recent cartography of the entire zone (see report 2020), no new surveys were planned.

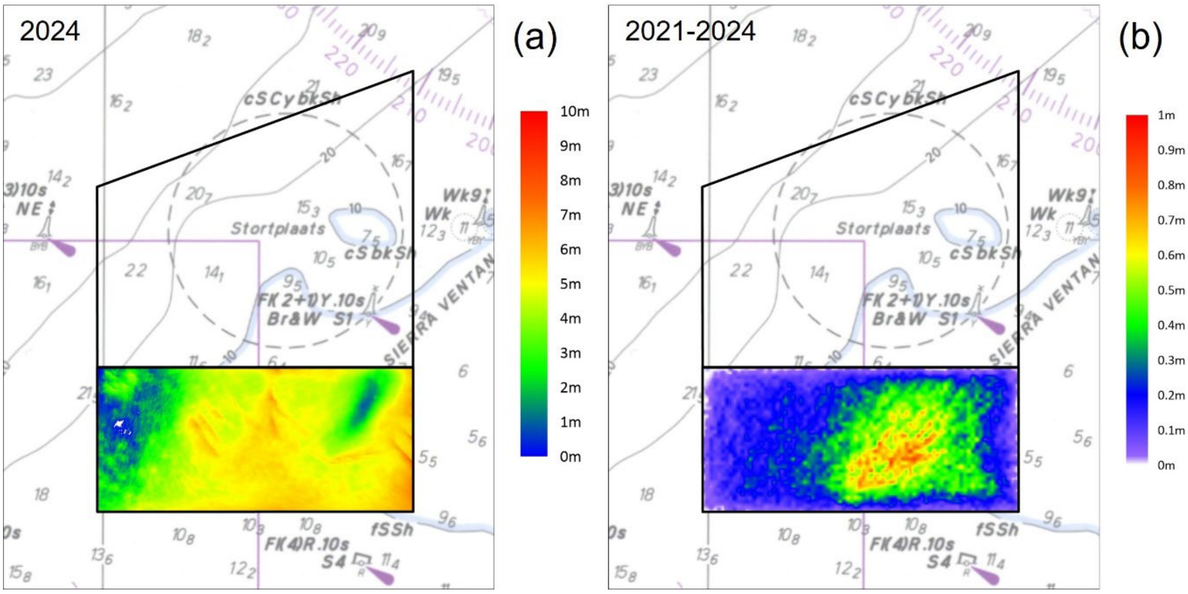

Figure 11. (a) Thickness of the available sand layer (m) in zone 3 in 2024– white = reference surface reached. (b) Total extracted depth (m) in zone 3 over the period 2021–2024 – white = no extraction.

As for zone 1, the monitoring strategy for zone 4 was completely turned upside down. As laid down in the Marine Spatial Plan 2020–2026, Sector 4a (see Figure 2) will be closed for extraction to allow the construction of the first wind farm in the Princess Elisabeth Zone. In response, the extraction activities moved to sector 4a (see Figure 12b).

The focus of the monitoring shifted accordingly and covered the entire sector 4a. This extension of the monitoring effort was necessary to provide a close and complete view of the impact of sand extraction on the sector 4a, to allow maximum use of the sector until its announced closure.

The present volumes for extraction on all sectors (see Figure 8a), especially compared to zone 1, are substantial, so that with the present extraction rate, only two zones were closed for extraction on the flanks of sector 4a on the Noordhinder. The bathymetric impact of extraction in sector 4a is described and analysed in a report by the Continental Shelf Service (Barette et al., 2023 and 2024).

The analysis by the Continental Shelf Service indicates an expected bathymetric impact of up to 2 m compared to 2020 (start of the intense extraction activities on S4a), concentrated on the top of the sandbank. Changes in sediment composition are not expected to be significant due to the thickness of the available homogeneous surficial sand layer. Only surficial impact due to the extraction (overflow) is expected. A more detailed sedimentological analysis of the impact on the Hinderbanken is provided in Kint et al., 2023.

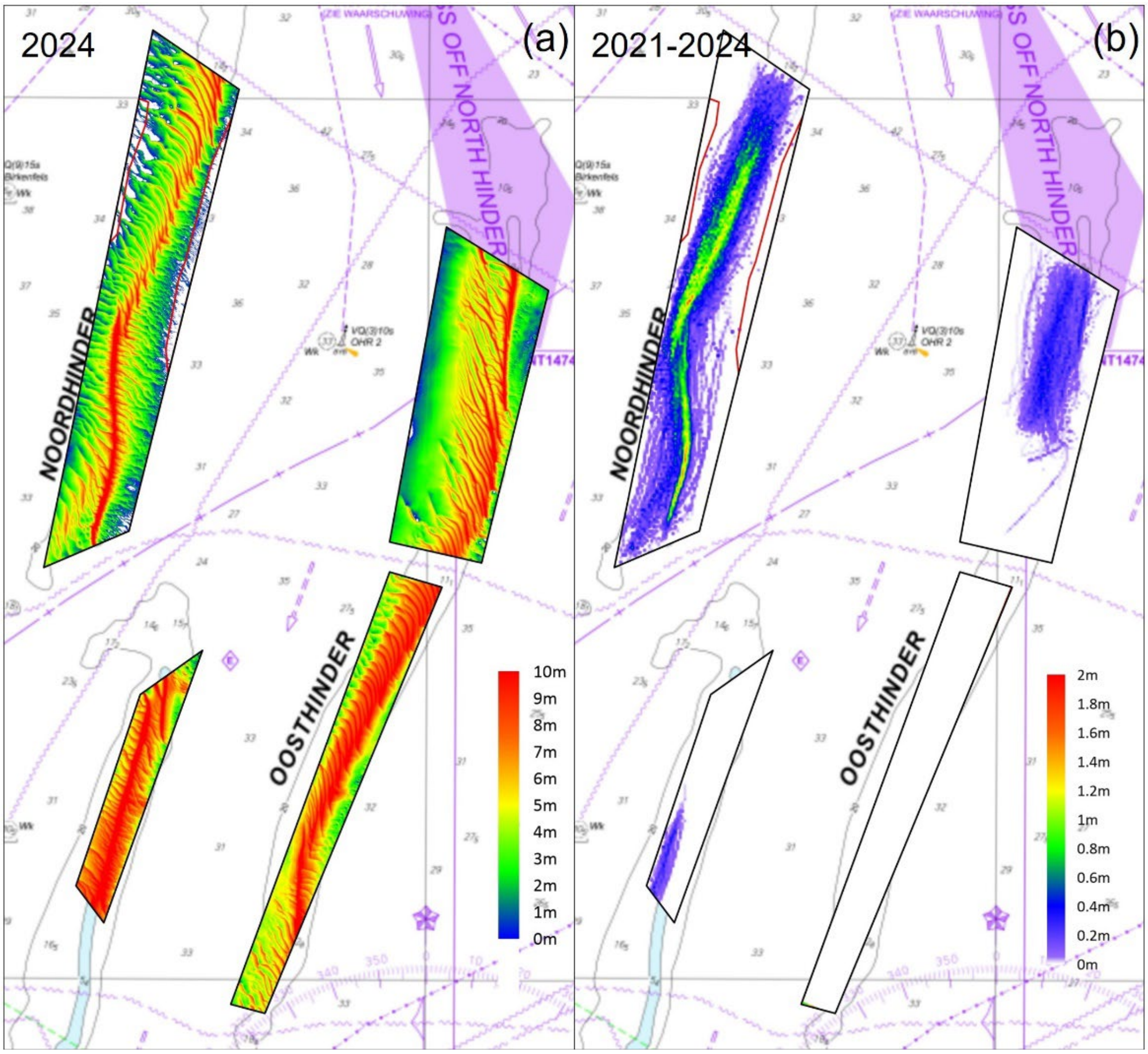

Figure 12. (a) Thickness of the available sand layer (m) in zone 4 in 2024– white = reference surface reached. (b) Total extracted depth (m) in zone 4 over the period 2021–2024 – white = no extraction.

► For more information: 2.5. Reference list / a. Monitoring the local impact of sand extraction

b. Monitoring Zones After Extraction

To analyse the evolution of impacted areas after extraction, a number of monitoring zones were regularly surveyed after the extraction ended. On zone 2 this was already the case with KBMA and KBMB on the Kwintebank, and BRMC on the Buiten Ratel. These were respectively closed for extraction in 2003, 2010 and 2015. After the introduction of the reference surface, the closure was lifted and the 3 zones were reopened for the extraction. The first evaluation of the available volume resulted in the renewed closure of the BRMC zone, while the KBMA and KBMB remained open for the extraction. Since no new extraction took place on the Kwintebank zones and the regular surveying continued, all three areas remain interesting targets for the evaluation of potential recovery. The conclusions from the former reports are confirmed: the zones remain stable (see Figure 13 summarizing the continued evolution of BRMC), with only for KBMA a clear recovery of the sand dunes. The study focused on the possible regeneration of sand waves after dredging (Krabbendam, 2022) attributed the difference in regeneration between the KBMA and KBMB/BRMC zones to differences in local hydrodynamics and sand availability.

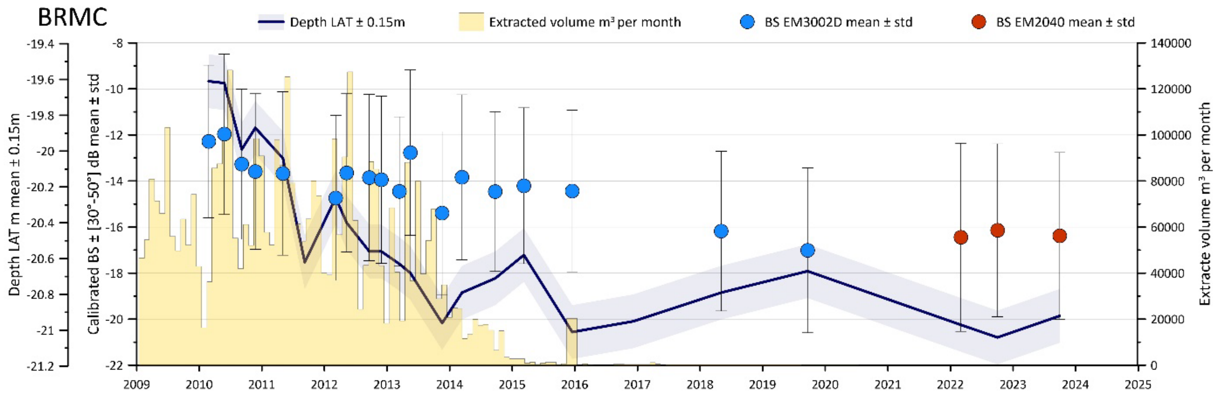

Figure 13. Monthly extracted volume (yellow bars), mean bathymetric depth (purple line) and mean BS values (blue and red points) for monitoring area BRMC, based on the successive MBES bathymetric and BS models until 2024.

As stated previously, the drastic changes in the management (closure of a large part of the control zone 1) in 2021, led to the end of extraction on the TBMAB monitoring zone (Figure 8). TBMAB was the logical extension of the TBMA zone (discussed in the previous reports) to encompass the spreading and intensifying extraction on the Thorntonbank (Figure 2). After the closure the zone was, in analogy of the above-mentioned zones on the Vlaamse Banken, regularly surveyed to evaluate a possible recovery. The first evaluation, condensed in Figure 14, is comparable with the BRMC findings: bathymetry remains stable, BS values drop in the first year after closure.

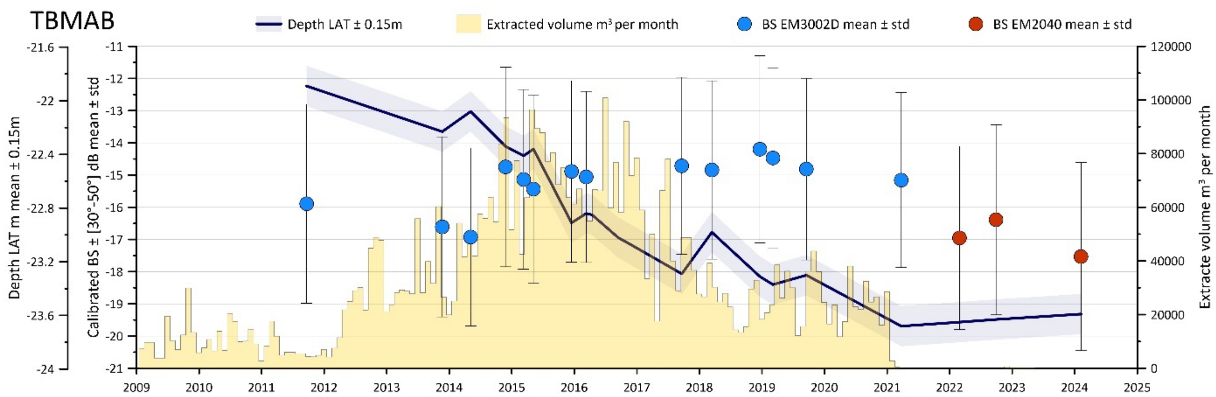

Figure 14. Monthly extracted volume (yellow bars), mean bathymetric depth (purple line) and mean BS values (blue and red points) for monitoring area TBMAB, based on the successive MBES bathymetric and BS models until 2024.

► For more information: 2.5. Reference list / a. Monitoring the local impact of sand extraction

2.5. Conclusions

The monitoring results from 2020 to 2024 confirm and consolidate findings from the past two decades. The impacts on bathymetry and sediment are directly related to the extraction intensity and are limited to the extraction period.

Regular bathymetry and BS measurements in areas where extraction has ceased, provide new insights into potential seabed restoration processes. Clear evidence of natural seabed recovery is observed in various monitored zones. Indeed, while sandbank depressions from dredging activities persist, MBES data indicate that partial recovery of sand waves with a reestablishment of the original sediment has occurred. This recovery is contingent upon local hydrodynamic conditions and sand quality and availability.

Substantial innovation has been achieved in enhancing the scientific quality of MBES data, which is critical for evaluating the environmental impacts of sand extraction. Notably, the streamlining of the bathymetric processing and the calibration of BS data now enables cross-referencing between datasets obtained from different MBES systems, ensuring greater consistency and comparability in the analysis, guaranteeing the continuity of the monitoring time series.

The organization of monitoring requires certain adaptations, the implementation of which has already started. Further improvement of the reference surface approach will support an adaptive strategy for zones 1, 3, and 4, based on variations in dredging intensity and focus. The objective is to cover an entire sector each year, allowing for regular updates to the reference surfaces and ensuring accurate evaluations. The accuracy of the use of AIS/EMS data over extended periods for the estimation of changes in bathymetry should be estimated and if possibly refined. For zone 2 where the extraction is quite stable (both intensity and focus), the current monitoring zones system will be maintained.

The calibration and ground truthing of BS data put in evidence the need for a more comprehensive ground truthing sample evaluation. Presently some sedimentological aspects (coarse fractions, shell fractions) are not always and consistently examined.

In the coming years, the development of an operational model capable of providing real-time estimates of sediment plume dispersion from dredging activities is expected. This model will be validated through in situ measurements of sediment plumes using various sensor technologies. Initial data collected with the MBES has already demonstrated its effectiveness in tracking plumes generated by sand extraction, indicating its potential as a key tool for model validation and plume monitoring.

Future management of sand extraction, incorporating strict extraction quotas, spatial limitations defined by reference surfaces, and comprehensive monitoring of both seabed impacts and sediment plume dispersion, aims to enable a full transition to optimized extraction practices. This approach is designed to mitigate the environmental impact of sand extraction to the greatest extent possible.

2.6. Reference list

Relevant scientific papers, conference contributions, and reports published or ongoing from 2020 to 2024:

a. Monitoring the local impact of sand extraction

Wyns L., Roche M., Barette F., Van Lancker V., Degrendele K., Hostens K. and De Backer A.: 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, Continental Shelf Research, 2021, Volume 229, 104546, https://doi.org/10.1016/j.csr.2021.104546

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Barette, F., Degrendele, K., Roche, M. Bathymetric evolution of sector 4a. Current level and projections. Report Continental Shelf Service, 2024, 13p.

b. Water Column Backscatter knowledge and measurement of sediment plumes

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c. MBES quality control, bottom backscatter knowledge and calibration

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3. Evaluating the ecological effects of sand extraction and optimising monitoring methods for impact assessment

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3.1. Introduction

Sand extraction imposes an impact on the marine ecosystem through 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. 2011, Tillin et al. 2011). A legal monitoring is therefore obliged and for many years, ILVO conducts the biological monitoring aimed at evaluating the potential ecological effects of sand extraction in the Belgian part of the North Sea (BPNS). Biological monitoring is mainly done by means of a Van Veen grab targeting macrobenthos (invertebrate species larger than 1 mm living in the sediment) and by means of an 8-meter beam trawl (22 mm mesh size) targeting epibenthos (invertebrate species living on top or just above the seabed) and demersal fish (fish species living in close association with the seabed). For each extraction area, impact and reference stations have been allocated enabling to assess potential ecological impact (Figure 1).

