Marine sedimentary habitats seminar for European Atlantic Biogeographic region

(North Sea, Celtic Sea, South European Atlantic Shelf)

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The underlined names in the various articles correspond to the speakers.

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We also warmly thank all the speakers who shared their research, experiences, and insights. Their contributions were invaluable and greatly enriched the discussions on marine sedimentary habitats and their conservation. Beyond the presentations, the many thoughtful questions and discussions from participants helped deepen the debate, challenge perspectives, and open new avenues for reflection.

Thanks to you, this conference became a true platform for exchange and debate, an essential step in advancing the management and protection of these ecosystems.

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Nous remercions également chaleureusement tous les intervenants qui ont partagé leurs recherches et leurs expériences. Leurs contributions ont été précieuses et ont largement enrichi les échanges autour des habitats sédimentaires et de leur préservation. Au-delà des présentations, les nombreuses questions et discussions des participants ont permis d'approfondir les débats, de confronter les perspectives et d'ouvrir de nouvelles pistes de réflexion.

Grâce à vous, cette conférence est devenue une véritable plateforme d'échange et de débat, une étape essentielle pour faire progresser la gestion et la protection de ces écosystèmes.

CONTENT

INTRODUCTION

Marine sedimentary habitats encompass a wide range of substrates, including sand, mud, gravel, and shell beds, and are found – in Europe - across the north-western continental shelf of the Atlantic, the English Channel, and the North Sea. They play a vital role in carbon sequestration, acting as natural carbon sinks, and contributing to the stabilisation of the seafloor, which helps prevent erosion and sediment movement. They are also critical for the life cycles of many commercially and ecologically important species, such as fish, shellfish, and benthic organisms. These habitats provide essential feeding, breeding, and nursery grounds, as well as a substrate for key biogeochemical processes that maintain ocean health. However, they are subject to significant pressures, including overfishing, habitat degradation, climate change, and pollution, yet they are often overlooked in marine management strategies and regulatory frameworks. **Despite their importance, they are often undervalued in comparison to more visible or well-studied habitats like coral reefs or seagrass meadows.**

The Life Marha Conference on March 12 and 13, 2025

Given these multiple ecosystem services, there is a **growing need to better understand, protect, and manage these habitats**. To address this need, the Life Marha project organised its last conference on the sedimentary marine habitats of the mid-, infra-, and circalittoral zones with a geographical focus on the continental slope in the European Atlantic biogeographical region, encompassing the North Sea, Celtic Sea, and South European Atlantic shelf.

The LIFE Marha project, led by the French Biodiversity Office (OFB), has played a key role in advancing scientific knowledge and promoting the sustainable management of marine habitats across Europe

Les habitats marins sédimentaires regroupent une grande diversité de substrats, dont les sables, vases, graviers et lits de coquilles, et se répartissent – en Europe – sur tout le plateau continental nord-ouest de l'Atlantique, la Manche et la mer du Nord. Ils jouent un rôle essentiel dans la séquestration du carbone, agissant comme des puits naturels, et contribuent à la stabilisation des fonds marins, aidant à prévenir l'érosion et le déplacement des sédiments. Ces habitats sont aussi cruciaux pour le cycle de vie de nombreuses espèces d'importance commerciale ou écologique, comme les poissons, les coquillages et les organismes benthiques. Ils offrent des zones essentielles d'alimentation, de reproduction et de nurserie, et constituent un support pour des processus biogéochimiques clés qui assurent la bonne santé des océans. Cependant, ces habitats subissent de fortes pressions : surpêche, dégradation, changement climatique, pollution... et restent pourtant souvent négligés dans les stratégies de gestion et les cadres réglementaires. **Malgré leur importance, ils sont régulièrement sous-évalués par rapport à des habitats plus visibles ou mieux connus, comme les récifs coralliens ou les herbiers de posidonie.**

La conférence LIFE Marha – 12 et 13 mars 2025

Compte tenu de ces nombreux services écosystémiques, **il est aujourd'hui nécessaire de mieux comprendre, protéger et gérer ces habitats.** Pour répondre à ce besoin, le projet LIFE Marha a organisé son dernier événement consacré aux habitats marins sédimentaires des zones médio-, infra- et circalittorales, avec un focus géographique sur le talus continental de la région biogéographique atlantique européenne, englobant la mer du Nord, la mer Celtique et le plateau atlantique sud-européen.

Porté par l'Office français de la biodiversité (OFB), le projet LIFE Marha a joué un rôle majeur dans l'avancement des connaissances scientifiques et dans la promotion d'une gestion durable des habitats marins en Europe.

It has successfully organised several events aiming to better understand marine habitats, from the Posidonia seagrass beds, the Atlantic infralittoral and mid-littoral rocks, to the deep habitats in the Western Mediterranean. **The conference organised from 12 to 13 March 2025 aimed to bring together scientists, national authorities, and marine protected area managers to exchange knowledge on the state, monitoring, and management experiences of marine sedimentary – or "soft-bottom" - habitats**.

The proceedings of this conference will support the sharing of the latest research and initiatives, discussing effective management strategies, and fostering a collaborative approach to ensuring the sustainability of sedimentary habitats. By highlighting the importance of these often-underappreciated environments, the conference aimed to emphasize their role in maintaining marine biodiversity, supporting fisheries, and contributing to global climate regulation.

Through this document gathering the exchange of experiences and insights, the Life Marha project hopes to pave the way for more informed decision-making and better protection of these invaluable marine ecosystems.

All presentations are available on the LIFE Marha website on this link (until 2030).

Il a permis d'organiser plusieurs événements pour améliorer la compréhension des habitats marins : des herbiers de posidonie aux habitats profonds de Méditerranée occidentale, en passant par les zones rocheuses médio- et infralittorales de l'Atlantique. **La conférence des 12 et 13 mars 2025 visait à rassembler scientifiques, autorités nationales et gestionnaires d'aires marines protégées afin d'échanger autour de l'état de ces habitats, de leur suivi et des retours d'expérience en matière de gestion.**

Les travaux issus de cette conférence ont vocation à partager les connaissances les plus récentes, à débattre des stratégies de gestion efficaces et à encourager une approche collaborative en faveur de la durabilité de ces habitats sédimentaires. En soulignant l'importance de ces milieux souvent oubliés, la conférence a souhaité rappeler leur rôle dans le maintien de la biodiversité marine, le soutien aux pêcheries et la régulation climatique à l'échelle mondiale.

À travers ce document rassemblant les retours d'expériences et réflexions partagées, le projet LIFE Marha espère ouvrir la voie à une prise de décision plus éclairée et à une meilleure protection de ces écosystèmes marins inestimables.

Les présentations sont disponibles sur le site du LIFE Marha sur ce lien (jusqu'en 2030).

Photo: Charlotte Genest / French Biodiversity Office (FR)

Photo: Aurélie Dessier / French Biodiversity Office (FR)

SESSION 1 – IMPROVING KNOWLEDGE OF SEDIMENTARY ECOSYSTEMS: HABITATS AND ASSOCIATED BENTHIC COMMUNITIES

AMÉLIORER LA CONNAISSANCE DES ÉCOSYSTÈMES SÉDIMENTAIRES: HABITATS ET COMMUNAUTÉS BENTHIQUES ASSOCIÉES

Session moderator – *Animateur de session*: **Nicolas Desroy**, French Research Institute for Exploitation of the Sea, (IFREMER), France

Access the presentations from this session here – *Accédez aux présentations de cette session ici*.

Understanding and preserving sedimentary habitats and their associated benthic communities, is crucial for sustainable marine management. This session brings together four complementary studies that contribute to improving our knowledge of these dynamic environments (species and functional diversity to habitat structuring, carbon cycling, and population dynamics).

The first presentation by **Robin Van Paemelen** (Univ. Caen, France) explores the structure and functioning of benthic communities in coarse substrates of the English Channel. Given the increasing anthropogenic pressures in this region—including aggregate extraction, bottom-contact fishing, and offshore wind farm developments—this study employs both taxonomic (BTA) and functional diversity approaches to assess ecosystem resilience. By

La compréhension et la préservation des habitats sédimentaires et des communautés benthiques associées sont cruciales pour une gestion durable du milieu marin. Cette session rassemble quatre études complémentaires qui améliorent notre connaissance de ces environnements dynamiques (diversité des espèces et des fonctions, structuration de l'habitat, cycle du carbone et dynamique des populations).

La première présentation de **Robin Van Paemelen** (Univ. Caen, France) explore la structure et le fonctionnement des communautés benthiques dans les substrats grossiers de la Manche. Compte tenu des pressions anthropiques croissantes dans cette région - notamment l'extraction d'agrégats, la pêche au chalut et le développement de parcs éoliens - cette étude utilise des approches de examining seasonal and spatial variability, it highlights the role of sediment as an environmental filter and the importance of functional redundancy in maintaining ecosystem stability.

Nathan Chauvel's (Univ. Caen, France) study further investigates the role of sediment characteristics in shaping benthic communities, focusing on the Dieppe-Le Tréport offshore wind farm site. Using bathymetric data, grain size analysis, and trophic group assessments, this research emphasizes how sediment morphology, particularly submarine dunes, influences benthic biodiversity. The study reveals the presence of habitat mosaics and raises important questions about how wind turbine installation may alter these sedimentary structures and their associated communities.

Moving beyond habitat structuring, **Kentin Plègue's** (Univ. Lille, France) research shifts the focus to biogeochemical cycles, specifically carbon fluxes in the intertidal estuaries of the Eastern Channel. This study highlights the complex interplay between biological, physical, and chemical processes in estuarine sediments, with an emphasis on blue carbon sequestration. The findings underscore the need for long-term monitoring to fully capture seasonal variations and better quantify total carbon budgets in these critical transition zones.

Finally, **Johan Craeymeersch** (Univ Wageningen, the Netherlands) presents an analysis of population dynamics of the American razor clam (*Ensis leei*) in Dutch coastal waters. Using long-term survey data, this study examines the influence of environmental factors, climate change, and human activities such as fisheries and sand extraction on shellfish populations. The research highlights the importance of considering all life stages in population assessments and provides insights into how habitat characteristics and anthropogenic pressures drive species distributions and abundance.

Together, these studies provide valuable insights into the mechanisms that shape sedimentary ecosystems. By integrating biodiversity assessments, habitat structuring, carbon flux

diversité taxonomique (BTA) et fonctionnelle pour évaluer la résilience de l'écosystème. En examinant la variabilité saisonnière et spatiale, elle souligne le rôle des sédiments comme filtre environnemental et l'importance de la redondance fonctionnelle dans le maintien de la stabilité de l'écosystème.

L'étude de **Nathan Chauvel** (Univ. Caen, France) porte sur le rôle des caractéristiques des sédiments dans la formation des communautés benthiques, en se concentrant sur le site du parc éolien de Dieppe-Le Tréport. À l'aide de données bathymétriques, d'analyses granulométriques et d'évaluations des groupes trophiques, cette recherche souligne l'influence de la morphologie des sédiments, notamment des dunes sous-marines, sur la biodiversité benthique. L'étude révèle la présence de mosaïques d'habitats et soulève des questions importantes sur la façon dont l'installation d'éoliennes peut modifier ces structures sédimentaires et les communautés qui y sont associées.

Au-delà de la structuration des habitats, les recherches de **Kentin Plègue** (Univ. Lille, France) se concentrent sur les cycles biogéochimiques, en particulier les flux de carbone dans les estuaires intertidaux de la Manche orientale. Cette étude met en évidence l'interaction complexe entre les processus biologiques, physiques et chimiques dans les sédiments estuariens, en mettant l'accent sur la séquestration du carbone bleu. Les résultats soulignent le besoin d'une surveillance à long terme pour saisir pleinement les variations saisonnières et mieux quantifier les bilans totaux de carbone dans ces zones de transition critiques.

Enfin, **Johan Craeymeersch** (Univ. Wageningen, Pays-Bas) présente une analyse de la dynamique des populations de couteaux (*Ensis leei*) dans les eaux côtières néerlandaises. À partir des données d'enquête à long terme, cette étude examine l'influence des facteurs environnementaux, du changement climatique et des activités telles que la pêche et l'extraction de sable sur les populations de mollusques et de crustacés. Ses recherches soulignent l'importance de prendre en compte tous les stades de vie dans les évaluations des analyses, and population dynamics, this session contributes to a more comprehensive understanding of how sedimentary habitats function and respond to environmental changes. Such knowledge is essential for developing effective conservation strategies and ensuring the resilience of benthic ecosystems in the face of ongoing human and climate-related pressures.

populations et donne un aperçu de la façon dont les caractéristiques de l'habitat et les pressions anthropiques déterminent la distribution et l'abondance des espèces.

Ensemble, ces études fournissent des informations précieuses sur les mécanismes qui façonnent les habitats sédimentaires. En intégrant les évaluations de la biodiversité, la structuration de l'habitat, les analyses des flux de carbone et la dynamique des populations, cette session contribue à une compréhension plus complète du fonctionnement de ces habitats et de leur réaction aux changements environnementaux. Ces connaissances sont essentielles pour développer des stratégies de conservation efficaces et assurer la résilience des écosystèmes benthiques face aux pressions humaines et climatiques actuelles.

Structure and functioning of benthic communities in coarse substrates of the English Channel. A case study of the future offshore wind farm “Centre Manche 1 & 2” off the Bay of Seine

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1. Introduction

The English Channel (EC) is a shallow epicontinental sea extending approximately 700 km along a northeast-southwest axis, separating the United Kingdom from France (Larsonneur et al. 1982). Its morphological characteristics, combined with strong tidal currents, have led to the widespread accumulation of coarse sediments, which cover more than 80% of its seafloor (Dauvin 2015). These habitats are subject to significant anthropogenic pressures, including aggregate extraction and bottom-contact fishing. More recently, the development of marine renewable energy has further intensified human activities, making the English Channel one of the most anthropogenically impacted seas in the world (Halpern et al. 2008). Although these habitats are generally considered resilient, a deeper understanding of benthic communities associated with coarse substrates is essential for developing effective management and conservation strategies.

Traditionally, these habitats have been described using taxonomic approaches, which, although informative, do not fully capture the complexity of ecosystem functioning. In contrast, the functional diversity approach complements structural descriptions by focusing on the ecological roles of species. Biological Trait Analysis (BTA) is a powerful tool for characterizing ecosystem functioning, as it integrates species’ morpho-anatomical, behavioral, and life-history traits. By quantifying functional diversity and examining trait-based community composition, this approach provides insights into ecosystem resilience and resistance to environmental change through functional redundancy.

This study aims to describe the seasonal and inter-habitat variability of benthic communities and to explore how functional diversity analysis can enhance traditional structural assessments. At the local scale, variations in species diversity (i.e., species richness, Shannon index, and Pielou’s evenness) will be compared with changes in functional diversity (i.e., functional richness, functional divergence, and functional evenness). At a broader spatiotemporal scale, shifts in community structure will be analyzed in relation to both species and trait composition. Evaluating functional diversity and redundancy will offer valuable insights into the resilience and stability of benthic communities in response to environmental and anthropogenic pressures.

2. Methodology

2.1. Sampling and sample processing

As part of the baseline assessment of benthic communities at the sites of the future offshore wind farms "Centre Manche 1 & 2", a sampling program was conducted between October 2022 and February 2024. Four sampling campaigns were conducted at the end of the summer 2022 and 2023 and at the end of the winter 2023 and 2024. During each campaign, 35 stations were sampled using a Rallier du Baty dredge. For each station, 30 liters of sediment were retained for benthic fauna analysis, and approximately 1 liter was collected for granulometric and organic matter analyses. Biological samples were sieved to retain all attached fauna as well as macrobenthic invertebrates larger than 1 mm, then preserved in a buffered 10% formaldehyde solution.

In the laboratory, faunal samples were sorted and identified to the highest possible taxonomic resolution. Species were counted and expressed as the number of individuals per 30 liters of sediment (ind.$30L^{-1}$). Individual biomass estimates for each species were obtained using the Loss-On-Ignition (LOI) method and are expressed in grams of ash-free dry weight (gAFDW). Granulometric analyses were conducted at each station using a 33-sieve column, for detailed characterization of grain size distribution. Additionally, the organic matter content in the sediments was quantified using the Loss-On-Ignition method.

2.2. Structural analysis

At each station, species richness (S), abundance, biomass, and the Pielou's evenness (J) and Shannon diversity (H') indices were calculated. Differences between parameters were tested according to season and year using paired t-tests, while differences between sediment types were assessed using an independent Student's t-test. Hierarchical Ascending Clustering (HAC) were performed separately on granulometric and faunal datasets for each campaign using R software. Sedimentary variables were standardized, and biological data were log(x+1) transformed to reduce the influence of dominant species. Distance matrices were then computed using the Manhattan distance for sedimentary data and the Bray-Curtis dissimilarity for faunal data. A square-root transformation was applied before performing Ward's clustering method to ensure Euclidean properties. A SIMPER analysis was performed on the HAC of granulometric data to identify which variables contributed the most to differences between groups. The characteristic species of faunal groups were identified using the IndVal index (Dufrêne and Legendre 1997), which accounts for both the fidelity and specificity of a species to its group. Finally, RV coefficients, a multivariate generalization of the squared Pearson correlation coefficient, were computed to assess the relationship between sedimentary and faunal matrices.

2.3. Biological traits analysis (BTA)

2.3.1. Biological traits matrix

To carry out functional diversity analysis, eight biological traits, subdivided into 36 modalities, were selected to describe the life cycle as well as the morphological and behavioral characteristics of the taxa. The selected traits are as follows: mobility, maximum length, feeding mode, lifespan, living habit, sediment position, larval development location and egg development location.

No universally recognized method exists for selecting biological traits (Marchini et al. 2008). However, a consensus has emerged that trait selection and their associated modalities should be guided by their relevance to the study objectives and the independence of their expressions (Beauchard et al. 2017). Furthermore, although research on functional diversity through trait-based analysis is rapidly expanding, data on species' biological traits remain limited for many taxonomic groups, restricting the accessibility of information (Bolam et al. 2014). In this study, which aims to assess the baseline state of benthic communities at the site of a future offshore wind farm, we focused our analysis on response traits, which determine how organisms respond to a disturbance or change in the environment (Hooper et al. 2005).

Information on the biological traits of taxa was collected from various sources, including published journal articles and books, pre-existing databases (Clare et al. 2022; Garcia 2010) and websites of scientific institutions (e.g., http://marlin.ac.uk/biotic/). However, for certain species where data were missing from these sources, particularly for less-documented traits such as lifespan, the trait matrix was supplemented through expert knowledge, from specialized taxonomists. To account for intraspecific variability in trait expression due to specific environmental conditions and resource availability, each taxon was evaluated using a "fuzzy coding" approach (Chevenet et al. 1994), assigning a score between 0 and 3 to each modality, depending on the affinity of that taxon for that modality (0 conveys no affinity, 3 indicates total and exclusive affinity). Finally, the fuzzy-coded trait matrix will be combined with the taxon biomass matrix per station to generate the final station-trait matrix, which will be used for functional diversity analyses.

2.3.2. Functional diversity

Functional diversity indices quantify the functional space occupied by a biological community and describe how this space is structured (Schleuter et al. 2010). Three complementary indices are used to assess different facets of functional diversity: functional richness (FRic), functional evenness (FEve), and functional divergence (FDiv) (Villéger et al. 2008). FRic represents the total range of functional traits within a community, illustrating its functional breadth. FEve measures the evenness of species distribution within the functional space, reflecting the homogeneity of functional contributions within the assemblage. FDiv assesses the dispersion of traits around the functional centroid, indicating the degree of functional specialization among species. These indices were computed in R using the station-trait matrix with the FD package (Laliberté and Legendre 2010). Similarly to taxonomic diversity indices, these three functional diversity indices were compared across seasons and sampling years using paired t-tests, and across sediment types using independent Student's t-tests.

3. Results & discussion

3.1. Sediment distribution

Hierarchical Ascending Clustering (HAC) of granulometric data from the four sampling campaigns identified two distinct sedimentary facies at the Centre Manche site (**Figure 1**). SIMPER analysis revealed that the stations in the northwest were characterized by high gravel content and the presence of pebbles, whereas those in the southeast exhibited higher proportions of sand and silt, distinguishing gravel stations from sand-covered gravel stations. A transition zone, referred to as "mixed gravels," included stations that displayed a gravel facies 50% of the time and a sandy gravel facies 50% of the time over the sampling period. A southeast-to-northwest granulometric gradient was observed, potentially linked to increasing depth and proximity to the channel, where currents are stronger.

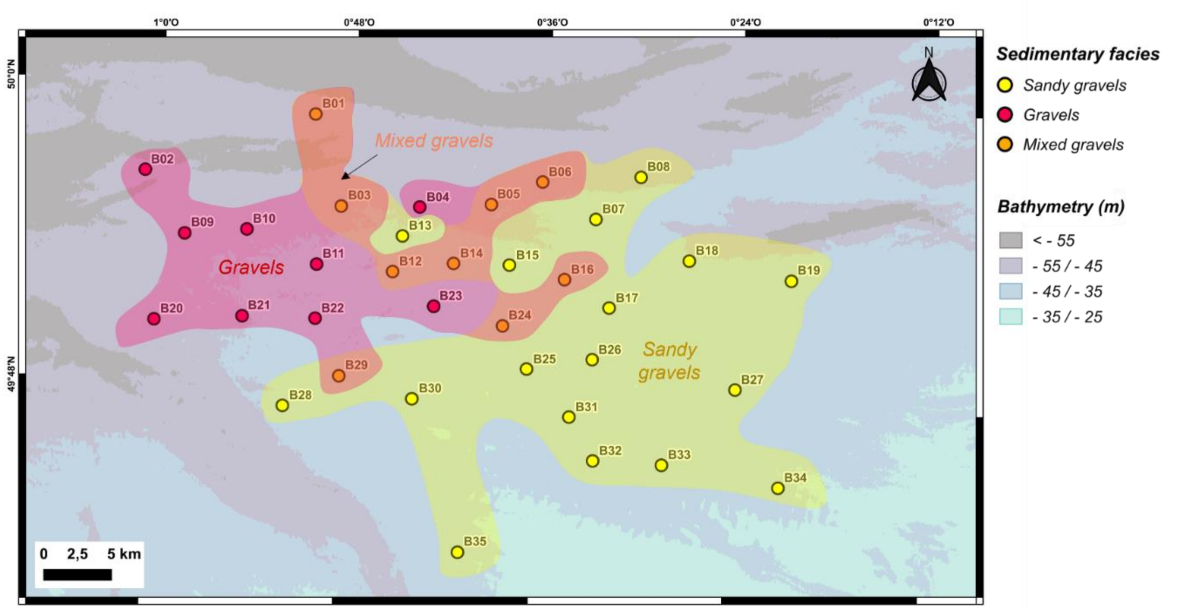

Figure 1 : Spatial distribution of sedimentary facies from HAC analyses at the Centre Manche 1 & 2 sites

3.2. Structural and functional analysis

A total of 247,618 individuals belonging to 392 species were identified. In addition, 36 non-quantifiable species were recorded but not included in the analyses, as individual counts were not feasible, primarily due to their colonial lifestyle (e.g., species from the phyla Bryozoa, Cnidaria, and Porifera). Hierarchical Ascending Clusterings (HAC) analyses performed on faunal matrices identified two distinct faunal groups. IndVal analyses were used to determine the characteristic species of each group. Between 24 and 75 characteristic species were identified for Group 1, which was associated with coarse to very coarse substrates, including the dominant species Ophiothrix fragilis, as well as Pilumnus hirtellus, Buccinum undatum, and Sabellaria spinulosa (Dauvin 1997). The second group had fewer characteristic species (4 to 11), primarily associated with sandy substrates, such as Branchiostoma lanceolatum, Laevicardium crassum, Ophiura albida, and the decapod Upogebia deltaura (Dauvin 1997).

The RV coefficients calculated between granulometric and faunal matrices were all significant, ranging from 0.34 in the first campaign to 0.43 in the last, indicating a moderate but significant correlation between granulometric and faunal structure. These results suggest that sediment type may play a structuring role in the organization of associated benthic communities.

The **Table 1** presents the mean values of structural and functional diversity indices according to sediment structure, season, and sampling year. A strong seasonal effect is evident in both structural and functional diversity indices, with mean species richness, abundance, biomass, and functional richness being significantly higher in autumn than in winter. In contrast, Pielou's evenness and functional evenness indices are higher in winter, likely due to higher recruitment success in autumn, followed by community homogenization caused by the decline of dominant species in winter. A significant interannual effect is also detected, with species richness and Shannon, Pielou, functional richness, and functional evenness indices being significantly higher in the second sampling year. This increase suggests more favorable environmental conditions for the development of benthic communities, potentially linked to a lower intensity of disturbances (e.g., fishing, extreme events), thus favoring higher recruitment success.

Sediment type mainly influences species richness and abundance, both of which are significantly greater in gravel than in sand-covered gravel. However, no significant effect is observed on functional diversity, suggesting that, despite taxonomic differences between facies, communities perform redundant ecological roles, maintaining functional stability. Finally, the functional divergence index (FDiv) remains high and stable, regardless of season, year, or sediment type. This suggests that benthic communities are structured into well-defined functional groups, adapted to the strong environmental constraints of their habitat.

Table 1: Structural and functional diversity indices (mean ± SD) by year, season, and sediment type. Significant values (p < 0.05) highlighted in yellow.

		Species richness	Abundances	Biomass	Shannon index	Pielou index	FRic	FEve	FDiv
Sediment types	Gravels	100 ± *26*	2027 ± *1159*	36,35 ± *28,57*	4,96 ± *0,57*	0,75 ± *0,08*	12,07 ± *1,31*	0,40 ± *0,06*	0,92 ± *0,05*
	Sandy gravels	89 ± *25*	1589 ± *1128*	29,54 ± *23,85*	5,01 ± *0,68*	0,78 ± *0,11*	11,84 ± *1,65*	0,42 ± *0,06*	0,90 ± *0,06*
Season	Autumn	97 ± *26*	2086 ± *1179*	41,53 ± *31,21*	5,02 ± *0,76*	0,77 ± *0,07*	12,18 ± *1,36*	0,40 ± *0,05*	0,91 ± *0,06*
	Winter	90 ± *25*	1449 ± *1049*	23,01 ± *14,64*	4,96 ± *0,76*	0,77 ± *0,12*	11,58 ± *1,60*	0,43 ± *0,06*	0,92 ± *0,05*
Year	2022-2023	85 ± *21*	1734 ± *1174*	32,09 ± *23,96*	4,79 ± *0,60*	0,76 ± *0,10*	11,62 ± *1,18*	0,40 ± *0,07*	0,91 ± *0,06*
	2023-2024	102 ± *27*	1800 ± *1147*	32,53 ± *28,05*	5,19 ± *0,61*	0,78 ± *0,10*	12,25 ± *1,51*	0,42 ± *0,05*	0,92 ± *0,05*

4. Conclusion

At the Centre Manche 1 & 2 future offshore wind farm site, two main sedimentary facies were identified: gravel habitats in the northwest and sand-covered gravel habitats in the southeast, forming a granulometric gradient with increasing depth. These habitats exhibit high temporal variability, particularly due to the migration of sandbanks along this gradient.

Sediment type plays a structuring role by acting as an environmental filter, leading to benthic communities that share a common species pool but also include habitat-specific characteristic species. A marked spatiotemporal variability was also observed, with seasonal and interannual effects on the structural and functional diversity of communities.

However, functional diversity does not appear to be influenced by sediment type, suggesting that, despite taxonomic differences, species perform redundant ecological functions. This functional homogeneity is confirmed by the stability of the Functional Divergence Index (FDiv), indicating the presence of specialized yet functionally equivalent communities, regardless of substrate type, season, or year. This stable functional organization suggests high resilience of benthic communities in coarse habitats, ensuring the maintenance of ecosystem processes despite natural environmental variations.

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Q&A

On the need for reference sites: have you compared your results to reference sites with no anthropogenic pressure?

- The results are recent, and unfortunately, there are no sites without pressure in the English Channel. The data used will serve as a baseline for future comparisons once the offshore wind farm is installed.

On seabed morphology data: do you have seabed morphology data to help explain your findings?

- Granulometric data is available but not 3D bathymetric data. It might be acquired in the future when the offshore wind farms are set up.

On analysis resolution (1mm vs. 2mm):

- Both were used. Historical samples were taken with a 2mm sieve, so consistency was maintained. The finer resolution (1mm) revealed many additional species, proving its added value.

On distinguishing anthropogenic pressures from natural variability:

- It's a complex question. Many interacting factors influence the results, and fisheries seem to have a significant negative impact on recruitment. Large-scale experimental work would be needed to disentangle human and environmental drivers, but it's not easy. In very dynamic coastal areas, fisheries can alter a site in a single day.

Influence of sediment grain size and morphology on the benthic community (Dieppe-Le Tréport offshore wind farm, France)

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Abstract: submarine dunes form a unique landscape shaped by local hydrodynamic and sedimentary conditions, creating a distinctive habitat with notable spatial and temporal variability. Despite the unique features of these habitats, few studies have examined the impact of these bedforms on sediment composition and benthic community structure. This study uses bathymetric data, grain size analysis, and benthic macrofauna assessments to investigate habitat structuring at the planned offshore wind farm site of Dieppe-Le Tréport. The influence of sedimentary characteristics—including grain size and dune morphology—on benthic community structure was evaluated through multivariate and trophic group analyses. The results revealed a habitat mosaic within the dune system. Troughs and adjacent no-dune areas are characterized by coarser substrates that support a diversified community dominated by deposit feeders and filter feeders. In contrast, the stoss and lee sides of the dunes host a less diverse community, which is primarily composed of scavengers and predators such as *Nephtys cirrosa*. Several mechanisms, including sediment transport, hydrodynamics, and trophic interactions, have been proposed to explain the structuring of this community. These findings provide valuable insights into the potential evolution of this site following wind turbine installation. A critical question is whether the observed diversity hotspots within the inter-dune troughs will persist, despite possible morphological changes to the dune landscape.

Keywords: Benthic diversity, Grain size gradients, Morphological gradients, Dune morphodynamics, Sediment movements, Trophic interactions.

1. Introduction

Benthic community distribution in the English Channel has been extensively studied since the mid-20th century (Dauvin, 2015), revealing the key environmental drivers which structure them. Among them, sediment properties play a major role, explaining at least 20% of community variability in the eastern Channel (Chauvel et al., 2024a). However, sediment characteristics are often examined solely through their grain size properties, overlooking broader sedimentary complexities such as composition (bioclastic vs. lithoclastic), stratification, organic content, and bedform influence (Snelgrove and Butman, 1994).

Bedforms encompass sedimentary patterns formed at various spatial and temporal scales, often with nested structures. At smaller scales, sand ripples (a few centimeters in size) form transversely to dominant currents and can be reworked within a tidal cycle. At the meter scale, transverse subaqueous dunes can be observed, whereas at the kilometer scale, sandbanks (or tidal banks) typically exceeding ten meters in height align parallel to dominant currents.

A limited number of studies have explored the influence of these bedforms on benthic community structure, with findings suggesting that the effects depend on the specific sedimentary features considered. However, bedform surfaces are often described as unfavorable for the development of a diversified benthic community, in contrast to the depressions or troughs between these features, which may support greater diversity depending on bedform morphology and sediment transport dynamics (Ellis et al., 2011; Van Lancker, 2017).

As part of the development of the Dieppe-Le Tréport offshore wind farm in the eastern English Channel, sediment samples, benthic community surveys, and bathymetric measurements were conducted off the French Picardy coast. This site is characterized by subaqueous dunes exhibiting morphological evolution across the area (according four sectors), coupled with a decreasing grain size gradient from west to east (Figure 1). These datasets provide an opportunity to investigate how dunes and sediment grain size properties can shape benthic community structures in such environments.

2. Material & methods

2.1. Sampling and data collection

Grain size and benthic fauna data were collected during Jean-Philippe Pezy (2017) PhD. Four sampling campaigns (two in summer and two in winter) were conducted between 2014 and 2016, with 25 stations (Figure 1) sampled with a van Veen grab (0.1 m²). At each station, five replicates were taken to analyze the benthic community (>1 mm), and one additional replicate was collected to assess sediment grain size. Bathymetric data were acquired with a multibeam echosounder during various campaigns in 2011, 2014, 2015, 2016, and 2018.

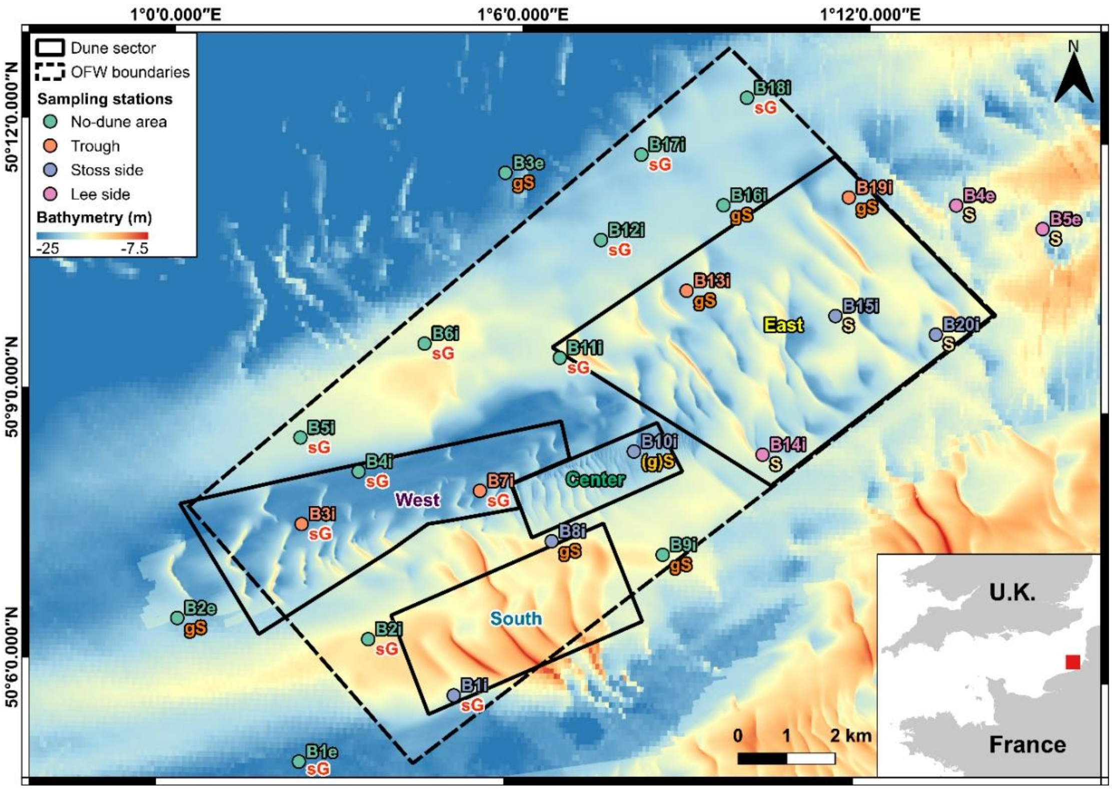

*Figure 2 : Sampling station location map on the planned offshore wind farm of the Dieppe-Le Tréport site. Each point is labeled with a station name (upper labels) and a sedimentary facies classified according to **Folk (1954, lower labels)**. sG, sandy gravel; gS, gravelly sand; (g)S, slightly gravelly sand and S, sand. The position of each station on the nearest dune (trough, stoss or lee side) is indicated by the color of the point and the station label.*

2.2. Data treatment & statistical analyses

Biotic indices—including total abundance, taxonomic richness, Shannon diversity, and Pielou evenness—were derived from macrofauna data. The benthic organisms were also categorized into six trophic groups, as reported in **Chauvel et al. (2024b)**. The sediment properties (mud, sand, gravel percentages and mean grain size) were calculated. Bathymetric data were used to determine various morphological features of the bedforms (*e.g.*, height, width, surface area, and shape) and their dynamics (*e.g.*, migration rates and sediment flux). The influence of sediment grain size and bedforms on biotic indices was analyzed considering three factors: (1) the sediment type, which was determined on the basis of the **Folk (1954)** classification; (2) the station's relative position on the dune (no-dune area, trough, stoss or lee side); and (3) the grouping of stations into sectors with homogeneous dune characteristics (Figure 2). Similar analyses were performed for the different trophic groups. The influence of sediment morphodynamic properties and composition on benthic community structure was further investigated using multivariate analysis (RDA, clustering).