Previous papers mainly focused on macrobenthos and showed that the extraction regime and local geological context determine the impact of aggregate extraction on the seabed and macrobenthos. Furthermore, the macrobenthic community response always matches changes in the seabed and especially changes in sediment characteristics. Moreover, the impact is most drastic when high continuous extraction coincides with a varying nature in local geology and sediment types as for instance on the Thorntonbank and Buiten Ratel (De Backer et al. 2014, Wyns et al. 2021).

Over the past three years, we built further on our knowledge base increasing on the one hand our understanding of the direct impact of sand extraction (again for macrobenthos, but also for other ecosystem components like epibenthos, fish and bacteria), and on the other hand investigating innovative DNA-based methods to optimise monitoring efforts. This is key for a sustainable management of extraction activities.

Within this contribution, we focus on 1) potential changes in epibenthos and fish for the most intense extracted area, the Thorntonbank, 3) effects on functional diversity and benthic ecosystem functioning, 4) impact on bacteria in the sediment on the Thorntonbank, 4) benthic recolonisation dynamics after closure of an area for extraction, and 5) DNA sequence data for biomonitoring. We aim to summarise the main messages and conclusions for each of these topics.

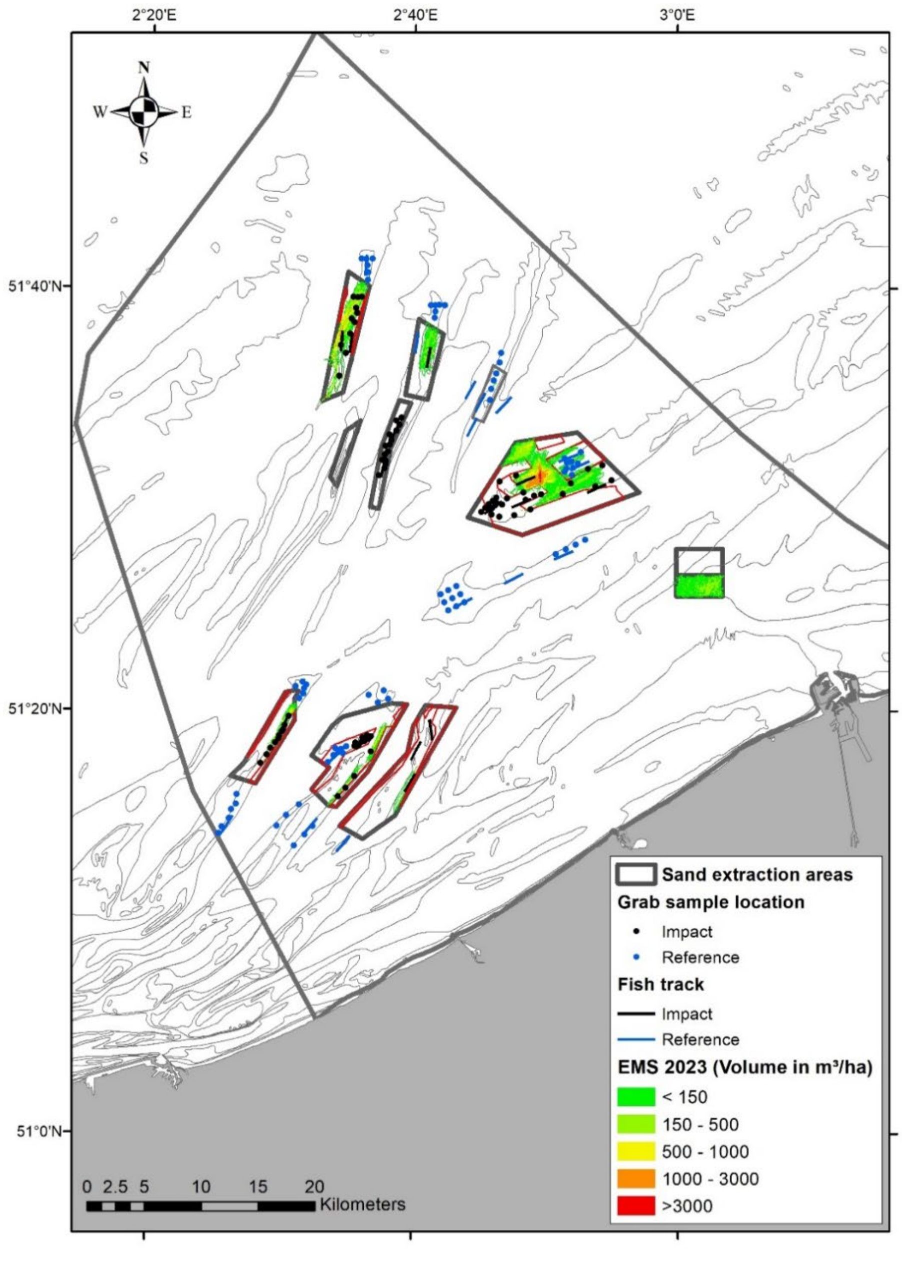

Figure 1: Overview map showing Van Veen (grab) locations and fish tracks locations, both reference (blue) and impact (black), for ecological impact monitoring of ILVO.

3.2. Effects of sand extraction on epibenthos and fish

Most studies looking into the effects of sand extraction on the marine ecosystem have focused on macrobenthos (e.g. Desprez 2000, Cooper et al. 2011, Wyns et al. 2021), since they are good indicators to measure changes because of their strong relationship with sediment habitats (Van Hoey et al. 2010). However, incorporating higher trophic levels, when assessing impacts, is important for a more holistic evaluation of induced changes on the marine ecosystem. Hence, we study how epibenthos and demersal fish communities are affected through sand extraction, discussing the possibility of direct disturbance effects, as well as indirect cascading effects of extraction through the food web. We focus our study on the Thorntonbank, currently the most actively extracted area in the Belgian Part of the North Sea (BPNS). After sand extraction began on the site in 2003, the extracted volumes have increased gradually over the years. This has led to the Thorntonbank becoming the epicenter of industrial sand extraction after 2014 when the central zone of the Buiten Ratel extraction site was closed for extraction (Roche et al. 2017).

To investigate potential changes in epibenthic and fish communities, a yearly beam trawl survey (2004-2023) was performed in (impact) and outside (reference) the Thorntonbank extraction area (Figure 2a). The biomass per species per 1000 square meter was estimated for each sampling location based on the length measurements. Whether or not species composition based on biomass was affected by sand extraction was assessed through multivariate statistical techniques. Potential explaining variables included in the analyses relate to extraction time and volume derived from the Electronic Monitoring System (EMS) on board (i.e. the volume of sand extracted, as well as the number of days dredged one year prior to the sampling of the fish track and within a fifty-meter buffer around the fish track) and to sediment composition (the relative proportion of the various grain size fractions). Main messages from these analyses are discussed below:

High levels of extraction cause changes in epibenthos and fish communities but effects are most obvious for the less mobile epibenthos

The history of sand extraction on the Thorntonbank is characterized by a Low Extraction Period (LEP) before 2015 and a High Extraction Period (HEP) from 2015 onwards. It is within the HEP that we observe the largest impact, and this was most distinct for the epibenthos community (Figure 2b). This indicates that sand extraction only induces changes when a certain impact threshold has been exceeded. The fact that the species community in sampling locations where sand extraction took place for a higher number of days, shifts away from the species community in other locations corroborates this (Figure 2c).

Also, for fish communities, a shift coincides with the number of extraction days, albeit less pronounced (Figure 2d). This confirms previous findings by Wyns et al. (2020) and is most probably a result of fish being more mobile and, hence, more able to escape and immediately return once the hopper dredger has gone (Magris & Ban 2019, Goedefroo et al. 2023). Epibenthos, on the other hand, is more related to a smaller area because of their lower mobility and as a consequence are more responsive to disturbances by the drag head.

Scavengers and omnivores thrive in areas with high levels of sand extraction

By looking at the ecology of the species that are mainly responsible for the observed shifts, we can start to derive the processes behind such shifts. Unraveling such processes can provide insights in how the ecosystem will develop over the long term and whether restoration to the original state is possible (Borja et al. 2010).

We observed higher biomasses of opportunistic predators and scavengers such as the starfish (*Asterias rubens*), green sea urchin (*Psammechinus miliaris*), and harbour crab (*Liocarcinus depurator*) at high-impact sites, which could indicate direct extraction effects (Figure 2c). These scavengers may be attracted by the higher food availability in the form of injured or dead macrobenthic fauna and of resuspended organic matter from disturbance by the drag head of the hopper dredgers (Smith et al. 2006, Wyns et al. 2020). On the other hand, these species could also benefit from the increases in macrobenthic densities at extraction sites (Wyns et al 2021). Ultimately, the increased biomasses in scavengers are likely the result of a combined direct and indirect effect of extraction.

Our analyses indicate additional indirect cascading effects for higher levels within the marine food web. Increases in epibenthic scavengers in combination with the increases in macrobenthos may at least in part have led to the observed raises in benthic generalist fish such as hooknose (*Agonus cataphractus*), dab (*Limanda limanda*), and sole (*Solea solea*) (Figure 2d). Whether this positive impact has actual population-level effects within the commercially relevant species is to be determined.

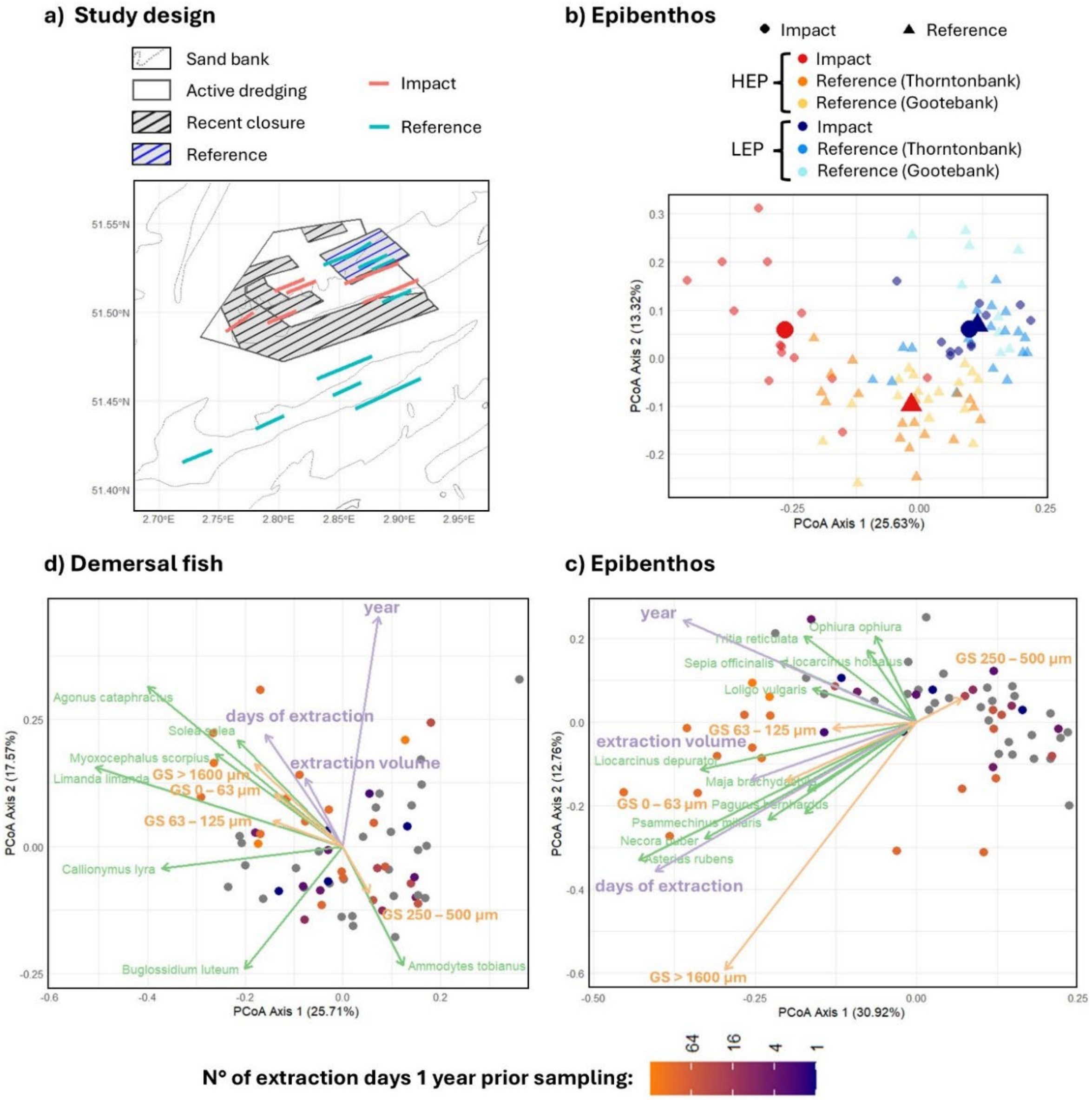

Figure 2: Study design (a) and multivariate results for epibenthos (b,c) and demersal fish species (d). a) Fish tracks are located within the Thorntonbank extraction area (impact), within the reference area on the Thorntonbank (reference) and on the nearby Gootebank (reference). Some zones have been closed to extraction within the last three years of the studied period following years of activity, fish tracks in these areas are labeled as impact. b, c, d) Principal Coordinate Analyses plots based on Bray-Curtis dissimilarity for square-root transformed species biomasses, for epibenthos (b) with indication of High (HEP) and Low Extraction Period (LEP) and impact and reference fish tracks on both Thornton and Gootebank. In (c) epibenthos and (d) demersal fish, Gootebank samples were excluded to assess extraction impact in more detail with coloring indicating the numbers of days dredged within the year prior to sampling and grey meaning no extraction occurred. Arrows represent predictors for species composition.

Changes in sediment composition due to extraction seem to affect a key species: the small sandeel (*Ammodytes tobianus*)

High and continuous extraction on the Thorntonbank increased both the shell fraction (> 1600 µm) and the mud (<63 µm) and very fine sand (63-125 µm) fraction due to exposure of older geological layers and dredging processes such as screening and overflow (Wyns et al., 2021, and references therein). Some species ecologically require specific substrates and might experience deleterious effects due to these sediment changes. Our results indicate that the small sandeel (*A. tobianus*), which prefers sediments with less than 2 % silt and clay fraction, becomes less abundant on the most extremely extracted fish tracks where those finest sediment fractions relatively increase (Figure 2d). This confirms earlier indications of sandeels being impacted by sand extraction (de Groot 1986). Sandeels play an essential role in the marine food web, where they form an important food source for a number of predators (Staudinger et al. 2020). Also, commercially they are an important species (van Deurs et al. 2012). Hence, although the overall community might cope with the effects of sand extraction, some essential species can experience negative effects. It is, therefore, important to further monitor specific indicator species, such as the sandeel, to prevent affecting the processes in which they play a key role (Rogers et al. 2010).

Manuscript in preparation:

Van Moorleghem C, Hostens H. and De Backer A. Near-field changes in epibenthic and demersal fish communities due to marine aggregate extraction.

3.3. Effects of sand extraction on functional diversity and benthic ecosystem functioning

Several studies have demonstrated the impact of sand extraction on benthic communities in terms of density, diversity and species composition (Barrio Froján et al. 2011, De Backer et al. 2014, Wyns et al. 2021). Although these changes in structural properties are good indicators to assess ecosystem health, there is increasing awareness that knowledge on the functional counterpart is equally important to understand how marine ecosystems respond to human activities (Gogina et al. 2014, Lam-Gordillo et al. 2020). A well-functioning ecosystem is crucial for human well-being as it provides essential services such as food provisioning and the regulation of nutrients (e.g. nitrogen) and carbon within the ecosystem. It is, therefore, necessary to improve our understanding of how functional diversity and benthic ecosystem functioning are affected by sand extraction.

To do so, we used existing longer-term datasets gathered during the environmental benthic monitoring for sand extraction in the Belgian part of the North Sea (BPNS) (De Backer et al. 2014, Wyns et al. 2021). Instead of looking into structural properties of the macrobenthos, we focused on the behavioral, morphological and other life-history characteristics, known as functional traits. Based on these traits, we calculated functional diversity indices (e.g. Functional Richness, Functional Evenness, Functional Divergence) along with functional indices that serve as proxies for bio-transport activities and energy transfer. Proxies for bio-transport include the bioturbation (BPc) and bioirrigation potential (IPc) of the macrobenthic community, while the secondary production (SPc) is a measure for biomass production and energy transfer. We further investigated the biological trait composition of the benthic community, focusing on how sand extraction affects response traits (e.g. mobility) that define a species' reaction to environmental change or disturbances, and effect traits (e.g. feeding mode) that exert an impact on ecosystem properties. Main conclusions from these studies are:

High volumes of sand extraction affect functional diversity through changes in sediment composition

Only at high volumes of extracted sand (>2000 m^3/year/7800 m^2), functional diversity was affected. This indicates that the benthic communities of the BPNS can cope with a rather high level of pressure before significant changes in functional biodiversity are found.

High extraction volumes on Buiten Ratel and Thorntonbank led to increased values for most functional diversity indices (except for functional divergence). At Hinderbanken, however, no or an opposite trend for functional evenness was observed (Figure 3). This opposing trend for functional evenness can potentially be linked to the duration and timing of the pressure, since Buiten Ratel was continuously extracted with high volumes, while Hinderbanken only for a few months per year. This periodicity possibly results in the recovery of some species, leading to dominance of certain traits, which is not or less the case under continuous exploitation. Another, probably more plausible or additional reason is that sediment composition changed differently in both areas: medium grain size decreased at the Hinderbanken leading to a shift from the *Hesionura elongata* community to the *Nephtys cirrosa* community (naturally lower diversity values), while at Buiten Ratel an increase of very fine sand led towards a shift from *H. elongata* into *Abra alba* community (naturally higher diversity values) (De Backer et al. 2014, Wyns et al. 2021). The increase of functional index values of samples undergoing higher sand extraction seems to indicate that the change towards the habitat type *Abra alba* has led to an increase in new species that link to the new habitat (Wyns et al. 2021), which probably exhibit additional trait modalities (e.g. downwards conveyor & larger max size).

Functional richness was the most responsive index and is therefore put forward as most useful for environmental impact assessment (EIA). This index does not respond to changes in the relative proportion of species and thus can be highly sensitive to functionally unique “outliers” that may be present at low abundances (Villéger et al. 2008, Laliberté & Legendre 2010). Functional richness, and evenness as well, can be interpreted as indicators for productivity, buffering against environmental fluctuations, or vulnerability to invasion (Mason et al. 2005). Functional divergence on the other hand was not responsive and less useful for future EIAs. This makes sense, since trait divergence is expected to arise from strong competitive interactions, which are generally thought to be rather weak in soft-bottom environments like the BPNS (Wilson 1991, Defeo & McLachlan 2005).

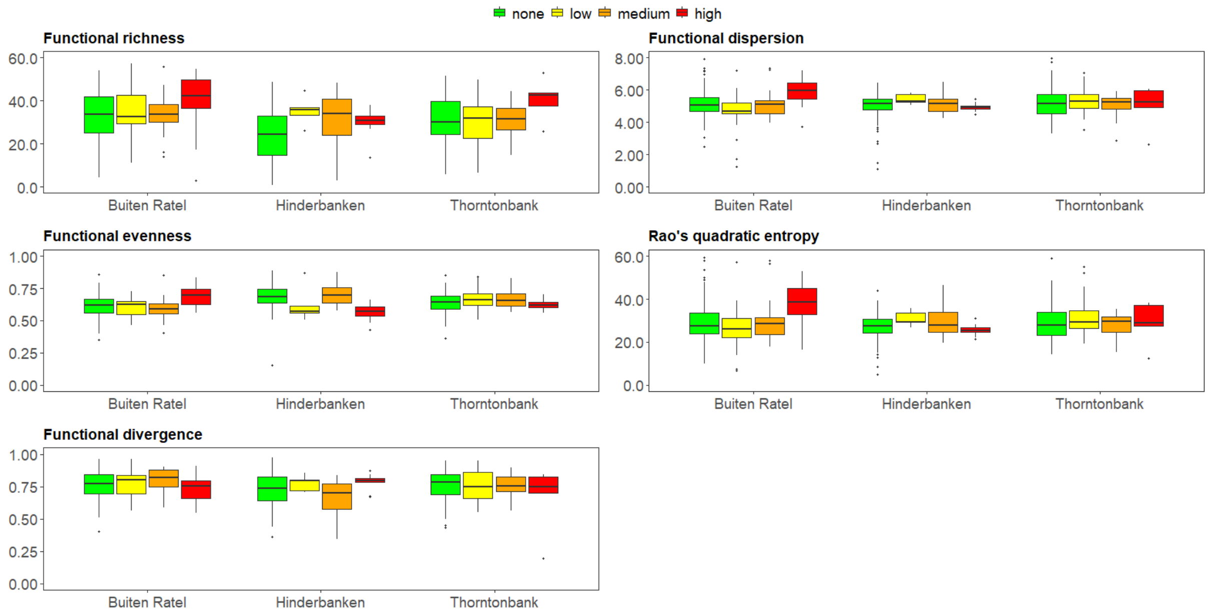

Figure 3: Boxplots of the functional diversity indices for the three sand extraction concession zones (Buiten Ratel, Hinderbanken and Thorntonbank).

Sand extraction can indirectly impact benthic functional indices by altering sediment composition.

Sediment parameters such as the medium sand fraction (250 – 500 µm) and median grain size showed significant effects on all functional indices, whilst sand extraction variables only significantly affected the secondary production estimates. The secondary production of the macrobenthic community decreased following annual high extraction intensities, whereas a high cumulative (10-year period) extraction intensity resulted in a slightly increased secondary production. Species-specific responses revealed that these high cumulative extraction volumes increased the abundance of opportunistic species, which could have contributed to the higher SP_c values observed in long-term disturbed areas. Constant deposition of fine sediments from overflow processes causes a fining of sediment which in turn traps more organic matter (OM). This increased food availability in the sediment may ultimately stimulate the production of naturally occurring benthic species and attract new opportunistic species (Pearson and Rosenberg 1978, Dolbeth et al. 2015). Given that sediment parameters were the primary variables explaining changes in the functional indices, it is likely that sand extraction indirectly affects these functional indices by altering the medium sand fraction or the median grain size of the sediment (Wyns et al. 2021).

Sand extraction changes biological trait composition of the benthic community

Biological trait analysis revealed that organisms capable of escaping sand extraction by burrowing were favored by short-term sand extraction, while crawling species or those that lay eggs on the seabed were negatively affected. On the contrary, longer-term sand extraction disturbance (cumulative extraction) had a positive impact on tube-living and sessile individuals with pelagic egg development, indicating a more disturbance-tolerant community (Figure 4A). In terms of effect traits, both sand extraction scenarios favored deposit-feeding organisms. This feeding behavior directly influences the vertical distribution of organic matter in the sediment, thereby affecting oxygen dynamics and nutrient cycling (Figure 4B). To further increase our understanding of how these proxies relate to ecosystem functioning under the pressure of sand extraction, additional in-situ measurements of processes within the carbon and nitrogen cycle are needed.

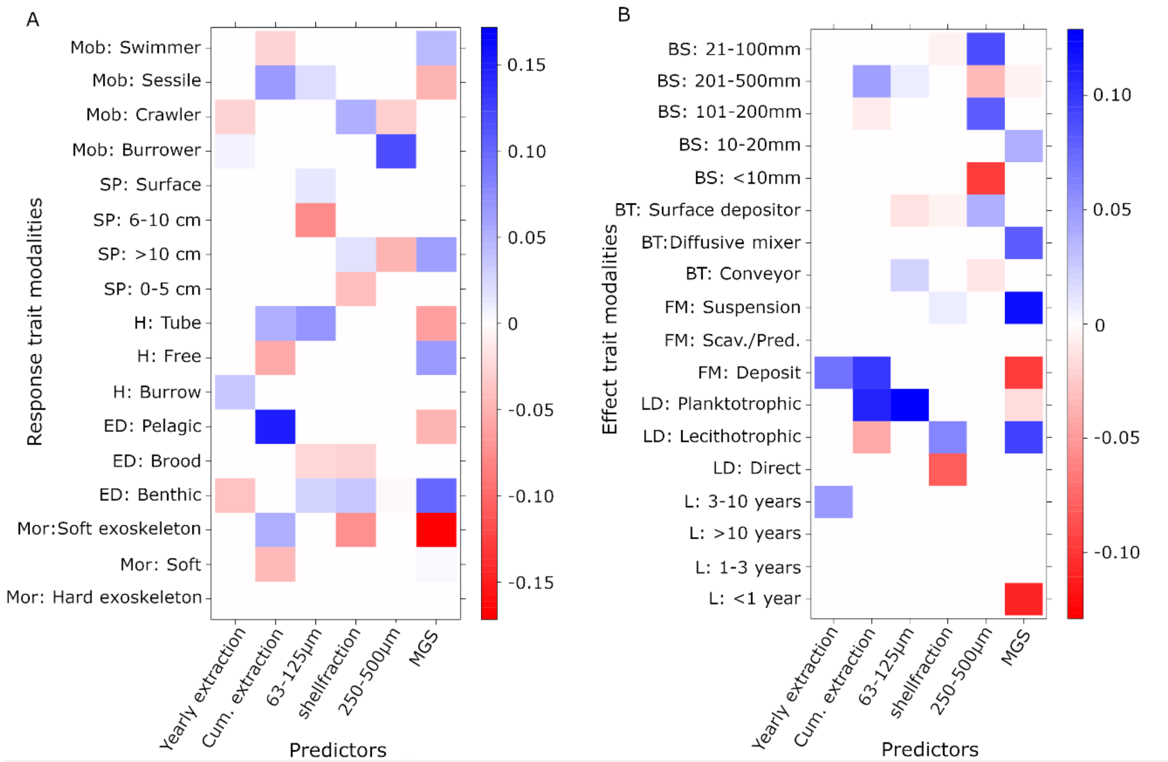

Figure 4: Fourth-corner plots showing (A) response and (B) effect traits and their relationships with sediment (very fine sand- 63-125 µm, shell fraction - >1600 µm, medium sand- 250-500 µm and Median Grain Size – MGS) and extraction (yearly extraction= volume extracted in 1 year prior to sampling, cum.extraction = volume extracted within 10 years prior to sampling) variables. Blue shades represent significant positive associations and red shades show significant negative associations. Mob= Mobility, SP= Sediment Position, H= Living Habitat, ED= Egg Development, Mor= Morphology, BS= Body Size, BT= Bioturbation, FM= Feeding Mode, LD= Larval Development, L=Longevity.

More details to be found in:

Festjens F., Buyse J., De Backer A., Hostens K., Lefaible N., Vanaverbeke J. & Van Hoey G. (2023). Functional trait responses to different anthropogenic pressures. Ecological Indicators, 146, 109854, https://doi.org/10.1016/j.ecolind.2022.109854.

Goedefroo N., Braeckman U., Hostens K., Vanaverbeke J., Moens T. & de Backer A. (2023). Understanding the impact of sand extraction on benthic ecosystem functioning: a combination of functional indices and biological trait analysis. Frontiers in Marine Science, 10. https://doi.org/10.3389/fmars.2023.1268999

3.4. Effects of sand extraction on bacteria in the sediment

Sediment bacterial communities are a crucial component of shallow coastal marine environments. Through biodegradation, biotransformation and biogeochemical cycling of nutrients, combined with a tight coupling between the sediment and the water column, sediment bacterial communities have a substantial influence on the functioning of marine ecosystems (Probandt et al. 2018). As such, they provide essential ecosystem services that are related to important environmental issues such as eutrophication and climate change. A limited number of studies have shown that anthropogenic disturbances to the seabed, such as bottom trawling and dredging, can affect the structure and functioning of sediment bacterial communities (e.g. Bonthond et al. 2023). This can in turn influence the ecosystem services they provide such as regulation of the marine nitrogen cycle (Ferguson et al. 2020). Although there are indications that disturbances to the seabed can impact sediment bacterial communities, the specific impact of sand extraction on their composition and functioning was unknown. Therefore, we assessed the impact of sand extraction in the BPNS on the abundance, structure, and functioning of sediment bacterial communities. In addition to describing overall patterns, we also specifically focussed on genes involved in nitrogen metabolism, given their relevance to the environmental issue of marine eutrophication.

We assessed the impact of sand extraction on sediment bacterial communities by combining digital PCR (dPCR) and shotgun metagenomics on sediment samples from four sand extraction and four reference stations located on the Thorntonbank. For each station, we separately analysed six one-centimetre depth slices to assess if the measured impact was dependent on sediment depth. The dPCR measurements provided information on bacterial abundance in the sediment by quantifying the number of 16S rDNA genes (a gene shared by all bacteria). The shotgun metagenomic data was used to infer the relative abundance of bacterial taxa (taxonomic composition) and protein-coding genes (functional composition) in a sample. For each sample, the sediment granulometry and the amount of chlorophyll a (as a proxy for organic matter content) was recorded. Two major conclusions from this study are discussed below:

Sand extraction indirectly impacts sediment bacterial communities through the accumulation of organic matter.

Shotgun metagenomic results showed that both the taxonomic and functional composition of the sediment bacterial community was significantly different between the sand extraction and reference zones, irrespective of sediment depth (Figure 5A). An increase in the abundance of Bacteroidota (especially Flavobacteriaceae) and Rhodobacterales was the most prominent change in the sand extraction zone (Figure 5B). Interestingly, these groups are known specialists for degrading fresh phytoplankton-derived organic matter. This was also reflected in the most prominent change in functional composition in the sand extraction zone: an increase in *SusC*, the gene encoding the TonB-dependent transporter (Figure 5C). This gene is specific for Bacteroidotal polysaccharide utilisation loci, which are genetic elements required for their ability to degrade complex polysaccharides. Chlorophyll a, as a measure for fresh phytoplankton-derived organic matter, was the sediment variable that explained most of the variation in bacterial abundance (Figure 5D) and taxonomic- and functional composition between samples. From these observations, we inferred that the primary impact of sand extraction on sediment bacterial communities is an indirect one, mediated by an increased accumulation of fresh phytoplankton-derived organic matter. This is potentially a widespread impact, as other studies have shown that dredge tracks and depressions commonly act as a sediment trap, resulting in the accumulation of organic matter (e.g. Kint et al. 2023).

Sand extraction potentially increases fixation, recycling, and retention of nitrogen in the sediment

A total of 31 genes involved in various nitrogen metabolism pathways (nitrogen fixation, assimilatory nitrate reduction, dissimilatory nitrate reduction to ammonia/DNRA, denitrification, nitrification and annamox) were found in the sediment bacterial communities. Sand extraction was shown to cause a significant increase in the abundance of genes involved in nitrogen fixation (*nifD* and *nifK*), assimilatory nitrate reduction (*narB* and *NIT-6*), and DNRA (*nirB* and *nrfA*). Importantly, sand extraction did not affect the abundance of genes involved in denitrification (e.g. *nosZ*). The increase in genes involved in DNRA, but not those involved in denitrification, is expected to cause a larger fraction of the available NO_3^- to be retained in the sediment through ammonification instead of being lost through denitrification (Figure 5E). Furthermore, the increase in nitrogen fixation genes is expected to increase the amount of bioavailable nitrogen in the sediment. These results provide strong indications for a potential impact of sand extraction on the benthic nitrogen cycle. However, further research is warranted to quantify the impact on the stoichiometry of nitrogen compounds in coastal ecosystems and how this relates to broader eutrophication-related environmental impacts.