3. Results and discussion

3.1. Influence of sediment grain size and morphology on biotic indices

The biotic indices indicate that coarser sediments support more diverse, abundant, and less-dominated benthic communities than finer ones (Table I). These findings align with previous studies showing that coarse sediments provide structural complexity, promoting biodiversity (Taniguchi and Tokeshi, 2004; Kostylev et al., 2005; Foveau et al., 2013; Gutow et al., 2022).

Stations located in no-dune areas present biotic indices similar to those in dune troughs, characterized by high diversity, abundance, and low dominance. In contrast, stations on dune slopes (lee or stoss sides) show lower diversity, reduced abundances, and greater dominance (Table I). These results suggest that dune slopes are less favorable for diverse benthic communities, consistent with observations on other bedforms (Ramey et al., 2009; Ellis et al., 2011; Damveld et al., 2018; Robert et al., 2021).

Finally, regarding the influence of dune morphology on biotic indices, stations in areas with large, closely spaced dunes (east sector) present lower biotic indices than those in zones with small, widely spaced dunes (west sector). Since dune morphology is influenced by hydrodynamic forces and sediment supply (Flemming, 2000), smaller and isolated dunes, which reflect sandy sediment depletion (Le Bot, 2001; Vah et al., 2020), appear to be more favorable for benthic community development than larger dunes, which are associated with greater sediment transport (Van Lancker et al., 2012).

Table I: Biotic indices across analyzed factors. S: Taxonomic richness, N: Total abundance, H': Shannon index, J': Pielou index. sG, sandy gravel; gS, gravelly sand; (g)S, slightly gravelly sand and S, sand.

		S	N	H'	J'
Sediment nature	sG	70.79 ± 19.80	2762.89 ± 2200.88	4.42 ± 0.83	0.73 ± 0.12
	gS	70.25 ± 17.51	1683.20 ± 1072.71	4.79 ± 0.44	0.78 ± 0.05
	(g)S	48.00 ± 13.59	1129.50 ± 990.39	3.82 ± 0.14	0.69 ± 0.05
	S	30.95 ± 7.57	605.80 ± 510.48	3.19 ± 0.41	0.65 ± 0.06
Dune position	No dunes	71.27 ± 18.42	2690.75 ± 2181.51	4.49 ± 0.72	0.74 ± 0.11
	Trough	75.25 ± 18.85	2124.50 ± 1403.49	4.86 ± 0.71	0.78 ± 0.09
	Stoss side	37.25 ± 11.71	736.00 ± 552.44	3.40 ± 0.52	0.66 ± 0.07
	Lee side	32.42 ± 8.62	714.17 ± 635.18	3.23 ± 0.42	0.65 ± 0.06
Dune sector	Outside	66.00 ± 21.85	2351.62 ± 2128.94	4.35 ± 0.81	0.73 ± 0.11
	West	79.17 ± 17.80	2892.67 ± 1519.97	4.75 ± 0.76	0.76 ± 0.09
	South	43.50 ± 5.74	928.00 ± 85.28	3.52 ± 0.71	0.64 ± 0.11
	Center	48.00 ± 13.59	1129.50 ± 990.39	3.82 ± 0.14	0.69 ± 0.05
	East	40.00 ± 20.20	723.38 ± 710.94	3.60 ± 0.92	0.69 ± 0.10

3.2. Influence of sediment grain size and morphology on trophic composition

Coarse sediments are dominated by deposit and filter feeders, while finer sediments support more predators and scavengers. Trophic group distribution also varies with dune position: filter and deposit feeders are most abundant in no-dune areas and troughs, whereas predators and scavengers dominate dune slopes. Similarly, small isolated dunes support more filter and deposit feeders than large, extensive dunes, which harbor more predators and scavengers. These findings suggest that filter feeders concentrate in dune troughs, where depressions provide shelter from sediment abrasion (Robert et al., 2021) and concentrate food resources (Van Lancker and Jacobs, 2000; van Dijk et al., 2012; Van Oyen et al., 2013; Robert et al., 2024), as observed for sand ripples (Ramey et al., 2009). In contrast, predators and scavengers are more abundant on large dune surfaces, which are ideal for ambush predation due to higher sediment transport (Kaiser et al., 2004; Ellis et al., 2011; Robert et al., 2021).

3.3. Grain size and morphodynamic influences on the benthos structure

Multivariate analyses (Figure 2) highlight the complex interplay between dune morphology and sediment grain size. Sandy-depleted areas are characterized by small dunes with extensive gravelly troughs, supporting highly diverse benthic communities, including Galathea intermedia, *Spirobranchus triqueter*, and *Leptochiton cancellatus*. In contrast, sandy accumulation zones feature large, continuous dunes with lower diversity, dominated by species like *Nephtys cirrosa*. At the Dunkirk site, Robert et al. (2021) suggested that high sediment flux homogenizes benthic communities between dune troughs and crests. At Dieppe-Le Tréport, where significant heterogeneity was observed between troughs and slopes, annual dune migration rates ranged from 1.2 to 8.05 m/year—an order of magnitude lower than at Dunkirk. This suggests that sediment and dune dynamics are key structuring factors: high migration rates homogenize communities, while low migration rates promote heterogeneity. A potential migration threshold of 10–15 m/year for distinguishing homogeneous vs. heterogeneous benthic structures warrants further investigation.

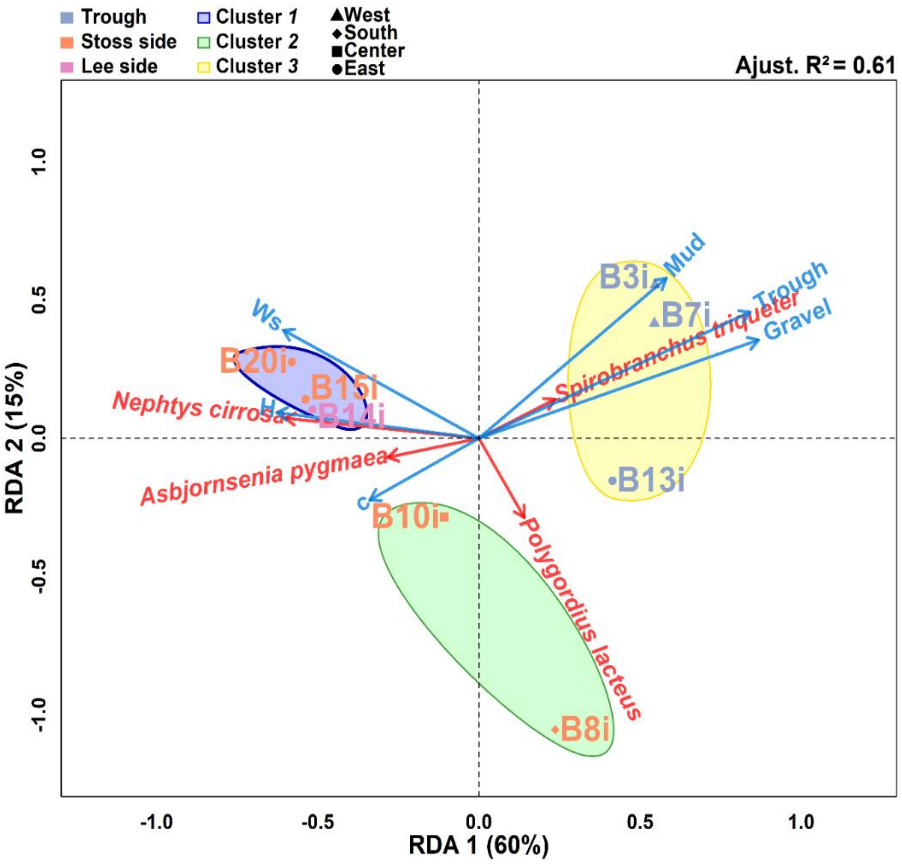

Figure 2: RDA illustrating the relationship between substrate grain size characteristics, morphometric indices of the surrounding dunes, and dune position with Hellinger-transformed benthic abundances. Ws: Stoss side width, H: Dune height, C: Dune mig

4. Conclusion

By integrating benthic macrofauna, grain size, and bathymetric data, this study highlights the influence of sediment grain size and morphodynamics on benthic community structure. At Dieppe-Le Tréport, benthic heterogeneity is driven by sediment interactions, with distinct communities forming in inter-dune troughs vs. dune slopes. Sediment availability and transport shape dune morphology, which in turn influences benthic communities. Future research should assess how wind turbine-induced morphological changes could impact the benthic communities supported by these dunes.

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Q&A

On dune migration rates: a similar study in Dunkirk showed dune migration of up to 100m per year. What about your site?

- In Dieppe, dune movement is slower, around 10m/year. This dynamic might help explain the results.

On resilience to wind farm installation: Dunkirk has high levels of recovery between high and low dunes. Would Dieppe be less resilient?

- Yes, due to slower dune movement, Dieppe could indeed be less resilient. However, the impact on benthic communities remains hypothetical at this stage.

On anthropogenic pressures and sediment granulometry: have you assessed how human activities impact sediment granulometry?

- Yes, human activities influence granulometric characteristics. Offshore wind farms can lead to increased fine sediments.

On offshore wind farm effects on dune systems:

- There is numerical modelling to predict these effects. Turbine positions were correlated with dune structures, and some dunes are likely to be affected.

On macro vs. micro-scale differences: at a macro scale, do you see greater differences compared to the micro scale (e.g., west vs. east)?

- It hasn't been quantified yet, but in the western sector, dune structures play a major role in shaping communities. This is less evident in the east. Both scales are important, though macro patterns may have a stronger influence.

Carbon budgets in intertidal estuaries of the Eastern Channel: Example of the Canche estuary

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Keywords: Carbon budgets, Carbon fluxes, saltmarshes, estuary

Introduction

At the interface between atmospheric, terrestrial and oceanic realms, estuaries constitute buffer areas between freshwater and coastal marine water and therefore play a key role in global biogeochemical cycles, although they represent only 4% of the coastal environment. Physical (aggregation/flocculation), chemical (precipitation/dissolution) and biological (organic matter production/mineralization) processes are involved in these cycles that are also influenced by a low depth and hydrodynamics forcing, promoting particulate and dissolved matter exchanges between the water column and the benthic compartment (Griffiths *et al*., 2017).

In tidal estuaries, salt-marshes located in the highest intertidal levels are colonized by halophytic plants and provide important ecosystem services (*e.g.* protection against erosion, water purification, nursery for coastal fishes and a high capacity for CO_2 uptake and carbon sequestration; Mcleod *et al.,* 2011; Alongi, 2020).

The part of carbon sequestered over short (decennial) and long (millennial) time scales in marine biomass or marine sediment is called "Blue Carbon" (Duarte *et al.,* 2005; Lo Iacono *et al.,* 2008). In salt-marshes, less than 10% of the carbon fixed through photosynthesis is buried into the sediment (Howes *et al*., 1985). However, because of their high productivity, these ecosystems might be considered as important carbon sinks, like mangroves or seagrass, but further investigations are needed to assess carbon fluxes dynamics in intertidal estuaries. Carbon budgets must be calculated, but this task is difficult in intertidal zones. To account for the specific dynamics occurring in these systems, emersion times during both day and night, as well as immersion time, must be considered in this calculation.

This study aims to serve as an initial step in understanding the dynamics of carbon fluxes at different scales in the Canche estuary. The unique characteristic of this type of estuary (referred to as 'Picard' estuaries, such as the Authie and Somme) is its mouth, which is formed by a sandy dune barrier, and a tidal range that varies between 4.9 and 8.5 m (Voltz, 2020). In this study, we present the preliminary results of a sampling campaign conducted from July 8th to 11th, 2024.

Methods

Study site

The Canche estuary, located in the North of France (Figure 1), is characterized by semi-diurnal tides and various habitats, such as mudflats or salt-marshes (Voltz, 2020). The immersion time depends on the tidal range. For example, the highest part of the salt-marshes is only inundated during spring tides, while mudflats are emerged twice a day, whatever the tidal amplitude. Our study focused on three stations located along a transect: the mudflat, the lower part of the salt-marsh (LS) and the higher part of the salt-marsh (HS). The sufficient width of the mudflat and the short distance between each station (50 m from the mudflat to the HS) guided the selection of these sites

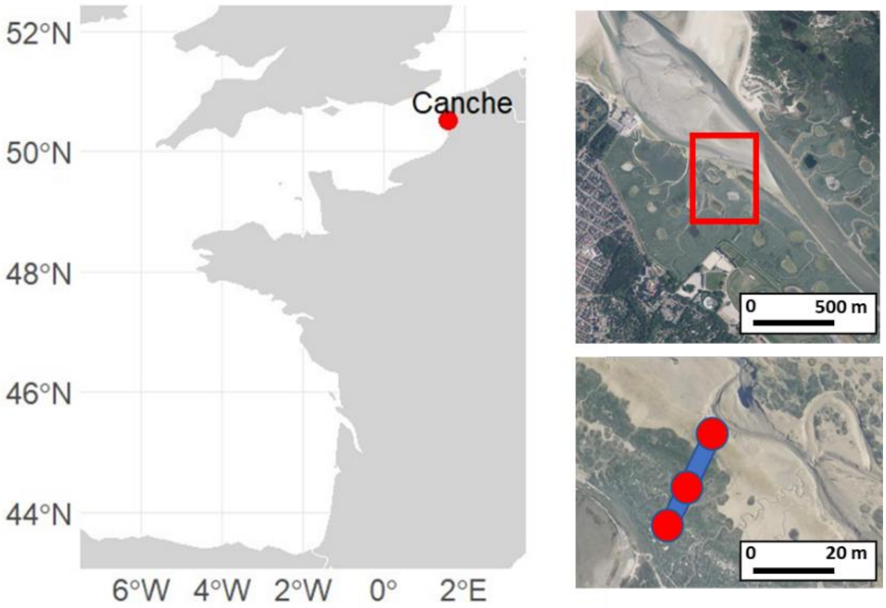

Figure 1: Location of the Canche estuary (North of France, Figure 1A) and the transect with the different stations sampled during July 2024 (Figure 1B, Figure 1C)

Methods used

During emersion, gaseous carbon dioxide (CO_2) fluxes between the sediment and the atmosphere were measured using dark and clear benthic chambers, coupled with a CO_2 analyser (InfraRed Gas Analyzer, LI-8100A – Li-Cor Biosciences). Both small (dark: 3800 cm³, 6 replicates; light: 4000 cm³, 10 replicates) and larger (light: 52,000 cm³, 6 replicates) benthic chambers were used to either include or exclude large halophytic plants (*e.g. Halimione portulacoides*) during the incubations. Incubations lasted 3 min for the small benthic chambers, and 6 min for the large one.

During immersion, sediment-water fluxes of Dissolved Inorganic Carbon (DIC) were measured using whole-core incubation method (Denis *et al*., 2001). For each station, three sediment cores were sampled at low tide. Freshwater was also collected and mixed with seawater to recreate the salinity measured *in situ* (Master-S/Mill alpha – Atago) in the interstitial water (i.e., 25). Back to the laboratory, cores were filled with this mixture as overlying water and sealed after removing any air bubbles. The incubations were performed in laboratory at dark and *in situ* water temperature, during 7 hours in an incubator with a sampling of overlying water every hour. All the samples were poisoned with using mercury chloride at saturation and DIC concentrations were measured later with an analyzer (DIC analyzer, Li-5300A – Apollo-Sci-Tech). For each incubated core, the fluxes were determined from the temporal evolution of DIC concentrations, with corrections applied using a control core containing only the overlying water.

Statistical analyses

Analyses were performed with the software R-Studio 4.4.2 (R Core Team, 2024). To compare the spatial variability of the fluxes, 1-way ANOVAs was performed and completed by a post-hoc test of Tukey. A t-test of Welch was also performed to compare the mean fluxes in the two sizes of benthic chambers, to be in adequation with the non-homogeneity of the variances in this case.

Results

During emersion, CO_2 uptake was consistently observed under light conditions, except at HS with the small benthic chamber. This contrasts with the results obtained in darkness, where CO_2 efflux was observed at each station (Table 1). There was a spatial difference of fluxes between stations, with highest fluxes measured in LS whatever the condition (ANOVA: $p<0.05$, Table 1). An efflux of CO_2 was observed with the small chamber, whereas there was an uptake with the large one (t-test of Welch: $p<0.05$, Table 1).

Table 1: Mean CO_2 fluxes (± SE) measured in July 2024 during emersion using clear (with two different sizes of Benthic Chambers (BC Size)) and dark benthic chambers. The letters correspond to the groups of stations without statistical differences, determined by a Tukey test to complete the ANOVA (p<0.05). Large and small chambers was treated separately. Significant statistical differences between the two BC sizes on a same station (t-test of Welch, p<0.05) was represented with a "".*

Station	BC Size	CO_2 Flux (mmol m^{-2} h^{-1}) Light	Dark
Mudflat (without vegetation)	Small	-6.49 ± 3.34^{a} n = 10	3,10 ± 1.54 n = 6
	Large	-3.41 ± 2.97^{A} n = 5	
Low salt-marsh (with *s. anglica*)	Small (*s. anglica* included)	-10.37 ± 8.10^{a} n = 6	20.51 ± 7.93 n = 6
	Large (*s. anglica* included)	-6.73 ± 2.26^{A} n = 6	
High salt-marsh (with *h. portulacoides*)	Small * (*h. portulacoides* non-included)	1.50 ± 3.07 n = 6	12.03 ± 3.32 n = 5
	Large * (*h. portulacoides* included)	-4.10 ± 2.63^{A} n = 4	

During immersion, efflux of DIC were measured at all stations (Table 2) without any significant difference between Mudflat and LS, while HS was characterized by lower fluxes (ANOVA: $p<0.05$, Table 2).

Table 2: Mean DIC fluxes (±SE) calculated using laboratory whole-core incubation technique. The letter "a" correspond to the group of stations without statistical difference, determined by a Tukey test to complete the ANOVA (p<0.05).

Station	DIC Flux (mmol m^{-2} h^{-1})
Mudflat (without vegetation)	27.30 ± 6.35^{a} n = 3
Low salt-marsh (with *s. anglica)*	20.56 ± 3.83^{a} n = 3
High salt-marsh (with *h. portulacoides*)	7.14 ± 1.73 n = 3

Discussion

During emersion, two major biological processes drive CO_2 fluxes: primary production supported by photosynthesis, and respiration/mineralization of organic matter driven by fauna and bacterial activities. Halophytic vegetation cover, or its absence, can account for most of the differences in CO_2 fluxes observed between stations, as species vary in productivity, which may explain the observed differences between the two salt-marsh zones. In darkness, photosynthesis is stopped and exchanges only reflect the intensity of respiration/mineralization, hence resulting in CO_2 efflux.

In HS, large benthic chambers included an entire *H. Portulacoides* plant, whereas the small one can only be inserted between the roots and stems of the plants, which probably explains the differences observed between the sizes of the benthic chambers (Table 1).

Moreover, sediment characteristics such as grain size, cohesion, and permeability may partly drive variations of CO_2 fluxes due to processes like evaporation. A cohesive mud remains saturated in seawater during emersion, whereas sandy sediment will allow advection processes (Migné *et al*., 2016). For example, Sasaki *et al.* (2009) measured a rapid increase of CO_2 efflux during the first emersion hour in sandy sediment, whereas Klaasen and Spilmont (2012) measured maximum values after 3 hours in a Wadden sea mudflat.

During immersion, the flooding of sediments causes resuspension, leading to high turbidity in the water column, which inhibits photosynthesis. Environmental factors such as salinity, tidal zone, sediment type, and compaction determine macro-organism diversity in salt-marshes. For example, mollusks, crustaceans, and annelids are only found in mudflats (Brain *et al*., 2017; Buiyan *et al*., 2025). Faunal bioturbation and biodiffusion mix the sediment layer, introducing water, solutes, nutrients, and particulate organic matter, which enhance bacterial respiration.

Each station had different immersion and emersion time (Table 3) along the transect. Based on these times and the fluxes, a global carbon budget was estimated for each station during this campaign.

Table 3: Mean immersion and emersion time on the sites during the campaign of July (SHOM, 2024)

Station	Emersion (light)	Emersion (dark)	Immersion	Carbon budget (mmol m^{-2} h^{-1})
Mudflat	13h18	4h59	5h43	5.26
Low salt-marsh	14h10	5h47	4h03	4.43
High salt-marsh	15h49	7h26	0h45	1.24

These budgets showed that the sediment from the three stations in the Canche was mainly a source of carbon. Moreover, these budgets decrease along the transect, with lower values observed in high salt-marshes. This trend can be explained by the difference in immersion time between each station. Factors mentioned previously, such as temperature, also directly influence the variability of these budgets. It is important to understand that these budgets do not represent the total amount of carbon released into the atmosphere but the carbon that will be released from the sediment to the water column or the atmosphere. However, most of this DIC will be exported to the ocean depending on the tidal regime (Chu *et al.,* 2018), with only a small fraction being released as CO_2 into the atmosphere and further investigations are needed to quantify this fraction.

Conclusion

This campaign, conducted in July 2024, revealed significant spatial variability in CO_2 and DIC fluxes during emersion and immersion. This variability can be explained by multiple biotic and abiotic factors, such as vegetation cover and assemblages, duration of immersion, day-night alternation, fauna diversity, or sediment properties like compaction or organic matter content. A methodological aspect must be considered for future studies due to the presence of large halophytic plants, such as *Halimione portulacoides*, which are difficult to include in measurements using small chambers, even though these plants strongly influence carbon fluxes under light conditions. The global carbon budget indicates that the sediment of this estuary was a source of carbon during this campaign. However, this system can act as a CO_2 sink under light conditions during emersion (cf. Table 1). Moreover, it is important to consider that our station HS is located near *Spartina anglica* and that the higher parts of salt marshes are less frequently inundated than the sampled station. These budgets must be integrated into the surface area to obtain a global estimation of carbon emissions and fixation in this ecosystem. In the future, further investigations must be conducted to estimate the global carbon budget across different seasons, considering variations in immersion/emersion times and different biotic and abiotic conditions, such as vegetation cover. It is also crucial to focus on DIC to determine the proportion released into the atmosphere versus that exported to the ocean in order to quantify total CO_2 emissions.

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Q&A

On seasonal biodiversity monitoring: you plan to conduct seasonal surveys to quantify CO_2 fluxes. Will you also assess biodiversity changes between summer and winter?

- Sediment biomass quantification was conducted across the study sites. Preliminary observations indicate low biomass and a lack of large organisms at these locations. In contrast, the mudflat sampled exhibited higher biomass and greater biodiversity. However, seasonal variations have yet to be fully explored.

On calcification processes in CO_2 cycling:

- *In situ* monitoring is lacking for calcification rates. Alkalinity is being measured, but current results are inconsistent with CO_2 data. More work is needed for a precise carbon budget.

On long-term carbon storage: do you have information on long-term carbon storage? That could support conservation efforts.

- Another PhD project in the laboratory is investigating this aspect. Currently, the focus is on studying instantaneous fluxes, rather than dating carbon stocks.

On climate change impacts on carbon fluxes:

- Based on the literature, the hypothesis of increased CO2 uptake in sediments is put forward. However, there is controversy. Duarte et *al.*, 2005 suggest that while there might be greater CO_2 uptake from the atmosphere, human-induced disturbances could also increase emissions.

Population dynamics of *Ensis leei* in the coastal waters of the Netherlands

J.A. Craeymeersch, J. de Fouw, P. van Horssen, I. Tulp, K. Troost

Introduction

As a basis for the Dutch fisheries policy, the quantities, spatial distribution and composition of a number of shellfish stocks (mussels, cockles, razor clams, oysters) in Dutch coastal waters and estuaries are monitored through stock surveys. The policy for the management of shellfish stocks in Dutch coastal marine waters (North Sea, Wadden Sea, Westerschelde, Oosterschelde, Lake Grevelingen, Lake Veere) is presently based on an integration of fishery-related and ecological objectives (Troost et al. 2024, Troost 2025, 28 feb-a). Major elements of management are closed areas, catch quotas and considerations on nutrition needs for birds (Fijn et al. 2017, van de Wolfshaar et al. 2023). The assessments in all different areas are carried out using research vessels and chartered vessel, and in close cooperation with fisheries inspectors.

Surveys in the North Sea are going on since 1995. The focus is on the cut through shell (*Spisula subtruncata*) and the American razor clam (*Ensis leei*). The North Sea survey also monitors other benthos species and is part of a time series which indicates considerable changes in the benthic fauna over the period the survey has been carried out, such as changes in distribution (Craeymeersch & Rietveld 2005), the arrival of alien species (Craeymeersch et al. 2019, Craeymeersch 2021), shore nourisments (Baptist & Leopold 2009) or the effects of the MSC Zoe cargo lost (Herman et al. 2021). The distribution and population trends of various species of shellfish (density and biomass) in the saline Dutch coastal waters can be seen via the Shellfish Monitor (Troost 2025, 28 feb-b).

The data can also be used to improve the control over human activities. The permit conditions for sand extractions, for instance, require since 2008 maintaining a 100-meter distance from living shellfish banks during extraction). However, applying this law is challenging due to the lack of an accepted definition of a shellfish bed. Recently, we explored some approaches to define shellfish beds, focusing on minimum density and minimum bed size (Craeymeersch & Velilla 2024).

The extensive time series further allows to explore the effects of climate change, change in the intensity of human activities, such as fisheries and sand extraction, and environmental drivers onto the population dynamics of the species. Recently, an analysis on the population dynamics of *Spisula subtruncata* was published (de Fouw et al. 2024). Model results revealed that medium sediment grain size was key determinant of *S. subtruncata* occurrence and density. Increasing sea water temperatures during winter and the post-settlement phase positively affected annual population densities, while strong north-westerly winds led to lower densities. Shrimp and flatfish beam trawling overlapped with *S. subtruncata* occurrence and were negatively related to densities, suggesting higher beam trawling intensity in these areas may negatively impacts densities. Overall, the effects were stronger at medium to finer sediments where the highest densities occurred, indicating a strong habitat-dependent effect. Despite identifying multiple drivers, unexplained annual variation suggests other not included factors like predation pressure, also play a role. We presently are analyzing the population dynamics of *Ensis leei* in the coastal waters (Craeymeersch et al. in prep.). This manuscript presented at the LIFE seminar in Lille, 12-13 March 2025 highlight a few of the results, focusing on the importance of early life stages in the population dynamic of *E. leei*.

Material and Methods

Each year in spring (April-June) samples are taken at 800-1000 stations in the coastal area (Figure 1). Samples are taken using a stratified systematic sampling design. The surveyed area is divided into a number of strata according to prior knowledge of or expectation on the distribution and density of commercially exploited species. Samples are organized within each stratum by cells in a grid. The cell size of the grid is depending on the stratum. In strata with high clam densities, a smaller cell size is used than in areas with low densities of clams. Sampling points are placed at the grid nodes.

Most of the stations are sampled either with a trawled dredge or a modified hydraulic dredge, covering 15 to 30 m^2. Mesh size is 5 mm and sampling depth 9-10 cm. All animals are identified and counted on board. For razor shells, often only the anterior part of the animals or the siphons are present in the samples. Therefore, siphons were counted. From 2010 onwards, the width of the shell tips around the siphons were measured with an accuracy of 0.01mm. Shell width was converted to length using the equation published by (Craeymeersch & van der Land 1998). Based on the length frequency distributions we distinguished two cohorts: 1-year old juvenile animals (1st cohort) and older animals.

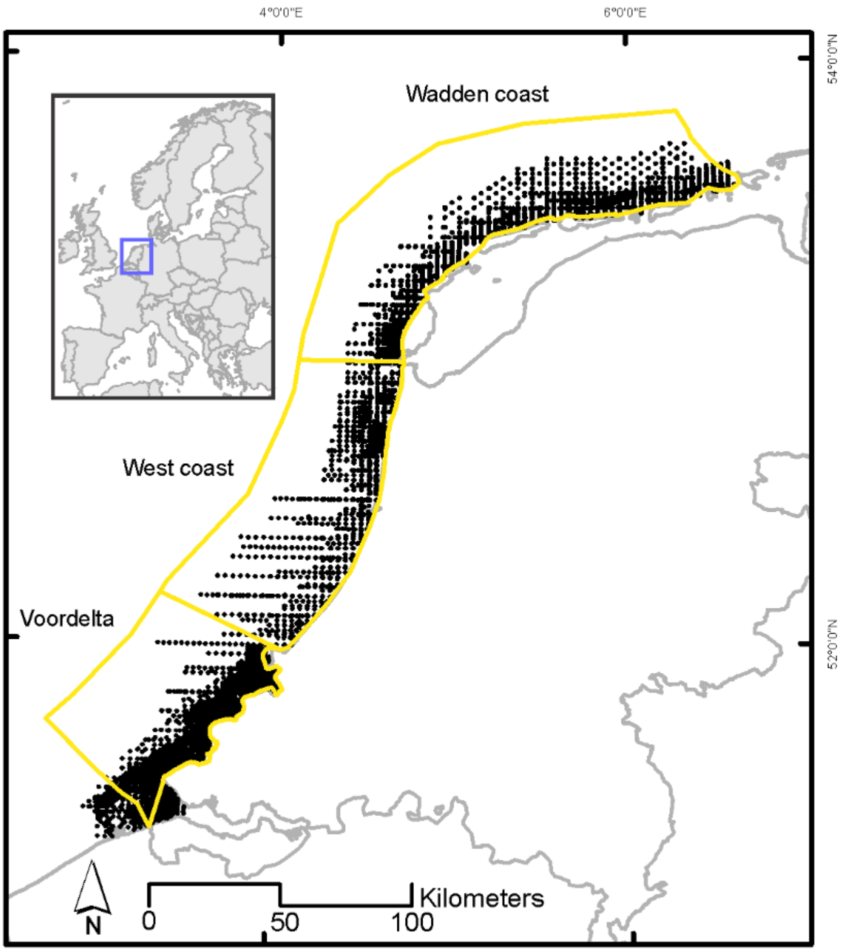

Figure 3. Study area with sampling grid with total sample stations and coastal areas: Voordelta, West coast and Wadden coast (de Fouw et al. 2024).

To investigate the potential effect of climate, biological and anthropogenic related factors data on juvenile *L. leei* numbers (years 2010-2021) we identified several variables: the moment of spawning, mean water temperature between spawning and settlement, mean water temperature during post-settlement period, the number of days with strong winds coming from the northwest (winddays), winter temperature, the fishing intensity of different fisheries, median grain size, distance to the nearest sand nourishment, the density of adult razor clams and the total density of other filter feeding bivalves. All following de Fouw et al. (2024), and a literature review on life history characteristics.

To test the potential effect of these covariates a generalized linear mixed effect model with Negative Binomial distribution was used. Several covariates are not independent and, therefore, different models were used and compared according to their AIC. In this manuscript we will focus on the relationship with sea surface temperature, number of winddays and adult numbers.

Results

The total stock of *Ensis leei* varied yearly between 27000 10^6 (2016) and almost 225000 10^6 (2019) (Figure 2). In 2014 recruitment failed, leading to almost no 1-year old individuals in spring 2015. After that year, the population showed very large fluctuations, in the total stock and in the number of 1-year old individuals.

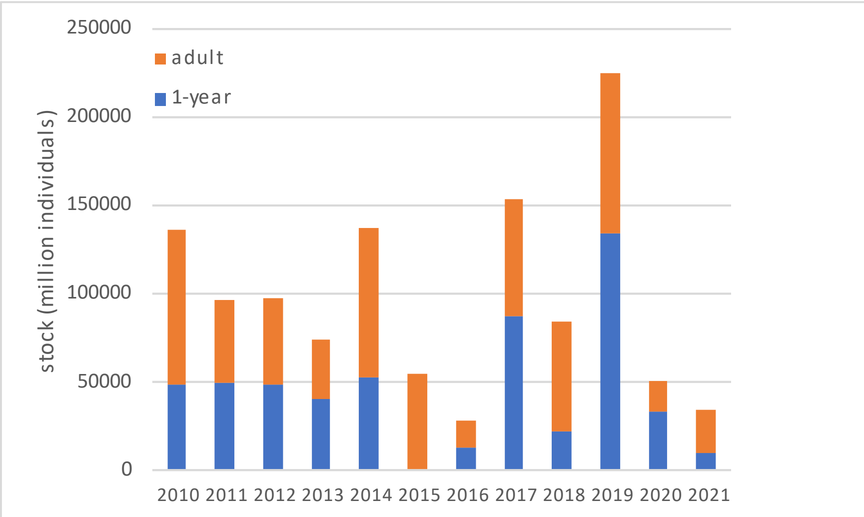

Figure 4 Total stock of juvenile (1e year) and adult (>1e year) E. leei for the entire shallow Dutch North Sea coast (Craeymeersch et al. in prep.).

Juvenile numbers show a negative relationship with both winter and pelagic larvae sea surface temperature and with strong NW winds (Tabel 1). There is a positive relationship with the adult numbers.

covariate	effect
Sea surface temperature during pelagic phase	red
Sea surface temperature in proceeding winter	red
Number of winddays	red
Density of adults	green

Table 2. covariate effects (green = positive, red = negative)

Discussion

The classical model of the life cycle of benthic marine invertebrates includes a planktonic larval stage, followed by a benthic juvenile-to-adult stage. The larval stage is the primary dispersal period, and is followed by settlement and metamorphosis to a sedentary juvenile (Baker & Mann 1997). The different life cycle events, i.e. reproductive output, recruitment and post-recruitment development and larval transport and settlement, all play an important role in the benthic community (Birchenough et al. 2015). This is demonstrated repeatedly for bivalves. High variability of recruitment success and between-year variability in mortality rates of settled individuals result in a high variability of total stocks of a bivalve species (Nakaoka 1993, Ripley & Caswell 2006, Beukema et al. 2010).