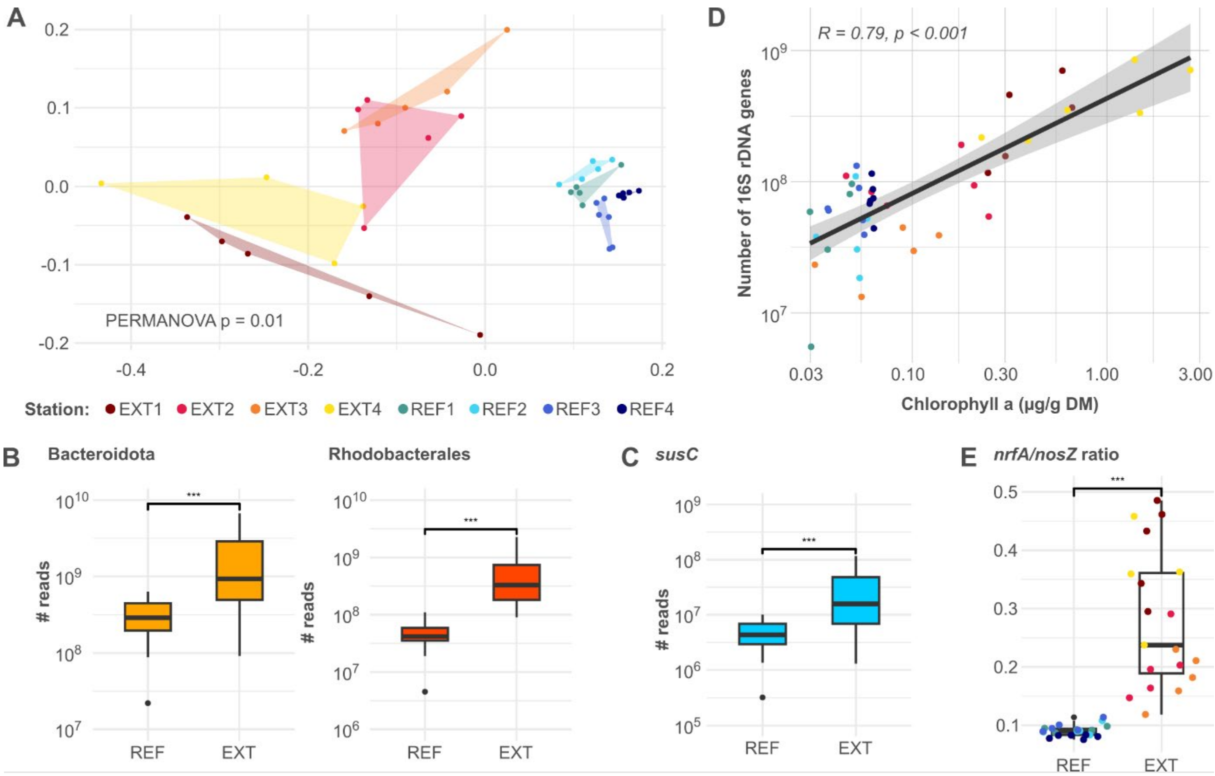

Figure 5: Comparison between sand extraction (EXT) and closed referene zone (REF). A) Ordination based on the taxonomic composition of samples (multiple depth slices from each station). B) Differences in number of reads of taxa having a large contribution to differences between sand extraction and reference zones. C) Differences in the abundance of susC between sand extraction and reference zones. D) Correlation between chlorophyll a content in the sediment and 16S rDNA gene copies (as a proxy for bacterial abundance). E) differences in nrfA/nosZ ratio between sand extraction and reference zones. A higher nrfA/nosZ ratio indicates an increase in ammonification relative to denitrification. Station colors in D and E are the same as in A.

Manuscript in preparation:

Callens M., Goedefroo N., De Backer A., and Derycke S. Local accumulation of organic matter in marine sand extraction areas drives changes in sediment prokaryotic communities with potential consequences for nitrogen cycling.

3.5. Recolonization dynamics of macrobenthos and sediment characteristics following sand extraction cessation

Most studies on marine aggregate extraction have focused on what the direct effects of extraction on the marine ecosystem are with ongoing extraction (e.g. Desprez 2000, Barrio Frojan et al. 2008, Wyns et al. 2021) These studies showed that sand extraction can cause changes in seabed characteristics and bathymetry, in sediment composition and as a result of these, changes in benthic faunal composition are observed. Fewer studies looked into how an (intensively) extracted area evolves after it is closed for extraction, while these insights are important to evaluate whether an impact is reversible and whether the marine benthic ecosystem can recover to pre-dredged or reference conditions.

Benthic recovery is typically inferred when post-dredging species numbers (diversity) return to pre-disturbance levels (Hill et al. 1999, Lewis et al. 2001). The existing studies show that benthic recovery can take from a couple of months (Van Dalfsen et al. 2000), over a couple of years (Sarda et al. 2000, De Backer et al. 2011), to over 15 years (Waye-Barker et al. 2015), influenced by the stocks of recolonizing species and their proximity to undisturbed areas (Bonsdorff 1983). Variability in recovery rates is further complicated by factors such as sediment type, extraction intensity and environmental conditions, which can lead to prolonged or irreversible disruptions in ecosystem structure and function (Ceia et al. 2013, De Backer et al. 2014). Therefore, it is important to extend our understanding on the dynamics of macrobenthic recovery following cessation of sand extraction. Furthermore, the new Belgian legislation, providing a maximum extraction limit or reference surface for each extraction area based on resource thickness and sediment characteristic criteria, results in more frequent closure of subzones within extraction areas (Degrendele et al. 2021). This offers an additional reason to look into how the benthic community within these closed extraction areas evolves over time.

We therefore focused on three closed extraction zones, one on the Buiten Ratel (BRMC_IMP) and two on the Thorntonbank (TB_WEST and TB_CENTER) (Figure 6). The extraction zone on the Buiten Ratel was the extraction 'hotspot' in the BPNS from 2008 till 2014 and was closed in 2015. Afterwards in 2015, Thorntonbank became the epicentre of industrial sand extraction in the BPNS, and because the maximum depth limit was exceeded in certain subzones, these have been closed for extraction resp. in 2021 (TB_WEST) and 2022 (TB_CENTER). In this study, we examine grab sample data (macrobenthos and sediment) of impact and reference locations from surveys conducted over a range of years starting two or three years before closure (-2 or -3) till 2023 i.e. 8 years post-extraction for Buiten Ratel (2013-2023) and 1 or 2 years post-extraction for the subzones on Thorntonbank (2019-2023). We investigated how the sediment composition and benthic community evolved over time and whether they return to reference conditions. Our main findings are:

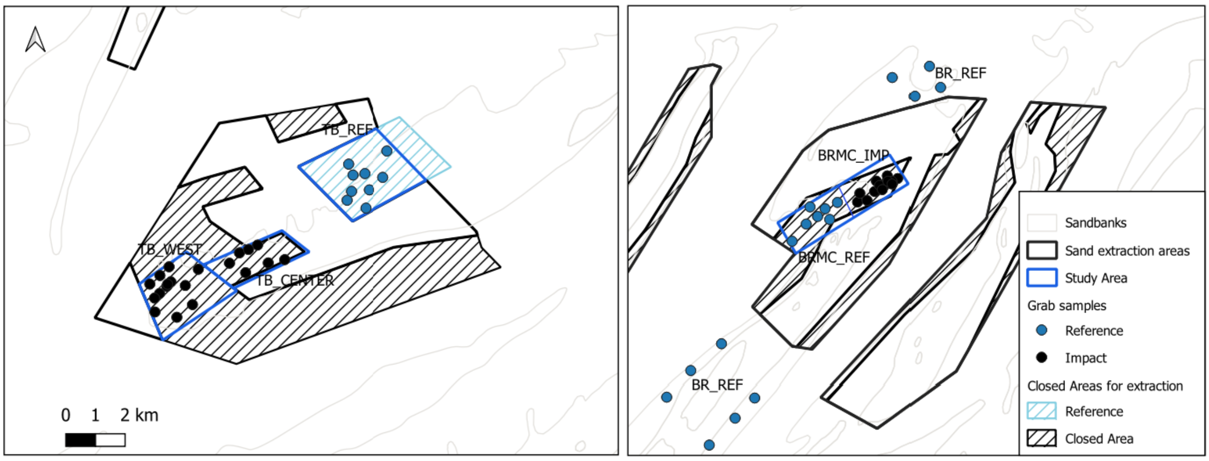

Figure 6: Map of the study areas showing grab sample locations within the Thorntonbank (left) and Buiten Ratel (right) extraction areas on the Belgian part of the North Sea. Points represent sample locations, with blue points indicating reference areas (REF) and black points indicating impact areas (IMP).

Following cessation of sand extraction, sediments gradually homogenise as a consequence of sediment fining in impact zones

The high and continuous extraction on both the Buiten Ratel and Thorntonbank increased surface heterogeneity and created a local depression with mixed sediments (combination of higher fractions of both mud/very fine sediment and gravel) (De Backer et al. 2014, Wyns et al. 2021). Following cessation of extraction, we observed in all three subzones a consistent trend towards finer median grain sizes (Figure 7), probably reflecting a reorganisation of sediments in the area covering the coarser gravel fractions.

For the Buiten Ratel area, where extraction ceased in 2015, the fining is mainly due to a decrease in gravel fraction (>1600 µm) and a relative increase in medium sand (250-500 µm). Four years post-extraction, from 2016 onwards upto 2023, sediment composition stabilises and is largely similar to the reference locations (Figure 7 top).

Both post-extraction areas on the Thorntonbank have only recently been closed but show an initial shift towards finer sediments within the first year after cessation of extraction. Fining here is due to an increase in the finest sediment fractions (0-63 µm, 63-125 µm and 125-250 µm), in combination with a decrease in the gravel fraction and coarse sand (500 - 1000 µm). Sediment composition is, however, still fluctuating between years and stabilisation has not yet occurred and the post-extraction area is after two years not reflecting the reference locations (Figure 7 bottom).

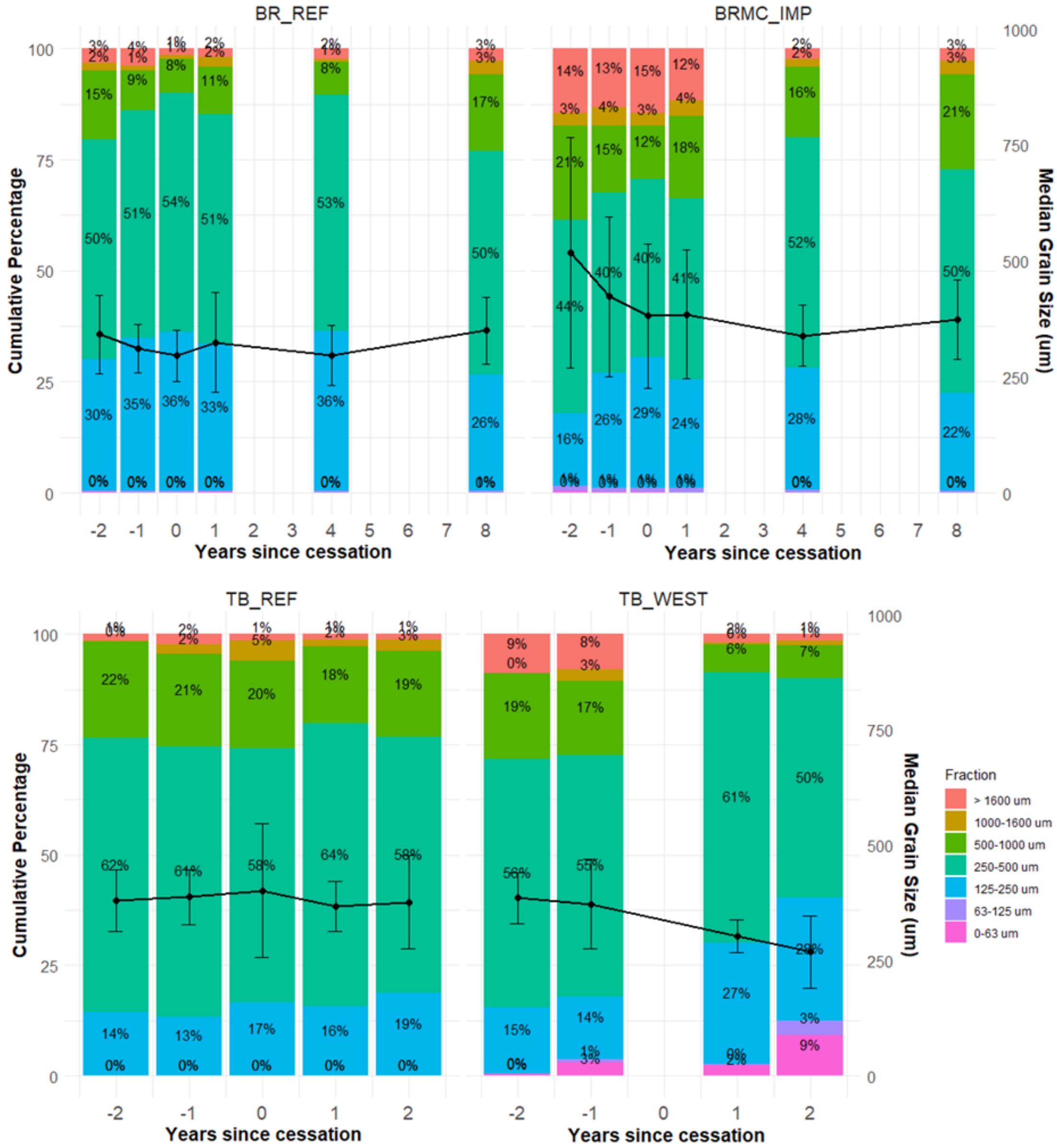

Figure 7: Sediment grain size distributions and median grain size over time for impact and reference area for Buiten Ratel (top) and Thorntonbank (bottom).

Macrobenthic community composition in post-extraction areas gradually shifts towards reference conditions over time

During the period of intensive sand extraction on Buiten Ratel and Thorntonbank, the benthic community shifted away from the reference locations towards a distinct, heterogenic, dynamic community including opportunistic species and species typically associated with muddy sands (De Backer et al. 2014, Wyns et al. 2021). In this study, we observed that after closing the areas for extraction, community composition gradually shifted towards the community structure observed in the reference locations. This shift was driven by changes in sediment composition.

Right after closure at the Buiten Ratel (year 0 and 1), the benthic community starts shifting with increased abundances of opportunist species like *Poecilochaetus serpens* and juvenile *Ophiura* but especially

Spiophanes bombyx (Figure 8 top). With time increasing after closure, the shift continued and from 4 years post-extraction onwards, the community resembled the *Nephtys cirrosa* community from the reference area (BR-REF), typical for medium sands. The reference area, on the other hand, remained stable over the entire study period (Figure 8 top).

At the Thorntonbank, a similar trend was observed for both areas: a stable community over time in the reference area, while the community in the impact area shifted immediately after closure for extraction related to a shift in finer sediments with increased abundances of species as *Spiophanes bombyx*, *Lanice conchilega* and *Nephtys cirrosa* (Figure 8 bottom). Time after closure (only 2 years) is not yet long enough to reach reference conditions but the current shift suggests a progressive recovery towards a reference-like community structure over time.