Our results point to a positive impact of adult densities. This can be explained by either a cue related to the presence of adults that attracts juveniles or they simply favour the same habitat. Settlement induced by conspecific adults has been described for many benthic species. In the Voordelta, however, high densities of juveniles were found everywhere, whereas 1-year old individuals were found in much smaller areas (Craeymeersch et al. 2015). The co-occurrence of 1-year old and older individuals must therefore be due to post-settlement processes, most likely a higher mortality in first months/winter in less suitable habitats.

Our results point to the negative impact of temperature during the pelagic phase on the 1-year old cohort. An advanced spawning and faster development during the pelagic phase might result in a mismatch between the time of the pelagic phase and the phytoplankton bloom. Such nutritional food limitation during larval development has been shown for several bivalve species, sometimes resulting in a larger juvenile mortality (Phillips 2002, Bollmohr et al. 2011). Temperature during the subsequent winter has a negative effect on 1-year old individuals, as well as the number of days with strong north-westerly winds. This is in accordance with our expectations. High temperatures causes higher mortality rates of juvenile bivalves (Rato et al. 2022), probably due to higher energy demands at times when food abundance is limited. Strong winds (speed and direction) might have a huge effect on the larval dispersion and retention of larvae (Bento de Almeida et al. 2021) or resuspension of juveniles (Strasser et al. 2001). Thus, although the reproductive capacity of *E. leei* is high (Gollasch et al. 2015), climate change indeed might result in a reduction of the recruitment and juvenile survival and the final adult stock. The results do not explain the absence of juveniles in 2015.

Our study points to the importance of settlement and recruitment success. Several studies already showed that the spatial structure of the meroplanktonic species is related to environmental variables such as sea surface temperature, salinity distribution and wind direction and intensity (see e.g. results of the RENORA project; Belgrano et al. 1990, Belgrano et al. 1995). Thus, to understand how and why populations change over time data are needed on all life history stages, including the meroplanktonic phase, on a small scale. Unfortunately, understanding of plankton abundance and diversity is highly fragmented due to, among others, the high costs of zooplankton monitoring. Recently, new techniques now increased the ability to collect data on a fine spatial and temporal scale, such as DNA metabarcoding (Van Walraven et al. 2025).

Conclusion

To understand the importance of biotic and abiotic drivers, and of humans impact (including climate change) on population dynamics, we need a comprehensive understanding, including all life stages.

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Q&A

On declines in species alongside bivalves: have you observed declines in other species? What about phytoplankton?

- This hasn’t been analysed yet, but there's hope that it can be done in the future.

On the use of remote sensing data (Copernicus – chlorophyll A): could Copernicus remote sensing data help?

- Possibly. However, surveys take eight weeks, meaning temporal changes occur even within a single campaign. Weather conditions also delay surveys, influencing results.

On the drivers of observed changes:

- Wind-driven effects were considered, but they didn't fully explain the results obtained. Initially, the quality of the data was questioned, but fishermen confirmed the findings. A clear explanation is lacking.

On long-term sustainability of the monitoring program: is your monitoring program sustainable?

- Historically, there were 2000 stations, but fisheries have changed, reducing the sampling effort. Currently, there are only four *Ensis* fishermen left, making extensive monitoring financially unfeasible. However, the Marine Strategy Framework Directive (MSFD) supports national reporting, ensuring at least five-year agreements. The future depends on political decisions.

On isolating specific anthropogenic pressures:

- It's challenging due to many interacting factors. Fisheries seem to have a strong negative effect on recruitment. Large-scale experiments would be necessary to differentiate human and environmental influences. In highly dynamic coastal areas, fisheries can transform a site in a single day.

On data reliability and sampling method (hydraulic dredging): your sampling method involves hydraulic dredging. How do you ensure data reliability given its impact?

- We use a specialized dredge designed to collect intact samples. Commercial fisheries also use similar equipment to retrieve undamaged shells.

Photo: Alain Pibot / French Biodiversity Office (FR)

SESSION 2 – SEDIMENTARY HABITATS RESPONSES TO CHANGING CONDITIONS: HUMAN AND ENVIRONMENTAL PRESSURES

RÉPONSES DES HABITATS SÉDIMENTAIRES AUX CHANGEMENTS : PRESSIONS HUMAINES ET ENVIRONNEMENTALES

Session moderator – *Animateur de session*: **Jacques Grall,** European University Institute of the Sea (IUEM), University of Bretagne-Occidentale, France

Access the presentations from this session here – *Accédez aux présentations de cette session ici.*

Sedimentary habitats are dynamic ecosystems that are increasingly subject to human and environmental pressures, leading to significant alterations in their structure and function. Understanding how these habitats respond to disturbances, whether from anthropogenic activities or natural environmental changes, is essential for effective conservation and management strategies. This session brings together three studies that investigate different aspects of sedimentary habitat responses, from the impacts of bottom trawling to long-term ecological shifts and carbon sequestration in estuarine environments.

The first presentation, by **Natalia Montero** (AZTI, Spain), assesses the impact of bottom-contact fishing gear on sedimentary habitats in the southeastern Bay of Biscay. Bottom trawling is known to cause physical disturbances to the

Les habitats sédimentaires sont des écosystèmes dynamiques soumis aux pressions humaines et environnementales, entraînant des altérations de leur structure et fonction. Il est essentiel de comprendre comment ces habitats réagissent aux perturbations, qu'elles soient dues à des activités anthropogéniques ou à des changements naturels, pour mettre en place des stratégies de conservation et de gestion efficaces. Cette session rassemble trois études qui examinent les réponses de ces habitats, des impacts du chalutage de fond aux changements écologiques à long terme et à la séquestration du carbone dans les environnements estuariens.

La première présentation, par **Natalia Montero** (AZTI, Espagne), évalue l'impact du chalut de fond sur les habitats sédimentaires dans le sud-est du golfe de Gascogne. Le chalutage de fond est connu pour provoquer des perturbations seabed, potentially leading to habitat degradation and shifts in benthic communities. This study evaluates how fishing intensity influences macrobenthic and megabenthic organisms, highlighting that while environmental factors primarily dictate macrobenthic presence, fishing effort significantly affects the distribution of sensitive megabenthic species. The findings contribute to ongoing efforts to monitor seafloor integrity and develop sustainable fisheries management strategies.

Adeline Tauran's (Univ. Bordeaux, France) study shifts the focus to long-term ecological changes in Arcachon Bay, a coastal lagoon facing multiple environmental stressors, including the regression of dwarf eelgrass meadows and shifts in nutrient dynamics. Using benthic community surveys spanning over three decades (1988, 2002, and 2023), this research identifies key spatial and temporal variations in subtidal macrozoobenthic communities. The results underscore the role of sediment characteristics, depth, and current speed in structuring these communities while raising questions about the cascading effects of habitat loss on benthic ecosystem stability. The study highlights the need for continued long-term monitoring to better understand ecosystem trajectories in response to environmental change.

Finally, **Camille Décultot** (Univ. Lille, France) explores blue carbon sequestration in the Authie estuary, particularly in the context of an upcoming dyke removal project. Using lipid biomarker analysis, this study identifies the dominant sources of organic carbon in saltmarsh sediments, revealing that terrestrial plant inputs exceed aquatic contributions. The research lays the groundwork for further investigations into carbon fluxes within these sedimentary environments, providing critical insights into how estuarine management interventions may influence carbon sequestration and ecosystem functioning. This work emphasizes the importance of quantifying carbon pools and fluxes to better assess the role of saltmarshes in climate change mitigation.
Together, these studies offer valuable perspectives on how sedimentary habitats respond to diverse pressures, from direct human disturbances to broader environmental shifts. By

physiques sur les fonds marins, pouvant entraîner une dégradation de l'habitat et des changements dans les communautés benthiques. Cette étude évalue l'influence de l'intensité de la pêche sur les organismes macrobenthiques et mégabenthiques. Elle souligne que, si les facteurs environnementaux déterminent principalement la présence des organismes macrobenthiques, l'effort de pêche affecte de manière significative la distribution des espèces mégabenthiques sensibles. Ces résultats contribuent aux efforts en cours pour surveiller l'intégrité des fonds marins et développer des stratégies de gestion durable de la pêche.

L'étude d'**Adeline Tauran** (Univ. Bordeaux, France) met l'accent sur les changements écologiques à long terme dans le bassin d'Arcachon, une lagune côtière confrontée à de multiples facteurs de stress environnementaux, notamment la régression des herbiers de zostères naines et les changements dans la dynamique des nutriments. À l'aide d'études sur les communautés benthiques couvrant trois décennies (1988, 2002 et 2023), cette recherche identifie les principales variations spatiales et temporelles des communautés macrozoobenthiques subtidales. Les résultats soulignent le rôle des caractéristiques des sédiments, de la profondeur et de la vitesse du courant dans la structuration de ces communautés, tout en soulevant des questions sur les effets en cascade de la perte d'habitat sur la stabilité de l'écosystème benthique. L'étude souligne la nécessité d'une surveillance continue à long terme pour mieux comprendre les trajectoires des écosystèmes en réponse aux changements environnementaux.

Enfin, **Camille Décultot** (Univ. Lille, France) explore la séquestration du carbone bleu dans l'estuaire de l'Authie, en particulier dans le contexte d'un projet d'enlèvement de digues à venir. En utilisant l'analyse des biomarqueurs lipidiques, cette étude identifie les sources dominantes de carbone organique dans les sédiments des marais salants, révélant que les apports végétaux terrestres dépassent les contributions aquatiques. Cette recherche jette les bases d'études plus approfondies sur les flux de carbone dans ces environnements integrating assessments of habitat integrity, long-term community changes, and carbon dynamics, this session contributes to a more comprehensive understanding of sedimentary ecosystems, supporting informed management and conservation strategies in the face of ongoing environmental change.

sédimentaires, fournissant des informations essentielles sur la manière dont les interventions de gestion des estuaires peuvent influencer la séquestration du carbone et le fonctionnement de l'écosystème. Ces travaux soulignent l'importance de quantifier les réserves et les flux de carbone afin de mieux évaluer le rôle des marais salants dans l'atténuation du changement climatique.

Ensemble, ces études offrent des perspectives précieuses sur la manière dont les habitats sédimentaires réagissent à diverses pressions, qu'il s'agisse de perturbations humaines directes ou de changements environnementaux plus larges. En intégrant les évaluations de l'intégrité des habitats, les changements à long terme des communautés et la dynamique du carbone, cette session contribue à une compréhension plus complète des écosystèmes sédimentaires, permettant une gestion éclairée et des stratégies de conservation face aux changements environnementaux en cours.

Assessing the impact of bottom trawling on the sedimentary habitats of the SE Bay of Biscay

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Keywords: Benthic habitats, seabed impact, infauna, epifauna

Introduction

Physical disturbances on the seabed caused by bottom-contact fishing gears can result in structural loss of habitats and relevant taxa, thereby negatively impacting the environmental status and the provision of ecosystem services1-4. The severity of this impact will depend on several factors, including gear type, seabed characteristics, and the frequency and intensity of fishing activity5-7. The impact and recovery time after a trawling event will also depend on the vulnerability of the species present, which is determined by various biological traits, including body size, fragility, position in the sediment, growth rate and longevity8,9. Therefore, a comprehensive impact assessment requires the acquisition of data about the spatial and temporal distribution of fishing activity, the physical and morphological characteristics of the seabed, and the inhabiting organisms.

This study presents the results of the assessment of the impact of bottom trawling fisheries on sedimentary habitats of the Basque continental shelf (SE Bay of Biscay), which is crucial for the establishment of effective management strategies to safeguard benthic vulnerable ecosystems.

Methodology

Three oceanographic surveys were conducted on the continental shelf off the Basque coast (SE Bay of Biscay) over two consecutive years (2022-2023). Sampling stations (Figure 1) were selected based on depth (120-253 m), seabed characteristics, fishing intensity (derived from Vessel Monitoring System (VMS) data merged with logbook data10), and existing fishing regulations (i.e., stations located within fishing closure areas or subject to varying degrees of fishing pressure). A total of 40 beam trawls were conducted to characterize epifaunal organisms (megabenthos) and 30 sediment samples were collected using a Smith-McIntyre grab to determine the grain size distribution and the organic matter content and characterise infaunal organisms (macrobenthos). Mean density, species richness and biomass of epifaunal and infaunal organisms were determined. Sampling stations were classified based on the presence/absence of macrobenthos species and their taxonomic similarity (Primer v7, Γ+)11. Additionally, an in-depth analysis of the impact on the megabenthos was conducted, using trawling-specific indicators (i.e., the Benthos Sensitivity Index to Trawling Operations (BESITO) index12,13 and the Sentinels of Seabed (SoS) indicator14).

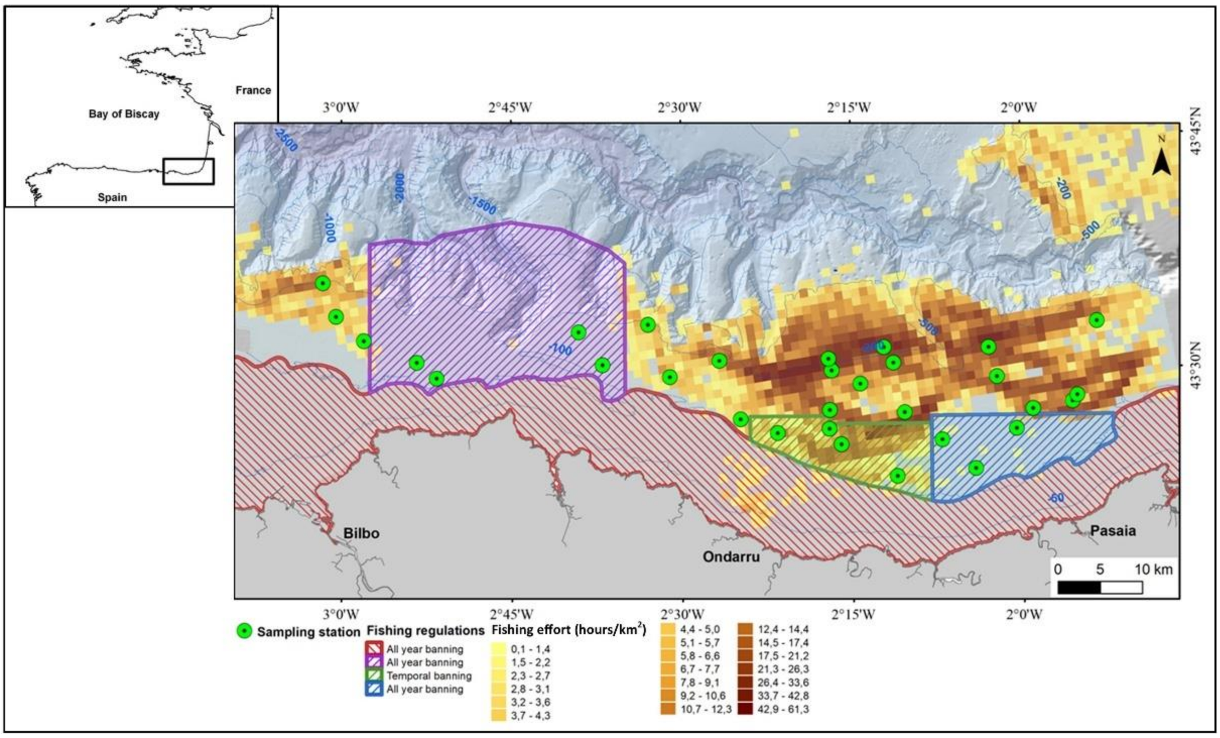

Figure 1. Study area showing the sampling stations, fishing effort (h·km-2) and existing fishing regulations.

Results and discussion

The results derived from the grab samples reveal substantial variability in sediment grain size (61-260 µm), and mud (0.7-79.4%) and sand (21-99%) content. Accumulation of muddy material is observed on the continental shelf between Ondarru and Pasaia, at depths of approximately 100 to 150 metres. A similar accumulation pattern is also observed for the organic matter content (1.4-5.0%). In terms of density, annelids (52-95%), followed by molluscs and arthropods, constitute the dominant macrobenthos groups. Based on the gamma+ (Γ+) analysis, sampling stations are classified into five distinct groups, which seems to be primarily driven by environmental factors (i.e., sedimentological characteristics, depth and organic matter content) (Figure 2).

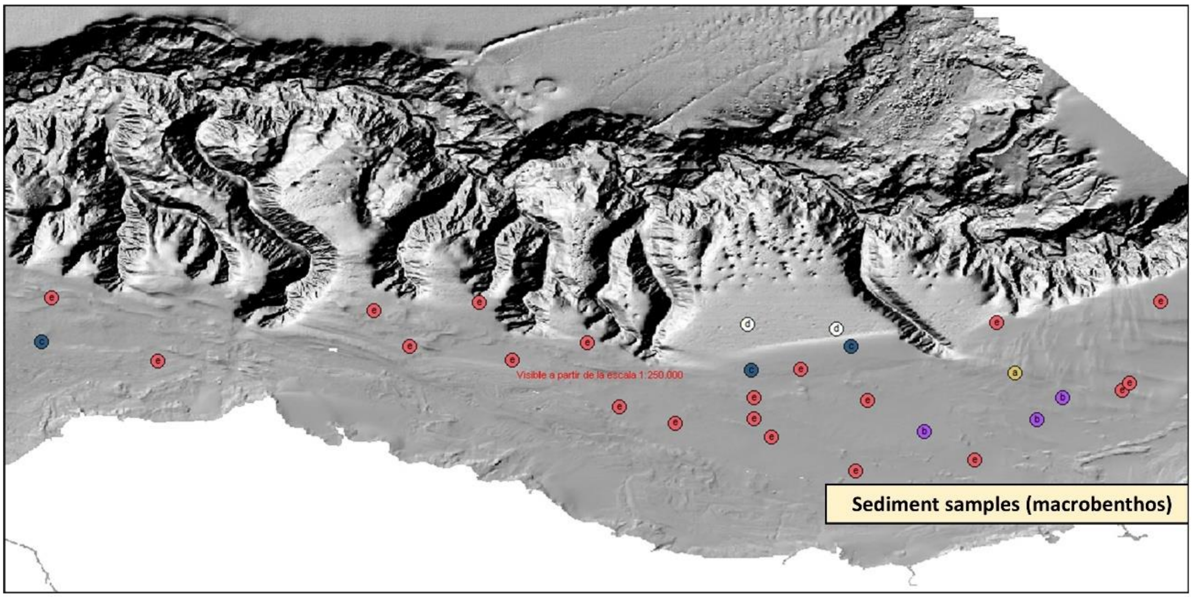

Figure 2. Classification of sampling stations based on the presence/absence of macrobenthos species in the sediments and their taxonomic similarity.

Regarding megabenthos, echinoderms (10-93%) are generally the dominant group in terms of density and biomass, followed by molluscs (3-59%) and fish (1-52%). While higher density and specific richness values are observed in the coastal area between Ondarru and Pasaia, no evident spatial pattern is observed for biomass. The BESITO index, calculated using eight biological traits, reveals an increase in the relative biomass of opportunistic (BESITO score 1) and tolerant (BESITO score 2) species along the trawling intensity gradient, while the opposite is observed for sensitive species (BESITO scores 3-5) (Figure 3A). Similarly, a marked decrease in the relevance of sentinel species (i.e., 9 species associated with offshore circalittoral sand, sensitive to trawling) is observed at higher trawling efforts (Figure 3B).

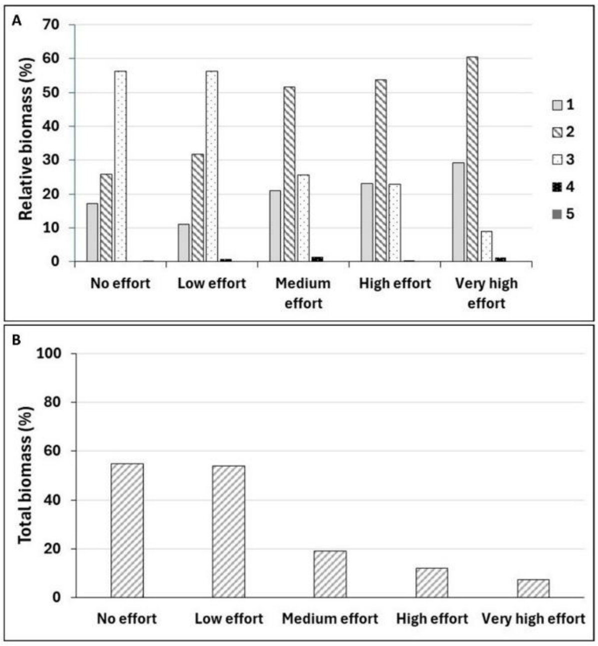

Figure 3. BESITO index (A) and SoS indicator (B) results along trawling effort gradient.

Conclusions

The presence/absence of macrobenthos is primarily influenced by environmental factors, with fishing effort exhibiting a comparatively minor role in shaping macrobenthic community composition. Regarding megabenthos, there is no clear spatial pattern of total biomass in relation to fishing intensity. However, in the stations presenting higher levels of trawling effort, the biomass measured corresponds mainly to opportunistic and tolerant species, while sensitive species decrease along the trawling effort gradient. These results suggest that fishing intensity determines, to a large extent, the presence/absence of sensitive megabenthic organisms, and consequently, smaller, short-lived and fast-growing organisms are observed in seabed impacted by trawling. These results can contribute to the assessment of seafloor integrity, the monitoring of the environmental status of benthic habitats and the impacts produced by bottom-contact fishing gears, and the development of effective fisheries management strategies.

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Long-term evolution of subtidal macrozoobenthic communities in the context of environmental changes in a coastal lagoon (Arcachon, Bay, France)

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Keywords: Benthic macrofauna, Subtidal community structure, Spatiotemporal evolution, Arcachon Bay, Environmental changes.

Introduction

Coastal ecosystems face important environmental changes, both natural and anthropogenic, sometimes leading to regime shifts (Rocha et al. 2015). Regime shifts can be defined as the transition from an initial stable ecological state to a new stable state different from the initial conditions (deYoung et al. 2008). Such phenomena and their consequences are largely reported in the literature (Steneck et al. 2002; Ling et al. 2015; Chevillot et al. 2016).

Numerous environmental changes have been reported over the past 20 years in Arcachon Bay (south-west of France). The most noticeable is the severe decline of the dwarf-eelgrass meadows (*Zostera noltei*), especially after 2005, with a recorded loss of 44% (Plus et al. 2010; Rigouin et al. 2022). In addition, modifications in the ratios of several sea-water nutrient concentrations were also reported by Lheureux et al. (2022), and the introduction of several new exotic and sometimes invasive species was recorded by various authors (Bernard et al. 2020; Lavesque et al. 2020; Massé et al. 2023).

The influence of these environmental changes on the lagoon's macrozoobenthic communities remains unknown, yet benthic communities are known as good indicators of environmental changes. Based on benthic communities' surveys performed in 1988, 2002 and 2023, our aim was to assess whether changes in benthic communities could be observed in relation to this ecological shift.

Methodology

Arcachon Bay is a 180km² semi-enclosed lagoon on the Atlantic coast (SW France) known for harbouring significant *Zostera* spp. meadows (*Zostera noltei* and *Zostera marina*). The main freshwater inputs come from the Leyre River on the east part of the lagoon.

In 2002 and 2023, scuba divers sampled 28 stations in winter (January-March) using an Ekman grab (0.045m² per station). Each sample was sieved on a 1-mm mesh sieve and preserved in 4% buffered formaldehyde stained with Rose Bengal. Samples from 1988 were collected by boat using various grabs by Bachelet et al. (1996). The macrofauna was sorted, and all individuals were identified to the lowest taxonomic level. Sixteen stations were selected to study the benthic communities' pluriannual evolution (1988-2002-2023).

To study the subtidal macrozoobenthic communities in 2023, a hierarchical clustering analysis (HCA) was performed on the fauna abundances using the Hellinger distance and the Ward method to identify the different macrozoobenthic communities. The characteristic species were identified for each community using the Indicator Value (IndVal) method developed by Dufrene and Legendre (1997). The key abiotic factors structuring the communities were identified using non-metric multidimensional scaling (NMDS) on the Hellinger-transformed abundances, later superimposed with environmental variables (salinity, currents speed, depth, coarse sand and mud fraction, presence or absence of engineer species). The same methods (HCA, IndVal and NMDS) were used to study the community changes from 1988 to 2023. Rarefaction curves were used to study the diversity in 1988, 2002 and 2023. Kruskal-Wallis test followed by Dunn post-hoc test when significant were used to test for differences in the sediment type, salinity, sea-water temperature, the Leyre river's flow and rainfalls between 1987 (1988 if 1987 not available), 2001 and 2022 (the year before sampling was selected whenever data were available as macrofauna recruitment is impacted by the environmental conditions from the previous year). All analyses were performed using the R programming language (R Core Team 2022).

Results

Characterisation of the macrozoobenthic subtidal communities in 2023.

In 2023, 2774 individuals from 151 taxa were identified, and annelids were dominants in terms of abundance (77%). The results from the HCA show four distinct communities. (1) The internal sandy muds, characterised by shallow depths (0.4 ± 1.14m), a mean current speed of 0.14 ± 0.04m/s, a high proportion of sand and mud and the lowest mean salinity recorded (28.4 ± 1.1). The main indicator species (IndVal) include *Melinna palmata* (polychete), *Ruditapes philippinarum* (bivalve) and *Streblospio shrubsolii* (polychete). This community is located in the internal part of the bay with the highest mean distance to the ocean among the four communities (14.9 ± 1.9km). (2) The muddy sands community is characterised by an average depth of 2.5 ± 2.5m, a mean sand fraction of 75 % ± 24 and mean currents of 0.15 ± 0.04m/s. The main indicator species (IndVal) include the polychaetes *Prionospio parapari* and *Mediomastus fragilis*, the molluscs *Abra alba* and *Crepidula fornicata* and the echinoderm *Amphipholis squamata*. (3) The mobile sands community, in the external part of the bay, is characterised by the highest depths (9.2 ± 4.8m), the lowest distance to the ocean (6.8 ± 4.7km) and the strongest mean currents (0.2 ± 0.03m/s). The main characteristic species include the polychaetes *Nephtys cirrosa* and *Ophelia neglecta* and the crustaceans *Gastrosaccus spinifier* and *Hippomedon denticulatus*. (4) The slightly muddy sands community is characterised by relatively deep sandy bottoms (4.4 ± 2.5m) and a high distance to the ocean (10.3 ± 2.7km). The main characteristic species include the polychaete *Polycirrus glasbyi* and the crustaceans *Bathyporeia elegans*, *Diogenes curvimanus*, *Bathyporeia guilliamsoniana* and *Urothoe brevicornis*.

The results of the NMDS performed on the log-transformed abundances per sampling station in 2023 (stress = 0.16) show a clear distinction between the four communities along axis 1 with depth, currents speed and the sediment type as the key structuring abiotic factors with currents speed, depth and the coarse sand fraction negatively correlated with axis 1 coordinates and the mud fraction positively correlated with axis 1 coordinates. Locally present biogenic structures, such as *Zostera* spp. eelgrass meadows and *Sabellaria spinulosa* reefs, also appear as a key structuring parameter and show a strong positive correlation with axis 1 coordinates.

Characterisation of the macrozoobenthic subtidal communities' evolution from 1988 to 2023.

The results from the HCA performed on the Hellinger-transformed abundances of 16 stations from 1988, 2002, and 2023 show four distinct macrozoobenthic communities distinguishing sandy and muddy substrates, close to the ones found in 2023. The Slightly muddy sands community was split into two different facies from 1988 to 2023, hereafter referred to as Slightly muddy sands (A) and Slightly muddy sands (X), the former only being found from 2002 onwards.

The Muddy sediments community is associated with the shallow (3.18 ± 2.47m) internal muddy bottoms of the bay (mean distance to the ocean 9.14 ± 3.23km) and the characteristic species include Oligochaeta and the polychetes *Mediomastus fragilis*, *Notomastus latericeus* and *Spio* spp

The Mobile sands community regroups stations located in the deepest (11.5 ± 4.3m) and most dynamic parts of the bay at the entrance (0.2 ± 0.0m/s in 2023), close to the ocean (5.1 ± 3.2km). This community is characterised by sandy sediments. The main characteristic species include the crustaceans *Gastrosaccus spinifier* and *Hippomedon denticulatus* and the polychaetes *Ophelia neglecta* and *Neptys cirrosa*. This community is found from 1988 to 2023 and shows a spatial extension inwards starting in 2002.

The Slightly muddy sands (X) community is located in relatively deep (6.5 ± 4.7m) areas towards the internal part of the bay (mean distance to the ocean 8.4 ± 4.29km). It is found from 1988 to 2023, although with a reduced spatial distribution. The characteristic species include the amphipods *Urothoe* sp. and *Apherusa ovalipes*, the polychaete *Goniada emerita* and the bivalve *Tellina tenuis*.

Finally, the Slightly muddy sands (A) community is restricted to the northern part of the bay in the Ares channel (mean depth 6.5 ± 0.6m and man distance to the ocean 10.5 ± 1.7km) and is only present in 2002 and 2023. The characteristic species include the polychaetes *Polycirrus* spp. and Polyplacophora.

Results from the pluriannual NMDS (stress = 0.21) show higher variability in 2002 than in 1988 and 2023. The main environmental factors structuring the communities appear to be the sediment type and depth, whose effect is reinforced by locally present biogenic structures or engineer species such as *Sabellaria spinulosa* reefs, *Zostera* spp. meadows, or *Crepidula fornicata* beds. Results from the rarefaction curves highlight 2002 as the year with the highest observed species diversity (131 sp.), followed by 1988 (121 sp.) and 2023 (96 sp.).

The mean annual salinity showed differences between 1988, 2001 and 2022 ($p < 0.001$) with 2001 showing a significantly higher salinity than 1988 and 2022 ($p < 0.001$ and $p = 0.004$, respectively). There were no significant differences between 1987, 2001 and 2002 regarding the sea-water temperature ($p = 0.23$), Leyre river's flow ($p = 0.13$) and sediment type ($p = 0.9$). Regarding rainfalls, the only significant difference ($p = 0.01$) was for the maximum monthly rainfall in 24h (mm) between 2001 and 2022 ($p = 0.023$).

Conclusions

Four main subtidal benthic communities were identified in Arcachon Bay with fluctuating spatial extension from 1988 to 2023: the Mobile sands community, the Muddy sediments community, the Slightly muddy sands community facies A and facies X. The main structuring environmental factors appeared to be sediment type, depth and current speed, reinforced by locally present biogenic structures or engineer species. Overall, the results show moderate changes from 1988 to 2023, the main findings being the spatial extension of the mobile sands community inwards and the split of the Slightly muddy sands community into facies X and A.

The consequences of the *Zostera noltei* meadows regression on the temporal evolution of the macrozoobenthic communities need to be addressed more specifically. Indeed, Ganthy et al. (2015) showed that resuspension increased following the seagrasses regression, leading to changes in suspended matters and sedimentation rates in internal channels. The macrozoobenthic communities being largely influenced by sediment type, this raises the question of the influence of the seagrass's regression on their distribution.

This study illustrates the importance of long-term monitoring programs, especially in the context of increasing pressures on coastal habitats, both natural and anthropic. These results will need to be strengthened by additional data, both faunistic and environmental, to fully investigate the long-term temporal trajectory of the subtidal communities.

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Q&A

On the choice of the French typology over the European (EUNIS) classification

- Some habitats in the studied area are not represented in the EUNIS typology. The objective is to produce an updated habitat map for the bay, which is required for the MPA. Since the French typology has been used until now, consistency was prioritised. Both typologies were compared: EUNIS was well-suited in some cases, but in others, the French classification was a better fit.
  → This information should be reported to EUNIS and the EU to improve the system.

On benthic community vs. habitat-based approaches: it seems difficult to identify the drivers of change in your observations. Do you see structural factors that could complement your data? Are there additional parameters to consider beyond biological traits?

- During the PhD, isotopic signatures were also used. Combining these with the current dataset could be highly informative for understanding the trophic shifts observed.

On the influence of seagrass regression on benthic communities

- This hasn't been explored in depth yet, but a PhD at IFREMER focused on this issue (seagrass decline and modeling). Seagrass decline has led to significant decreases in overall benthic abundance. In areas where seagrass loss is most severe, sediment deposition rates are notably higher.

On hydrodynamic change: seagrass regression vs. broader factors

- Seagrass loss alone cannot fully explain these changes. The overall hydrodynamics of the bay have evolved, particularly at its entrance. In inner bay areas, seagrass regression has likely increased local current velocities. According to IFREMER studies, this relationship is more evident in the inner channels than at the bay's entrance.

On bay restoration strategies and priorities

- Existing studies have identified potential sites for restoration, including areas where replanting could be viable. Seed-based restoration has shown limited success.
→Predator presence might be a key factor influencing restoration outcomes.
→ Simply identifying suitable locations is not enough. We still lack critical knowledge.

On full-scale restoration feasibility

- Given the ecological importance of seagrass, it's definitely worth pursuing. However, we need to better understand the causes of its decline and address those first.

On challenges in evaluating seagrass restoration success

- To date, most, if not the only successful seagrass restorations actions involved areas with mooring buoys, where chain-based systems were replaced with less disruptive alternatives.
→ In the UK, eco-moorings were introduced, and seagrass recovery took about four years. However, success required intensive active replanting, which might not be sustainable on a larger scale.

On changes in mapping resolution from 1988 to 2023

- Yes, mapping methods have evolved. In 1988, mapping relied more on direct field observations, whereas today, we use aerial and drone-based surveys validated by field data.

On the use of trajectory analysis

- CTA (Chronological Trajectory Analysis) works well in certain cases. However, in this case, only three data points were established over time, which is insufficient for CTA to be truly effective. It was tested, but it wasn't more conclusive than other methods. It remains an interesting approach, but this project may not be the best fit for it.

Blue Carbon in the Authie estuary: Carbon sequestration and exchanges in surface sediments in a context of dyke removal

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1. Contextual introduction

Estuaries are transition areas between terrestrial and marine domains, whose abiotic parameters such as salinity, turbidity and tidal influence vary along their length (Elliott & McLusky, 2002; Potter *et al.*, 2010). Estuaries also form an ecological unity composed of diverse habitats, including saltmarshes (Interpretation manual of EU habitats, 2013). Those habitats provide numerous ecosystem services (Millennium Ecosystem Assessment, 2005; Barbier *et al*., 2011): serving as feeding and nesting sites for coastal birds (Hughes, 2004), being a nursery for fish species (Martinho *et al.*, 2007), purifying water (Hasani *et al*., 2017; Hadikhani *et al*., 2024) and participating in many biogeochemical processes (Negrin *et al.,* 2016). Especially, saltmarshes sequester carbon (Bulmer *et al*., 2020; Mazarrasa *et al.*, 2023) (i) through autochthonous input, with the burial of biomass in sediments, after atmospheric carbon absorption during photosynthesis (Mcleod *et al.*, 2011; Mason *et al.*, 2023) and (ii) through allochthonous input, with the burial of organic matter in sediments from suspended particles captured by vegetation (Mason *et al*., 2023). However, mineralization processes, such as biomass respiration or subsurface methanogenesis, constitute carbon outputs for the ecosystem (Mason *et al*., 2023). In this context, when carbon inputs exceed the outputs, the resulting upper sediment carbon pool is defined as "blue carbon" (Nellemann *et al*., 2009; Lovelock & Duarte, 2019). Depending on estimations, on a global scale saltmarshes can sequester between 4.8 and 87.2 Mt of carbon within their upper sediments (McLeod *et al.*, 2011). However, a quarter of the global area of these blue carbon ecosystems, along with the associated ecosystem services, has been lost over the two past centuries (Nellemann *et al.*, 2009; Mcleod *et al.,* 2011). This lost is mostly due to anthropogenic stressors such as the artificialization of coastal zones (Macreadie *et al.*, 2017; Bulmer *et al.*, 2020). For example, polders are coastal areas reclaimed from the sea by means of drainage and dike embankment. Although polders fulfilled many demographic and agricultural challenges of the past centuries, they are currently facing emerging concerns about climate change and sea level rise (Goeldner-Gianella, 2013; Macreadie *et al.*, 2017). Indeed, when high tidal coefficients and elevated river flows occur simultaneously, flooding is expected upstream these artificially altered areas. To address this issue, current local management plans consider removing or breaching protection dikes to facilitate rewilding and inundating these areas, but also enabling them to act as buffer zones again (PAPI - Authie, 2020). This approach allows both tidal and river flows to evolve more naturally, without threatening urbanised areas. However, the breaching of dikes induces geomorphological and ecological modifications to the newly rewilded zones, subsequently impacting carbon sequestration processes (Wolters *et al.,* 2005; Garbutt & Wolters, 2008; Spencer *et al.,* 2008; Burden *et al.,* 2019; Cahoon *et al.*, 2019).

The Authie estuary, located in the North of France (Fig. 1), is the subject of a planned dike removal, although the implementation timeline is yet to be determined and this process is unlikely to occur for several years. In the meantime, the fluxes and stocks of carbon throughout the ecosystem can be assessed in preparation for this transition, that can be summarised through important scientific concerns: what are the actual carbon fluxes in the various sediment facies of the Authie estuary? How is the sediment carbon pool characterized in an unaltered saltmarsh within the Authie estuary?

Here, preliminary results of lipid biomarkers from a saltmarsh sediment sample in an unaltered zone of the Authie estuary are investigated. The objectives are to (i) identify the repartition of organic carbon source type within allochthonous or autochthonous inputs and (ii) identify more precisely the sources of this organic carbon.

2. Methodology

Site location

This study was conducted in the saltmarsh of the Authie estuary (Fig. 1), in the region of Hauts-de-France (Fig. 1). Samples of subsurface sediment and two typical plants of the studied site, *Halimione portulacoides* and *Puccinellia maritima*, were collected jointly in April 2019.

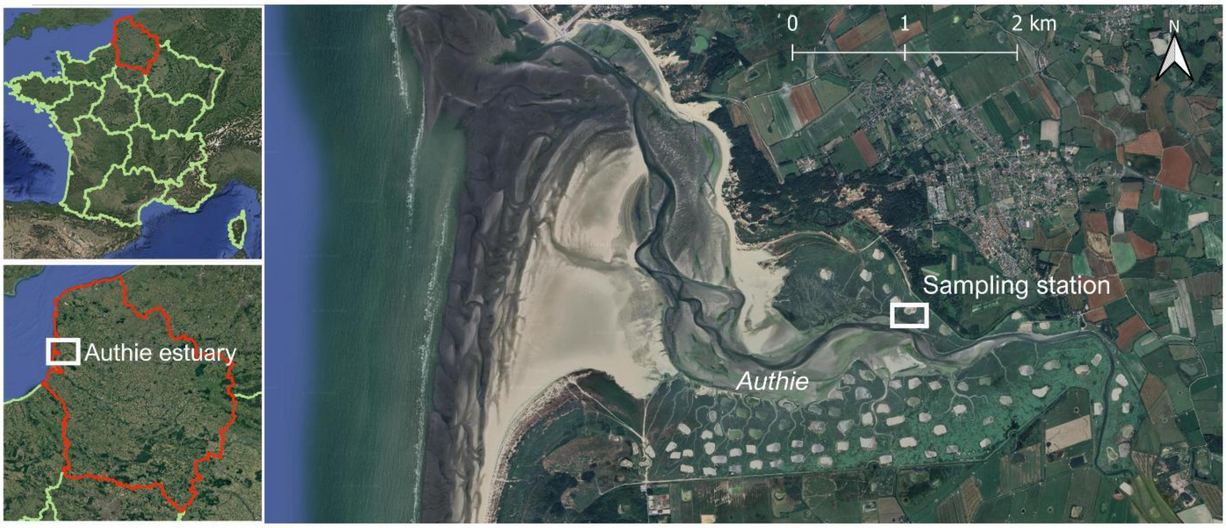

Figure 1. Location of the sampling station in the Authie estuary (region Hauts-de-France).

Sediment organic carbon: a molecular organic geochemical approach (lipid biomarkers)

A molecular biomarker is defined as "a complex organic compound having little to no changes in its chemical structure" compared to the molecules that once existed in living organisms (Derrien *et al*., 2017). Basically, lipids are organic molecular compounds synthesised by living organisms, and are not easily degraded by microbial activity after organisms death (Carreira *et al.*, 2016). Thereby, lipid biomarker features may be used to identify organic matter sources and biogeochemical processes associated with sedimentary organic matter remineralization (Chevalier *et al*., 2015; Derrien *et al.*, 2017). Thus, different main groups of lipids can be investigated, based on their chemical properties: *n*-alkanes (hydrocarbons), sterols, alcohols and fatty acids. Some of these compounds are associated with specific sources (Carreira *et al*., 2016). For example, within hydrocarbon fraction, short-chain *n*-alkanes (≤ C21) are typical of aquatic inputs (marine and freshwater phytoplankton), whether long-chain *n*-alkanes (≥ C27) are synthesised by terrestrial vascular plants (Chevalier *et al.,* 2015).

First, lipids are extracted from all samples using a mixture of organic solvents. Then, three fractions of lipids are analysed: hydrocarbons, alcohols/sterols and fatty acids (FAs). For each lipid fraction, a step of separation using silica chromatographic column is carried out before the analyses on Gas Chromatography-Mass Spectrometry (GC-MS). Results from the two plant samples are used as reference lipid signature for the sediment sample.

3. Results

In the three studied lipid fractions (*n*-alkanes, alcohols/sterols and FAs) sediment sample, short chain molecules are detected in very low abundance such as C17 *n*-alkane (Fig. 2), C14 *n*-alcohol and C13 FA. Conversely, long chain molecules such as C27 and C29 *n*-alkanes (Fig. 2; Table 1), C28 *n*-alcohol and C28 FA (Table 1), are detected in higher abundance. Thereby, each of the three lipid fractions indicates a low contribution of aquatic organisms and a high contribution of terrestrial higher plants in the sedimentary organic carbon pool of the Authie saltmarsh.

Note that a large number of bacterial-specific FAs, such as *iso-/anteiso*-C15, unsaturated C16:1, C17:1 and C18:1 FAs, are detected in high concentrations, suggesting significant bacterial activity linked to the remineralization of organic matter in the saltmarsh sediments.

Interestingly, some of the studied lipids present in sediments are detected only within one of the two studied plants (*H. portulacoides* and *P. maritima*). The stigmastan-3,5-dien, specific of *H. portulacoides,* is more abundant (1.08 µg.g−1 dw) in sediments than the C33 *n*-alkane (0.56 µg.g−1 dw), specific of *P. maritima* (Fig.2; Table 1). The situation is similar for the alcohol/sterol results: two typical alcohols from *H. portulacoides* (C22 and C24 *n*-alcohols), are detected in higher concentrations (2.20 µg.g−1 dw and 2.69 µg.g−1 dw, respectively) than the Campestanol, a typical stanol from *P. maritima* (1.77 µg.g−1 dw) (Table 1). This suggests the relative predominance of *H. portulacoides* in sedimentary organic carbon pool, compared to *P. maritima*.

Furthermore, other lipids are produced in different quantities by both plants. For example, the C27 *n*-alkane is produced at a concentration of 19.5 µg.g−1 dw in *P. maritima* and 68.7 µg.g−1 dw in *H. portulacoides*. The proportion is inverted in each plant for C31 *n*-alkanes: 58.1 µg.g−1 dw for *P. maritima* and 3.8 µg.g−1dw for *H. portulacoides*. With a similar approach, C28 *n*-alcohol is more abundant in *H. portulacoides* (95.4 µg.g−1 dw) than in *P. maritima* (5.3 µg.g−1 dw; Table 1). The case is inverted for Campesterol, with concentrations of 276.7 µg.g−1 dw for *P. maritima* and 48.2 µg.g−1 dw for *H. portulacoides* (Table 1). Eventually, for the FAs, the C20 FA was found in high abundance in *P. maritima* (249.4 µg.g−1 dw), compared to *H. portulacoides* (154.8 µg.g−1 dw). Conversely, the C28 FA is detected in high abundance in *H. portulacoides* (1730.8 µg.g−1 dw) and in low abundance in *P. maritima* (203.9 µg.g−1 dw).

Hence, the establishment of concentration ratios such as $\frac{C27\ n-alkane}{C31\ n-alkane}$, $\frac{C28\ n-alcohol}{Campesterol}$ and $\frac{C28\ FA}{C20\ FA}$, allows the characterization of both studied plants relative contribution in sediment organic carbon accumulation. Calculated ratios are respectfully 1.5, 6.5 and 10.9, which seems to confirm a large predominance of *H. portulacoides* in organic carbon inputs, compared to *P. maritima*, in the sediments of the Authie saltmarsh.

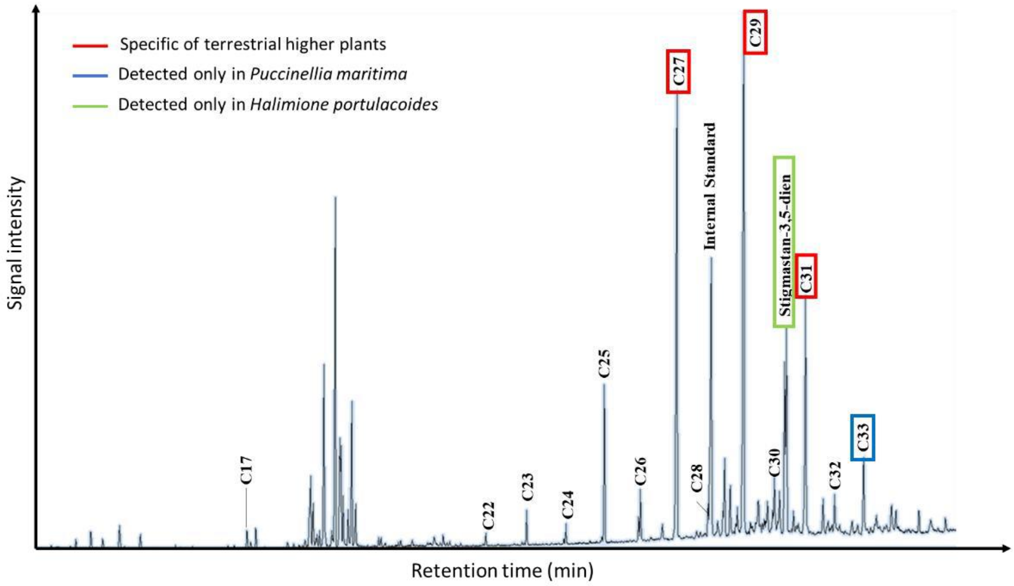

Figure 2. A GC-MS chromatogram of the hydrocarbon fraction extracted from the surface sediment sample in the saltmarsh of the Authie estuary.

	Sediment sample	*Puccinellia maritima*	*Halimione portulacoides*
n-alkanes	Molecular component concentration (µg. g^{-1}dw)		
C27	2.318	19.5	68.701
C29	2.968	49.059	37.418
stigmastan-3.5-dien	1.076	NA	15.848
C31	1.503	58.143	3.763
C33	0.56	43.093	NA
Alcohols/sterols	Molecular component concentration (µg. g^{-1}dw)		
C22-OH (I)	2.2	NA	5.77
C24-OH (I)	2.69	NA	10.01
C28-OH (I)	14.908	5.261	95.378
Campesterol	2.307	276.704	48.223
Campestanol	1.765	1.468	NA
Fatty acids (FAs)	Molecular component concentration (µg. g^{-1}dw)		
C20 FA	3.542	249.38	158.411
C28 FA	35.168	203.85	1730.793

Table 1. Concentrations of specific lipid biomarkers for the sediment sample of the saltmarsh of the Authie estuary and for the terrestrial higher plants P. maritima and H. portulacoides.

4. Conclusion and perspectives

Here, we present preliminary results from the characterization of organic content in saltmarsh sediments using a lipid biomarker approach to identify major sources of the organic carbon pool in the Authie estuary. This study shows that terrestrial higher plant inputs largely exceed aquatic inputs. Moreover, it has been determined that a majority of lipids found in the sediment is associated with Halimione portulacoides, among saltmarsh typical species. This provides a first understanding of the carbon pool within the Authie saltmarsh sediments. As this estuary is expected to undergo dike removal in the coming years, this study serves as a prerequisite for further evaluations of the impacts of such modifications on the saltmarsh.

To complete this saltmarsh carbon budget, "instantaneous" carbon fluxes may be investigated. Its calculation requires the quantification of fluxes during emersion (gaseous flux at light and at dark) and during immersion (dissolved fluxes always dark due to water turbidity). In order to monitor carbon fluxes ($CO_2$and CH_4) during emersion, benthic chamber will be used (Voltz, 2020). For fluxes at the sediment-water interface, cores sampled at low tide will be incubated in the laboratory, with overlying water from the site (Denis & Grenz, 2003) for determination of Dissolved Inorganic Carbon (DIC) exchanges. The combination of both approaches could help accurately quantify the carbon pools and exchanges in the saltmarshes of the Authie estuary, as well as the potential changes resulting from expected estuarine management such as dike removal or breaching, followed by rewilding.

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Q&A

On complementarity between approaches: you and A.Tauran (previous presentation) used very different approaches—do you think they could complement each other?

- Absolutely. The goal is to understand the ecological transition that will occur once the dyke is removed, and ideally, anticipate its effects. Currently, baseline conditions are being characterised so that future changes can be properly assessed.

On lipid profile variations and sterol-to-acid ratios:

- These differences appear to be linked to species morphology. Root and stem tissues do not exhibit the same biochemical signatures. It likely reflects physiological traits specific to each species.

On investigating plant or sediment age:

- The primary objective is to quantify carbon pools rather than date them. However, if deeper sediment layers are analysed, dating could become relevant.

On the selection of plant species for lipid analysis:

- These two species are dominant in the ecosystem, so they were the logical starting point. The expansion of the analysis is planned to include a broader range of species in future studies.

On local community perception of the dyke removal project:

- Without speaking on their behalf, it's certainly an important question that deserves further exploration.

SESSION 3 – LATEST ADVANCEMENTS IN SEDIMENTARY HABITATS MONITORING METHODS

DERNIÈRES AVANCÉES DANS LES MÉTHODES DE SURVEILLANCE DES HABITATS SÉDIMENTAIRES

Session moderator – *Animateur de session*: **Hugues Blanchet,** Oceanic and Continental Environments and Paleoenvironments (EPOC), University of Bordeaux, France

Access the presentations from this session here – *Accédez aux présentations de cette session ici.*

The continuous evolution of monitoring techniques for sedimentary habitats is essential for understanding and managing these dynamic ecosystems. This session brings together three approaches that enhance our ability to assess conservation status, analyse biodiversity, and interpret ecosystem functioning in marine sedimentary environments.

The first presentation, by **Laura Meudec** (Réserves Naturelles de France, France), focuses on the development of a standardized methodology for monitoring the conservation state of intertidal sedimentary habitats in French Marine Protected Areas. Initiated in 2007 and further refined under the Life Marha program, this method aligns with key European directives, such as the Water Framework Directive and the Marine Strategy Framework Directive. The study highlights the importance of harmonized

L'évolution constante des techniques de surveillance des habitats sédimentaires est essentielle pour comprendre et gérer ces écosystèmes dynamiques. Cette session rassemble trois approches qui améliorent notre capacité à évaluer l'état de conservation, analyser la biodiversité et interpréter le fonctionnement des écosystèmes dans les environnements sédimentaires marins.

La première présentation, par **Laura Meudec** (Réserves Naturelles de France, France), se concentre sur le développement d'une méthodologie standardisée pour le suivi de l'état de conservation des habitats sédimentaires intertidaux dans les Aires Marines Protégées françaises. Initiée en 2007 et affinée dans le cadre du programme Life Marha, cette méthode s'aligne sur les principales directives européennes, telles que la Directive-cadre sur indicators and proposes a structured approach to habitat assessment, paving the way for more effective management strategies.

The second presentation, by **Vincent Bouchet** (Univ. Lille, France), explores the functional diversity of benthic foraminiferal communities in soft-sediment habitats of the Eastern English Channel. By moving beyond traditional taxonomy-based assessments, this study reveals surprising insights into how natural and anthropogenic stressors shape community composition and ecosystem resilience. The findings challenge conventional assumptions about biodiversity loss in industrialised coastal areas, emphasizing the need for new approaches to differentiate human-induced impacts from natural variability.

Finally, **Eric Thiébaut** (Station Biologique de Roscoff, France) presents an innovative application of DNA-based methodologies for long-term monitoring of macrobenthic communities. By comparing high-throughput sequencing techniques with traditional morphology-based identification, this study demonstrates the potential of molecular tools to improve biodiversity assessments. The results from a fine-sand habitat in Morlaix Bay contribute to ongoing efforts to integrate genomic observatories into marine monitoring frameworks, offering a promising path toward more efficient and comprehensive ecosystem evaluation.

Together, these studies illustrate how advancements in methodology - from standardized monitoring protocols to functional trait analysis and genomic approaches - are transforming our ability to assess and protect sedimentary habitats. They also highlight the challenges and opportunities that come with implementing these new techniques in real-world conservation and management efforts.

l'Eau et la Directive-cadre sur la Stratégie pour le Milieu Marin. L'étude souligne l'importance de disposer d'indicateurs harmonisés et propose une approche structurée de l'évaluation des habitats, ouvrant la voie à des stratégies de gestion plus efficaces.

La deuxième présentation, par **Vincent Bouchet** (Univ. Lille, France), explore la diversité fonctionnelle des communautés de foraminifères benthiques dans les habitats sédimentaires meubles de l'est de la Manche. En allant au-delà des évaluations traditionnelles basées sur la taxonomie, cette étude révèle des informations surprenantes sur la façon dont les facteurs de stress naturels et anthropogéniques façonnent la composition des communautés et la résilience des écosystèmes. Les résultats remettent en question les hypothèses conventionnelles sur la perte de biodiversité dans les zones côtières industrialisées, soulignant le besoin de nouvelles approches pour différencier les impacts induits par l'homme de la variabilité naturelle.

Enfin, **Eric Thiébaut** (Station Biologique de Roscoff, France) présente une application innovante des méthodologies basées sur l'ADN environnemental (eDNA) pour la surveillance à long terme des communautés macrobenthiques. En comparant les techniques de séquençage à haut débit avec l'identification traditionnelle basée sur la morphologie, cette étude démontre le potentiel des outils moléculaires pour améliorer les évaluations de la biodiversité. Les résultats obtenus dans un habitat de sable fin de la baie de Morlaix contribuent aux efforts en cours pour intégrer cette nouvelle méthodologie dans le cadre des dispositifs de suivi environnemental, offrant ainsi une voie prometteuse vers une évaluation plus efficace et plus complète des écosystèmes.

Ensemble, ces études illustrent la façon dont les progrès méthodologiques - des protocoles de surveillance normalisés à l'analyse des traits fonctionnels et aux approches génomiques - transforment notre capacité à évaluer et à protéger les habitats sédimentaires. Elles mettent également en évidence les défis et les opportunités liés à la mise en œuvre effective de ces nouvelles techniques dans le cadre d'efforts de conservation et de gestion.

Monitoring conservation state of French intertidal sedimentary habitats

Laura Meudec, Emmanuel Caillot

Réserves Naturelles de France

Keywords: Intertidal sedimentary habitats, macrofauna, monitoring, trajectories, Ecological Quality Assessment, Natura 2000 areas

Contextual introduction

In order to monitor the conservation state of intertidal sedimentary habitats, and therefore adapt their management practices, marine protected area managers, with the support of Réserves Naturelles de France (RNF) and the Observatoire du Patrimoine Naturel Littoral (OPNL), designed a protocol in 2007. This protocol is similar to the one used to survey the French water bodies according to the Water Framework Directive, but it has been specifically designed to survey the major habitats within protected areas. In 2021, RNF joined the Life Marha program, which principal objective is to restore and maintain a good conservation status of marine habitats with all the operators engaged in the management of Natura 2000 areas. As an associate beneficiary, RNF has been committed to elaborate a method to evaluate the conservation state of intertidal sedimentary habitats. This work would also should be included in existent directives such as the Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD) and the Habitat Directive. In coordination with marine area managers, multiple objectives were set: (1) designing “station sheets” to resume the variation of principal parameters at each station and facilitate the definition of habitats according to national and European typologies, (2) compute and compare the results of existing indicators, and (3) define a method to evaluate conservation state with pertinent indicators with the assistance of a dedicated working group.

Methodology

The intertidal sedimentary habitats monitoring network is composed of 13 sites in France (Fig. 1). Contributors conduct the survey protocol every year around October 15th (Caillot & Hacquebart, 2012). Sediment samples are collected in the field by local managers and analysed in the lab for organic matter quantification, grain size and macrofauna identification.

Concerning numerical analysis, the first step was to identify habitats according to the national habitat typology (Gayet *et al.,* 2018; Michez *et al.,* 2019) using primary parameters at each station: species composition and abundance, sediment texture, organic matter percentage and species richness. Then, existing ecological indicators were tested to assess their relevance for evaluating the conservation state of intertidal sedimentary habitats: the AZTI’s Marine Biotic Index (AMBI) (Borja *et al.,* 2000), the Multivariate-AZTI’s Marine Biotic Index (M-AMBI) (Borja *et al.,* 2008a), the Benthic Ecosystem Quality Index adapted for French estuaries (BEQI-FR) (Fouet *et al.,* 2018), and the General-Purpose Biotic Index (GPBI) (Labrune *et al.,* 2021). Finally, a working group was built up to identify the appropriate method for evaluating the conservation state of these habitats. The first approach tested was the Ecological Quality Assessment (EQA) method (Sturbois *et al.*, 2023), coupled with the selected existing indicators: AMBI, M-AMBI, BEQI-FR, GPBI, and sediment texture according to Folk (1954). This technique allowed to determine a reference envelope, here the first five years at each station, and to assess whether the following points are included in this envelope. Indicators are then used to explain the "out" points.

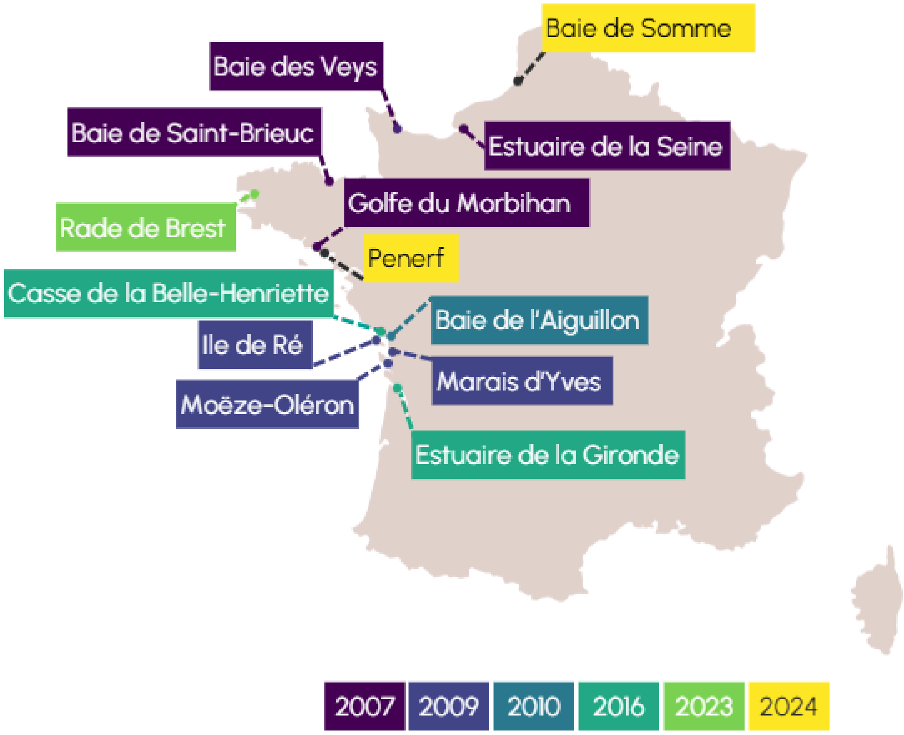

Figure 1: Map of the sampling sites and the year of their first participation (France)

Results

The analysis of the general parameters at each station allowed the identification of 16 habitats according to the NatHab-Atl habitat typology. Five of these habitats are represented in the two coastlines monitored (English Channel-North Sea and Atlantic Ocean), which allows inter-site comparison whereas habitats reduced in terms of spatial extent, enable to study regional specificity. Ecological indicators were computed and major differences in the results were found between indicators based on a pre-classification of species (AMBI, M-AMBI and BEQI-FR) and the GPBI one.

Concerning the method for evaluating conservation state, the first results of the EQA method paired with indicators was considered as promising by the dedicated working group. It allowed the identification of stations with points outside the reference envelope: 72% of the stations presented at least one point "out". The method also allowed determining the type of change: 27% presented a directional change, 45% were concerned by isolated points, 18% presented an exceptionally high variability and 9% were alternating between two identified states. In 40% of cases, indicators were able to give insights to why points ranged outside the reference envelope, revealing that supplementary indicators may have to be used to have a complete understanding of these processes.

Conclusion

The methodology developed here gives promising results for evaluating conservation states of intertidal sedimentary habitats. Further developments are required to improve the method: (1) studying the particular case of stations located in *Zostera noltei* habitats, (2) testing new indicators to better understand state/pressure relations, and (3) promote this method by building and distributing a support adapted to managers, with the contribution of the dedicated working group.

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Q&A

On EUNIS classification and station homogeneity:

- Level 3 was chosen based on the requirements of MPAs. Ongoing verifications are being conducted to ensure the homogeneity of substations. If needed, the protocol will be adjusted with managers.

On considering environmental pressures:

- No direct pressure data, only feedback from managers. After analysing the results, these aspects will be further explored with them.

On the choice of the five-year reference period:

- Five years were chosen to smooth interannual variability. A rolling five-year window approach could be considered, comparing each period to the next to better track changes. The goal is to observe changes rather than fix a reference point.

On the need for a reference site and the limitations of the approach:

- Finding a true reference site is difficult, as it requires the same habitat under different pressures. Defining a baseline remains a key but complex challenge.

On expanding the study to other biological groups (birds, macrofauna, etc.):

- Possibly in the future, but today, the protocol does not allow for establishing clear cause-and-effect relationships (e.g., does more macrofauna imply fewer birds?).

Beyond taxonomy: alpha and functional diversity of benthic foraminiferal communities in coastal soft-sediments in the Eastern English Channel

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Introduction

Marine sedimentary habitats in coastal and transitional areas are located at the interface between sea and land. Under the influence of both marine and freshwaters, these fragile ecotones are characterised by strong environmental gradients and high variability of physico-chemical parameters (e.g. salinity, temperature, oxygen; Elliott and Quintino, 2007). In addition, they can be naturally enriched in organic matter (Pusceddu et al. 2003). Transitional waters therefore appear as naturally stressed environments (Elliott and Quintino 2007) much more selective than classic terrestrial ecotones. Representing at least 13% of the world's coastline (Nixon 1982), they provide key ecosystems services such as habitat and food resources for migratory birds (Munari and Mistri 2012) and nursery habitats for juvenile fish species of high commercial value (e.g., eels, flatfishes; Beck et al. 2001, Couturier et al. 2007). They are, however, exposed to high levels of anthropogenic stresses such as aquaculture, habitat destruction, urban sewage and industrial activities (Dauvin et al. 2007, Bouchet and Sauriau 2008, Armynot du Chatelet et al. 2011).

In these areas, benthic communities' distribution patterns are largely constrained by environmental conditions (Rosenberg et al. 2002, Gröger and Rumohr 2006), in particular by changes related to human activities and climate (Gray et al. 1990, Hyams-Kazphan et al. 2009). Benthic foraminifera is one of the most abundant meiobenthic groups, representing up to 50% of the benthic eukaryotic biomass in coastal sediments (Moodley et al. 2000). Benthic foraminifera are recognized as indicators of human-induced stress (Alve 1995, Arieli et al. 2011), such as oil spills (Morvan et al. 2004), heavy metals (Cavaliere et al. 2021), urban sewage (Melis et al. 2019), and aquaculture (Bouchet et al. 2020). In complement to species richness, alpha diversity (the diversity of species within a particular area or ecosystem) and abundance, benthic foraminiferal trait-based approach may help capturing key changes in environmental conditions that taxonomic-based studies do not record (Cleary and Renema 2007, Hansen et al. 2023).

In this context, the main objective of the FORAM-Indic project, funded by the Artois-Picardie and Seine-Normandie water agencies, was to characterize the benthic communities of marine coastal and transitional sedimentary habitats along the coast of Normandy and Hauts-de-France in the eastern English Channel to understand the spatial distribution patterns of benthic foraminifera in both natural and heavily human-modified coastal water bodies. This was achieved by applying the Biological Traits Analysis (BTA) approach to benthic foraminifera. While the biological traits approach is already well-known for macroinvertebrates, it is barely used for foraminifera. This study was among the first to apply the BTA framework recently developed benthic foraminifera (Guy-Haim and Bouchet 2025).

Material and Methods

A total of 34 stations were sampled at seven sites in the eastern English Channel along French coasts (Fig. 1). Three sites were considered as more or less pristine areas moderately influenced by human activities, i.e. the Bay of Veys (BV), the Orne River (O) and the Authie Estuary (AE). The five other sites were harbours and were considered as water bodies heavily modified by human activities (WFD 2000/60/EC), i.e. Caen-Ouistreham (CO), Le Havre (LH), Calais (CL), and Dunkerque (DK). For all sites, more detailed informations can be found in Pavard et al. (2023). All stations of sites considered as less impacted outside harbours were sampled in intertidal environment. All stations from harbours were sampled in shallow subtidal environment (maximum depth: 18 m) and the station LH1 in Le Havre that were sampled in intertidal environment.

Sediment was sampled for grain size (n = 1), CHN analysis (n = 3), Chlorophyll-a (n = 3) and element trace metals (n = 1). Details on sediment samples processing can be found in Pavard (2023). A Principal Component Analyses (PCA) was performed on mean-centered data of environmental parameters to see how environmental parameters discriminated the stations of the study.

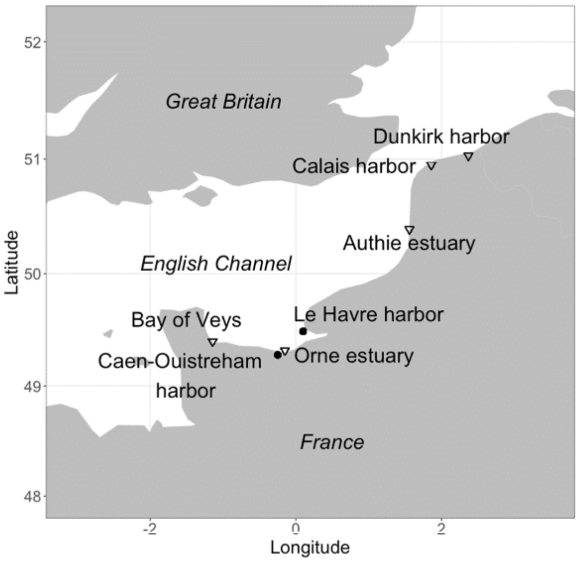

Figure 1: Location of sampled sites in the eastern English Channel (top right) and stations sampled in sites: Bay of Veys (BDV), Caen-Ouistreham harbor (C), Orne estuary (O), Le Havre harbor (LH), Authie estuary (A), Calais harbor (CL) and

Three replicates were taken for benthic foraminifera analysis from the 0-1 cm surface sediment layer (Reineck corer for subtidal or handcorer for intertidal). When possible, at least 300 individuals (all species included) were collected and identified for each sample for statistical validity. To describe the alpha diversity in foraminiferal assemblages, Exp(H'bc) was used (Hill 1973, Chao and Shen 2003). Based on the newly published BTA framework for benthic foraminifera (Guy-Haim and Bouchet 2025), a species x traits matrix was built using fuzzy-coding. To quantify the functional diversity, the functional dispersion (FDis), which measures the maximum functional distance between any two species in the community (Laliberté et al. 2014), was calculated.

All analyses were performed with R 4.4.1 'Race for Your Life'.

Results

The first axis of the PCA mainly discriminates stations according to the proportion of silt, TOC and TN contents in the sediment and concentrations of some trace metals (Fe, Ni and V) and explains 54.9% of the variability between stations (Fig. 2). The second axis explains 24.4% of the variability of stations mainly following C:N and two trace metals, Ti and Zn (Fig. 2).

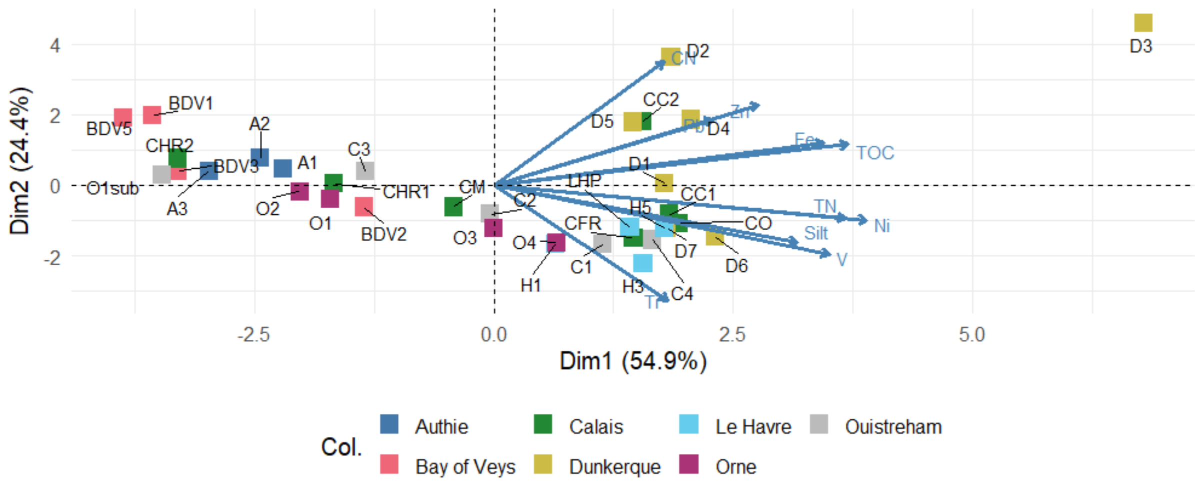

Figure 2: Principal Component Analysis of selected mean-centered environmental parameters among stations. Sites of stations are represented by colors. Two first dimensions of the PCA respectively explained 54.9 and 24.4% of the station variability.