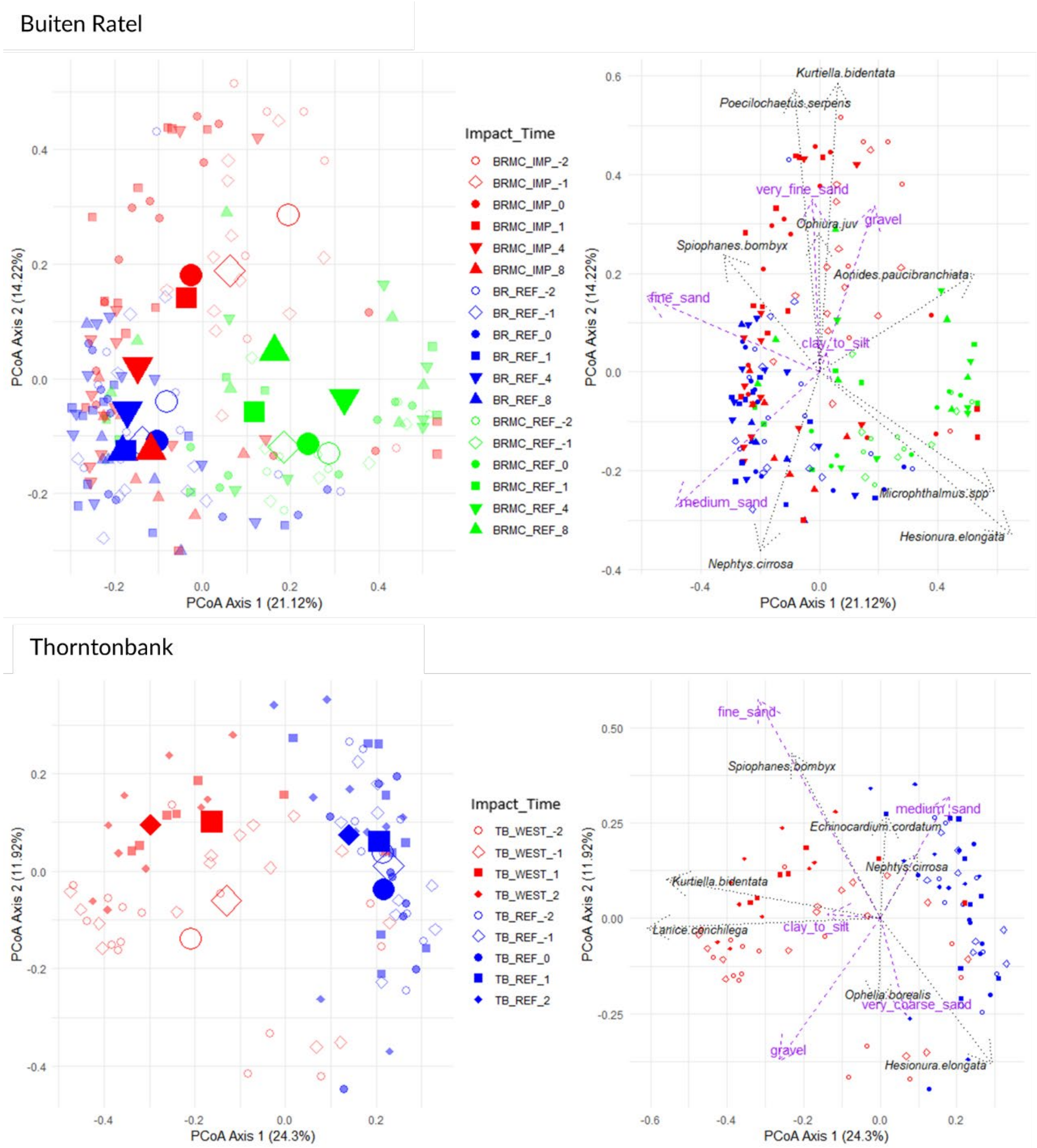

Figure 8: Principal Coordinate Analysis plot based on Bray Curtis similarity for square-root transformed macrobentos species abundance data with indication of the impact group and years since cessation of extraction. The top row displays Buiten Ratel and the bottom row shows Thorntonbank. The left plots show community centroids per impact group and year since cessation, while the right plots show vectors highlighting environmental drivers i.e. sediment characteristics (black, dotted) and species (dashed, purple) that drive the multivariate pattern.

Site specific-trends in macrobenthic density, species richness and biomass with time post-extraction

During extraction, a local increase in macrobenthos density, species richness and biomass was observed for both Buiten Ratel and Thorntonbank (De Backer et al. 2014, Wyns et al. 2021). For the Buiten Ratel, a gradual decrease over time in all three parameters is observed reflecting values of the reference area (BR-REF) after 8 years (Figure 9). This gradual decrease can probably be linked to the observed shift in community composition from a more species-rich, heterogenic community towards the *Nephtys cirrosa* community, which is known to be poor in terms of diversity and abundance (Breine et al. 2018). For the Thorntonbank, no clear trend can be observed in the years following extraction. The local increased values remain higher two years post-extraction compared to reference locations. The studied time period is probably not yet long enough to detect an evolution over time.

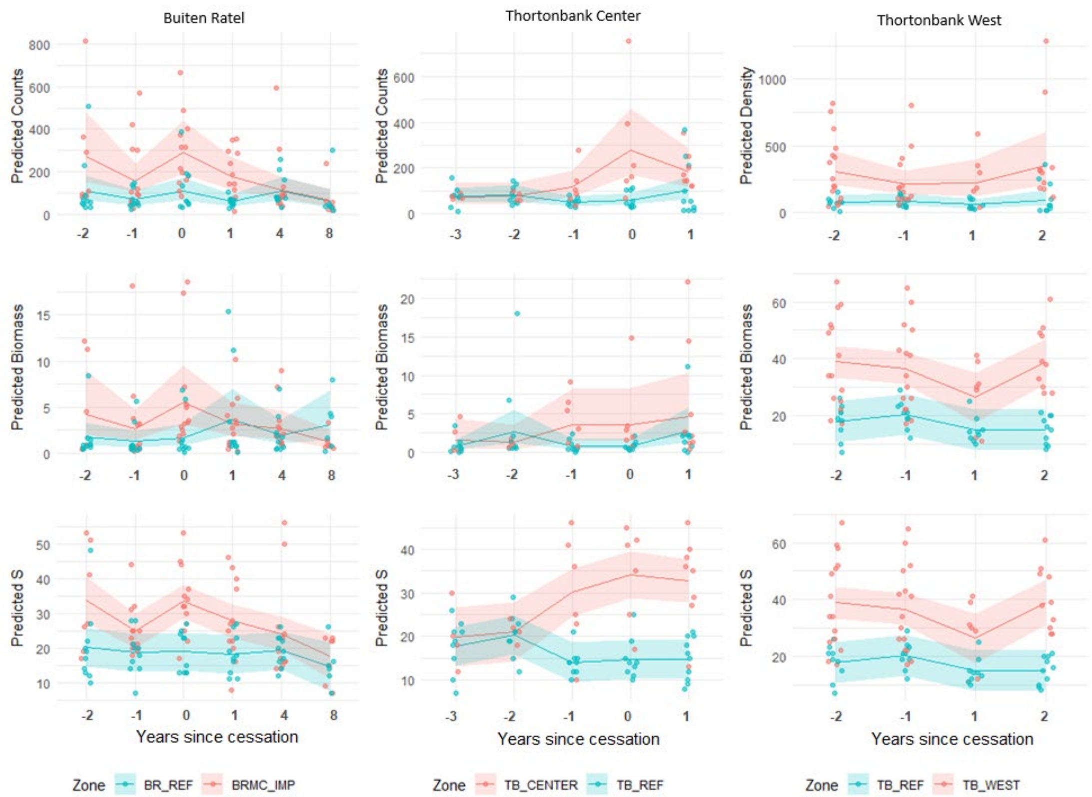

Figure 9: Evolution over time since cessation of extraction for macrobenthic abundance (Counts, n° individuals), biomass (g Wet Weight m^{-2}) and species richness for impact and reference locations for the different study areas: Buiten Ratel (left), Thorntonbank Center (middle), and Thorntonbank West (right).

<u>Manuscript in preparation:</u>

Lopez Lopez L., Barette F., Degrendele K.,Francken F., Roche M, Terseleer N., Vandeneynde D., Van Lancker V., De Backer A. Evolution of macrobenthos and morpho-sedimentary dynamics in areas closed for aggregate extraction.

3.6. Biomonitoring at speed: DNA sequence data pave the way to high resolution biodiversity analyses

Biological monitoring of sand extraction sites traditionally involves the identification of macrobenthic species based on morphological characteristics. Since animals must be sorted, counted and identified by a taxonomic expert, this method is time-consuming and costly. DNA-based methods have shown great potential for marine biodiversity monitoring (Aylagas et al. 2018) and typically involve sequencing DNA directly obtained from animal tissues (bulk DNA) or from traces in the environment (water or sediment = eDNA). The use of DNA sequence data for monitoring sand extraction impact in the Belgian part of the North Sea had not been investigated. Therefore, we optimised the bulkDNA methodology and then conducted traditional and DNA-based monitoring in parallel at three sand banks to compare species compositions, ecological status assignments and the cost and time associated with sample processing in both methods.

DNA-based biomonitoring reduces sample processing time, while detecting similar impact of sand extraction as morphology based identification

The bulk DNA metabarcoding protocol was optimised for routine monitoring by first examining the number of subsamples needed for DNA extraction and PCR amplification to adequately reflect macrobenthos species compositions. Substantial variability in species composition was observed between DNA replicates from the same macrobenthos sample which highlighted the need to take three DNA replicate samples which can then be pooled before PCR (Van den Bulcke et al. 2021). A ring test across four laboratories demonstrated high reproducibility and robustness of the DNA-based method, consistently detecting the abundant macrobenthos species (Van den Bulcke et al. 2023).

The optimized DNA metabarcoding protocol was then applied on macrobenthos samples from reference and impact sites in three sandbanks (Thorntonbank, Oostdyck and Hinderbanken). Sample processing time was 44% faster and 26% cheaper compared to morphology-based identification but many identified taxa differed between the two methods. DNA metabarcoding also struggled with abundance estimation. Despite these differences, both methods detected similar sand extraction impacts at Thorntonbank and Oostdyck, where species like *Lanice conchilega* and *Urothoe brevicornis* increased in highly impacted areas Van den Bulcke et al. 2024. At Hinderbanken, only morphological methods detected effects, as low read numbers led to sample exclusion in metabarcoding. These results highlight DNA metabarcoding's ability to detect ecological changes from sand extraction (Figure 10A). The DNA- and morphology-based species assemblages were then used to calculate the biotic index, Benthos Ecosystem Quality Index (BEQI), a measure that reflects the ecological status of the sampled area. The genetic BEQI correlated with morphological values but underestimated impacts, leading to mismatches in ecological status assignments (Figure 10B). Further research is now directed towards the development of a genetic indicator that can be used to describe the ecological status using DNA sequence data.

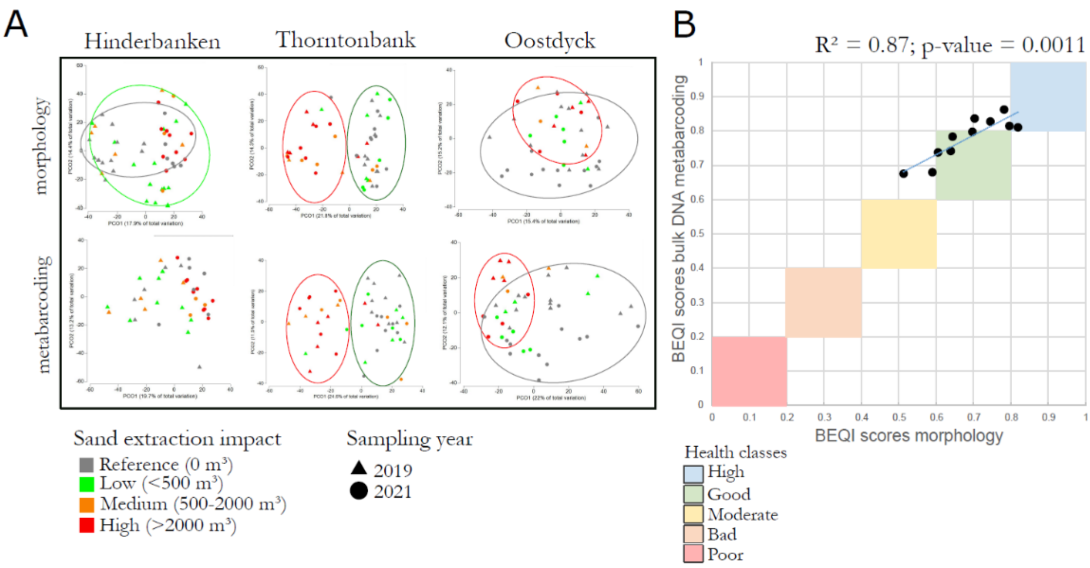

Figure 10: A) PCO plots per sandbank and method based on Bray-Curtis similarity for densities and read abundance data. The different colours indicate the sand extraction impact, and the two years are visualized by a different symbol. B) Comparison calculated BEQI with bulk DNA data (y-axis) and morphological identifications (x-axis).

DNA-based biomass estimations of macrobenthos species improve with PCR-free methods

Although metabarcoding proved to be successful in detecting changes in macrobenthos species diversity, a good estimate of the change in relative biomass was difficult to achieve. PCR bias, a methodological artifact causing the DNA of different species to amplify with varying efficiency, is assumed to be a major cause for this low predictive value of metabarcoding for relative biomass. To alleviate this issue, we developed a PCR-free technique to characterize the community composition from bulk DNA samples. We tested our technique on a subset of 26 macrobenthos species in 12 samples from an area with high sand extraction activity and a reference area. Results showed an improved relation between read counts and biomass, which in turn resulted in an overall better agreement between genetic- and morphology-based assessments of the community composition (Figure 11). Given the promising results of our initial test, we will further expand the reference database required for this technique and perform more extensive benchmarking to investigate the potential of our method to assess the ecological status of benthic ecosystems.

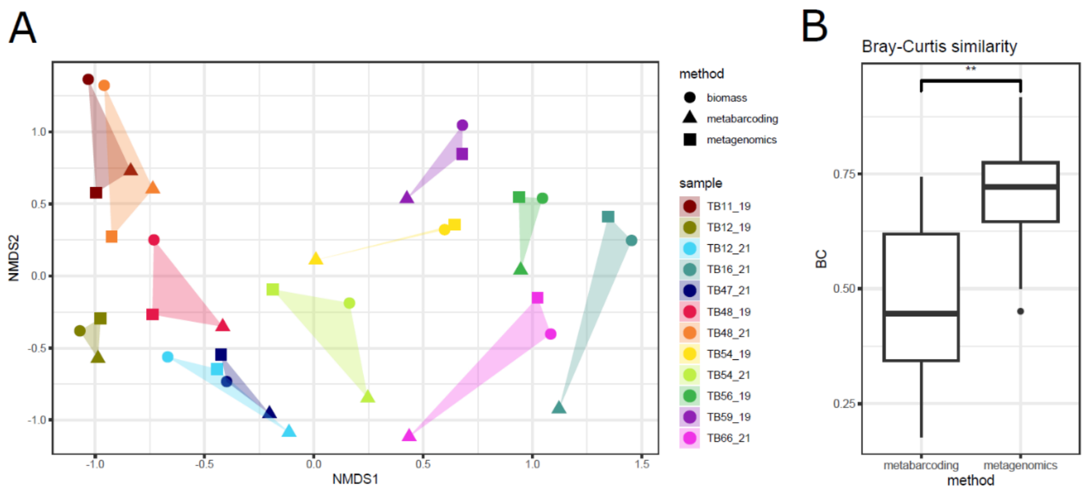

Figure 11: A) NMDS plots based on Bray-Curtis similarity, comparing the biomass retrieved from the traditional morphological method with the metabarcoding and metagenomics DNA-based methods. The different colours indicate the samples, and the three methods are visualized by a different symbol. B) Boxplots comparing the

Bray-Curtis similarity of community compositions obtained by metabarcoding or metagenomics relative to the morphological method.

Harvesting the best of both worlds: the new monitoring design of sand extraction combines DNA- and morphology based identification

With these results in mind, an optimized monitoring program currently combines DNA metabarcoding with morphological identification. This approach balances time and cost-effectiveness (DNA metabarcoding) with accurate quantitative measures and biotic indices (morphological identification). Metabarcoding should be used across the entire sand extraction gradient, with morphological samples taken at the extremes where impact is expected to be most pronounced (Figure 12). As such, abundance, life stage data and a comprehensive species list are provided at the high-impact and reference locations, and even minor disturbances will be detected through DNA in less impacted areas (Van den Bulcke et al., 2024).

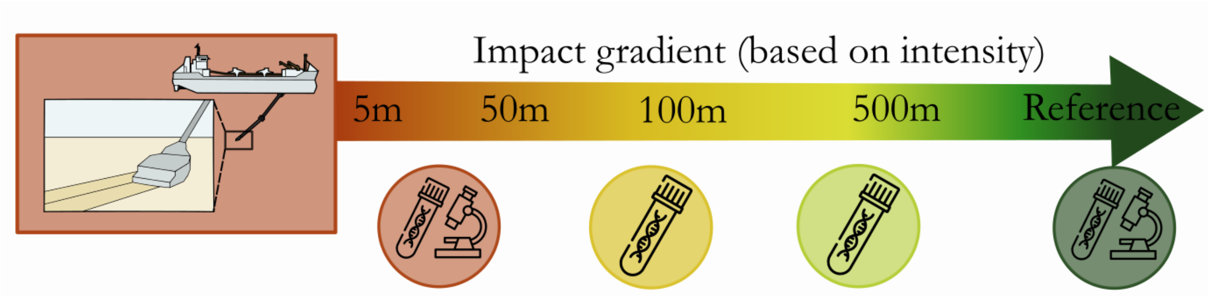

Figure 12: Visual representation of the new monitoring design combining DNA- and morphology based identification.