The diversity index Exp(H'bc) (Fig. 3) greatly varied from 2.2 ± 0.6 (BDV2) to 15.9 ± 3.1 (O1sub) in this study. However, this great variation was not reflected at the site scale where only a single significant difference (Dunn, p < 0.5) was observed for this index between the Authie estuary (9.7 ± 1.5) and the bay of Veys (6.4 ± 1.2).

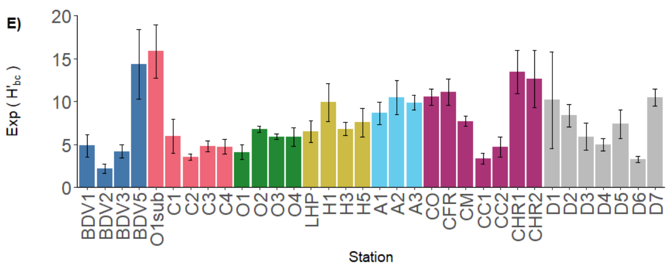

Figure 3: Mean ± sd of Exp(H'_{bc}) index of foraminiferal species assemblages by station. Colors indicate the site of the station (legend: see Fig. 2).

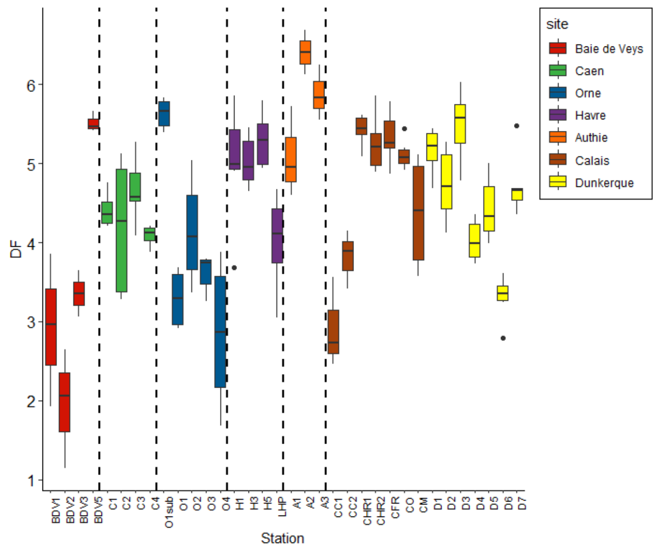

Figure 4: Boxplots of functional diversity at each sampling stations.

It is difficult to identify any specific trend in the functional diversity. Except for the Bay of Veys which exhibits a lower functional diversity, natural and anthropized sites tend to have similar values.

Discussion and conclusions

Silt proportion, TOC and TN contents and a major part of trace metals mainly contributed to explain the discrimination of stations in the English Channel. The first cluster included mostly natural stations, from the Bay of Veys and the two small estuaries of Orne and Authie. The second and the third clusters were respectively composed of stations from harbors in their semi-enclosed and industrialised basins. It is not astonishing to find marinas stations in the second cluster (e.g. LHP, CO, CM, D6,) as these areas are disturbed by the increasing activity of recreational boating. Finally, stations from the last cluster had more specific environmental conditions. Highest concentrations in trace metals and TOC contents at these stations were mainly explained by their location in very industrialised basins, separated from the sea by sluices in Dunkerque and Calais harbors, respectively third and fourth French harbors in terms of freight.

Alpha diversity is known to be influenced by surrounding environmental conditions, especially organic carbon (Pearson and Rosenberg 1978). Although we observed differences in the abiotic parameters between the natural and anthropized sites, we did not observe any clear trends with the alpha diversity. Indeed, species assemblages of naturally stressed environments, like the transitional areas where we sampled, appeared to be similar to those of anthropogenic stressed environments, although the species composition may be different. It made it impossible to decipher the effect of environmental stressors, either natural or anthropogenic, on the alpha diversity i.e. index exp(H'bc), which well-illustrated the concept of the Estuarine Quality Paradox (Elliott and Quintino 2007, Dauvin and Ruellet 2009). It confirms the known challenge of differentiating between the effect of nature and human on the diversity of benthic communities in transitional environments.

Our results showed that the functional diversity of natural coastal areas is comparable to that of harbors ones, despite the latter being heavily impacted by human activities. The functional diversity of foraminifera is high, but it cannot be directly compared to another since there are only two studies on the functional trait approach in foraminifera (Cleary and Renema 2007, Hansen et al. 2023). These studies aimed to characterize assemblages based on biological traits. However, they did not strictly calculate functional diversity.

Where does the observed high functional diversity in harbors come from, given that they are supposed to be unfavorable environments for pelagic and benthic species due to high pollution levels? Two hypotheses could provide an answer to this question. Firstly, although species may be lost because of the presence of the harbor, functional diversity may not be affected, as observed in the port of Mumbai in India (Dias et al. 2023). In other words, even if the number of species decreases, biological traits may be maintained as well as the functioning of the ecosystem (Dias et al. 2023). However, this does not seem to be the case in this study, since we observed that alpha diversity was similar in natural sites as in the polluted harbor sites. The second hypothesis is that the modification of the ecosystem due to the establishment of harbors allowed pre-existing species to survive and to further settle more effectively. Additionally, the arrival of non-indigenous species (NIS) introduced a whole new range of functional traits and diversity. In theory, these new traits can degrade, maintain, or improve the newly established ecosystem. It has been shown that the combined activity of native and non-native species can promote better regeneration of tropical forests, suggesting that a species' function is more important than its identity (Catterall 2016).

To conclude, the present study's findings are promising, showing (i) the relevance of developing the BTA approach for benthic foraminifera, and (ii) the urgent need for studies to understand the pressure driving the functional diversity of soft-sediment coastal areas, particularly in harbor ecosystems, which remain largely understudied. Furthermore, coastal urban ecology is an emerging field of research that requires a substantial effort in order to understand better the ecology of such modified ecosystems, particularly of marine sedimentary habitats.

Acknowledgements

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Q&A

On the impact of hydrodynamics and flooding on the studied stations:

- Ports are more sheltered, but since they are often located in estuaries, they can also be subject to flooding. That said, their conditions remain different from natural estuaries, which can influence observations.

On the biological traits and functions of foraminifera:

- For certain species, their role in bioturbation is known, but overall, knowledge of functional traits remains limited. We have a rough idea of their diet, but not enough to precisely characterize their function in the ecosystem.

The use of DNA-based methodologies for the long-term monitoring of macrobenthic communities: insights from a fine sand community in the Bay of Morlaix, France

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Introduction

In the current context of increasing global anthropogenic environmental disturbances of coastal marine ecosystems, there is an increasing demand to inventory marine biodiversity, depict the spatio-temporal dynamics of communities and assess the ecosystem health. Traditionally, such biodiversity assessments and biomonitoring are implemented using morphology-based methodologies. These rely on the identification and count of hundreds to thousands of specimens per sample which are extremely time-consuming and require a taxonomic expertise which tends to decline in most laboratories. Furthermore, they do not provide access to parts of the biodiversity that are less accessible (e.g. cryptic diversity). Recently, the rapid development of high-throughput sequencing technologies enables the use of DNA-based methodologies as a potential alternative to traditional morphology-based methodologies (Cordier et al., 2021). These methods are expected to be faster, more objective, robust and cost-effective tools.

In marine systems, DNA-based methodologies (i.e. metabarcoding, metagenomics and metatranscriptomics) have been applied to different taxonomic groups (e.g. micro-organisms, invertebrates, fish) and habitats (e.g. water column, hard substrate, sediment). DNA is either directly extracted from an environmental sample such as water or sediment (i.e. eDNA) or from preprocessed samples (i.e. bulk DNA) (Pawlowski et al., 2022). Although several pilot studies have highlighted the potential of DNA for biodiversity monitoring, some technical limitations and conceptual issues have hampered the routine deployment of these methods and its application by end-users (see Pawlowski et al., 2022 for soft sediment). In this context, the European Marine Omics Biodiversity Observation Network (EMO-BON) has been launched in 2021 to promote a pan-European, centrally coordinated network of genomic observatories along European coasts following standardized protocols (Santi et al., 2023; 2024). The present paper shows preliminary results from the bulk DNA monitoring of a benthic community from a fine sand habitat in Morlaix Bay (English Channel, France) initiated in September 2021. The relevance of bulk DNA is discussed by analysing results provided jointly by traditional morphology-based approaches and metabarcoding.

Materials and methods

Samples were collected at the Pierre Noire station (48°42,50’N; 3°51,96’W), one long-term monitoring site of benthic communities which have been surveyed since 1977 in the Bay of Morlaix (western English

Channel). This station is currently a reference station in the French monitoring programme of benthic macrofauna according to Water Framework Directive. It harbors a fine sand benthic community dominated by polychaetes and amphipods (Dauvin, 1998). Since September 2021, samples have been collected twice a year in early autumn (i.e. September-October) and end of winter (i.e. February-March) using a Smith-McIntyre grab. Ten replicates were sampled for the analysis of the community structure based on morpho-taxonomic approaches while three additional replicates were collected for the analysis of bulk DNA. All samples were sieved through a 1 mm circular mesh sieve. The three samples dedicated to the bulk DNA analysis were pooled together and DNA was extracted from two 10 mL sub-samples using the commercially available Quick-DNA Fecal/soil kit (Zymo Research). For each extract, a region of the cytochrome c oxidase subunit I (COI) gene was amplified using mlCOIintF and jgHCO2198 primers (Leray et al., 2013). Detailed description of the sampling protocol, DNA extraction and DNA sequencing is provided in Santi et al. (2024).

Data were processed using nf-core/ampliseq version 2.11.0 (Straub et al., 2020) of the nf-core collection of workflows (Ewels et al., 2020), utilizing reproducible software environments from the Bioconda (Grüning et al., 2018) and Biocontainers (da Veiga Leprevost et al., 2017) projects. Data quality was evaluated with FastQC (Andrews, 2010) and summarized with MultiQC (Ewels et al., 2016). Cutadapt trimmed primers (Martin et al., 2011) and all untrimmed sequences were discarded. Sequences that did not contain primer sequences were considered artifacts. Adapter and primer-free sequences were processed initially independently, but re-examined as one pool (pseudo-pooled) with DADA2 (Callahan et al., 2016) to eliminate PhiX contamination, trim reads, discard reads with > 2 expected errors, correct errors, merge read pairs, and remove polymerase chain reaction (PCR) chimeras. Between 53.59% and 82.57% reads per sample (average 74.5%) were retained. Taxonomic classification was performed by DADA2 with a user provided database. ASVs were clustered into Operational Taxonomic Units (OTUs) using Swarm v3 with d=6 (Mahé et al., 2022). OTUs with less than 25 reads for all samples were excluded. The taxonomic assignment of the representative sequences of each OTU was performed using Vsearch V2.18.0 with a 0.8 similarity score and MIDORI2 - Version261, a reference database of Eukaryota mitochondrial DNA sequences (Leray et al., 2022).

Results

For the 4 sampling dates between 2021 and 2023, the number of reads per sub-sample varied between 1.66 and 6.69 million (mean value: 4.89 million). A total of 7606 different ASVs were identified. After Swarm clustering and removal of rare OTUs, only 1095 OTUs remained, most (i.e. 1009) being assigned. As the aim of the present study was to compare metabarcoding data with morphospecies data on benthic macrofauna collected in the fine sand community, OTUs from non-metazoan eukaryotes (e.g. macroalgae), meiofauna taxa (e.g. Nematoda) and sessile epifauna taxa (e.g. Hydrozoa) were removed; 184 OTUs were assigned to macrobenthic infauna and vagile epifauna including 140 OTUs assigned at the species level. Among them, 94 OTUs (i.e. 51%) were assigned to one of the 540 species observed at least once at the Pierre Noire station since 1977. In some cases, multiple OTUs were assigned to the same species. Whatever the sampling date, the two most abundant phyla were Annelida and Mollusca (Figure 1). The 10 dominant OTUs were assigned to the polychaetes *Nephtys hombergii*, *Paradoneis armata* and *Diplocirrus seisuaiae*, the ophiuroids *Amphiura filiformis* and *Acrocnida brachiata*, the bivalve *Nucula nitidosa*, and one unknown Polychaeta. All these species are common at Pierre Noire except *Diplocirrus seisuaiae* recently described from Japanese waters.

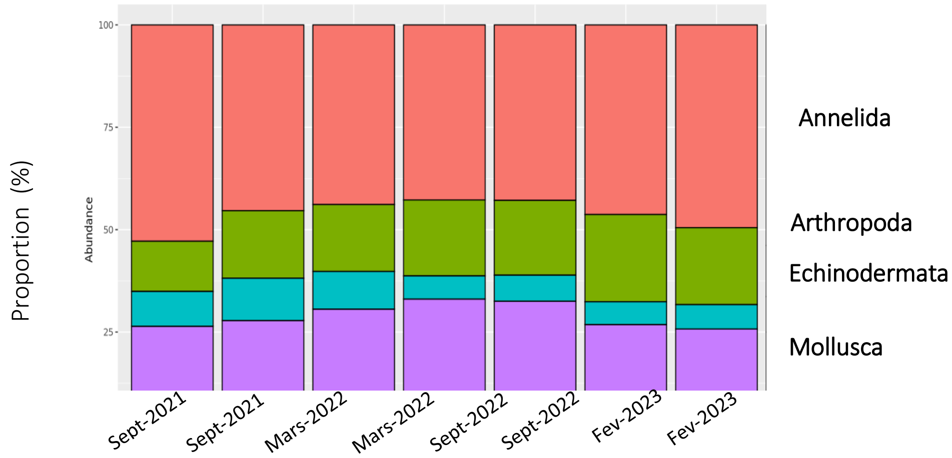

Figure 1. Read proportions of the different taxonomic phyla for metabarcoding data in the sub-samples collected at the Pierre Noire Station from September 2021 to February 2023.

While 104 to 176 different morphospecies were collected at each sampling date, only 28 to 41 species were present in both morphospecies and metabarcoding datasets (Figure 2). A total of 76 to 135 species were reported in the morphospecies dataset only while 37 to 61 species were reported in the metabarcoding dataset only. In addition, 18 to 32 OTUs were not assigned at the species level. For example in September 2021, 14 morphospecies among the 25 most abundant ones were not reported in the metabarcoding dataset including the polychaetes *Hyalinoecia bilineata*, *Spio decoratus*, *Scoloplos armiger*, *Ampharete lindstroemi* and *Marphysa bellii*.

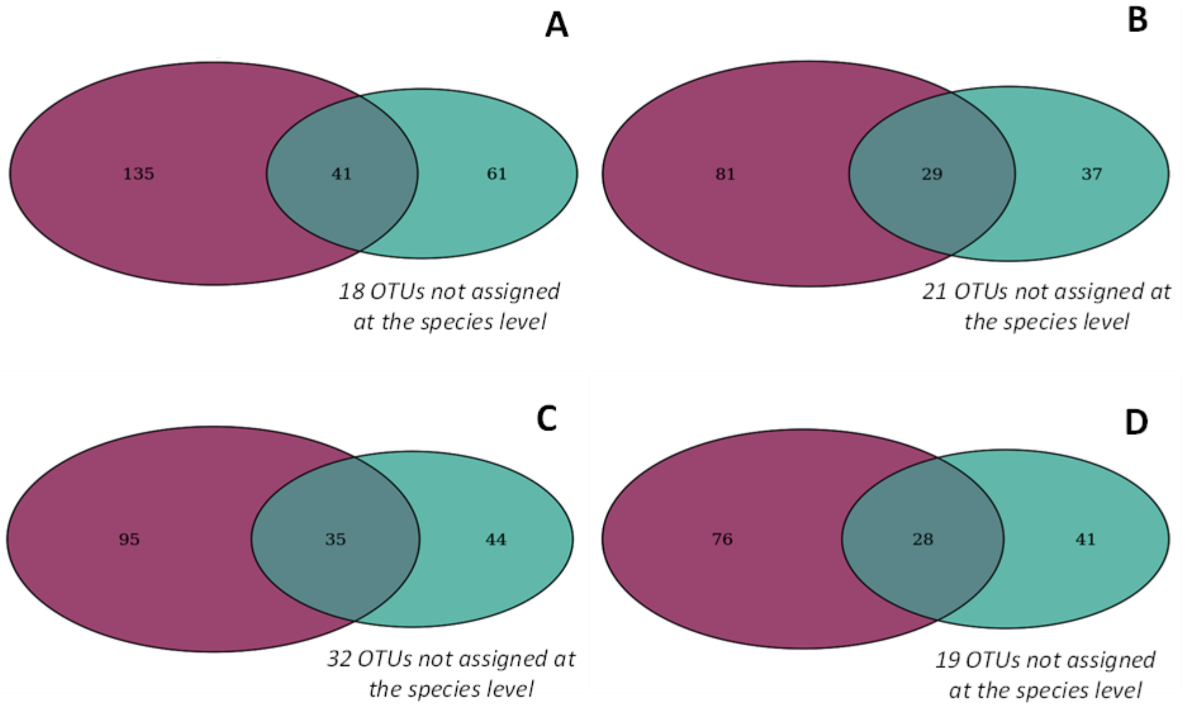

Figure 2. Venn diagrams showing the number of species identified by morphology-based methodologies and DNA metabarcoding for the different dates (A) September 2021, (B) March 2022, (C) September 2022 and (D) February 2023. Species identified from their morphology are in violet while species assigned from the OTUs are in duck blue. Numbers are the number of morphospecies or number of species assigned to OTUs. The number of OTUs which were not assigned at the species level is indicated in italics below each diagram.

Discussion

A large proportion of the OTUs identified in the present study was assigned at the species level, more than half of them corresponding to species already observed at the Pierre Noire site. However, at each sampling date, there was a significant discrepancy between the occurrence of species identified on the basis of morphological criteria and those identified on the basis of DNA sequences. Only 22.8 to 26.9% of the species identified by morphology were recovered by DNA metabarcoding. Several hypotheses, which are not mutually exclusive, can be proposed to explain these differences.

First, discrepancies between methodologies may result from a difference in sampling effort: 10 grab samples for morphological identifications compared to 3 for metabarcoding. As species richness is strongly influenced by sampling effort, many rare species would only be present in the samples used for traditional counting. However, this hypothesis does not explain why very abundant species such as the polychaetes *Hyalinoecia bilineata* and *Spio decoratus* are not detected by metabarcoding.

Second, the incompleteness and quality of the international reference databases used for assignment is commonly proposed to explain the non-detection of species by metabarcoding. For example, of the 540 morphospecies observed at least once at Pierre Noire, only 360 (60%) are present in the MIDORI2 database. At the genus level, 317 of the 371 genera recorded at Pierre Noire are present in the MIDORI2 database. Other problems for taxonomic assignment can also blur our results as proposed by Keck et al. (2023): (i) an error in the taxonomic identification of the specimen used to provide the reference DNA sequence, (ii) sequencing errors (e.g. PCR errors, contamination), (iii) sequence conflict when different taxa are assigned to the same genetic sequence, (iv) taxonomic conflict if the same organism is registered with different taxonomy, (v) low taxonomic resolution of reference sequences and (vi) the lack of intraspecific variants which may limit the assignment quality for closely related species with a high intraspecific diversity.

A final hypothesis is the potential identification errors in our morphospecies dataset. This problem is particularly important for polychaetes, where recent taxonomic revisions have revealed numerous cryptic species. As an example, while the polychaete *Ampharete lindstroemi* is commonly reported at the Pierre Noire station, one OTU in the metabarcoding dataset was assigned to *Ampharete santillani*, a new species which is morphologically very similar to *Ampharete lindstroemi* and has been described from individuals collected in shallow coastal waters off Galicia, NW Spain (Parapar et al., 2018).

To conclude, preliminary data acquired on 4 dates between 2021 and 2023 provide encouraging results on the relevance of metabarcoding to measure macrobenthic biodiversity of soft-sediments but the poor congruence between traditional methods and DNA-based methods highlight major issues concerning the OTUs assignment. Contrary to a widespread popular belief, the use of DNA metabarcoding requires considerable taxonomic expertise, whether to complete reference sequence databases, to describe intraspecific genetic variability, or to resolve the issue of cryptic species. The development of these approaches should promote integrative taxonomic studies and contribute to local and customized databases, and ultimately international databases. These advances in taxonomic assignment will enable a more robust and objective biomonitoring at local and regional scales.

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Q&A

On contamination related to sample rinsing water:

- Samples are washed with unfiltered seawater, which can induce contamination. However, since the study targets benthic macrofauna, irrelevant species are systematically excluded. The use of “clean” water at other stations reduces this issue.

On ways to limit contamination (eDNA from “cleaning water” as a reference):

- Analysing the rinsing water in parallel would help identify and exclude contaminant fragments afterward.

On the impact of currents and tides (contamination by intertidal species):

- No evidence of this issue in the study: no DNA sequences from terrestrial or estuarine fauna were detected. Insects were identified, but they are known to be present in the study area.

On the comparability of methods (beyond taxonomic groups):

- Methods are evolving rapidly (equipment, taxonomy, etc.), making long-term monitoring more complex. Some historical variations observed are not due to environmental changes but to improvements in tools and identification criteria.
- For functional analyses, eDNA does not yet provide robust quantitative data, but better taxonomic referencing of ASVs (Amplicon Sequence Variant) could improve the situation (e.g., richness calculation, Shannon index, etc.).

On the durability of DNA in the environment and its temporal relevance:

- DNA can persist, but its interpretation depends on the environment. In water, it can be transported by currents, making it difficult to determine the actual presence of a species. In sediments, it is more stable. Current results show a good correlation between dominant OTUs (Operational Taxonomic Unit) and *in situ* observations, so the method is promising.

On the future of eDNA as a monitoring tool:

- It will not immediately replace traditional methods. Complementary expertise will be necessary to validate its large-scale use. However, for certain applications, such as microorganism monitoring (e.g., salmon farms in New Zealand), it has already become an official indicator.

Photo: Alain Pibot / French Biodiversity Office (FR)

SESSION 4 – PUBLIC POLICIES AND REPORTING FOR THE CONSERVATION OF SEDIMENTARY HABITATS

POLITIQUES PUBLIQUES ET MECANISMES DE RAPPORTAGE POUR LA CONSERVATION DES HABITATS SÉDIMENTAIRES

Session moderator – *Animateur de session*: **Laurent Guérin,** International Scientific Expertise and Coordination Marine Biodiversity, OFB, France

Access the presentations from this session here – *Accédez aux présentations de cette session ici.*

Sedimentary habitats are not only essential ecosystems but also key components of marine conservation policies. As human activities and environmental changes increasingly impact these habitats, effective policy frameworks are needed to ensure their protection and sustainable management. This session explores the role of public policies and reporting mechanisms in the conservation of sedimentary habitats, with a focus on habitat classification, regulatory compliance, ecological assessments, and long-term monitoring.

The first presentation, by **Marie La Rivière** (Muséum National d'Histoire Naturelle-MNHN, France), discusses the development of NatHab-Atl and refinements in the HCI classification system, which have enhanced the scientific basis for benthic habitat conservation. By addressing gaps in the EUNIS classification and aligning

Les habitats sédimentaires sont non seulement des écosystèmes essentiels, mais aussi des éléments clés des politiques de conservation. Les activités humaines et les changements environnementaux ayant un impact croissant sur ces habitats, des cadres politiques efficaces sont nécessaires pour assurer leur protection et leur gestion durable. Cette session explore le rôle de ces cadres et des mécanismes de rapportage dans la conservation des habitats sédimentaires, en mettant l'accent sur la classification des habitats, la conformité réglementaire, les évaluations écologiques et la surveillance à long terme.

La première présentation, par **Marie La Rivière** (Muséum National d'Histoire Naturelle-MNHN, France), traite du développement de NatHab-Atl et de l'affinement du système de classification HCI, qui ont permis d'améliorer les bases national frameworks with European policies, these efforts contribute to more coherent management strategies. The upcoming 2025 EUNIS revision presents an opportunity to further standardize habitat classification at the European level.

Anne-Laure Janson (French Biodiversity Office, OFB, France) and **Diane Laforge** (MNHN, France) provide an overview of how sedimentary habitats are integrated into public policies, particularly within the Marine Strategy Framework Directive (MSFD) and the new Nature Restoration Regulation. Their study highlights gaps in monitoring networks, particularly for offshore sedimentary habitats, and underscores the need for methodological improvements to assess habitat loss and degradation under the MSFD framework.

Alexandre Robert (IFREMER, France) presents a retrospective analysis of methodological challenges encountered during the assessment of soft-bottom habitats under MSFD Cycle 3. In this context, the study critically evaluates the use of Water Framework Directive (WFD) data for habitat assessments, emphasizing the limitations of spatial extrapolations and the complexities of selecting appropriate indicators for Good Ecological Status.

José Manuel González-Irusta (Centro Oceanográfico de Santander, Instituto Español de Oceanografía, Spain) extends this discussion to the circalittoral and bathyal soft-sediment habitats in Spain, presenting insights into the assessment of seafloor integrity within the MSFD framework. This presentation (summarized as an abstract) contributes to a broader understanding of habitat monitoring across different European marine regions.

Finally, **Anna Lizinska** (Gdańsk University, Poland) presents findings from the Nea Panacea research project, which contributed to the OSPAR Quality Status Report 2023. This large-scale assessment synthesizes trends in North-East Atlantic benthic habitats over the past decade, analysing the impacts of human activities, climate change, and ocean acidification. The study highlights the urgent need for improved monitoring programs

scientifiques de la conservation des habitats benthiques. En comblant les lacunes de la classification EUNIS et en alignant les cadres nationaux sur les politiques européennes, ces efforts contribuent à des stratégies de gestion plus cohérentes. La prochaine révision du système EUNIS en 2025 offre l'opportunité de standardiser davantage la classification des habitats au niveau européen.

Anne-Laure Janson (OFB, France) et **Diane Laforge** (MNHN, France) donnent un aperçu de la façon dont les habitats sédimentaires sont intégrés dans les politiques publiques, en particulier dans le cadre de la directive-cadre « Stratégie pour le milieu marin » (DCSMM) et du nouveau règlement sur la Restauration de la Nature. Leur étude met en évidence les lacunes des réseaux de surveillance, en particulier pour les habitats sédimentaires offshore, et souligne le besoin d'améliorations méthodologiques pour évaluer la perte et la dégradation des habitats dans le cadre de la DCSMM.

Alexandre Robert (IFREMER, France) présente une analyse rétrospective des défis méthodologiques rencontrés lors de l'évaluation des habitats de fonds meubles dans le cadre du cycle 3 de la directive-cadre « Stratégie pour le milieu marin » (DCSMM). L'étude évalue de manière critique l'utilisation des données de la Directive Cadre sur l'Eau (DCE) pour l'évaluation des habitats, en soulignant les limites des extrapolations spatiales et la complexité de la sélection d'indicateurs appropriés pour le Bon État Écologique.

José Manuel González-Irusta (Centro Oceanográfico de Santander, Instituto Español de Oceanografía, Espagne) élargit cette discussion aux habitats de sédiments meubles circalittoraux et bathyaux en Espagne, en présentant des éléments d'analyse sur l'évaluation de l'intégrité des fonds marins dans le cadre de la DCSMM. Cette présentation (résumée sous forme d'abstract) contribue à une meilleure compréhension du suivi des habitats dans différentes régions marines européennes.

Enfin, **Anna Lizinska** (Gdańsk University, Poland) présente les résultats du projet de recherche to track these changes and inform science-based policy recommendations.

Together, these presentations illustrate the evolving landscape of sedimentary habitat conservation, emphasizing the importance of classification systems, regulatory frameworks, and long-term ecological monitoring in shaping effective marine policies.

NB: This session raised general comments from participants, addressing all presentations in a cross-cutting manner. A summary of these discussions is provided on page 107

Nea Panacea, qui a contribué au rapport OSPAR sur l'état de l'environnement 2023. Cette évaluation à grande échelle synthétise les tendances observées au cours de la dernière décennie dans les habitats benthiques de l'Atlantique Nord-Est, en analysant les impacts des activités humaines, du changement climatique et de l'acidification des océans. L'étude souligne l'urgence d'améliorer les programmes de surveillance afin de suivre ces évolutions et d'alimenter des recommandations politiques fondées sur la science.

Ensemble, ces présentations illustrent l'évolution du champ de la conservation des habitats sédimentaires, en mettant en lumière l'importance des systèmes de classification, des cadres réglementaires et du suivi écologique à long terme pour l'élaboration de politiques marines efficaces.

NB : Cette session a fait l'objet de remarques générales portant de manière transversale sur l'ensemble des présentations. Un résumé de ces échanges est proposé en page 107

Sedimentary habitat units in public policies: habitats classifications, correlations and regulatory implications.

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Introduction

Marine habitat classification is a fundamental component of conservation planning and policy implementation. It provides a common language between scientists, managers, and policymakers to describe, assess, and monitor marine ecosystems. The need for standardized habitat classification arises from multiple objectives:

- Defining consistent working units at local, national, and regional scales;
- Facilitating data collection and sharing on habitat occurrence, distribution trends, and ecological functions;
- Ensuring coherence between conservation frameworks under European and national regulations.

In Europe, several classification systems have been developed to meet different needs. We are working on harmonizing typological tools to facilitate the identification and monitoring of benthic habitats in France. These tools ensure the harmonization of habitat typologies and improve conservation assessment and reporting at multiple scales.

European and national habitat classifications (EUNIS and NatHab)

The EUNIS marine habitat classification is a hierarchical European system designed to categorize marine habitats across Europe based on physical, biological, and ecological characteristics. EUNIS aims to provide a standardized framework encompassing the full diversity of marine habitats across European waters. The consistency of the marine section of EUNIS is especially strategic, as it is the official classification used for the implementation of the MSFD (2008/56/CE) and the Nature Restoration Regulation (NRR, EU 2024/1991). EUNIS is also the classification used by the EUSeaMap (European Marine Observation and Data Network), the European broad-scale seabed habitat map.

However, EUNIS' latest revision (2022) only integrated British and Irish marine habitat units for the Atlantic section, leaving out broader European perspectives. This has resulted in a classification that lacks representativity for other Atlantic states, including France and this raised concerns about its adequacy in representing the full diversity of benthic environments across Europe, specially in the light of its crucial role in regulatory compliance and ecosystem monitoring.

To address this, the French national classification, NatHab-Atl, was updated following the new EUNIS hierarchical structure (Michez *et al.,* 2019). The NatHab-Atl typology provides a comprehensive and structured classification of benthic habitats for the French waters of the English Channel, the North Sea and the Atlantic. It includes 106 habitats units at the biocenotic level (hierarchical level 2), including 55 sedimentary habitats (Fig. 1).

This typology serves multiple purposes: ensuring accurate habitat description and mapping at the national level, establishing correspondences with other lists or classifications (including EUNIS), and supporting conservation planning at the national level. Moreover, NatHab-Atl is designed to be adaptable, enabling updates based on scientific advancements and conservation needs.

Figure 1. Extract from the hierarchical classification of benthic habitats NatHab-Atl showing level 2-sedimentary habitat units, available on the INPN (NatHab-Atlantique - Typology).

Each level 2 unit of the French classification has been described with ecological and environmental parameters (La Rivière *et al.,* 2022). All descriptive sheet includes information on abiotic factors, ecological characteristics, spatial variability, geographic distribution, characteristic and associated species, temporal dynamics, associated or neighbouring habitats, potential misidentifications, ecological functions, conservation status, and evolutionary trends. These descriptions provide the necessary foundation for precise mapping, assessment, and conservation planning.

This work, coupled with a correlation between EUNIS and NatHab, highlights the missing elements in EUNIS and will serve as a reference for updating EUNIS and aligning national and European classifications. In the OSPAR convention framework, France and the United Kingdom will be leading a proposal to update the EUNIS classification for the Atlantic section in 2025. This will also be the opportunity to address hierarchical discrepancies and precise some unclear units' descriptions.

National interpretation of marine Habitats of Community Interest (HCI)

Under the EU Habitats Directive, specific benthic habitat units are defined as Habitats of Community Interest (HCI), requiring designation of Special Areas of Conservation. However, the broad definitions in the official EU interpretation manual (European Commission, 2013) often lack clarity for national and site-level management.

Therefore, France has developed a refined national interpretation of nine marine HCIs. This work provides descriptive sheets detailing habitat identification criteria, potential overlaps, and national specificities (de Bettignies *et al.,* 2021).

A comprehensive correlation effort was conducted with the NatHab typology (345 matches for NatHab-Atl) to identify which habitat units would require management under the Habitats Directive. In the future, this will make it possible to do away with the use of the list of habitats in the Cahiers d'habitats côtiers (Bensettiti *et al.,* 2004), which is commonly used for Natura 2000 site management, but which does not provide a comprehensive list of HCIs.

A national-scale mapping initiative was then undertaken to improve spatial delineation of each marine HCI according to their national definition, for the Habitat Directive Article 17 reporting (biogeographical assessments of conservation status) to the European Commission. These refinements will improve coherence in Natura 2000 site management and will facilitate biogeographic-scale assessments. Further validation at the local level is still required to address potential conflicts with existing designations.

Sedimentary benthic habitats in public policies

Atlantic sedimentary habitats are covered by all public policies for marine environment conservation (Habitats Directive, MSFD, Regulation for Nature Restoration, OSPAR, WFD) with different units. For example, the MSFD targets "Broad-Scale Habitats" defined by EUNIS units that encompass all sedimentary habitats, while the HD only targets intertidal sediments (HCI 1140), infralittoral and circalittoral coarse and sandy sediments (HCI 1110) as long as broad geographical units (estuaries, coastal lagoons, and bays).

The OSPAR convention for the protection of the North-East Atlantic identifies a list of threatened and declining habitats (OSPAR, 2008), e.g. "Intertidal Mytilus edulis Beds on Mixed & Sandy Sediments", "Intertidal mudflats", "Maerl beds", "Zostera beds", "Seapen and Burrowing Megafauna".

As for the newly adopted Regulation for Nature Restoration, it targets in its Annex II, a broad group of habitat types (GHT) encompassing sedimentary habitats (Group 7 "Soft sediments not deeper than 1 000 metres of depth"), while more specific sedimentary habitat types are targeted in other overlapping GHT ("Seagrass beds", "Maerl beds", Shellfish beds" or "Sponge, coral and coralligenous beds").