Towards non-invasive biological monitoring with eDNA

Animals release DNA in the environment through the shedding of scales, faeces, gametes, slime and other body fluids. Although many studies have already demonstrated the potential of eDNA for monitoring marine biodiversity in a non-invasive manner, its applicability in shallow (< 30 m) and well mixed waterbodies remained unclear. We therefore collected eDNA from seawater and beam trawl data in parallel in 30 stations spread over the BPNS. eDNA metabarcoding retrieved 85.7% of the fish species caught in the beam trawls, whereas only 31.4% of the epibenthic invertebrate species were identified. Many additional species were detected with eDNA that were not caught in the beam trawl (26 fish species and 90 invertebrate species). Moreover, eDNA was able to detect significant differences in fish and invertebrate communities between the coastal, transition and offshore zones as well as on the smaller wind farm scales, which agreed with the morphological beam trawl data (Cornelis et al. 2024). In a follow-up study, we demonstrated that sampling depth did not significantly affect eDNA based spatial community patterns of fishes, indicating that one depth is enough for monitoring in the BPNS (Dukan et al. 2024). Future research aims to investigate the applicability of eDNA for monitoring sand extraction impact by comparing eDNA patterns in the sediment and in the seawater with bulkDNA metabarcoding data of the macrobenthos in impact and reference sites. Next to the non-invasive nature of eDNA analyses, sample collection from the seawater can be automated, which paves the way for achieving unprecedented spatiotemporal biodiversity data resolution.

More details to be found in:

Van den Bulcke L., De Backer A., Ampe B., Maes S., Wittoeck J., Waegeman W., Hostens K. & Derycke S. (2021) Towards harmonization of DNA metabarcoding for monitoring marine macrobenthos: the effect of technical replicates and pooled DNA extractions on species detection. Metabarcoding and Metagenomics, 5, e71107, https://doi.org/10.3897/mbmg.5.71107

Van den Bulcke L., De Backer A., Wittoeck J., Beentjes K., Maes S., Christodoulou M., Arbizu P.M., Sapkota R., Van der Hoorn B., Winding A., Hostens K. & Derycke S. (2023) DNA metabarcoding on repeat: Sequencing data of marine macrobenthos are reproducible and robust across labs and protocols. Ecological indicators, 150, 110207, https://doi.org/10.1016/j.ecolind.2023.110207.

Van den Bulcke L., De Backer A., Hillewaert H., Maes S., Seghers S., Waegeman W., Wittoeck J., Hostens K. & Derycke S. (2024) Comparative study of traditional and DNA-based methods for environmental impact assessment: A case study of marine aggregate extraction in the North Sea. Science of The Total Environment, 946, 174106 https://doi.org/10.1016/j.scitotenv.2024.174106.

Van den Bulcke L. (2024) Optimising DNA metabarcoding and machine learning for advanced impact assessment in the North Sea: A case study on sand extraction. PhD thesis

Cornelis I., De Backer A., Maes S., Vanhollebeke J., Brys R., Ruttink T., Hostens K., & Derycke S. (2024). Environmental DNA for monitoring the impact of offshore wind farms on fish and invertebrate community structures. Environmental DNA, 6, e575. https://doi.org/10.1002/edn3.575

Dukan N., Cornelis I., Maes S., Hostens K., De Backer A. & Derycke S. (2024). Vertical and horizontal environmental DNA (eDNA) patterns of fish in a shallow and well-mixed North Sea area. NPG Scientific Reports 14(1): 16748. https://dx.doi.org/10.1038/s41598-024-66912-2

Manuscript in preparation:

Callens M., Le Berre G., Van den Bulcke L., Lolivier M., Derycke S. Development of a PCR-free strategy for DNA-based characterization of metazoan bulk samples.

3.7. Conclusion

Sand extraction has multifaceted ecological effects, impacting various ecosystem components in both direct and indirect ways. The overall impact on the ecosystem is characterized by changes in species composition of different biological groups leading to alterations in functional diversity, functional characteristics and potentially ecosystem processes. These changes are typically driven by high volumes of sand extraction, which alter sediment composition, increase sediment heterogeneity and frequently result in the accumulation of organic material (OM). For bacterial communities, this leads to an increase in groups that are specialists in degrading fresh phytoplankton-derived organic matter. In macrobenthic communities, deposit-feeding organisms are favoured as a result, and a slightly increased secondary production in impact areas on the long-term can also be linked to the OM increase, while bio-transport activities are not directly affected by extraction. For the higher trophic levels, scavengers and omnivores characterise the community at high extraction levels related to higher food availability both as a result of mortality of local fauna and higher availability of OM. Changes in species composition are, however, more distinct for the less mobile epibenthos component than for more mobile fish species. These observed ecological responses can impact ecosystem processes and functions, influencing overall ecological balance.

Although impacts are plentiful with ongoing extraction, following the cessation of extraction, benthic environments begin a gradual ecological recovery process driven by progressive sediment homogenisation and gradual changes in sediment composition. This shift in benthic community starts immediately after extraction stops with colonisation of opportunistic species. After 4 to 8 years the community stabilises and returns to reference conditions provided that the sediment resembles reference conditions. While recovery processes are evident, the community-level and functional impacts of sand extraction underscore the need for careful management and monitoring to mitigate adverse effects on these crucial ecosystem components.

In that sense, optimising monitoring efforts is important for improving marine ecological assessments, and incorporating innovative DNA-based techniques represents a significant advancement. Bulk DNA metabarcoding of macrobenthos has improved sample processing efficiency and detects community shifts comparable to those identified through traditional morphological methods. However, accurately determining quantitative measures from DNA sequences remains challenging, even though PCR-free methods show promise for better biomass estimates. Consequently, we advocate for a benthic monitoring approach that combines both DNA and morphological identification to leverage the strengths of each method. Additionally, environmental DNA (eDNA) provides a non-invasive alternative to beam trawls, enhancing species detection and revealing shifts in fish communities similar to morphological beam trawl data. By integrating these advanced DNA techniques, we can significantly enhance our monitoring capabilities.

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4. Changes in seafloor integrity and hydrographic conditions, towards a spatio-temporal assessment at BPNS scale

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4.1. Introduction

4.1.1. Monitoring rationale

The Institute of Natural Sciences is responsible for monitoring the effects of aggregate extraction on the hydrodynamics and sediment (transport) of the marine environment. Quantification of such effects is needed to monitor progress towards good environmental status (GES) as required by the European Marine Strategy Framework Directive (MSFD; 2008/56/EC). With regard to the physical impact of aggregate extraction, this requires a follow-up of the GES descriptors seafloor integrity and hydrographical conditions. Seafloor integrity refers to the structure and functions that the seabed provides to the ecosystem, while hydrographical conditions refer to currents, turbidity and/or other oceanographic parameters, changes thereof possibly having a negative impact on benthic ecosystems. The geological substrate provides important preconditions for more sustainable extraction practices (e.g., quality and quantity) and its characterization is important to assess irreversible loss of a habitat. Habitat loss should be restricted to 2 % per broad habitat type (BHT, see 4.2.1). Hitherto, this is mostly evaluated based on direct ‘sealed’ loss through replacement of the seabed by another structure. However, indirect ‘unsealed’ loss may also occur depending on the frequency and persistency of bottom-disturbing activities (Raicevich et al., 2024).

The ZAGRI monitoring framework therefore comprises three main objectives:

(1) Quantification of natural and human-induced variability of sediment characteristics and processes.

(2) Process and system modelling of the activity-pressure chain effects, in the near and far field.

(3) Recommendations for a more sustainable use of marine resources (i.e., sand), in line with the MSFD, and contributing to the United Nations Environment Programme (UNEP) for a more collective management of mineral resources.

To realize the objectives several approaches are combined, comprising field measurements and observations, modelling, and long-term data analyses. For field measurements, the Institute of Natural Sciences keeps on investing in optical and acoustical sensors for water column measurements. The oceanographic vessel RV Belgica, with its state-of-the-art instrumentation, is pivotal in the monitoring.

4.1.2. Overview contributing projects

To reinforce the ZAGRI research lines, alignment is sought with other monitoring programmes and additional projects are developed, mostly together with consortia having multidisciplinary expertise and utilizing complementary approaches. For the period 2020-2024: (1) MSFD monitoring on seafloor integrity (Belgische Staat, 2025); (2) Monitoring the effects of sand extraction in the Hinder Banks (MOZ4; Flemish Authorities, Maritime Services); (3) Belspo TURBEAMS; and (4) Sustainable Use of Sand in Nature-based solutions (SUSANA; VLAIO cSBO). ZAGRI/MOZ4 are main contributors to the MSFD assessments, and reversely MSFD provides the European framework for environmental assessments. Tuning of both is critical. TURBEAMS is pivotal in making progress in turbidity assessments using a multi-sensor approach. SUSANA provided the opportunity to develop innovative approaches in the cumulative modelling of sediment dispersal from different bottom-disturbing activities.

4.2. Methodology

4.2.1. Seabed mapping

Acoustic seafloor classification and seabed change assessment

For the evaluation of seabed changes compliant with MSFD requirements, seabed mapping approaches were revisited. Emphasis was placed on consistent mapping over the entire Belgian part of the North Sea (BPNS), and this based on datasets representing a reasonable timespan. High-quality 1-m multibeam bathymetry datasets were therefore used, acquired by Flemish Hydrography (Flemish Authorities, Maritime Services) in the period 2015-2022. The assumption was made that the main substrate types, having significantly different sediment compositions (mud, sand, coarse sediment), have a different topographical expression at the seafloor that can be depicted by very-high resolution depth data and derivatives thereof. Hence, the mapping is steered towards characterization of sediments at the seafloor which is also most relevant from an ecological perspective. Typically, muddy sediments are associated with a flat, smooth seabed, whilst in environments with abundant sand supply high-amplitude (> 0.75 m high) regular bedforms occur. Sand thickness is minimal in areas where coarse sediments (incl. gravel) prevail, hence no to low-amplitude bedforms occur. Mostly, the latter are irregular in shape since not enough sand is available for full development. Goal of the mapping was to obtain seabed types in accordance with the Folk classification that is based on estimating the relative proportion of mud, sand, and gravel. This classification is most widely used in the European seas and aligns with MSFD requirements (i.e. Folk 5 classes link directly to the MSFD Broad Habitat Types[5] (BHT)). On the BPNS we relate the Folk class 'sandy Gravel' to 'gravel beds'; these are defined as a spatial aggregation of sediment types comprising natural surfacing non-mobile geogenic and/or bioclastic sediments (*sensu* Montereale Gavazzi et al., 2023a). Typically, such areas comprise a mixture of sediments, including compact clays from older geological formations, and also sand veneers that may show low-amplitude sand ripples. See Van Lancker et al. (2024b) for more detailed information.

The same seabed mapping approach was used on MBES time series in two zones in gravel bed areas to determine changes in the ratio of soft versus hard substrates: (1) Flemish Banks: in-between the Buiten Ratel and Kwintebank ('KWGS' area), and (2) Hinder Banks: the southwestern part of the Oosthinder sandbank where ecologically valuable gravel beds occur in the trough of barchan dunes ('OH-BD' area). The datasets and assessment method are outlined in Van Lancker et al. (2024c). Comparisons were made with the reference substrate map at a scale of 1:50.000, having a minimum mapping unit (MMU) of 0.01 km². The bathymetric datasets contributing to the reference map were collected in 2019 for the KWGS area, and 2018 for OH-BD.

To monitor seabed change over the entire BPNS, a network (SI-NET) of monitoring trajectories has been defined along the edges of the main substrate types. As an example, this allows mapping transitions between sand and sandy gravel over wider spatial scales. Sampling and visual observations with video are part of this dedicated monitoring. Time series are only recently built and will be reported in a later phase. See Van Lancker et al. (2024b) for the SI-NET rationale.

Meanwhile, also particle-size distribution related mapping products (PSD) are being updated. Since these are typically made using all available data (1900-2023), of which the old data is often needed in offshore areas, new approaches are experimented with to cope with variation through time. The long time span of the dataset complicates validation of the reference maps of which data was collected over shorter periods.

In a later phase the new products will be combined with the subsurface models as produced in the Belspo TILES project (Van Lancker et al., 2019).

[5] Commission Decision (EU) 2017/848: broad habitat types (BHT) are mud, sand, mixed and coarse sediments in the different biological zones (littoral, infralittoral, circalittoral, and offshore circalittoral). Exception are the littoral sediments that are undifferentiated in the BHT terminology, but kept separate at EUNIS Level 2. Gravel beds align with the occurrence of sandy gravel and is part of the coarse sediment BHT (Van Lancker et al., 2024a).

Morpho-sedimentary analyses combining MBES, sampling and video

For the Hinder Banks detailed morpho-sedimentary analyses have been carried out for sector 4a, 4c (Kint et al., 2023) and for the Bligh Bank (sector 5). Boxcores are taken considering the morphological position of the locations w.r.t. the sandbank. Subcores are then sliced at cm-level to better evaluate enrichment of fine fractions. In the gravel bed areas in the troughs in-between the sandbanks Hamon grab samples are taken, as well as video imaging. Dimensional analyses of the gravel and shells from the video data are underway. Since the availability of the new substrate map, a more systematic sampling strategy could be targeted, compared to the mere exploratory approach before. For all settings lithological descriptions and photographs are taken on board. On the samples particle-size analyses are carried out. Organic matter and carbonate content is determined on the sandbank samples. Multibeam depth and backscatter are recorded, following common procedures as set out by FPS Economy, Continental Shelf Service (FPS Economy-CSS). For more information, see Van Lancker et al. (2020, 2022a, 2023, 2024a,b,c); Montereale Gavazzi et al. (2021); Kint et al. (2023); and Montereale Gavazzi et al. (2023a,b).

4.2.2. Sediment plume measurements

FPS Economy re-initiated sea-going campaigns to enhance real-time monitoring of sediment plumes, with the new, state-of-the-art oceanographic vessel RV Belgica playing a pivotal role. Two campaigns were conducted in 2022 and 2023, following different trailing suction hopper dredgers involved in both sand extraction and dredged material disposal. These operations were carried out at various sites, including sand extraction areas on the Thornton and Noordhinder Banks and disposal zones near the Port of Zeebrugge. A variety of experimental designs were used to monitor plume dispersal, including zig-zagging patterns and stationary sampling near predicted plume boundaries. Pivotal in the execution of the measurements was the availability of the quasi-real-time sediment dispersal model (see 4.2.3). The combined field-modelling approach allowed capturing the spatial and temporal dynamics of the sediment plumes in a most flexible way.

Advanced sensor technology was deployed to measure the extent and properties of the plumes. Mounted on the hull of the ship, a high frequency multibeam echosounder (MBES; 300 kHz; depth and water column) was used for high-resolution plume detection; a multi-frequency, single-beam echosounder (SBES, 10-500 kHz), as well as an acoustic doppler current profiler (ADCP; 600 kHz) for tracking water currents and sediment concentration. At the side of the ship, a water carousel (Seacat CTD profiler, SBE09) was deployed in stationary mode. It was equipped with a Conductivity, Temperature and Depth (CTD) sensor, and a series of optical (Optical Backscatter Sensors (OBS) in different ranges; Laser In Situ Scattering Transmissometer (LISST)), and acoustical sensors (Acoustical Backscatter Sensor (ABS)) to be used for water-column profiling during periods that the MBES showed higher acoustic returns and under background conditions. Water samples were taken and filtered for suspended particulate matter concentration (SPMc), and particulate organic carbon and nitrogen (POC/PON). Salinity was determined, and a centrifuge sampler was used to filter particles from the water circuit entering the vessel during the different experiments. Filters and samples were analysed in the laboratory afterwards. The centrifuge samples were pre-treated to remove all organic matter, isolating the inorganic fraction of the SPM for further study. The MBES and SBES data were processed by FPS Economy, and UGent respectively and are not reported explicitly here. The same holds true for additional measurements carried out with an undulating video plankton recorder (VPR) equipped with multiple sensors; these data are processed by VLIZ.

4.2.3. Modelling

Sediment dispersal modelling

In support of the sediment plume measurements at sea, the Marine Forecasting Centre (MFC) of the Institute of Natural Sciences further developed on a hybrid Lagrangian/Eulerian method to simulate 3D drift and fate of sea surface and water column particles. As such, the displacement of each particle is modelled resulting from the combined actions of winds, waves, ocean currents, Stokes drift, buoyancy, turbulent diffusion, gravity, viscosity and surface tension. The adapted model guided successfully the plume measurements (see above). More details are described in Van Lancker et al. (2022b).

In a next phase, data and knowledge were compiled in support of cumulative sediment dispersal modelling. This comprised standardizing and harmonizing factual data on bottom-disturbing activities (fisheries, extraction, dredging, disposal; aligned with Kint and Van Lancker, 2024), collecting technical specificities of ships involved, and estimation of amounts. Ship categorization (small, medium, large) and indicative amounts released were reviewed and updated, starting from the earlier sediment plume studies conducted in the ZAGRI/MOZ4 framework (Van Lancker et al., 2016). Newest sediment data information was used as input. Particles were followed for 14-days, and their deposition was recorded. The basic research, i.e., development of the methodological approach, the modelling itself, and the production of a 4D dataset over an entire year (i.e., 2019) were executed in the cSBO VLAIO SUSANA project (Lepers et al., 2024). Minimum aggregation level is 1-day.

In ZAGRI further steps are taken in view of assessing far-field impacts. They build upon the combination of the methodologies described in 4.2 and are approached top-down and bottom-up. Top-down is related to the results of the Lagrangian modelling; bottom-up links to the water column and seabed mapping, in combination with sampling and video observations. Combination of several methodologies, and integration of modelling, mapping and sampling is needed to build confidence in the impact assessment. No guidelines exist at European levels, nor agreed methodologies, hence assessments remain research-based. Important steps have been taken in the methodological workflow.

4.2.4. Long-term data analyses

The Institute of Natural Sciences collaborated on long-term data analyses of bathymetric time series in relation to sand extraction. In Wyns et al. (2021) near-field impact is discussed on Thorntonbank (1), Oostdyck (2od), and Oosthinder (4c). Morphological regeneration was investigated of the extraction areas on the Kwintebank (2kb) and Buiten Ratel (2br) (Krabbendam et al., 2022), Sediment variability in the intermittently extracted Hinder Banks (4a, 4c) was assessed in Kint et al. (2023). ILVO is leading a paper on recovery dynamics of closed areas, focussing on time series of the Buiten Ratel (2br) and Thorntonbank (1a) (Lopez Lopez et al., in progress). Morphodynamic analyses are conducted in line with the approach of Terseleer et al. (2016). Methodologies are extensively described in the publications.

4.3. Results

4.3.1. Natural variability

Seabed nature and dynamics

New (sub)surface maps of substrate types have been produced as a reference for evaluation of changes in seabed and (broad) habitat types (Figure 1). Subsurface data (i.e., geology) was important to better understand the processes responsible for the sediment distribution and is critical for the assessment of irreversible ‘unsealed’ loss that may indirectly be the result of intensified human activities. Maps, with confidence attributes, have been produced at different scales (50k, 100k, 250k, 1M). The 50k and 100k scales are considered most valuable for monitoring, and management purposes respectively; the 250k for regional assessments at the larger scale (e.g., MSFD). A systematic seabed change analysis will only be attempted in the next MSFD cycle and will seek collaborative action with other monitoring and research programmes.

Meanwhile, multibeam time series are built along the SI-NET monitoring network. Some local cases of unsealed loss are mapped and linked to long-term marine aggregate extraction. The dynamical nature of shelf environments, the fragmented knowledge on the geology, but also the process of map making, and chosen scale, complicates the application of thresholds of irreversible change. However, within the environmental and operational constraints, most important is to prevent irreversible habitat loss. By imposing a lower limit of extraction, FPS Economy contributes pro-actively to the prevention of habitat loss (Degrendele et al., 2021).

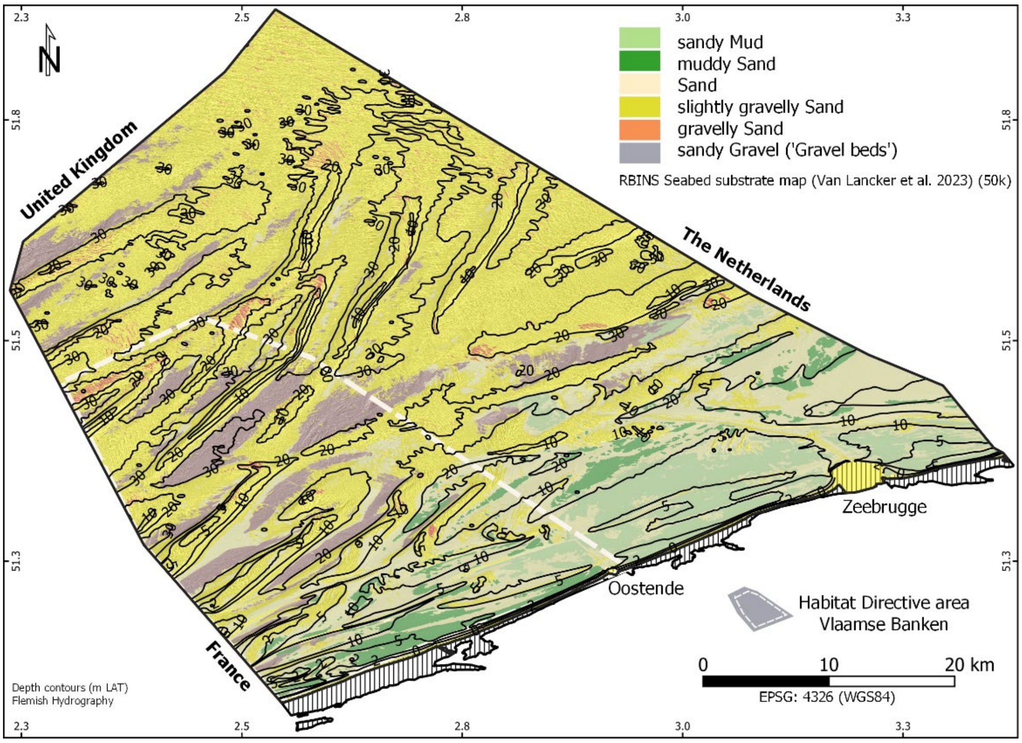

Figure 1: New seabed substrate delineations (here at scale 50k). The 250k scale is compliant with BHT mapping in MSFD context (Van Lancker et al., 2024b).

Results on mapping the ratio of hard versus soft substrates in two test zones (KWGS and OH-BD) showed limited long-term changes between 2009 and 2019 (Figure 2). On the short-term wider changes in the spatial extent of the sand cover did occur, however without major morphological changes (see Van Lancker et al., 2024c for more elaborate results, including those for the OH-BD area). SI-NET time series, comprising transition areas over the entire BPNS, together with FPS Economy's time series along decca lines, will allow a more comprehensive spatio-temporal appraisal of seabed changes.

Morpho-sedimentary characterisation

At the sandbank level, morpho-sedimentary dynamics are dictated by geomorphological position. For the Hinder Bank sectors 4a and 4c, changes within a BHT during extraction were mostly related to depletion of coarse-grained admixtures, leading to homogenization. After the extraction halt in 4c, slow recovery to original sediment characteristics was observed (Kint et al., 2023 for full results). In the far-field gravel bed areas sand thickness is minimal and therefore changes in bedform complexity are studied. Generally, the gravel bed delineations proved quite stable, though changes in sand ripple extensions did occur. Buried gravel of 5 to 10 cm, underneath a 10 cm sand cover, was sampled at the base of the Oosthinder sandbank, near sector 4c. The reversibility of this burial can yet not be assessed. For the gravel beds in the Hinder Banks and the area near the UK border, Montereale Gavazzi et al. (2023a) analysed the geomorphological context and fishing patterns using remote sensing tools. Following an extensive biological analysis, comparing exposed and sheltered areas, it was shown that bottom-contacting fisheries have the highest direct impact on the seabed.

Water column nature and dynamics

In the MOZ4 project reports several 13-hrs measurements have already been reported. Whilst highly valuable to document natural and human-induced variability in water-column properties, the lack of continuous or regular measurements at fixed stations hampers the establishment of baseline conditions (Fettweis et al., 2023 for a discussion). For natural variability and trend analyses, results are taken from the monthly sampling conducted in the biogeochemical monitoring programme (BGCmonit, Institute of Natural Sciences; Fettweis et al., 2022) (Figure 3). SPMc variation at the W08 station, located near the

Fairy Bank (Hinder Banks), is indicative for the deeper offshore conditions (in-between sandbanks). The variation of the more randomly distributed 13-hrs cycles are evaluated against those time series.

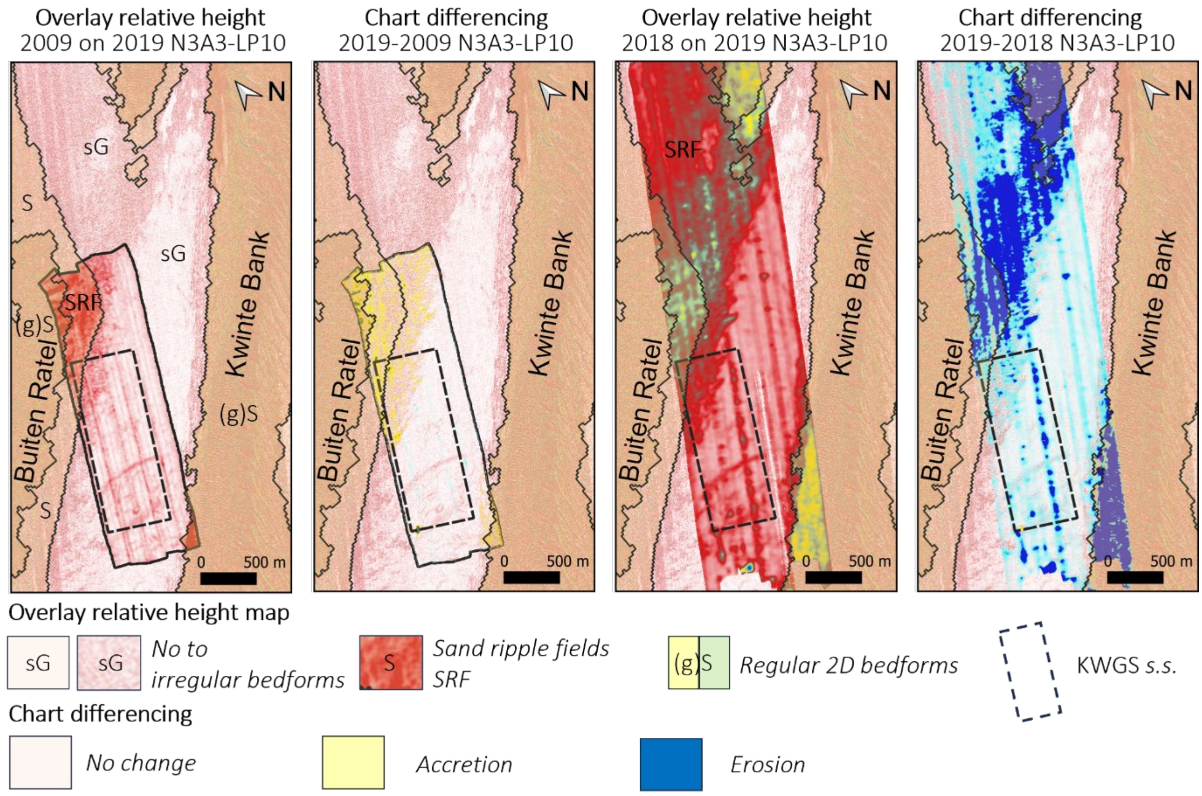

Figure 2: Short- and long-term changes in the time series of the KWGS area (trough in-between Buiten Ratel (2br) and Kwinte Bank (2kb)). Background is the relative height map of July 2019 (reference map for this area) with its delineation in terms of sandy Gravel (sG), sand (S), and slightly gravelly Sand ((g)S). Note the stability of the KWGS s.s. area (see also Roche et al. 2018), but also cross-bank sediment dynamics north of it (Van Lancker et al., 2024c for more context).

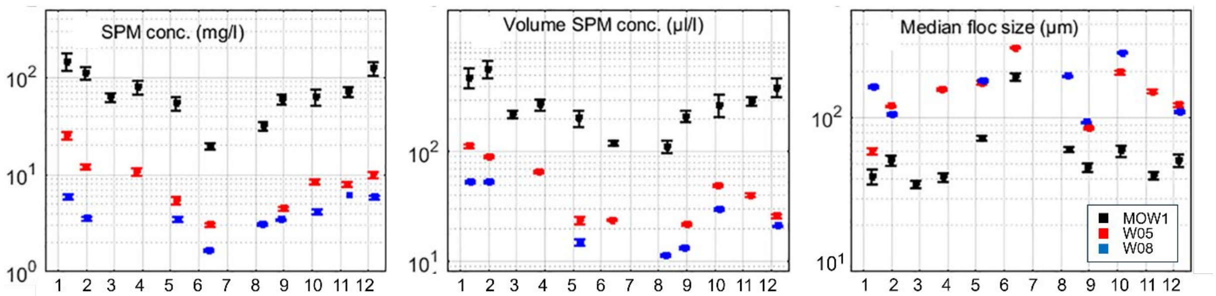

Figure 3: Monthly time series (1-12) of SPMc and floc size for a coastal station (MOW1, in the turbidity maximum around Zeebrugge; a station near the Gootebank (W05, mid-BPNS); and an offshore station in the Hinder Banks (W08). Floc sizes are highest in deeper waters pointing to important flocculation processes because of high amounts of organic matter from a degrading plankton biomass (Fettweis et al., 2022).

4.3.2. Near-field impact studies and recovery

Sediment plume results

Water properties in- and outside the plumes clearly differed in SPMc. Variations in the structure and composition of the sediment plumes was revealed by the combination of the optical and acoustic sensors. Optical sensors, measuring particle-size distribution and concentration (LISST-200X), detected more subtle changes in sediment characteristics compared to the OBS, which tended to underestimate SPM levels when larger sand particles were present. In the latter case, acoustical sensors (ABS, ADCP, EK80, MBES) performed better. They proved most effective in identifying periods of plume activity, with variations in backscatter intensity correlating well with the presence of suspended particles in the water column. The differences in sensor sensitivities highlighted the need for careful interpretation of sensor data and the need to measure sediment nature as well.

Important differences were revealed between the sediment plumes generated by sand extraction and those from disposal activities. During disposal SPMc was much higher, and the range of particle sizes was more varied. In contrast, plumes from sand extraction were more localized and exhibited less variation in SPMc. A publication on the results is underway (Van Roozendael et al.).

Recovery dynamics

Results are in preparation for the joint paper with ILVO and FPS Economy-CSS.

4.3.3. Towards far-field impact assessments

A first step in far-field impact estimation is bringing awareness on the relative spatial extent of the dispersal of fine sediments (silt and fine sand) upon release in the water column. The SUSANA dataset allows visualizing influence zones, though whether or not this leads to impact is subject of further research. As an example, Figure 4 shows a combination of the dispersal of fine sand from estimated draghead and overflow releases of all trips conducted in the BPNS in 2019. Although insight is provided into the relative importance of extraction in the different sectors, further analyses are needed of the frequency and persistency of the events and comparing those with natural cyclicities.

Generally, when comparing the cumulative sediment dispersal patterns of the other bottom-disturbing activities, fisheries came out as highest influencer, followed by disposal, dredging and extraction, though this changes towards the offshore. Further analysis targets the identification of hotspots of deposition to be validated with seabed mapping and dedicated field experiments as described in 4.3.1 and 4.3.2 respectively. It is envisaged to conduct fingerprinting of source and deposition areas to progress on establishing causal relationships with the different stressors. It is acknowledged that fine sand is a highly mobile sediment fraction, hence the significance of the varying spatio-temporal scale of deposition will need comparison to the overall sediment dynamics. Still, it is hypothesized that the increase in fine-grained sediments may affect bedform behaviour and dimensions. New insights will arise from systematic analyses of bedform complexities that will be conducted in the next 4 years (NWO BANX, see below).

4.4. Conclusions

4.4.1. Seafloor integrity and hydrographic conditions

The new (sub)surface maps of substrate types serve as a reference for the evaluation of changes in (broad) habitat types (BHT) *sensu* Marine Strategy Framework Directive (MSFD). Particularly, they support EIA assessments on seafloor integrity. A spin-off of the seabed substrate map was the gravel bed delineation (sandy Gravel) that was used to support studies on: (1) fisheries exclusion areas (MRP 2020-2026); (2) zones to be safeguarded in the future wind farm Princess Elisabeth; (3) defining gravel monitoring areas related to the Princess Elisabeth Island; and (4) pré-conditions for restoration.

Regarding near-field direct impacts, it is further confirmed that where the Quaternary cover is thin, extraction will deplete the upper habitat type. Whether or not this leads to irreversible habitat loss (a change lasting at least 12 years) will depend on the recovery potential of the sites, a process that is currently investigated jointly with FPS Economy-CSS and ILVO. A biophysical approach is followed in which also morpho-sedimentary dynamics and the hydro-meteorological regime are accounted for.