Since the targeted units differ between these policies, it is essential to understand how the units are defined and correlated. This is crucial to appreciate properly how work conducted on a unit within one policy can contribute (or not) to the efforts of another to ensure cross-cutting use of data and increase efficiency in knowledge acquisition and conservation efforts.

Available tools

All habitat classification data, including correlations and descriptions, are available through the HabRef repository (inpn.mnhn.fr/programme/referentiel-habitats?lg=en, Gaudillat *et al.,* 2023). This database compiles all habitat classifications and lists for metropolitan France and overseas territories, for both terrestrial and marine environments, supporting:

- Cross-referencing between classifications via unique habitat identifiers (CD_HAB).
- Integration with taxonomic databases (TaxRef).
- Public access through the INPN website, offering downloadable datasets and interactive tools for habitat visualization.

The INPN website (Inventaire National du Patrimoine Naturel, inpn.mnhn.fr) provides access to these data through downloadable spreadsheets (HabRef database, individual typologies, and correlations tables between 2 typologies) or through interactive typology trees and habitat pages.

Training sessions on marine habitat typologies were introduced in 2023 and remain accessible as online webinars, ensuring broader engagement in classification methodologies.

Conclusion

The development of NatHab-Atl and the refinement of HCI classifications have strengthened the scientific foundation for benthic habitat assessment and conservation at the national level. By addressing gaps in the EUNIS classification and aligning national typologies with European frameworks, these efforts contribute to more effective management, regulatory compliance, and international conservation strategies. Moving forward, the 2025 EUNIS revision represents a key opportunity to establish a comprehensive and coherent European classification system. The availability of all these typological tools on the INPN will facilitate their use, as well as the coherent assessment and management of benthic habitats at local, regional and national, and potentially international levels, through the various regulatory policies.

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How are sedimentary habitats taken into account in public policies (MSFD and Restoration Regulation)? Overview of the French Channel and Atlantic sea

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The MSFD (Marine Strategy Framework Directive)

In a few words

The Directive 2008/56/EC of the European Parliament and the Council of June 17, 2008, known as the Marine Strategy Framework Directive (MSFD), aims to maintain or restore the proper functioning of marine ecosystems (preserving biodiversity and ensuring correct interactions between species and their habitats, as well as maintaining dynamic and productive oceans) while allowing the use of marine resources for future generations.

In France, the MSFD applies to metropolitan marine waters under French jurisdiction, divided into four marine sub-regions: the English Channel–North Sea, the Celtic Seas, the Bay of Biscay, the Western Mediterranean.

For each marine sub-region, a Marine Environment Action Plan is implemented. This plan consists of five elements, revised every six years:

- An assessment of the environmental status of marine waters and the environmental impact of human activities on these waters;
- The definition of Good Environmental Status for these waters based on qualitative descriptors;
- The establishment of environmental objectives and associated indicators to achieve Good Environmental Status of the marine environment;
- A monitoring program to continuously evaluate the state of marine waters and periodically update environmental objectives;
- A program of measures aimed at achieving or maintaining Good Environmental Status of marine waters.

Assessment of sedimentary Habitats in the MSFD for the French English Channel and Atlantic Coasts

“Sedimentary habitats" refers here to benthic habitats composed primarily of unconsolidated sediments such as mud, sand, coarse, or mixed substrates. They support various macrofaunal communities and play a key role in ecosystem functions like nutrient cycling, carbon storage, and providing essential habitats for marine organisms.

European requirements

Sedimentary benthic habitats are a component of Descriptor 1 – Biodiversity in the MSFD. According to this descriptor, Good Environmental Status (GES) is considered achieved when: *"**Biodiversity is maintained. The quality and number of habitats, as well as the distribution and abundance of species, are appropriate to existing physiographic, geographic, and climatic conditions.**"* (Directive 2008/56/EC).

The assessment must be conducted by Broad Habitat Type (BHT, Table I), which corresponds to Level 2 habitats in the EUNIS classification (2022 version).

Table I: *Sedimentary Broad Habitat Types, including their associated biological communities, corresponding to one or more habitat types in the EUNIS classification (Decision 2017/848/EU).*

Broad habitat types (sedimentary) (COMMISSION DECISION 2017/848)	**Relevant EUNIS habitat codes (2022 version)**
Littoral sediment	MA3, MA4, MA5, MA6
Infralittoral coarse sediment	MB3
Infralittoral mixed sediment	MB4
Infralittoral sand	MB5
Infralittoral mud	MB6
Circalittoral coarse sediment	MC3
Circalittoral mixed sediment	MC4
Circalittoral sand	MC5
Circalittoral mud	MC6
Offshore circalittoral coarse sediment	MD3
Offshore circalittoral mixed sediment	MD4
Offshore circalittoral sand	MD5
Offshore circalittoral mud	MD6
Upper bathyal sediment	ME3, ME4, ME5, ME6
Lower bathyal sediment	MF3, MF4, MF5, MF6
Abyssal	MG1, MG2, MG3, MG4, MG5, MG6

French choices

Littoral sedimentary habitats

Monitoring of these intertidal habitats is based on a single monitoring network in the French English Channel and Atlantic coasts: the WFD Benthos network (benthic macroinvertebrates). It allows monitoring of nearly 40 sites on these marine regions.

In the frame of the French MSFD Ecological status assesment Cycle 3 (Robert *et al.*, 2023), criterion D6C4 (habitat loss) was not assessed because the mapping of French intertidal habitats is incomplete and insufficiently updated. Assessment of criterion D6C5 (adverse effects on the condition of the habitat type) was based on M-AMBI (Muxika *et al.*, 2007) and GPBI (Labrune *et al.*, 2021) indicators calculated at the sampling station scale. Methodological developments are yet required to assess ecological status of these habitats (at a larger spatial scale in particular).

Additional data, acquired at local scales (marine protected areas) could contribute to national MSFD assessments, either to characterize the state of the communities or to update the spatial distribution of these intertidal habitats.

Infralittoral and circalittoral sedimentary habitats

These habitats of French infra- and circalittoral areas are being monitored by the WFD Benthos network thanks to 40 subtidal sites located within the first nautical mile from the coastline.

As well as intertidal sedimentary habitats, criterion D6C4 was not assessed whereas M-AMBI et GPBI indicators were mobilized to assess criterion D6C5 at each sampling station scale. The latest GES assessment (Cycle 3; Robert *et al*., 2023) showed that the number of monitoring stations was insufficient (network restricted to the 1st nautical mile, mainly targeting fine muddy sands). The SHASICCÔ project (IFREMER/OFB) should allow to be better dimensioned this monitoring network. Starting in 2025, this project aims to analyze the spatial sufficiency of the WFD monitoring network with regards to the distribution of (i) sedimentary broad habitat types, (ii) environmental gradients and (iii) anthropogenic pressures in order to propose a spatial monitoring strategy.

Offshore circalittoral sedimentary habitats

To date, within the MSFD framework, there is neither monitoring network nor French assessment method for these offshore sedimentary habitats. The main data source comes from EMODnet Seabed Habitats (https://emodnet.ec.europa.eu/en/seabed-habitats) that provides us with predictive broad-scale seabed habitat map. On the Mediterranean coast, the French IMPEC project (University of Angers/OFB) focuses on the impact of abrasion pressure on offshore soft-bottom communities. By combining VMS data with biotic *in-situ* data (macrofauna, meiofauna, foraminifera, and benthic mega-epifauna), it aims to establish pressure-impact relationships and to test different biotic indicators. Assessing the environmental status of the offshore circalittoral sedimentary habitats, drawing on OSPAR's work where possible, will be one of the challenges to be met in the frame of the next MSFD Cycle (Cycle 4).

The Nature Restoration Regulation

In a few words

The Regulation (EU) 2024/1991 of the european parliament and of the council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 Nature Restoration Regulation, known as Nature Restoration Regulation (NRR), adopted in August 2024, aims to ensure the long-term and sustained recovery of biodiverse and resilient ecosystems, across the European territory of the Member States, through effective and area-based restoration measures with the aim to jointly cover, as a Union target, throughout the areas and ecosystems within the scope of this Regulation, at least 20 % of land areas and at least 20 % of sea areas by 2030, and all ecosystems in need of restoration by 2050.

Sedimentary habitats covered by NRR

This regulation covers several benthic habitats, classified into seven "Groups of Habitat Type" (GHT) presented in Annex II of the regulation. These groups are composed of lists of habitat types, distributed in biogeographical marine regions. In France, the NRR applies to metropolitan marine waters under French jurisdiction, in the two biogeographical marine regions Atlantic and Mediterranean Sea.

Sedimentary habitats are primarily considered in the NRR through a broad GHT encompassing these habitats (Group 7: "Soft sediments not deeper than 1,000 meters"; Table II). Additionally, more specific types of sedimentary habitats are covered under other overlapping GHTs, such as "Seagrass beds", "Maerl beds", "Shellfish beds", and "Sponge, coral, and coralligenous beds".

Table 2: Habitat types listed in Annex II from NRR for the GHT 7 "Soft sediments (not deeper than 1000 meters of depth)".

Groupe of Habitat Types n° 7 (Annex II, NRR)	**Habitat types (for Atlantique and Mediterranean Sea)**	**Relevant EUNIS habitat codes (2022 version)**
Group 7: Soft sediments (not deeper than 1 000 meters of depth)	Littoral coarse sediment	MA3
	Littoral mixed sediment	MA4
	Littoral sand	MA5
	Littoral mud	MA6
	Infralittoral coarse sediment	MB3
	Infralittoral mixed sediment	MB4
	Infralittoral sand	MB5
	Infralittoral mud	MB6
	circalittoral coarse sediment	MC3
	circalittoral mixed sediment	MC4
	circalittoral sand	MC5
	circalittoral mud	MC6
	Offshore circalittoral coarse sediment	MD3
	Offshore circalittoral mixed sediment	MD4
	Offshore circalittoral sand	MD5
	Offshore circalittoral mud	MD6
	upper bathyal coarse sediment	ME3
	upper bathyal mixed sediment	ME4
	upper bathyal sand	ME5
	upper bathyal mud	ME6
	lower bathyal coarse sediment	MF3
	lower bathyal mixed sediment	MF4
	lower bathyal sand	MF5
	lower bathyal mud	MF6

National Restoration plan and targets on sedimentary habitats

Each Member State must produce a National Restoration Plan by September 2026, which shall be revised in 2032 and 2042. Among the various pieces of information the plan must provide, it must include the quantification of areas to be restored to meet the restoration targets (including preparatory work and indicative maps of potential restoration areas). This therefore requires the ability to map the GHTs and spatially assess their condition.

For the soft sediments habitats covered by GHT 7, Member States must set a percentage X% of poor-condition area that need to be restore so as not to prevent Good Environmental Status, as determined in Article 9(1) of Directive 2008/56/EC, from being achieved or maintained (NRR, Art.5.1).

Due to its large spatial extent and its definition at the EUNIS level 3 scale, the targets for GHT 7 are offset compared to the six other GHTs, and there is no objective for recreating a favorable reference area for the GHT 7. Thus, Member States must have implemented restoration measures on two-thirds of the X% of the GHT 7 area to be restored by 2040, and on the entirety of this X% area by 2050. This target is accompanied by a knowledge acquisition target, requiring Member States to assess the condition of 50% of the areas covered by GHT 7 by 2040 and 100% by 2050.

State of Knowledge on GHT 7 to Support the French National Restoration Plan

A preliminary version of the mapping for French marine GHTs (Thomas Sleiman and La Rivière, 2023) was created based on the continuous benthic habitat mapping produced in 2018 as part of the CarpeDiem project (Quemmerais-Amice, 2020). This preliminary map illustrates the extensive area potentially covered by GTH 7, which corresponds to a large part of the French Exclusive Economic Zone.

Since the NRR (National Restoration Plan) requires an assessment of the ecological status of listed habitats and GHTs are new units, it is necessary to identify existing assessments (carried out under other public policies such as MSFD, WFD, HD, or through research projects, OSPAR conventions, etc.) that could help address the knowledge requirements of the NRR. This involves establishing correspondences between the units assessed in these evaluations and the GHTs. For GHT 7, some elements from WFD and MSFD assessments, OSPAR, and research work can be used to enhance the understanding and evaluation of this habitat. However, numerous knowledge gaps persist considering the vast extent of the habitat to be assessed. Ongoing French projects such as CaLHaMar, SHASSICÔ, and IMPEC might strengthen these insights, and a proxy pressure-based approach will be explored for specific areas.

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The Marine Strategy Framework Directive (MFSD) assessment of benthic habitats in France: a focus on soft bottom habitats

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The Marine Strategy Framework Directive (MSFD) aims to restore or maintain the Good Environmental Status of the Marine Environment. This is implemented via an ecosystem-based approach, considering both pressures and biological receptors through the assessment of various descriptors and criteria. Among these, the D6C5 criteria of the D1 Benthic Habitats descriptor ensures that the negative effects of human activities on the biotic and abiotic structure of the habitats, as well as on the associated ecological functions, should not exceed a certain proportion of the natural extent of the habitats. The habitats correspond to Broad Habitat Types, defined at a Eunis 2 level (bathymetry x substrate). It is however possible to perform a more accurate investigation of the vulnerable habitats, habitats listed in national red lists or in international conventions, etc. The criteria must be declined by Marine Sub-Regions. In Metropolitan France, 17 Broad Habitat Types occur in the English Channel and in the North Sea Marine Sub-Regions, whereas 22 Broad Habitat Types are present in the others Marine Sub-Regions.

Here, we present a retrospective of the methodological issues that we encountered during the quantitative assessment of the muddy and sandy-muddy habitats of the coastal areas (<1 nautical mile) during the MSFD cycle 3. These habitats are already monitored by the Water Framework Directive, and the associated data constitute the only real quantitative data source that is available and compatible with the MSFD requirements. The mutualisation of these data, although largely encouraged by the biodiversity managers in order to reduce the cost of the monitoring programs, has however raised serious questions. Indeed, the risk was that the same data produce different results, because of methodological discrepancies but also because the spatial and temporal scales of the assessments were not exactly the same between the Water Directive and the MSFD.

It became clear that extrapolating the assessment of water masses (Water Directive) to infer the ecological status of the habitats (MSFD) was a non-sense. Indeed, several habitats can coexist within one single water masse. On the other hand, one given habitat can spread over different water masses. The reporting by water masse was not consistent with the regulatory texts and was redundant with the assessment of another descriptor (D5 eutrophication). The choice was made to assess the ecological status at the scale of the sampling stations without extrapolating at the scale of the Broad Habitats Types. Indeed, a preliminary analysis revealed that the Broad Habitat Types were under-represented by the sampling stations so that extrapolating was not robust from a statistical point of view. The D6C5 assessment was therefore not fully complete.

An important methodological issue has also been raised about the choice of the indicators of Good Ecological Status. The AMBI (Western Mediterranean) or M-AMBI (other Marine Sub-Regions) are used for the Water Directive. They reflect the response of the benthic organisms to an enrichment of organic matter within the sediment. These indicators were combined with a second index: the General Purpose

Benthic Index (GPBI; Labrune et al., 2021). The GPBI is potentially sensitive to all the anthropogenic pressures that are likely to affect the specie's abundances. However, the drawback is that this indicator is also very sensitive to natural variations, which could hamper our ability to distinguish the anthropogenic sources of disruption and the natural disruptions. To avoid this, several references stations were used for each habitats and each sub-marine region. The combination of the WFD indicator and the GPBI was done using the One Out All Out approach.

Applying this method highlighted that the majority (56%) of the sampling stations were in Good Environmental Status (Figure 1). In the Celtic Seas, the coarse sediments of the Mont Saint-Michel Cherrueix IM station, initially classified in Good Status by the M-AMBI, appeared degraded with GPBI. On this station, the discard of undersized mussel (presence of mussel farms close to the sampling station) resulted in a change of grain size (presence of shell debris) and to an organic matter enrichment, which conducted to the proliferation of small deposit-feeding organisms and scavengers.

In the Northern Bay of Biscay, Les Moutiers IMF1 and La Berche intHZN, located in coastal muds were in bad ecological status, as regard to the results of the M-AMBI but also with the GPBI. This suggests that these stations suffered from an organic matter enrichment (eutrophication) during the MSFD cycle 3. This is also probably the case in the Southern Bay of Biscay, where muddy stations (Les Doux int HZN and Hossegor int HZN) as well as coarse sediments (Hossegor int - xBENT11) were in bad ecological status with the MAMBI but also with the GPBI. The stations Côte Basque SM - xBENT14 appeared in bad environmental status with the GPBI but this station is located in a mobile sand area (surf beaches of the Côte Basque) and this result is probably linked to natural disturbances rather than anthropogenic disruptions.

The Western Mediterranean was subdivided into 4 sub-regional units to take into account the influence of the Rhône river and the specific context of the Corsica. Many stations were classified in poor ecological condition. Most of them were located in infralittoral muds (at the exception of Agde ouest DC and Gruissan DC, located in infralittoral sands). At the mouth of the Rhône river, the stations Carteau DC, Fos DC, and Grau du roi DC were classified in poor condition. In the PACA Marine Reporting Unit, six stations were classified in poor condition: Antibes sud DC, Cassis DC, Menton DC, Rade Villefranche DC, St Raphael DC, and Toulon grande rade DC. Only one Corsican station appeared in poor condition (Bonifacio DC). All these stations were located close to harbours or urbanized areas and these results are certainly linked to anthropogenic pressures.

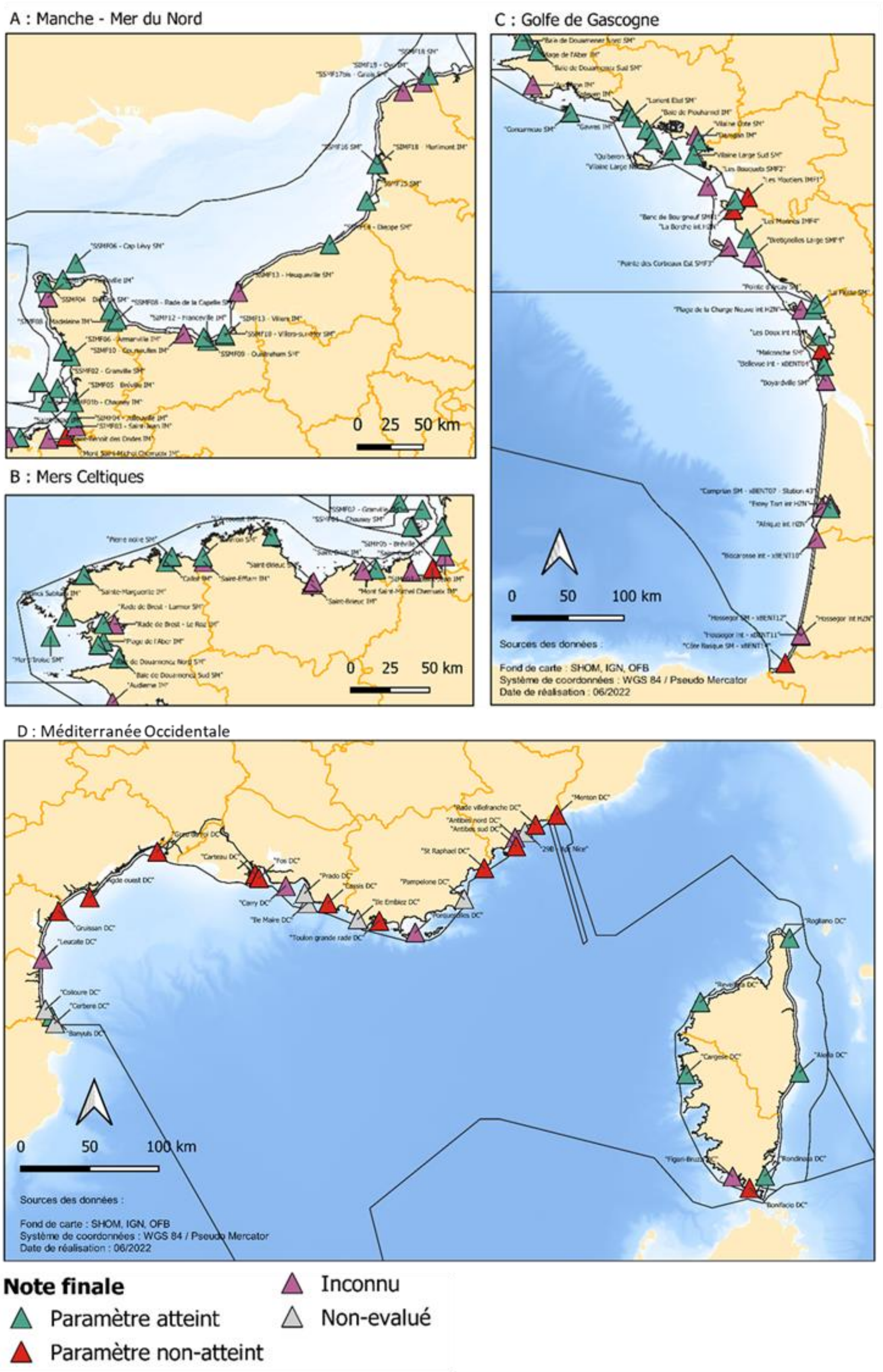

Figure 5 Results of the cycle 3 assessment of the D6C5 criterion (partial assessment at the scale of the sampling stations) based on the combination of AMBI (med.) or M-AMBI with the GPBI. Only muddy to sandy-muddy habitats of coastal areas were assessed this way.

Assessing the status of soft circalittoral benthic habitats in the frame of the Spanish marine strategy.

Abstract produced from the presentation made by José Manuel Gonzalez-Irusta during the LIFE Maha seminar on sedimentary habitats.

This study presents the methodology and results of assessing the status of soft circalittoral and bathyal benthic habitats within the framework of the Spanish Marine Strategy. Using both historical fisheries data and targeted Marine Strategy Framework Directive (MSFD) surveys, the assessment integrates two key OSPAR indicators: BH1 (Sentinel of the Seabed, SOS) and an adaptation (to Spanish specificities) of BH3 (habitat risk index). Sentinel species were identified based on frequency and sensitivity, with biological trait-based indices (e.g., BESITO) informing about sensitivity. Spatial patterns of habitat degradation were evaluated using generalised additive models (GAMs), and thresholds for environmental status were derived using the "distance to degradation" method. This combined indicator approach enabled full coverage of Spain's trawling footprint and highlighted regions under significant ecological pressure. The methodology was validated through application in the OSPAR Quality Status Report and supports future development of harmonised marine habitat assessments across Europe.

Decadal changes in North-East Atlantic benthic habitats: trends and recent prospects, by 400 biodiversity experts, in the context of global changes

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Abstract: these works are from the Nea Panacea research project, which directly contributed to the OSPAR Quality Status Report 2023 (QSR 2023, OSPAR 2023a), the most comprehensive assessment of the North-East Atlantic. It represents the joint efforts of 16 Contracting Parties to the OSPAR Convention, scientists, experts and their institutes, and the OSPAR Secretariat. In particular, it reviews the status of various biodiversity components and tracks changes since the previous QSR in 2010. The QSR 2023 provides a holistic assessment of the marine environment, carried out in collaboration with over 400 scientists and regional policy experts. It serves as a robust foundation for science-based policy recommendations.

Among the main conclusions, this presentation focuses on the impacts of benthic habitats that continue to be damaged by human activities. These impacts are analysed in the context of major observed or projected trends due to climate change and ocean acidification. While forecasts face significant uncertainties, further research is needed to improve predictions, particularly for coastal habitats. The lack of suitable and sufficient monitoring programs means that a wide range of data sets is not always available to systematically measure the effects of climate change and ocean acidification on benthic habitats and species.

However, considerable evidence highlights the impacts in different regions, which vary according to geography, physical characteristics of the seabed, and habitat types. In addition, rising mean sea levels and increasing storm frequency may requires enhanced coastal defences against flooding and erosion. At the same time, benthic habitats offer opportunities to mitigate and adapt to the effects of climate change.

Key words: Nord-Est Atlantic, OSPAR, assessments, benthic habitats, trends, impacts, global change, public policies

Introduction

The OSPAR Quality Status Reports provide an assessment of the marine environment in the North-East Atlantic, conducted through the join efforts of OSPAR Contracting Parties Convention, scientists, experts, and the OSPAR Secretariat. NEA PANACEA was an EU-funded research project that brought together eight partners from five OSPAR countries to support biodiversity assessments for OSPAR's QSR 2023. It focused on pelagic and benthic habitats, food webs, and marine birds, assisting EU member states in reporting under the MSFD. The project developed new biodiversity indicators, improved existing ones, and explored ways to integrate multiple indicators into comprehensive ecosystem assessments. The QSR 2023, was an assessment of the marine environment, delivered by over 400 experts. This 2023 report expands on previous assessments, QSR 2010 and Intermediate Assessment 2017, to provide an updated evaluation of biodiversity trends and the status of benthic habitats. Benthic habitats are vulnerable and exposed to both human activities (bottom trawling, coastal development, pollution), and impacts of climate change (Duarte et al., 2013).

The degradation of benthic habitats is a widely documented fact, more over increasing temperatures of the seas, ocean acidification, and changes in sediment cause changes in benthic communities (Gattuso et al., 2018a).Despite these negative challenges, benthic habitats offer potential for climate change mitigation and adaptation, such as carbon storage in sedimentary environments (Barbier et al., 2011).

This study shows state of benthic habitats in the North-East Atlantic, highlighting changes since the Intermediate Assessment in 2017 (McQuatters-Gollop et al., 2022). It also highlights the need of international cooperation to reduce habitat degradation and enhance ecosystem resilience in response to global change.

Methodology

This study presents the status of benthic habitats in five OSPAR regions of the North-East Atlantic (Figure 1). OSPAR benthic indicators (Table 1) integrating benthic species' community composition, benthic habitat mapping data, and spatial data of anthropogenic pressures, enable a broad and coherent assessment (Elliott et al., 2018).

Figure 1. The five regions of OSPAR Maritime Area: I - Arctic Waters, II -Greater North Sea, III - Celtic Seas, IV - Bay of Biscay and Iberian Coast, and V - Wider Atlantic. Source: OSPAR website (https://www.ospar.org/convention/the-north-east-atlantic).

Indicator name	Common in OSPAR Region	CEMP Guideline
BH1 – Common Indicator on Sentinels of the seabed	IV	(OSPAR, 2023c)
BH2 – Common indicator assessment on condition of benthic habitat communities: the common conceptual approach	I, II, III, IV, V	(OSPAR, 2023b)
BH2a – Common indicator assessment of some coastal habitats exposed to nutrient and organic enrichment	II, III, IV	(OSPAR, 2023b)
BH2b – Common indicator assessment on condition of benthic habitat communities	II	(OSPAR, 2023b)
BH3 – Common Indicator: Extent of Physical Disturbance to Benthic Habitats	II, III, IV	(OSPAR, 2017)
BH4 – Common indicator assessment on area of habitat loss. Pilot assessment	II	(OSPAR, 2022)

Table 1 Benthic indicator used for the OSPAR QRS 2023 assessment.

Benthic habitat mapping is based on EUNIS classification and EMODNet methodologies, using techniques like ground-truth sampling and acoustic surveys (Diaz et al., 2004; Ellwood, 2014; Kenny et al., 2003 in McQuatters-Gollop et al., 2022). To model and classify habitats, the environmental variables such as depth and sediment type were used, that also supported resilience and resistance assessments (Brown et al., 2011). Seabed disturbances were assessed using bottom-trawling impact data from ICES, providing valuable insights for OSPAR experts in evaluating habitat conditions.(OSPAR, 2017, 2022, 2023b, 2023c)

The methodological approach of the summary status of benthic habitat state was based on McQuatters-Gollop et all (2022) and Guérin et al. (2023) (Table 2). This approach is based on experts' judgement to classify indicator changes within the broader ecosystem context, using interpretation of indicator trends, assessment thresholds (where available), pressure links, and indicator states, c them into poor, uncertain, or good biodiversity status for scientific evaluation.

Not good	Indicator value is below assessment threshold, or change in indicator represents a declining state, or indicator change is linked to increasing effect of anthropogenic pressures (including climate change), or indicator shows no change but state is considered unsatisfactory
Uncertain	No assessment threshold and/or unclear if change represents declining or improving state, or indicator shows no change but uncertain if state represented is satisfactory
Good	Indicator value is above assessment threshold, or indicator represents improving state, or indicator shows no change but state is satisfactory
Unassessed	Indicator was not assessed in a region due to lack of data, lack of expert resource, or lack of policy support.

Table 2 Biodiversity status categories and colours used to present of indicator biodiversity state. (McQuatters-Gollop et al., 2022)

The literature review and experts' knowledges were the basis evidence to estimates potential influences of different pressures resulting from climate changes on benthic habitat. Six categories were chosen to present results: very strong effect, strong effect, moderate effect, low effect, no known effect and increased area / "positive" effect on habitat condition.

Results

The status of North-East Atlantic benthic indicators varies between indicators and OSPAR regions. The assessment results were presented by OSPAR agreed Assessment Units, developed through the Nea Panacea project (Table 3).

Region	Assessment Units
I - Arctic Waters	Arctic Waters
II - Greater North Sea	Central North Sea Southern North Sea Channel Norwegian Trench Kattegat
III - Celtic Seas	Northern Celtic Seas Southern Celtic Seas
IV - Bay of Biscay and Iberian Coast	Gulf of Biscay North Iberian Atlantic South Iberian Atlantic Gulf of Cadiz
V - Wider Atlantic	Wider Atlantic

Table 3 OSPAR regions ad and Assessment Units

Poor status is represented by red icons, orange means uncertain status, and green shown good status. Some indicators were not evaluated (grey) mostly because of the data limitations (Figure 2).

The Greater North Sea, had the highest number of assessed indicators.

BH2a in the the Celtic Seas and Central North Sea was the only indicator classified as in general good status. The majority of assessed benthic indicators across all OSPAR regions remain uncertain or not in good status.

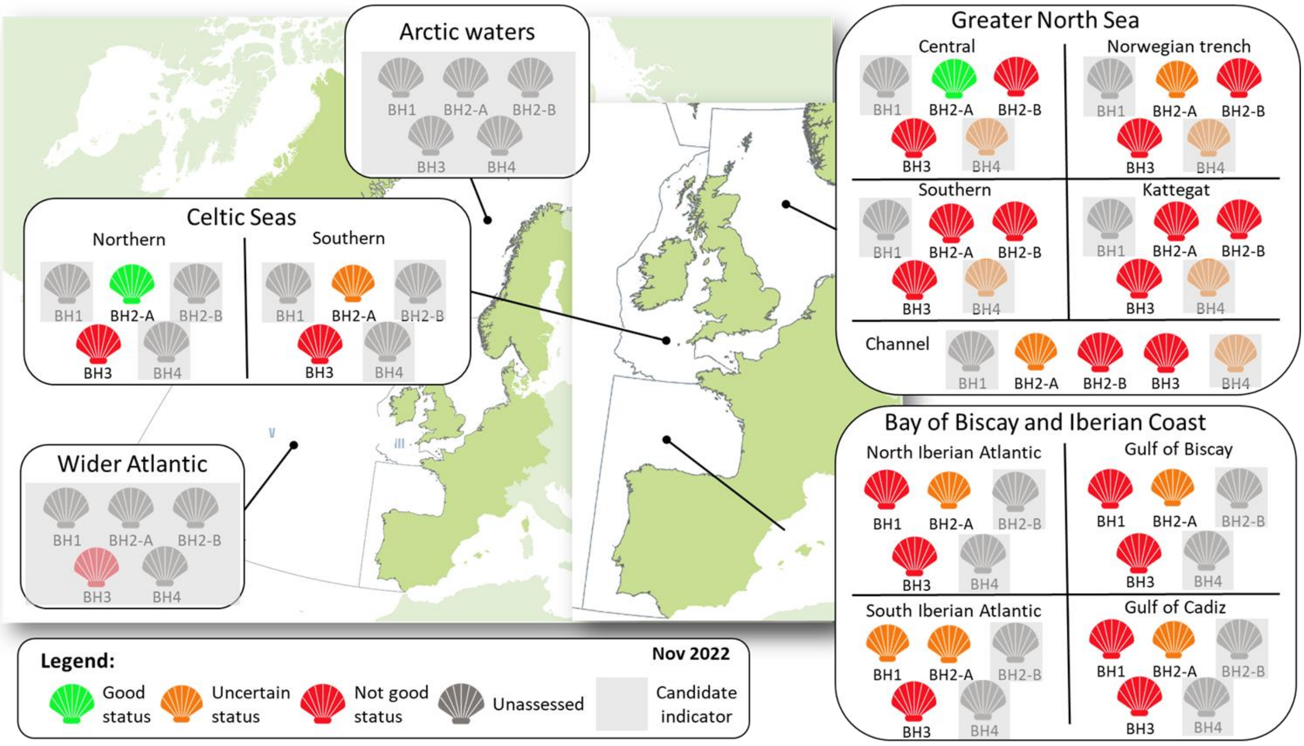

Figure 2 The status of benthic indicators in the North-East Atlantic assessment units (Guérin et al., 2022, 2023, 2024a, 2024b).

Benthic habitats are also increasingly affected by climate change and ocean acidification, leading to shifts in species distribution, community structures, and habitat suitability due notably to rising sea temperatures and decreasing pH levels (Table 4). There is not always a wide range of datasets available to systematically measure the effects of climate change and ocean acidification on benthic habitats and species, due to the paucity of the monitoring programme. However, there is a large volume of evidence of the impacts across different Regions. There are variations in the level and type of impacts due to geography (e.g., Arctic Waters) and the physical characteristics of the seafloor (e.g., depth), and in the typology of benthic habitat composition (e.g., calcifying species).

BHT versus pressure types	Increased sea T°	Reducing sea ice	freshwater input	salinity	atlantic currents	shelf stratification	Open ocean stratification	Increased storms	Increased sea level	Coastal erosion	biogeochemy	Acidification	Nutrient enrichment	Oxygen fluxes	upwelling	Extreme events
Littoral S	Very strong effect		Moderate effect	Moderate effect		Low effect	No known effect	Moderate effect	Very strong effect	Moderate effect		Strong effect	Strong effect		Very strong effect	Very strong effect
Littoral RB	Very strong effect			Moderate effect		Low effect	No known effect	Moderate effect	Very strong effect	Moderate effect		Strong effect	Strong effect	Moderate effect	Very strong effect	Very strong effect
Infralittoral S	Strong effect		Low effect	Low effect		Moderate effect	No known effect	Moderate effect	Very strong effect	Moderate effect		Very strong effect	Very strong effect	Very strong effect	Very strong effect	Very strong effect
Infralittoral RB	Very strong effect		Low effect	Low effect		Moderate effect	No known effect	Moderate effect	Very strong effect	Moderate effect		Very strong effect	Very strong effect		Very strong effect	Very strong effect
Circalittoral S	Strong effect		Low effect	Low effect		Moderate effect	No known effect	No known effect	No known effect	No known effect		Very strong effect	Strong effect	Very strong effect	Strong effect	Strong effect
Circalittoral RB	Strong effect		Low effect	Low effect		Moderate effect	No known effect	No known effect	No known effect	No known effect		Very strong effect	Strong effect	Very strong effect	Strong effect	Very strong effect
Offshore circalittoral	Strong effect		Low effect	Low effect		No known effect	Moderate effect	No known effect	No known effect	No known effect		Very strong effect	Moderate effect		Strong effect	No known effect
Offshore circalittoral	Strong effect		Low effect	Low effect		No known effect	Moderate effect	No known effect	No known effect	No known effect		Very strong effect	Moderate effect	Very strong effect	Strong effect	No known effect
Deep sea S	Strong effect		No known effect	No known effect		No known effect	Moderate effect	No known effect	No known effect	No known effect		Very strong effect	No known effect		Strong effect	No known effect
Deep sea RB	Very strong effect		No known effect	No known effect		No known effect	Moderate effect	No known effect	No known effect	No known effect		Very strong effect	No known effect	Very strong effect	Strong effect	No known effect

Very strong effect — Moderate effect — No known effect
Strong effect — Low effect — Increased area / "positive" effect on habitat condition

Table 4 Predicted ranges of effects and impacts by climate change on North-East Atlatnic benthic habitats (experts' judgment, from Guérin et al., 2023; OSPAR, 2023a)

Discussion

Many benthic habitats within the OSPAR Maritime Area are under threat from various pressures (Figure 2, table 4). These include physical disturbance, modification of substrate or loss (such as abrasion by bottom trawling, sediment extraction or man-made structures) and chemical (by nutrients enrichment or contaminants) and biological impacts (e.g., spread of non-indigenous species or native species exploitation). Their impact is not uniform, and thus the state of benthic habitats and the level of threat varies across the OSPAR Regions. The indicators, data and methodology that support this thematic assessment also differ across the OSPAR Regions. The results of this thematic assessment should therefore be considered on Region by Region and cannot be directly compared.

The assessment of benthic habitats in the North - East Atlantic highlights variations in benthic biodiversity status across regions and indicators. This situation did not change much from OSPAR Intermediate Assessment 2017. However, direct comparison was not possible do to analyses made there in OSPAR regions while, due to better data availability, our focus was on finer scale. The improvement of data availability allows us to confirm that almost all assessed indicators in assessment units indicate not good or uncertain condition of the benthic environment.

Two common indicators *Assessment of coastal habitats in relation to nutrient and/or organic enrichment* (BH2-A) and *Extent of physical disturbance to benthic habitats* (BH3*)* were assessed in most of assessment units.

Indicator BH2-A was the only one that indicate a general good status of coastal benthic habitats in Greater North Sea and Northern Celtic Sea, even if some local persistent problem areas were also highlighted all over the OSPAR maritime area. This indicator utilises standardised methods of the WFD monitoring of biological quality elements. The good status for each biological quality element was intercalibrated within same types of water bodies by EU Member States (Neto et al., 2018); (Wilkes et al., 2018), (Van Hoey et al., 2019). The overall results show that eutrophication in the coastal marine areas is still an actual problem (Devlin et al., 2023).

The not good status of indicators assessing physical disturbances to benthic habitats (BH3, BH1, BH2b), suggest that fishing activities remaining a main factor responsible for degradation of benthic habitats, leading to declines in species diversity and reduced ecosystem resilience. (Pitcher et al., 2022, Bastardie et al., 2024, Zhao & Li, 2022)

The combined effects of various pressures, including climate change and human activities, are not yet fully understood (Elliott et al., 2018). A biggest challenge remains the lack of data, which resulted in many indicators being classified as uncertain or were not assessed. The impacts on benthic habitats continue to be a significant problem, with fishing, coastal development, and offshore energy and sediments extraction being the primary causes of damages.

These adverse impacts are further increase by the effects of climate change and ocean acidification described in various publications, which vary across different regions and habitat types. (Gattuso et al., 2021, Gattuso et al., 2018b), (Duarte et al., 2013), (IPCC, 2023)

Direct and indirect pressures driven by climatic change and ocean acidification factors can significantly alter the environmental conditions (e.g., increase in sea surface temperature, decreases of pH) necessary for benthic ecosystem processes and functions, and therefore affect habitat suitability for sensitive benthic species, species distributions, community structures and diversity patterns (Harley et al., 2006; Hoegh-Guldberg and Bruno 2010; Poloczanska et al., 2013, 2016; Gattuso et al., 2015; Nagelkerken and Connell 2015; Weinert et al., 2016). Climate change could lead to increases in mean sea level rise and changes in storminess, leading to a greater need for flood and coastal erosion defences. There are some uncertainties in the predictions, which will require additional research in order to increase accuracy on the future impacts of benthic habitats, particularly along the coastline.

There is not always a wide range of datasets available to systematically measure the effects of climate change and ocean acidification on benthic habitats and species, due to the paucity of the monitoring programme. However, there is a large volume of evidence of the impacts across different Regions. There are variations in the level and type of impacts due to geography (e.g., Arctic Waters) and the physical characteristics of the seafloor (e.g., depth), and in the typology of benthic habitat composition (e.g., calcifying species).

Benthic habitats may also provide solutions for the mitigation and adaption of climate change effects. For example, the natural carbon storage and sequestration capacity of some benthic habitats highlights their major role in the context of climate change and in mitigating the carbon inputs to the atmosphere from human activities.

Conclusion

In those areas where the OSPAR Common Indicators were applied, physical disturbance remains the main pressure contributing to widespread reduction in diversity and changes in sensitive benthic communities. The Common Indicators assessing physical disturbance to the seabed by bottom trawling (BH3a) and changes to sensitive species (BH1) showed that most benthic habitats in areas where such fishing activities take place are under significant threat or impact. The diversity of benthic communities (BH2b) is particularly poor in inshore habitats of the Greater North Sea Region (the only one assessed with this indicator). Coastal waters show mainly high/good status for benthic vegetation and invertebrates with regard to eutrophication, but this remains an issue in the eastern part of the Greater North Sea, including Kattegat, and the Channel (BH2a). However, in the Arctic Waters Region climatic factors are the most significant variables driving the trends detected in benthic habitats.

In the face of climate change and ocean acidification, as well as increasing production of food and energy there is more than ever an urgent need to lower the pressures on benthic habitats. This can be achieved through a combination of responses including effective area-based management, sustainable use and other regulation of human activities and innovations. Where they are assessed, i.e., in the Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast, benthic habitats are already impacted by human activities.

It is difficult to assess the effectiveness of measures to improve the status of benthic habitats, due to the multiple activities and pressures involved. In addition, the effects of measures on the recovery of habitats may take a long time to become evident. However, the lack of clear signs of improvement reported here suggests that current measures have been inadequate or ineffective.

This assessment provides an evidence base to help develop future response measures, for example targeted action plans. These need to be supported by improved monitoring and access to data alongside better resolution and geographic coverage in the next iteration of assessments and measures.

The findings from the NeaPanacea Projects highlight the urgent need for enhanced monitoring and research to better understand the complex interactions between human activities, climate change, and the health of benthic habitats in the North-East Atlantic (Schertenleib et al., 2023, Selig et al., 2014, Gattuso et al., 2018b).

These works were communicated at several international conferences (Guérin et al., 2022; McQuatters-Gollop & Guérin, 2022; Guérin & Lizińksa, 2023; Guérin & McQuatters-Gollop, 2023; McQuatters-Gollop et al., 2024; Guérin et al, 2024a, 2024b), and are still progressed for publications through future OSPAR standards and scientific articles.

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SESSION 4 - Q&A

This session raised general comments from participants, addressing all presentations in a cross-cutting manner. A summary of these discussions is provided below.

Data utilization and challenges in offshore assessments:

- Use of existing data in MSFD assessments: questions were raised about why existing offshore data, such as epifauna data from Spain, was not incorporated into Marine Strategy Framework Directive (MSFD) assessments. Concerns were expressed that waiting for new surveys could lead to significant delays.
- Challenges in data utilization: several factors were identified, including resource constraints, government prioritization decisions, and a tight reporting timeline. While offshore habitat assessments were recognized as necessary, limitations in implementation hindered progress.
- OSPAR considerations: it was noted that an upcoming OSPAR data call could allow French offshore data to be included in broader assessments, with results expected by 2029.
- Harmonization issues: differences in reporting timelines meant that some countries were unable to benefit from collective discussions on data harmonization. France submitted MSFD reports a year earlier than other countries, which prevented them from benefiting from discussions on data harmonization.

Methodological considerations in environmental assessments:

- Use of AMBI and M-AMBI indicators: limitations of these widely used assessment tools were discussed. The criteria used for setting Good Environmental Status (GES) boundaries were uniform across habitats, but ongoing efforts aimed to refine these distinctions.
- Challenges of intermediate classification: some participants pointed out that MSFD's classification scheme sometimes lacks the granularity needed to assess intermediate states of environmental disturbance.
- Multi-indicator approaches: experts emphasized the need to combine multiple indicators for a more comprehensive assessment. A method presented the previous day (cf. Laura Meudec, Session 3) was mentioned as a potentially complementary tool, as it does not rely on strict numerical thresholds.
- Expert interpretation is key: the combination of indicators and expert judgment was highlighted as crucial for deriving meaningful assessments.

Intercalibration and standardization across regions:

- Intercalibration for MSFD: questions were raised about whether intercalibration methods, similar to those used in the Water Framework Directive (WFD), should be applied to MSFD indicators.

- **Challenges in implementation**: it was suggested that full intercalibration may not be feasible due to the complexity of adapting indicators at the European level. However, standardizing monitoring protocols across countries was strongly recommended to enhance comparability.

Habitat typology and mapping efforts:

- **European mapping initiatives**: updates to European habitat maps were discussed, with confirmation that a new update is expected next year. However, the focus remains on improving mapping accuracy rather than revising typology.
- **Challenges in habitat surface calculation**: accurately determining the surface area of different habitat types remains a challenge. Participants highlighted the need for continuous updates and the importance of integrating new data into national and European databases to maintain consistency.

Addressing uncertainty in environmental assessments:

- **Impact on decision-making**: concerns were raised about how uncertainty in assessment indicators is acknowledged by policymakers. Comparisons were made to fisheries management, where uncertainty in scientific data is often overlooked, creating challenges for stakeholders.
- **Lack of transparency in reporting**: it was noted that reports with inconclusive classifications were sometimes not fully communicated to European public authorities, as there was reluctance to acknowledge data gaps.
- **Scientific and policy interactions**: the balance between scientific rigor and policy constraints was discussed, highlighting the challenges in ensuring timely and accurate assessments.

Implications for restoration planning:

- **Uncertainty in restoration strategies**: given the necessity for Member States to develop restoration plans, questions arose regarding how uncertainty factors into these initiatives.
- **Progressive approach**: it was explained that the first version of restoration plans aims to incorporate as much available information as possible, with the expectation that subsequent versions will be refined as knowledge advances.

Broader conservation perspectives:

- **Shift in conservation priorities**: the need to move beyond emergency conservation measures and focus on protecting broader biodiversity was emphasized, rather than prioritizing only high-profile species.
- **Urgency in marine protection**: the increasing pressures on marine environments and the urgency for proactive measures were highlighted, calling for immediate collective action to address environmental challenges.

SESSION 5 – CONSERVATION AND MANAGEMENT PRACTICES FOR SEDIMENTARY HABITATS IN MARINE PROTECTED AREAS

PRATIQUES DE CONSERVATION ET DE GESTION DES HABITATS SÉDIMENTAIRES DANS LES ZONES MARINES PROTÉGÉES

Session moderator – *Animatrice de session*: **Aurélie Lutrand,** Benthic habitats project manager, LIFE Marha, OFB, France

Access the presentations from this session here – *Accédez aux présentations de cette session ici.*

The conservation and management of sedimentary habitats within Marine Protected Areas (MPAs) are essential for maintaining biodiversity, ecosystem services, and compliance with regulatory frameworks such as the EU Habitats Directive and the Marine Strategy Framework Directive (MSFD). As these habitats face increasing pressures from human activities, including fisheries and coastal development, science-based approaches are critical for their protection and restoration. This session explores different methodologies and case studies that contribute to the sustainable management of sedimentary habitats in MPAs.

The first presentation by **Gert Van Hoey** (Flanders Research Institute for Agriculture, Fisheries and Food, Belgium) examines the process of selecting and managing habitat features within the Flemish Banks MPA in Belgium. It highlights the challenges in determining priority areas for protection, balancing ecological integrity with

La conservation et la gestion des habitats sédimentaires au sein des aires marines protégées (AMP) sont essentielles pour préserver la biodiversité, les services écosystémiques, ainsi que pour assurer le respect des cadres réglementaires tels que la directive Habitats de l'UE et la directive-cadre sur la stratégie pour le milieu marin (DCSMM). Face aux pressions croissantes exercées par les activités humaines, notamment la pêche et l'aménagement côtier, des approches fondées sur la science sont indispensables pour protéger et restaurer ces habitats.

La première présentation de **Gert Van Hoey** (Flanders Research Institute for Agriculture, Fisheries and Food, Belgium) examine le processus de sélection et de gestion des habitats au sein de l'aire marine protégée des Flemish Banks en Belgique. Elle met en lumière les défis liés à l'identification des zones prioritaires de protection, à l'équilibre entre l'intégrité socio-economic considerations, and implementing fisheries restrictions to improve habitat conditions. By adopting a scientific and data-driven approach, this case study demonstrates the importance of stakeholder engagement and evidence-based decision-making in conservation efforts.

In France, the Aiguillon Bay National Nature Reserve has undertaken a comprehensive effort to update the mapping of its benthic habitats, as presented by **Audran Chenu** (Ligue de Protection des Oiseaux, LPO, France). The study emphasizes the significance of intertidal mudflats in carbon sequestration and their role in broader climate mitigation efforts. Through advanced mapping techniques, researchers have identified and classified distinct bio-morphosedimentary habitats, improving the reserve's capacity to manage these critical ecosystems in alignment with carbon neutrality objectives.

Julien Lanshere and **Ronan Launay** (Créocean, France) introduce the HABISSE project, which focuses on improving knowledge of intertidal sedimentary habitats within the Picardie Estuaries and Opale Sea Marine Nature Park. The study provides valuable insights into habitat diversity, sediment composition, and benthic macrofaunal communities. By creating a detailed atlas of these habitats, the project enhances the understanding of their spatial distribution and supports more effective conservation strategies within the park.

Finally, **Silvana Birchenough** (Environmental Resources Management, ERM, UK) emphasizes the critical role of long-term benthic time series in understanding ecological change, supporting marine management, and informing policy, drawing on transversal analysis led by the Benthos Ecology Working Group of ICES. This presentation (summarized as an abstract) highlights the need for interdisciplinary collaboration, consistent monitoring, and adaptive strategies in the face of climate and anthropogenic pressures.

Together, these presentations highlight the evolving methodologies used in MPA management, from habitat mapping and monitoring to regulatory decision-making and

écologique et les considérations socio-économiques, ainsi qu'à la mise en place de restrictions sur la pêche afin d'améliorer l'état des habitats. En adoptant une approche scientifique fondée sur les données, cette étude illustre l'importance de l'implication des parties prenantes et de la prise de décision fondée sur des données probantes dans les efforts de conservation.

En France, la Réserve naturelle nationale de la baie de l'Aiguillon a entrepris un travail approfondi de mise à jour de la cartographie de ses habitats benthiques, comme présenté par **Audran Chenu** (LPO, France). L'étude souligne l'importance des vasières intertidales dans le stockage du carbone et leur rôle plus large d'atténuation du changement climatique. Grâce à des techniques de cartographie avancées, les chercheurs ont pu identifier et classifier des habitats bio-morphosédimentaires distincts, renforçant ainsi la capacité de la réserve à gérer ces écosystèmes critiques en cohérence avec les objectifs de neutralité carbone.

Julien Lanshere et **Ronan Launay** (Créocean, France) présentent le projet HABISSE, qui vise à améliorer les connaissances sur les habitats sédimentaires intertidaux au sein du Parc naturel marin des Estuaires Picards et de la mer d'Opale. L'étude apporte des éclairages précieux sur la diversité des habitats, la composition des sédiments et les communautés de macrofaune benthique. En élaborant un atlas détaillé de ces habitats, le projet permet une meilleure compréhension de leur répartition spatiale et soutient des actions de conservation plus efficaces au sein du parc.

Enfin, **Silvana Birchenough** (Environmental Resources Management, ERM, UK) souligne le rôle essentiel des séries chronologiques benthiques à long terme pour comprendre les changements écologiques, soutenir la gestion marine et informer les politiques, en s'appuyant sur l'analyse transversale menée par le groupe de travail sur l'écologie du benthos du CIEM. Cette présentation (résumée sous forme d'abstract) souligne la nécessité d'une collaboration interdisciplinaire, d'une surveillance cohérente et de stratégies stakeholder collaboration. They collectively underscore the importance of integrating scientific research into conservation policies to ensure the resilience and sustainability of sedimentary habitats in protected marine areas.

adaptatives face aux pressions climatiques et anthropiques.

Ensemble, ces présentations mettent en lumière l'évolution des méthodologies utilisées dans la gestion des aires marines protégées, allant de la cartographie et du suivi des habitats à la prise de décision réglementaire et à la collaboration avec les parties prenantes. Elles soulignent collectivement l'importance d'intégrer la recherche scientifique dans les politiques de conservation afin de garantir la résilience et la durabilité des habitats sédimentaires au sein des espaces marins protégés.

Scientific based approach in selecting the habitats and habitat features to manage within the 'Vlaamse banken' MPA

Van Hoey Gert, Ellen Pecceu, Katrien Verlé

Flanders Research Institute of Agriculture, Fishery and Food; Jacobsenstraat 1; 8400 Oostende.

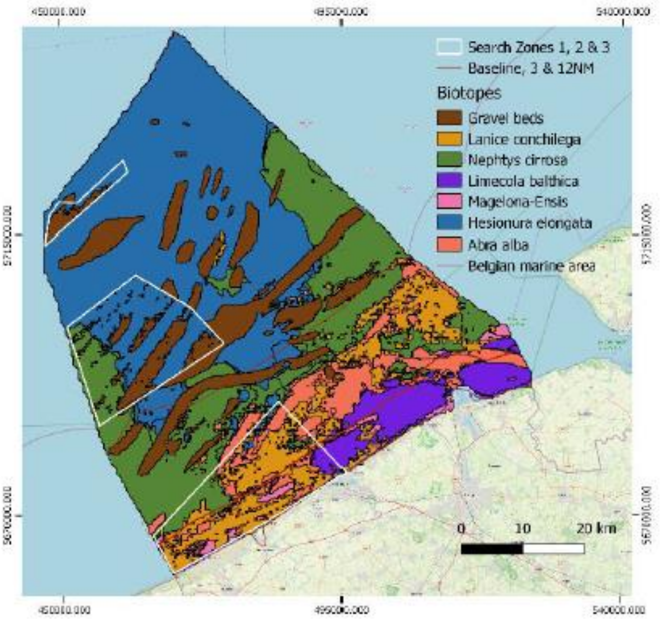
Introduction

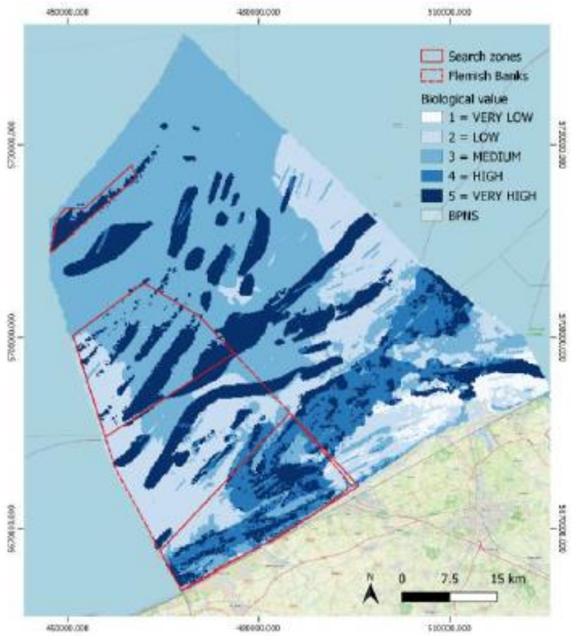
In the European Union, two key legal instruments exist for the protection of marine habitats: the EU Habitats Directive (HD) and the EU Marine Strategy Framework Directive (MSFD). The evaluation of the environmental targets and the conservation objectives under the MSFD and HD has revealed that the GES (as evaluated by MSFD) or the favourable conservation status (as evaluated by HD) is not reached for the benthic habitats. To accomplish GES and favourable conservation status, management measures for protecting and restoring the habitats need to be taken. For protection of a network of marine protected areas, the Natura 2000 network is designated. In Belgium, the zone 'Vlaamse Banken' was designated as a marine protected area and there are two habitat types that need protection. The first habitat – type 1110 "Sandbanks which are slightly covered by sea water all the time" - represents the main habitat type of the Belgian part of the North Sea (BPNS) covering its entire surface area with a geologically unique sandbank system. Gravel beds and *Lanice conchilega* biogenic aggregations, that can be found within sandbank systems, are classified as habitat type 1170 "Reefs", which is the second habitat type to protect. For protecting and improving the state of those habitats, the pressures need to be reduced or removed. In our area, the habitats are mostly threatened by mobile bottom fishery activities. Therefore, fishery restrictions need to be taken to preserve the bottom integrity, which is essential in order to reach GES and the conservation objectives under the HD.

Taking the right fishery measures and having a scientific underpinned methodology to delineate the zones for protection is required. How to select the most valuable or vulnerable habitats or biological communities? How much of each habitat to protect? Where can we protect those habitats in sufficient amount, also considering the economic value for the fishery. Stakeholder engagements before and during the process? Many questions that needs to be tackled before you can implement it, and are ideally based on an objective and data-driven approach. This presentation will guide you through the process we executed for delineating the fishery management zones within the 'Vlaamse banken' MPA.

How to select the most valuable or vulnerable habitats or biological communities?

The biological value and the distribution maps of seafloor habitats were updated to build a solid scientific basis to guide the delineation of fishery restriction areas. A compilation of over 3000 macrobenthos community samples from 1994 and 2018 was used to map the distribution of the five identified macrobenthos communities in the BPNS by habitat suitability modelling using R-INLA-SPDE (a Bayesian geospatial modelling approach specific for geographically referenced data, advantageous in ecology as it accounts for spatial effects). The macrobenthos samples and 1400 epibenthos and demersal fish samples from the same period, together with the updated distribution map of gravel beds and the distribution map of *Lanice conchilega* aggregations were used to produce an updated biological valuation of the BPNS as described in Derous *et al.* (2007b). The data were used to answer a series of assessment questions based on values of biodiversity, rarity, aggregation, and key-species occurrence. The results of the biological valuation indicated that all gravel beds have a very high biological value (5 on a scale of 1 to 5). Very High biological values (value 5) were also assigned to the rich and dense *Abra alba* community and to the *Lanice conchilega* reefs. Low and very low biological values (values 2 and 1) were assigned to the *Nephtys cirrosa* and *Limecola balthica* communities due to lower densities and biodiversity. In total, 31% of the BPNS was classified as value 4 or 5, with much of this surface lying within the three defined search zones in the MPA.





The vulnerability of the habitat features of the BPNS was based on the sensitivity information available on MarLIN (marlin.ac.uk), a site that hosts the largest review yet of the effects of human activities and natural events on marine species and habitats. MarLin defines sensitivity as a product of (1) the likelihood of damage (intolerance or resistance) due to a pressure and (2) the rate of (or time taken for) recovery (recoverability or resilience) once the pressure has been reduced or been removed. We determined a sensitivity score (1: low sensitivity; 2: low to medium sensitivity; 3: medium sensitivity; 4: medium to high sensitivity and 5: high sensitivity) of each benthic habitat feature based on the impact of abrasion/removal of substratum. The sandy habitats (*Nephtys cirrosa, Hesionura elongata*) received score 1 (low sensitivity), due to their high resilience. The *Magelona-Ensis leei* habitat is also not very sensitive to abrasion (score 1). The *Abra alba* and *Limecola balthica* habitats received a sensitivity score of 2 (low to medium sensitivity). The *Lanice conchilega* habitat received score 2 due to the fact that the sensitivity of *L. conchilega* itself is low, as the majority of individual worms can survive a single trawl passage, and they can quickly recover (1-2 days) their 3D structures. However, the associated community and species are more sensitive to disturbance. Based on the MarLin classification, gravel biotopes have a medium sensitivity. In the past, however, boulders and gravel have been removed by fishing activity, creating loss of the habitat (physical change of the seabed/sediment). In combination with the low or non-resistance of many species within this habitat, this has led to a score 5 (highly sensitive) for gravel beds in the BPNS.

How much of each habitat to protect?

We want to protect sufficient surface area of habitat type 1110 (and the related biological communities) and habitat type 1170 from bottom disturbing activities. For reaching the conservation objectives we need to strive to protect a sufficient amount of those habitat features. At this point, no scientific method exists for defining the amount of surface area that needs to be protected in order to reach the conservation objectives. Therefore, we have developed an objective reasoning, as explained in this section and as reflected in the scenario settings, to come to a sufficient protection of the different habitat features and this in a balanced way**.**

Our methodological approach used a 10% protection target value as a guidance, which is in line with several conventions or strategies (convention on biological biodiversity, UN Sustainable Development Goal 14, Target 14.2 and 14.5, EU biodiversity strategy). This 10% is a policy driven target value and not specifically defined on habitat level. To come to surface area values on habitat level, we relied on their biological value characteristics and their sensitivity classification to bottom disturbing fisheries. We have used a combination (sum) of these characteristics in order to prioritize the different habitat features and in order to rank them according to their need of protection against bottom disturbing fisheries. This means that the areal extent to protect was estimated higher for habitat features characterized by a higher biological value and/or sensitivity to bottom abrasion.

Where can we protect those habitats in sufficient amount, also considering the economic value for the fishery?

For answering this question, we used Marxan, a software-based decision support tool to suggest zones where the predefined environmental targets (habitat extent) can be achieved at the lowest fishery cost. In this case, the aim is to delineate a sufficiently large area to allow preservation and restoration of the seabed while also taking into account the potential impact for the commercial fishery sector. The commercial value of the area was in detailed analysed based on both effort (days at sea), landing value and landing weight from 2009-2022 were used for all the European member states active in the region. To translate the conservation objectives into concrete targets, the different habitat features were ranked based on sensitivity and their biological value score. This one score allowed us to determine the proportion to protect of each habitat feature (more valuable and sensitive habitat features get more protected area). To explore how much we want and can protect of each habitat feature, different ambition levels (15, 20, 25% protected) for gravel beds (highest biological value, most sensitive) were tested. The biological values and sensitivity ranking was then used to determine the relative proportion of each of the other habitat features to protect. Several scenarios were executed and revealed that scenario C has the highest potential. Primarily with regard to conservation objectives, but also in terms of enforceability (minimal fragmentation), fishery cost and favorable spatial overlap with other sectors. Within these scenarios, the ambition level of 20% protection was pursued for gravel beds, 14% for *Abra* and *Lanice*, 8% for *Hesionura* and *Magelona-Ensis* (only scenario C) and 6% for *Nephtys*.

Stakeholder engagements before and during the process?

In order to gain support for taking fishery restrictions in the MPA, a thorough stakeholder process needs to be set-up. The fishery sectors are informed and consulted before and during the process by ad-hoc meetings, presentations at official stakeholder group meetings and bilateral consultations. During this process and based on input from different stakeholders, the delineated areas under scenario C were slightly adapted to come to a supported interpretation of the protected zones within the MPA area. With this outcome, the process of a joint recommendation in accordance to the Common Fisheries Policy (Regulation 1380/2013, Article 11) was started in 2024. Belgium acted as the ‘initiating Member State’ and started interacting with neighbouring member states outlining the rationale, scientific evidence, and implementation details of the proposed fisheries restrictions. Denmark and Germany accepted the measures without further bilateral consultations. The Netherlands accepted the proposal after a bilateral meeting. The bilaterial negotiations with France are still ongoing.

This contribution is based on the report of “Pecceu Ellen & Paoletti Silvia, Van Hoey Gert, Vanelslander Bart, Verlé Katrien, Degraer Steven, Van Lancker Vera, Hostens Kris, Polet Hans, 2021. Scientific background report in preparation of fisheries measures to protect the bottom integrity and the different habitats within the Belgian part of the North Sea. ILVO-Mededeling 277.

Q&A

On communicating scientific data to managers

- Thanks to Belgium’s solid history of benthic monitoring and detailed habitat modelling, the maps and their interpretation were well received. The prioritization of habitats was based on ecological importance and location.

On regulatory understanding of monitoring work:

- The monitoring approach was well understood and appreciated by stakeholders and policymakers, despite inherent uncertainties. The ability to model habitats and provide statements on aspects such as productivity was beneficial for communication.

On exclusion of specific habitats:

- The *Limecola balthica* habitat wasn’t ignored but less prioritised in the assessment because it falls outside Natura 2000 and consists of a mobile, muddy environments with lower biodiversity. Protection efforts focused on habitats with greater biodiversity or ecological importance. The exclusion was a policy choice rather than a scientific oversight.

On citizen science contributions:

- To address the issue of regular monitoring of areas (see questions in the next Q&A box), voluntary sampling by citizens can be used, especially in Marine Parks. There are a lot of people in voluntary teams in terrestrial ecology, but also in the intertidal area. Volunteers can help reduce costs and increase coverage, especially if equipped and trained to collect standard data.

Updating of habitat mapping of intertidal mudflats in the Aiguillon bay

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Abstract: Characterised by high primary production and elevated sedimentation rates, intertidal mudflats play an important role in carbon sequestration. However, their type, ecological state and bioturbation mechanisms can modify this trapping capacity. In this context, the Aiguillon bay National Nature Reserve, in partnership with the LIENSs (Littoral Environnement et Sociétés) laboratory in La Rochelle, undertook to update the mapping of its benthic habitats, which is also in line with the carbon neutrality objectives of the 'La Rochelle Territoire Zéro Carbone' project. To achieve this, a core sampling protocol was implemented to the entire mudflat. Spatial interpolation, together with a Bray-Curtis dissimilarity matrix and a hierarchical clustering, were then used to identify and locate six bio-morphosedimentary habitats specific to the European EUNIS 2022 typology to an accuracy of 50m. The Aiguillon bay was found to be mostly muddy (>99%). Its habitats followed the distribution of characteristic species, themselves dependent on bathymetric or granulometric variations.

Key words: benthic habitats, habitat typologies, benthic macrofauna, sediments, Bray-Curtis.

1. Introduction

Intertidal mudflats are among the most productive ecosystems in the world (McLusky & Elliott, 2004). Due to the many physical constraints they face on a daily basis, benthic invertebrate communities of estuarine mudflats are often characterised by low species richness, but high densities and biomasses (Elliott & Whitfield, 2011). These high concentrations of life then attract higher trophic levels such as fish (at high tide) or coastal birds (at low tide) (Dyer *et al.*, 2000; Verger & Ghirardi, 2009).

Since the creation of the Aiguillon bay National Nature Reserve, several management plans have highlighted the need to update the mapping of benthic habitats in order to monitor their evolution and support conservation strategies. In 2021, the city of La Rochelle (located 8km from the Aiguillon bay) is launching a project entitled "La Rochelle Territoire Zero Carbone" (LRTZC) aimed at achieving carbon neutrality for its area by 2040, with the blue carbon axis led by the LIENSs laboratory of La Rochelle University. Intertidal mudflats, one of whose ecological functions is to sequester carbon over the long term, underline the need to characterise these habitats. Indeed, the capacity of mudflats to sequester carbon differs according to their type, ecological status and bioturbation mechanisms.

Therefore, the main objective of this study is to update and accurately map the benthic habitats of the estuarine mudflats of the Aiguillon bay, which will enrich the predictive models of the LRTZC project. On the basis of benthic macrofaunal assemblages and using sedimentary characteristics, we will use the

European typology 'EUNIS 2022' to classify and spatially define the various benthic habitats encountered. We will also indicate the correspondences with the EUNIS 2012 typology and NatHab-Atlantic, which corresponds to the French typology of benthic marine habitats.

2. Methods

2.1. Study site

The Aiguillon bay covers 4900 ha on the Atlantic coast, and is mainly made up of estuarine mudflats (3700 ha) and salt marshes (Figure 1). These mudflats, formed by the accumulation of fine marine and fluvial sediments, are retreating in favour of salt marshes, which have gained 67ha on the mudflats between 2010 and 2020. Indeed, the sedimentation rate of +1.59 ± 0.52 cm.yr-1 measured between 2000 and 2021 ranks the Aiguillon bay among the tidal estuary with the highest sedimentation rates in the world (Olivier & Chaumillon, 2022). In addition, Aiguillon bay is also one of France's most important sites for migratory waterbirds (Moussy *et al*., 2022).

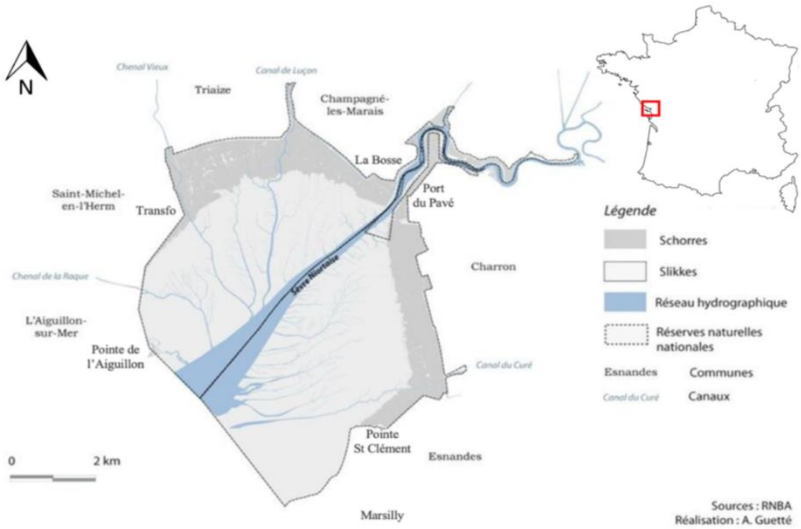

Figure 1: Map of the Aiguillon bay national nature reserve, its topography and hydrographic network (from Guetté, 2014).

2.2. Sampling strategy

The sampling period ran from November 2023 to February 2024. The winter period avoids the main fluctuations in benthic invertebrate numbers and biomass (Philippe, 2016). Thus, 535 coring stations were positioned according to a pre-established grid covering the entire study area, following a method already applied (Van Gils *et al*., 2006; Bocher *et al.,* 2007) (Figure 2). Stations were spaced 250m apart. The majority of stations (96.6%) were sampled by boat, at the rhythm of the incoming tide and when the water level was high enough to access the area. Two cores per station were taken using a 10cm-diameter corer covering an area of around 0.0079 (1/127) m2 to a depth of 20 to 25cm.