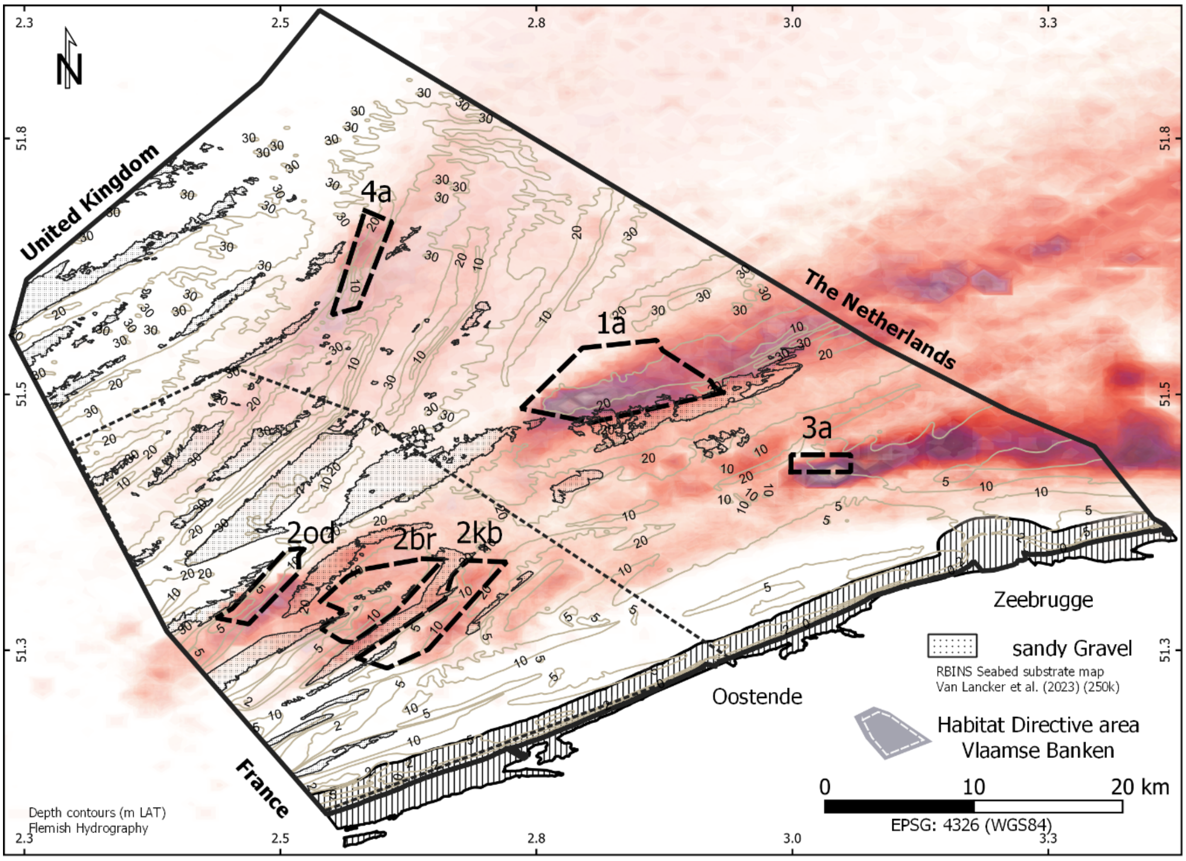

Figure 4: Patterns of influence of the dispersal of fine sand (125 µm) from the combined extraction activities in the Belgian part of the North Sea in 2019. Background are the gravel bed areas. Monthly calculations are here superimposed. The darkest colours give an indication of the highest frequency of occurrence of sediment deposition. See Lepers et al. (2024) for the underlying methodology of the original dataset.

In view of estimating far-field impact, significant methodological advances were made in the in-situ and remote sensing measurements, and validation of sediment plumes. State-of-the-art instrumentation on RV Belgica was pivotal in this process, but also the development of quasi real-time predictive models of sediment dispersal. Adequate interpretation of the plumes required the combined use of advanced optical and acoustical sensors since particle structure and composition mattered in plume detection. A clear difference was seen between sediment plumes arising from sand extraction and disposal activities, with the latter having higher SPMc and a more diversified particle spectrum, including larger sediment fractions. The relative importance of the different activities leading to sediment dispersal, and their cumulation over an entire year was also simulated by 3D drift models of particles released by the main bottom-disturbing ships. Of direct relevance is the combined influence of extraction in the different sectors over this period. Different influence zones can be delineated following the orientation of the sandbank groups, with a predominant human-induced sediment spreading in a northeastern direction. The dataset is now analysed in view of providing meaningful data products that assist in decision making (e.g., delineating secondary impact areas around sand extraction sectors). Pilot assessments are made on the potential impact on gravel beds since persistent burial (i.e., by sandification) may lead to irreversible habitat loss.

Many challenges still exist in the assessment of changes in seafloor integrity and hydrographic conditions, the more these are often slow and low-amplitude and triggered by multiple stressors and climate change (Raicevich et al., 2024; Van Lancker et al., 2024b). In the context of rapidly changing aggregate and space demands and acknowledging that the BPNS is a relatively sediment-scarce environment, knowledge and tools are therefore needed increasingly to aid decisions on short- to medium-time frames. Sediment nature and process understanding are important to minimize impacts (i.e., preserving integrity and good ecosystem functioning), to prevent loss, and to provide the necessary reference conditions where habitats need safeguarding, and to increase the success of restoration. Long-term (investigative) monitoring strategies are therefore pivotal to inform sustainable management and exploitation practices.

4.4.2. Future outlook and innovations

Research innovations

Aligned with the cSBO VLAIO project SUSANA, the Institute of Natural Sciences is investigating the use of alternative sands in nature-based solutions (Kint & Van Lancker, 2023), and targets a first assessment of the impact of sediment dispersal on gravel beds embedded within an ecosystem services evaluation framework. Further research innovations are needed to validate the spatio-temporal scales and significance of the effects, and the way multiple stressors contribute to seabed and ecosystem change. This also assists in the choice of most appropriate mitigation measures. The TURBEAMS outcome will further elucidate how to quantify best SPMc from multi-sensor field measurements, e.g., as input to renewed sediment dispersal models.

To define new exploitation strategies under increasing sand scarcity, the Institute of Natural Sciences will investigate long-term changes in tidal sandbank dynamics (BANX project, Dutch Research Council, NWO). An innovative data-modelling framework will be developed involving the exploitation of long-term bathymetric time series (e.g., FPS Economy, Flemish Hydrography) and sand extraction data (e.g., FPS Economy). Geological data and models, as resulting from the Belspo TILES project (Van Lancker et al., 2019) will be used to generate boundary conditions. The development of morphodynamic indicators of change is targeted, investigating changes in bedform complexity.

Last but not least, the Institute of Natural Sciences further invests and innovates (e.g., video monitoring, and multi-sensor approaches) to speed up the mapping of geo- and biodiversity. Valuable habitats and sensitive species are targeted in particular, for safeguarding, and to provide the background for restoration where needed.

Geological knowledge base

Extending upon the Belspo TILES' legacy (Van Lancker et al., 2019) geological data have been further compiled and derived products were delivered to EMODnet-Geology (www.emodnet.eu). Meanwhile, via its Belgian Geological Survey, the Institute of Natural Sciences is innovating on geological data infrastructures, developed through transnational initiatives (Geological Service for Europe; https://www.geologicalservice.eu/). Geological frameworks and knowledge systems are being built, that are able to integrate hybrid models (2D/3D) and datasets, and covering land and sea. Following a feasibility assessment, the offshore datasets may be directed toward these approaches. An overview of mapping products is given at https://odnature.naturalsciences.be/seabed4u/.

Knowledge exchange at the local to global level

Acknowledging major challenges in the sustainability of long-term sand extraction, active knowledge exchange takes place at the local (Federal and Regional), European (ICES WGEXT, OSPAR, EU TG Seabed) to global level (UNEP). With the Global Sand Observatory initiative, UNEP provides the platform for active global cooperation, aligning with the agenda of the United Nations Environmental Assembly. Contributions relate to expert discussions, co-authorship of UNEP's 2022 Sand and Sustainability report (UNEP, 2022), and participation to round table debates.

4.4.3. Acknowledgements

ZAGRI, funded by revenues of the private sector, is the fundament of the monitoring activities. In the period 2020-2023 various synergies were established with this programme: (1) the Belgian assessment of Good Environmental Status (GES) for descriptors 'D1 Biodiversity - Benthic Habitats', 'D6 Seafloor Integrity' and 'D7 Hydrographical Changes' (EU Marine Strategy Framework Directive (MSFD; 2008/56/EC)); (2) MOZ4 project, financially supported by the Agency for Maritime and Coastal Services, Coastal Division (MDK) of the Flemish Authorities (contract 211.177, 219.078) (3) VLAIO cSBO SUSANA

(HBC.2022.0548); (4) Belspo RV/21/TURBEAMS. RV Belgica officers and GENAVIR team are thanked for the cooperation during acoustic data acquisition, sampling and observations. Belgian Science Policy (Belspo) and OD Nature (Institute of Natural Sciences) are acknowledged for providing ship time. The Flemish Marine Institute (VLIZ) provided the Hamon grab and video frame. Sediment analyses were done at the sedimentological laboratory of the Department of Geology (Ghent University). Bathymetric and hydro-meteorological data were acquired from 'Meetnet Vlaamse Banken' of the Agency for Maritime and Coastal Services, Coastal Division (MDK) of the Flemish Authorities. The Continental Shelf Department of FPS Economy and ILVO are thanked for active cooperation throughout the research. Via the ZAGRI programme, several RBINS teams contribute to the monitoring: Measuring Service Ostend (MSO) for sensor preparation; the Marine Chemistry Lab (ECOCHEM) for water filtration equipment, and water sample analyses; the Marine Ecology team (MARECO) for joint gravel bed sampling and observations; Marine Forecasting Centre (MFC) for sediment dispersal modelling.

4.4.4. Scientific output

In the period 2020 to 2024 the research contributed to the following scientific papers, conference contributions, and reports (alphabetical; contributors of the Institute of Natural Sciences in bold).

Papers

Kint, L., V. Hademenos, R. De Mol, J. Stafleu, S. Van Heteren and **V. Van Lancker,** 2020. Uncertainty assessment applied to marine subsurface datasets. Quarterly Journal of Engineering Geology and Hydrogeology. https://doi.org/10.1144/qjegh2020-028

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Reports

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Montereale Gavazzi G., Degraer, S. & Van Lancker, V., 2023b. Chapter 1. Predictive modelling of seafloor surficial gravel distribution within the Princess Elisabeth offshore wind farm zone, Belgium), pp. 27-63. In: Degraer et al. (eds), 2023. EDEN 2000. Exploring options for a nature-proof development of offshore wind farms inside a Natura 2000 area. Memoirs on the Marine Environment. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management. https://www.health.belgium.be/nl/eden2000-studies

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Van Lancker, V., M. Baeye, F. Francken, L. Kint, G. Montereale Gavazzi, N. Terseleer and D. Van den Eynde, 2021. Effects of marine aggregate extraction on seafloor integrity and hydrographical conditions. New insights and developments. In: Degrendele & Vandenreyken (eds.). Proceedings Study Day Sea sand in a 360° perspective. Zwin Natuur Park – Knokke, 19/11/2021, 43-56.

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Mapping products

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Maps are integrated in European data products that are available via the European Marine Data and Observation Network (EMODnet, www.emodnet.eu.). An overview of mapping products is also given at the Seabed4U platform: https://odnature.naturalsciences.be/seabed4u/ Links are provided to available datasets, and sub(surface) models.

4.4.5. Other references

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4. Conclusions and future actions

In Belgium, the impact of sand extraction on the marine environment is monitored collaboratively by the Continental Shelf Service of the FPS Economy, the Institute of Natural Sciences, and the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO). Each of these organizations has contributed separately to this report, highlighting key findings and developments from the past three years based on their respective areas of expertise. This conclusion provides an integrated overview of the main achievements and insights gained over this period related to the management and monitoring of sand extraction activities in the Belgian part of the North Sea.

Two new management measures came into force that further improved the management and sustainability of sand extraction activities. A first measure is the application of strict extraction quota for the industry (i.e. a total of 3 million m^3 per year instead of the previous maximum of 15 million m^3 over a period of 5 years). Secondly, a new vertical reference level for sand extraction was implemented to ensure that extraction levels remain within sustainable limits.

Furthermore, a number of technological and methodological innovations took place, optimizing monitoring capabilities and aiding management decisions. The following innovations can be highlighted:

- The adoption of new backscatter processing techniques, which enhanced time series analysis, allowing for better monitoring of seabed conditions over time.
- The improvement of the monitoring of sand extraction activities with new near real-time control systems for the declaration of activities, AIS and EMS.
- The advances made regarding the real-time monitoring of sediment plumes using a multi-sensor approach, combined with modelling.
- The integration of DNA-based methods into ecological monitoring, providing more detailed insights into the health of marine ecosystems.
- The incorporation of functional information in the ecological analyses, increasing our understanding on how sand extraction affects ecosystem functioning.
- The development of new seabed substrate maps to better assess seabed changes; these were used to adapt monitoring designs for far-field impact estimation.
- The development of a more systematic approach to assess cumulative impacts by analysing 1-year of results of sediment dispersal modelling of the main bottom-disturbing activities.

These advancements, along with the available data from longer-term monitoring, have led to increased knowledge on how extraction activities affect the marine environment. Clearly, sand extraction leads to a physical disturbance of the seabed with direct physical loss being prevented by imposing extraction limits. It was shown that the seabed nature and processes are driven primarily by the geology and the sandbanks' geomorphology which are important drivers in impact assessments. We found that sand extraction has complex ecological effects, influencing various components of the ecosystem through both direct and indirect pathways. The overall ecological impact is reflected in shifts in species composition across multiple biological groups (bacteria, macrobenthos, epibenthos, and demersal fish), which can alter functional diversity, functional traits, and potentially affect ecosystem processes. These shifts are primarily driven by high intensity sand extraction activities, which modify seabed morphology and sediment composition, increase sediment heterogeneity, and often lead to the accumulation of organic material (OM). After the cessation of extraction, gradual recovery processes begin to take place. While sandbank depressions caused by dredging activities persist, clear evidence shows that sediments within these depressions start to resemble reference conditions after 4 to 8 years, with partial recovery of sand waves as well. These morpho-sedimentary recovery processes are a key driver of changes in the benthic community, beginning with the colonization of opportunistic species shortly after extraction ends and stabilizing after 4 to 8 years, ultimately resulting in a community structure similar to the reference conditions. Regeneration does vary spatially, likely related to differences in water depth and local sediment availability. The mechanism is mostly the result of a local redistribution of sand.

Building on the new insights and methodological advancements from the past three years, several strategic actions are being considered to further enhance the monitoring and management of sand extraction in the coming period. These actions emphasise the need for a stable and well-equipped monitoring infrastructure -such as the research vessel Belgica- to support long-term data collection and foster innovation in monitoring technologies.

A key priority is to establish a more integrated monitoring strategy, ensuring that data collection efforts are even better coordinated across the institutes, both spatially and temporally. This approach will incorporate multiple monitoring techniques, such as multibeam echo sounders (MBES), different ground-truthing and imaging methods (both water and seabed-related) and hydrodynamic measurements, to generate comprehensive datasets. The strategy will also be adaptive, targeting areas with high extraction activities indicated by AIS- and EMS data, but also steered towards areas where far-field impacts are expected, as predicted by models.

Building and maintaining time series is essential, especially to increase our understanding of the recovery dynamics of ecosystems affected by sand extraction. The use of innovative technologies will be expanded, with planned enhancements to MBES for improved data resolution, calibration, and quality in bathymetry, backscatter, and water column measurements. Additional methods such as environmental DNA (eDNA) sampling, techniques to measure functional processes, visual inspections via video, and ground-truthing techniques will further enhance the accuracy and reliability of collected data.

A focus area in particular is the development of real-time sediment plume models and improved measurement techniques for monitoring plume dynamics. These efforts will aid in validating both the cumulative and indirect impacts of sand extraction on marine environments, as well as providing data to further constrain the relative contribution of sand extraction to sediment plume formation, compared to other marine activities. Additional to the particle drift model that is applied now, also a process-based three-dimensional morphodynamic approach will be used, based on the COHERENS model suite. This will allow differentiating better between human activities and evaluating their relative importance. Further development of this model will increase the accuracy and the reliability of the model results, which is an important aspect in the validation process.

Ultimately, these actions will be framed within an ecosystem-based approach to ensure that the full spectrum of environmental impacts is considered and managed in a sustainable manner.