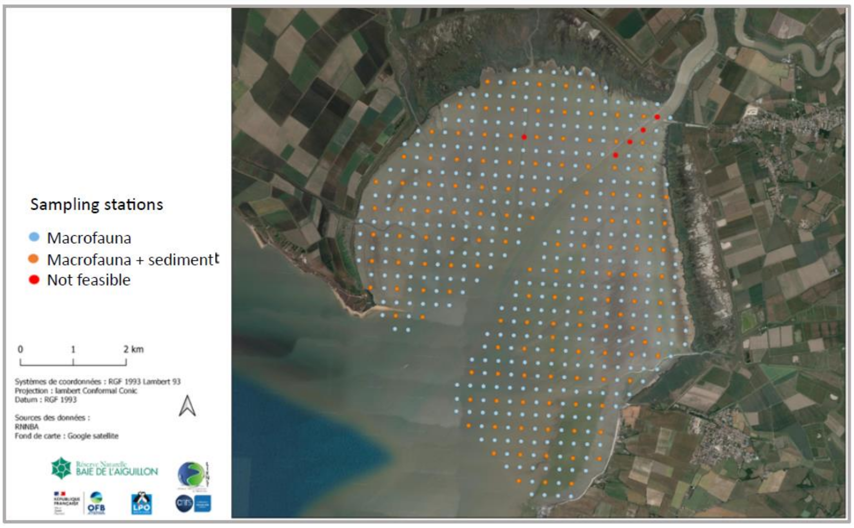

Figure 2: Location of sampling stations for benthic macrofauna and sediment surveys.

2.3. Sample processing

After sieving, the molluscs were placed in a freezer at -20°C until identification in the laboratory. Annelid worms, on the other hand, were placed in tubes containing 90% alcohol to preserve tissue integrity and facilitate identification. In laboratory, all molluscs with flesh (considered alive at the time of sampling) were counted and identified under binocular loupe. Similarly, annelid worms were counted and identified. The support of a benthologist (Jérôme Jourde - LIENSs) helped to clarify any doubts throughout the identification process.

Sediment samples were stored in a freezer at -20°C prior to analysis. After cleaning the samples by removing coarse debris and sediment aggregates using sieves, sediment particle diameter and the proportion of silt (fraction <63µm) were obtained using the Mastersizer2000 (Malvern, UK) by laser diffraction.

2.4. EUNIS 2022 typology

The EUNIS typology used in this study is a classification system for natural, semi-natural and anthropogenic habitats in Europe. It standardises the description of habitats across Europe. The most recent update of the marine habitat classification dates from 2022 (the previous one was from 2012). It identifies and describes habitats on several hierarchical levels, from the most general to the most specific. Each habitat type is referenced with an alphanumeric code and classified according to its general nature (e.g. forest, marine...), its biotic and abiotic specificities. Thus, benthic marine habitats can be broken down into seven main categories governed by their bathymetric level, which in turn are divided according to the nature of the substrate observed, and then according to the geographical area considered. Thus, Atlantic mid-littoral muddy habitats are further refined by the salinity conditions associated with the species assemblages (fauna or flora) encountered. Once we had identified and counted the species we had sampled, we were in a position to accurately identify the muddy habitats of the Aiguillon bay.

2.5. Analysis and mapping

The nature of the sediment first guided the choice of habitats. Indeed, according to the EUNIS nomenclature, when the mud fraction was less than 60%, the choice of habitat was oriented towards sandy or sandy-muddy environments. Spatial interpolation using ordinary kriging enabled us to refine the sediment profile of the bay to a resolution of 50m.

The second stage involved spatial interpolation by universal kriging of densities for the six dominant species also useful for EUNIS habitat discrimination: *Macoma balthica, Abra tenuis, Scrobicularia plana, Cerastoderma edule, Hediste diversicolor, Nephtys hombergii.*

For this purpose, altimetry data for each station were extracted from a LiDAR topographic survey carried out in 2021. We thus had altimetry and density of individuals (N/m^2) for each of the 530 stations sampled. A generalized additive model (GAM) of the density of individuals as a function of altimetry was established with these data for each species and the variogram prior to interpolation was based on GAM residuals, in order to avoid the systematic relationship between density and altimetry, and to better capture local variations. This also reduced the risk of over- or underestimating predicted values. As for sediment, spatial interpolation was carried out with an accuracy of 50 meters.

The data obtained for each species were then compiled and used to calculate a dissimilarity matrix using the Bray-Curtis distance followed by a hierarchical ascending classification (HAC) using the ward.D2 method to generate a number of predefined clusters, corresponding to future habitats. The previous mapping of benthic habitats in the Aiguillon bay (Bocher *et al*., 2013) combined with the interpretability of the results guided the choice of the number of clusters to be used.

3. Results and discussion

3.1. Sediment profile

The sediment in Aiguillon bay is largely comprised of the muddy fraction (<63µm), with an average proportion of mud equal to 89.1 ± 8.6%. This proportion is very similar to the particle size data obtained during the winter of 2003/2004, which reported 89.8% silt over the whole bay (Bocher *et al*., 2013). Also, the median size of sediment particles ranged from 195.3µm to 6.6µm with a mean equal to 11.0 ± 16.6µm. The latter value was limited to 8µm 20 years ago (Bocher et al., 2013). The bay's sedimentary characteristics appear to have been relatively stable over the past 20 years. It ranks among the most homogeneous and muddy estuaries in Europe (Bocher *et al*., 2007) (Figure 3).

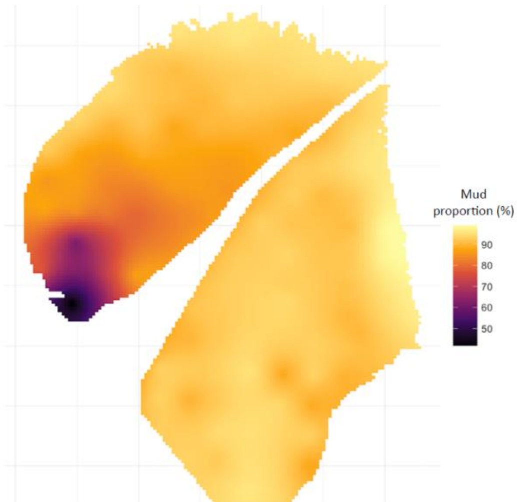

Figure 3: Mapping the proportion of mud in Aiguillon bay.

3.2. Distribution

Each of dominant species seems to adopt spatial preferences reflecting varied ecological requirements. The bivalves *Scrobicularia plana* (Figure 4) and *Abra tenuis* appear to share an arcuate distribution around the mudflat, on the middle part of the mediolittoral, likely reflecting preferences closely linked to the tidal rhythm and repeated phases of emersion and immersion (Philippe et al., 2016). *Cerastoderma edule* and *Macoma balthica* are concentrated mainly in the north-western part of the bay, on the mudflats and near the Aiguillon's sandy tip. Finally, the two species of polychaete annelid worms seem to prefer distinct zones. *Hediste diversicolor* prefers the upper half of the foreshore. It

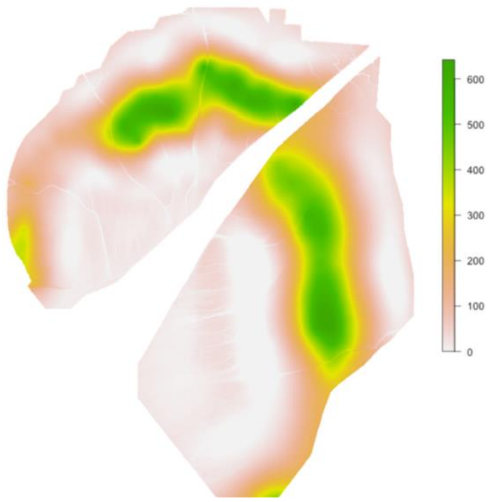

Figure 4: Example of an interpolated distribution map of Scrobicularia plana (N/m^2).

is one of the few species to occupy the upper mudflats. Conversely, *Nephtys hombergii* limits itself to the lower half

3.3. Mapping estuarine mudflat habitats in Aiguillon bay

Finally, six types of muddy and sandy habitats were identified. The upper mediolittoral mud (MA6-227), relatively poor in benthic macrofauna and dominated by the polychaete worm *Hediste diversicolor*, covers 737.8ha (Figure 5). Habitat MA6-225, the only habitat of Atlantic mid-littoral mud with variable salinity to mention the presence of *Scrobicularia plana*, dominates the mudflat and covers 1172.6ha. Classification of the lower parts of the mudflat was more difficult, as there is currently no habitat type describing the presence of *Cerastoderma edule* in muddy environments. However, given the non-negligible cockle densities and the slight influx of sand from the west, we have chosen to distinguish two habitat types that more accurately represent the reality on the ground. Thus, habitat MA5-252, characterized by the abundance of cockles on the middle or lower foreshore, is attributed to the majority of lower mudflats (657.4ha). On the other hand, habitat MA6-223 has been assigned to the remaining mudflats of the lower foreshore, where *Macoma balthica* and *Nephtys hombergii* are present in smaller proportions (582.2ha). The habitat near Aiguillon's sand tip (Figure 1) is characterised by a higher sand content than elsewhere in the bay (sand fraction >40%). It is therefore part of the Atlantic mediolittoral muddy sands MA5-25. Aiguillon's sand tip was classified on the basis of photographs and field observations, revealing typical patterns of clean, mobile sands shaped by wave and current action. As for the mediolittoral muddy sands, we will restrict ourselves to code MA5-23, as we were unable to find species that are characteristic of this type of environment. These last two habitats together account for 28.4ha. Finally, the EUNIS 2022 typology does not mention the existence of biogenic reefs made up of oysters. Considered as a habitat type in its own right, oyster-farming wastelands are included among the habitats of the Aiguillon bay, but no EUNIS 2022 code has been assigned to them. However, these reefs, made up locally of *Magallana gigas* Japanese oysters, total 72.7ha.

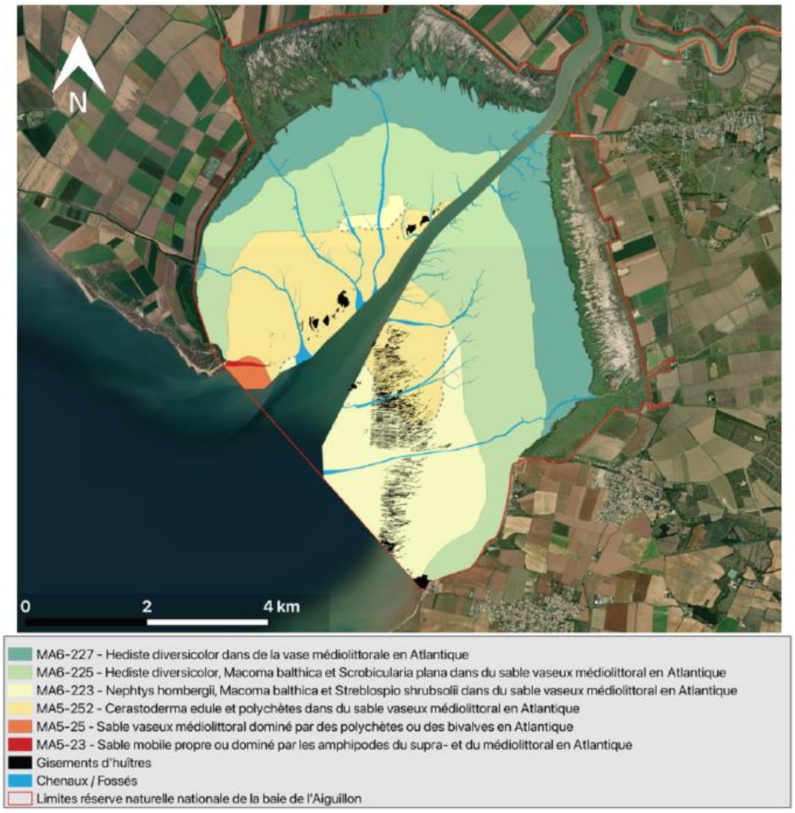

Figure 5: Mapping of benthic habitats in Aiguillon bay in 2024 according to EUNIS 2022 typology.

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Q&A

On agricultural pressures: Data shows little change from 2004 to 2024, even though the area is surrounded by farmland. Could the impact of agriculture be underestimated?

- A new project has just been launched to investigate chemical pressures (e.g., pesticides, nutrients). It's still too early to confirm an impact, but undetected effects on microfauna, reproduction, or higher trophic levels (fish, birds) are possible. Community structure alone may not reveal all pressures.

On potential impact on macrofauna:

- While density changes were not observed, it is possible that pollutants concentrate in macrofauna, necessitating further investigation.

On using results to guide management strategies:

- It is still early, but the goal is to assess, for example, whether bird species show habitat preferences that could inform future management.
- Annual monitoring is carried out on a smaller number of stations to track changes in biomass and biodiversity over time.

On long-term monitoring:

- Ideally, revisiting sites every 1–2 years would allow better tracking of habitat dynamics, but funding and logistical constraints remain major challenges.

The value of benthic long-term series: compilation of science to support management decisions

<u>Abstract produced from the presentation made by Silvana Birchenough during the LIFE Maha seminar on sedimentary habitats.</u>

Long-term ecological data are crucial to detecting patterns, assessing ecosystem responses, and informing marine management. This presentation emphasized the ecological and policy value of benthic time series. Drawing from laboratory experiments, legislative frameworks, and collaborative analyses led by the Benthos Ecology Working Group of ICES, the talk highlighted the role of benthic organisms as sensitive indicators of biotic and abiotic changes - including climate-driven stressors such as ocean acidification, hypoxia, and warming. The need for interdisciplinary collaboration and standardized monitoring approaches was underscored, particularly in adapting to legislative demands (e.g., MSFD, SDGs). Time series not only support robust assessments and model validation but also serve as essential tools for detecting long-term trends and guiding adaptive management. Challenges include funding continuity, methodological consistency, and a declining taxonomic workforce. Ultimately, the speaker called for flexible, ecosystem-based monitoring strategies that integrate benthic indicators with evolving technologies and policy needs.

Q&A

On application of technological innovations:

- New technologies offer complementary tools: eDNA reveals species presence/absence, video mapping shows habitat extent and transitions, biological trait analysis helps understand ecosystem functions. These methods provide a more complete picture of ecological states.
- No single tool is sufficient—a combination of approaches is needed to support effective MPA management.

HABISSE 2020-2022 - mapping of intertidal loose benthic habitats 1130 and 1140 (eur28) and analysis of their chemical contamination in the EPMO Marine Natural Park (France)

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Key words: Mapping, benthic habitat, intertidal, conservation status, marine biodiversity, HABISSE, PNM EPMO, OFB.

Context

The Estuaires Picards and Mer d'Opale Marine Nature Park, or PNM EPMO, is located on the French coasts of the Channel and North Sea (**Figure 6**). It is the first one of its kind and the fifth on the scale of metropolitan France and its overseas territories. The PNM EPMO covers 2,300 km² of exclusively marine surface areas and extends over three French departments, from the commune of Ambleteuse to Le Tréport. This is the most northerly of French Marine Nature Parks. On the land side, it extends to the high-water mark, the limit of the public maritime domain (DPM). On the marine side, it finds its external limit at the maritime traffic separation device (OFB, 2025).

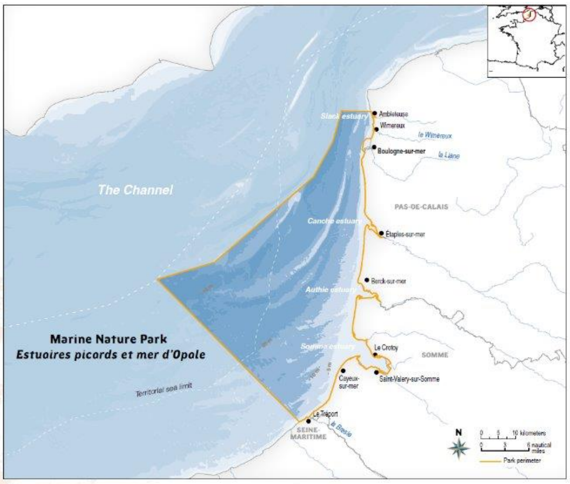


Figure 6 – Location of the Estuaires Picards and Mer d'Opale Marine Nature Park (source: OFB)

The Marine Nature Park was created by Ministerial Decree 2012-1389 of December 11th, 2012. The three aims of this category of marine protected area are: to improve knowledge of the natural and cultural heritage, to ensure the protection of marine ecosystems and to support the sustainable development of maritime activities that depend on it. It is managed by the French Biodiversity Agency (OFB), a public establishment under the supervision of the French ministries in charge of ecology and agriculture.

The Marine Nature Park management plan sets out all the Park management objectives. The document was validated by the management board in December 2015 and is valid for 15 years (2015 - 2030). When more that 50% of Natura 2000 sites areas are located within the perimeter of a Park, the Document of Objectives (DOCOB) is integrated into the management plan. The HABISSE project is part of the Life Marha[1] project and aims to improve knowledge of intertidal soft habitats of community interest in the PNM EPMO, and to draw up an inventory of the chemical contamination affecting them.

Objectives of the HABISSE project

The aim of the HABISSE (standing for French "Habitats Benthiques Intertidaux Sensibles") project was to improve knowledge of the intertidal sedimentary habitats that can be observed along the coastline of the PNM EPMO, and gain a better understanding of their spatial distribution and the macrozoobenthic communities that inhabit them. Two intertidal Habitats of Community Interest (HIC) were concerned by the HABISSE project on PNM EPMO coastline: *1130 "Estuaries"*, and more specifically its subdivision into 1130-1 "Slikke in tidal waters (Atlantic coast): estuarine mediolittoral mudflats" (CH2004) and *1140 "Mudflats and sandflats not covered by seawater at low tide"* and its subdivisions into elementary habitats.

Teams from CREOCEAN, GEMEL and LOG joined forces between 2020 and 2023 to map the intertidal benthic habitats in three main typologies Eunis 2012, NatHab v.3 and Natura 2000 Eur28 and CH2004 (Bensettiti & al., 2004; European Environment Agency, 2013; Michez & al., 2019) and analyse their chemical contamination within the perimeter of the PNM EPMO. This work will contribute to a management tool for the Marine Nature Park to define actions and strategies for long term surveys. The project was also in line with three environmental goals of the management plan.

For the purpose of the marine sedimentary habitats seminar for European Atlantic Biogeographic region held in Lille in March 2025, only the results on intertidal habitats characterization and mapping were presented.

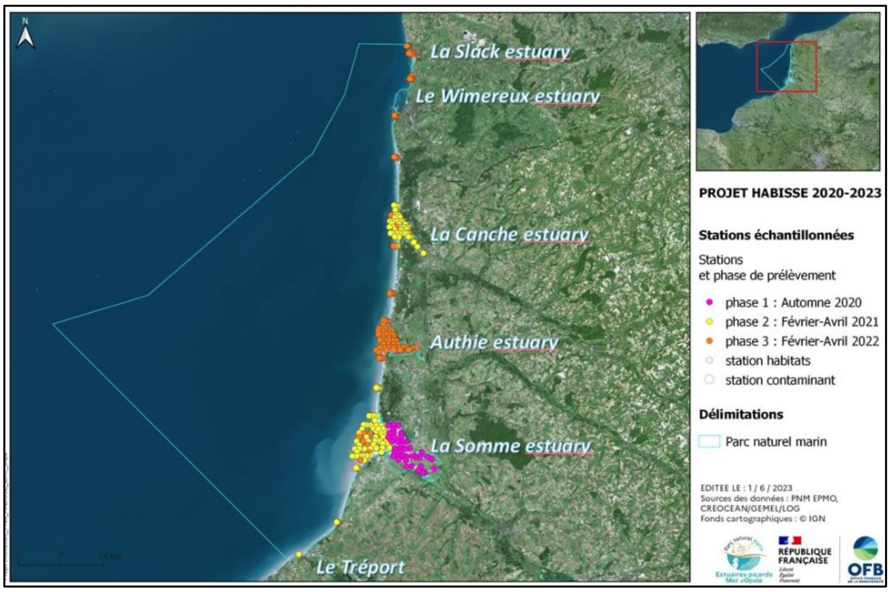
Method

A collection of sediment samples was carried out throughout 250 stations distributed along the marine nature park intertidal zone (Figure 7). Sampling effort was split into 3 phases, running from 2020 to 2022, notably in accordance to the Water Framework Directive 2000/60/EC (WFD) seasonality sampling recommendations (Garcia & al., 2014):

- Phase 1 (pink dots): WFD Transitional waters of Baie de Somme in early autumn 2020-2021;
- Phase 2 (yellow dots): WFD Coastal waters FRAH18 and FRAC05 in the south of the Park in

[1] As part of its missions, the OFB is piloting the Life integrated Marha (LIFE 16 IPE FR001), a European project aimed at improving the effectiveness of Natura 2000 at sea and restore a favourable conservation status for marine habitats of community Interest. The project concerns 164 SACs in metropolitan France. Life Marha began in 2017 and will end in 2025: https://www.life-marha.fr/

early spring 2021;



Phase 3 (orange dots): WFD Coastal waters FRAC05, FRAC04 and FRAC03 in the nor th of the Park early spring 2022.

Figure 7 – Habisse Project (2020 – 2023) sampling plan

Sampling tools used for this collection of biosedimentary samples were in accordance with the stational monitoring protocol for benthic macroinvertebrates on soft subtidal and intertidal substrates as part of the WFD (Garcia & al., 2014): 0.029 m² hand corer mainly and Van Veen or Eckman grabs for stations with no easy foot access. At each station, sampling strategy was divided into 3 benthic macrofauna replicas (FAU), 1 sample for sediment particle size analysis (GR) and 1 sample for sediment organic matter (OM) : Figure 8.

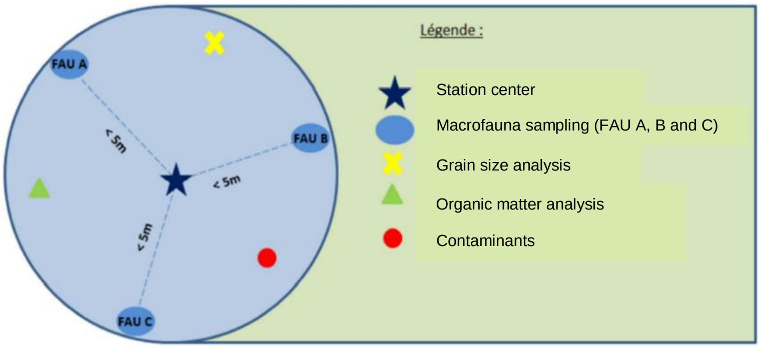


Figure 8 – Sampling strategy on each HABISSE station

Other than the usual ecological indices measured (species richness, abundance, density, biomass, Shannon and Pielou eveness, grain size analysis and organic matter content), statistical analyses were conducted as part of the work to classify habitats into Eunis typology: Ascending Hierarchical Classification AHC using the Bray-Curtis dissimilarity, non-metric multidimensional scaling NMDS and SIMPER procedure. Analyses were gathered by sectors (coastlines, estuaries) to strengthen the analysis. Method implemented enabled to group stations showing similarities in species composition, then describe each group with characteristic species and abiotic environmental conditions) and finally attribute a Eunis classification code.

Sorting and determination of macroinvertebrates species, as well as grain size analysis were then carried out by the Lille University laboratory LOG. The usual indices were interpreted at each station: specific richness, abundance, density, biomass, Shannon diversity and Piélou Eveness indices, sediment fractions (Larsonneur, 1977), medians and quartiles.

A statistical analysis (AHC, nMds and SIMPER) was undertaken by main sector (beach, estuary) in order to:

1. Group stations showing similarities in species composition;
2. Characterize each group with characteristic species and abiotic conditions (grain size, level on the intertidal zone…);
3. Assign a Eunis 2012 classification code.

Results

Results showed a diversity of benthic intertidal habitats along the soft sediments shores and estuaries. The fraction of fine sediment (i.e. sediment less than 63 µm in diameter) varied between 0 and 85%, and fine particles were not in the majority at most stations. Logically, the finest sediments were found in estuaries, with a more or less marked upstream-downstream gradient depending on the estuary.

Out of all the 250 sampled stations, only 7 did not show any macroinvertebrates, these barren middles being mostly located at the top of the beach. Species richness remained relatively low throughout the area of study, with 1 to 18 species in average per station. The stations with the highest species richness were mainly located on the low foreshore at the boundary between the intertidal and subtidal zones, as well as in the common edible cockle beds of the Canche, Authie and Somme bays.

The highest abundances were found in the Slack, Canche, Authie and Somme estuaries. Only a few species show high numbers of individuals like *H. diversicolor*, *P. ulvae* or *P. elegans*. The upper beach stations showed very low abundances.

High-biomass stations were mainly found in the cockle beds of the Authie and Somme bays. The upper beach stations had all very low biomasses.

The project enabled to draw up a detailed atlas of maps (ex. Figure 9) of these habitats, according to the 3 habitat typologies in force at the time of the study, and their stational characteristics along the entire coastline of the Marine Nature Park.

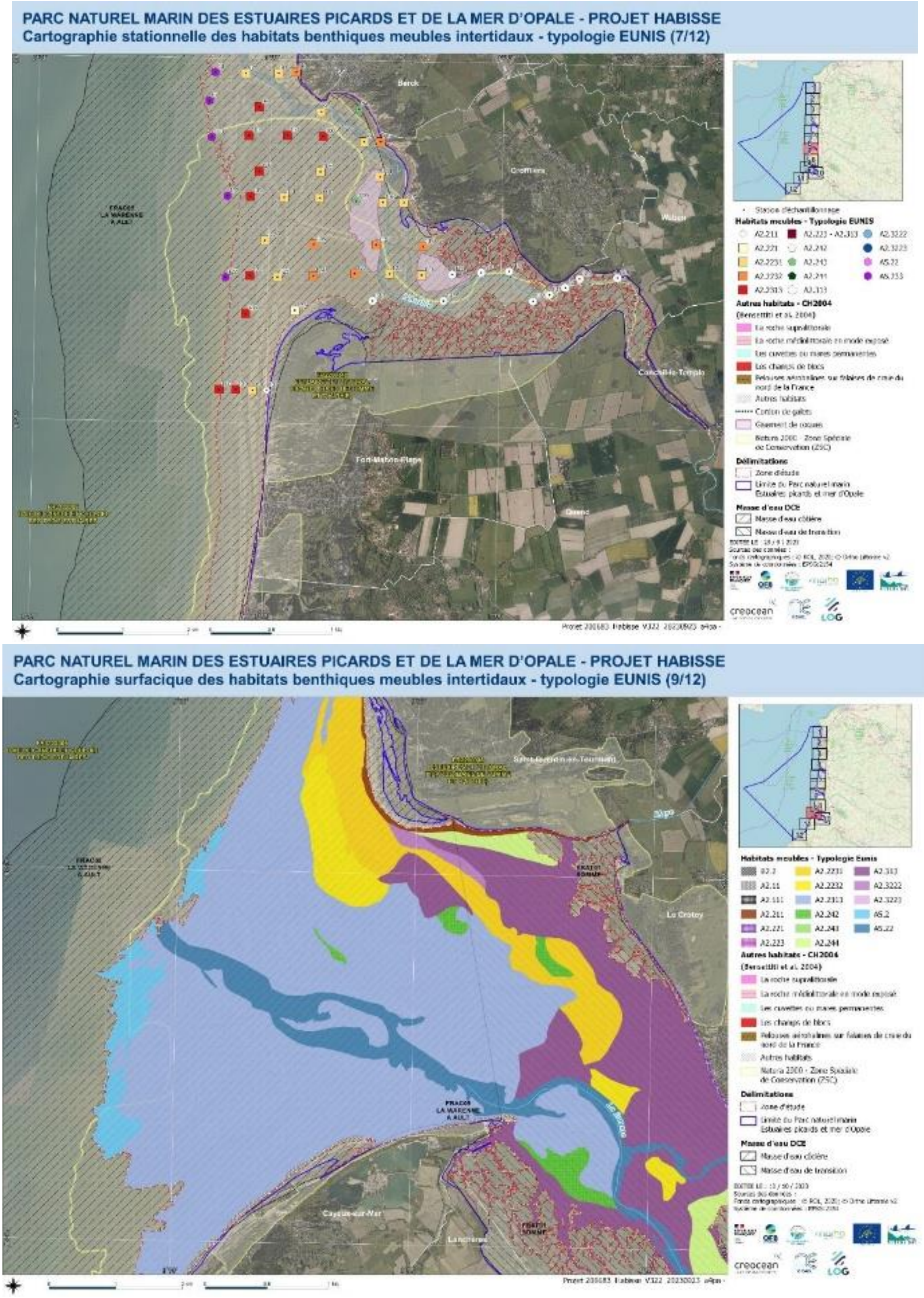


Figure 9 – Examples of maps produced to illustrate stational and surface information of benthic intertidal habitats

A total of 15 Eunis marine habitats were characterised, up to the level 6 of this classification, and correspondence bridges were identified with other typologies: Table 3.

Table 3 : List of the 15 Eunis marine habitats characterised during the HABISSE project and correspondence with other typologies

Eur28 typology	Declinations in Cahiers d'habitats Natura 2000	Eunis 2012 typology for marine habitats	French national typology V3 NatHab-Atl : Atlantic marine benthic habitats
1130 – Estuaries	1130 – Estuaries	A5.32 – Sublittoral mud in variable salinity (estuaries)	B6-4 : Vases infralittorales en milieu à salinité variable
		A5.22 – Sublittoral sand in variable salinity (estuaries)	B5-4 : Sables mobiles infralittoraux en milieu à salinité variable
	1130-1 – Slikke en mer à marée (façade Atlantique)	A2.313 – *Hediste diversicolor, Macoma balthica* and *Scrobicularia plana* in littoral sandy mud	A6-3.1.1.6 – Vases médiolittorales en milieu à salinité variable à *Hediste diversicolor* , *Limecola balthica* et *Scrobicularia plana*
		A2.3222 – *Hediste diversicolor and Corophium volutator* in littoral mud	A6-3.1.1.4 – Vases médiolittorales en milieu à salinité variable à *Hediste diversicolor* , *Limecola balthica* et *Corophium volutator*
		A2.3223 – *Hediste diversicolor* and *oligochaetes* in littoral mud	A6-3.1.2.2 – Vases médiolittorales en milieu à salinité variable à *Hediste diversicolor*
1140 - Mudflats and sandflats not covered by seawater at low tide	1140-1 – Sables des hautes de plage à Talitres (façade Atlantique)	A2.211 – Talitrids on the upper shore and strandline	A5-1.1 – Laisses de mer des sables supralittoraux / A5-1 – Sables supralittoraux
	1140-2 – Galets et cailloutis à *Orchestia* (façade Atlantique)	A2.11 – Shingle (pebble) and gravel shores	A3-2.1 – Galets et cailloutis médiolittoraux
	1140-3 – Estrans de sables fins (façade Atlantique)	A2.221 – Barren littoral coarse sand	A5-2.1 - Sables médiolittoraux mobiles propres
		A2.2231 – *Scolelepis spp* . in littoral mobile sand	A5-2.1.2.1 – Sables médiolittoraux mobiles à *Scolelepis spp.*
		A2.2232 – *Eurydice pulchra* in littoral mobile sand	A5-2.1.2.2 – Sables médiolittoraux mobiles à *Eurydica pulchra*
		A2.2313 – *Nephtys cirrosa* -dominated littoral fine sand	A5-3.3 – Sables fins médiolittoraux dominés par *Nephtys cirrosa*
		A2.242 – *Cerastoderma edule* and polychaetes in littoral muddy sand	A5-4.2 - Sables fins envasés médiolittoraux à *Cerastoderma edule* et polychètes
		A2.243 – *Hediste diversicolor* , *Macoma balthica* and *Eteone longa* in littoral muddy sand	A5-4.3 - Sables fins envasés médiolittoraux à *Hediste diversicolor* , *Limecola balthica* et *Eteone longa*
		A2.244 - *Bathyporeia pilosa* and *Corophium arenarium* in littoral muddy sand	A5-4.4 - Sables fins envasés médiolittoraux à *Bathyporeia pilosa* et *Corophium arenarium*
		A2.245 – *Lanice conchilega* in littoral sand	A5-4.5.1 – Banquettes à Lanice sur sables médiolittoraux

The work represents more than 180 maps and exhaustive recordings of data for each of the 250 stations (banking in Quadrige[2]) and information sheets.

Perspectives

These habitat maps and all the stationary data acquired as part of the HABISSE project will be used to initiate the discussions required to set up a long-term monitoring strategy for soft mediolittoral habitats at park scale.

The results obtained will enable further work to be undertaken to assess the state of conservation of these intertidal loose habitats, particularly with regard to the chemical pressures identified. Another ongoing project called HAPOR will bring complementary results on the subtidal area as well as in coastal harbours to complete the characterisation and mapping marine habitats in the Marine Nature Park.

Finally, in terms of management, these results will feed into the revision of the Natura 2000 annex to the Marine Natural Park's management plan.

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Q&A

On continuation of long-term monitoring

- For scientific reason the most interesting thing would be to have annual monitoring, several times a year. The site managers have objectives, especially due to the presence of Natura 2000 site (data to be provided to the EU). For the management plan you need a starting point to establish actions.

SESSION 6 – TOWARDS BETTER MANAGEMENT PRACTICES

VERS DE MEILLEURES PRATIQUES DE GESTION

Session moderator – *Animatrice de session*: **Lynne Barratt,** ELMEN-EEIG, Europe

Access the presentations from this session here – *Accédez aux présentations de cette session ici.*

As human activities continue to impact marine ecosystems, the need for improved management strategies for sedimentary habitats has never been greater. This session brings together four distinct scientific presentations that explore innovative approaches to managing these environments, from assessing the impacts of human activities to implementing technological advancements and regulatory measures.

The first presentation, by **Camille Delage** (French Biodiversity Office, OFB, France), introduces the Dredge Disposal Sediment Index (D^2SI), a multicriteria management tool developed to evaluate and mitigate the impacts of dredged sediment disposal at sea. The tool integrates environmental and biological variables to assess the extent of disturbance caused by sediment deposition. Through its application across various dredging sites, the D^2SI has been refined to enhance its predictive capacity, offering a valuable resource for marine managers in ensuring the sustainability of soft sediment habitats.

Silvana Birchenough (Environmental Resources Management, ERM, UK) shifts the focus to an

Alors que les activités humaines continuent d'affecter les écosystèmes marins, le besoin d'une gestion améliorée pour les habitats sédimentaires n'a jamais été aussi pressant. Cette session réunit quatre présentations scientifiques qui explorent des approches innovantes pour la gestion de ces habitats, de l'évaluation des impacts des activités à la mise en œuvre des avancées technologiques et des mesures réglementaires.

La première présentation de **Camille Delage** (OFB, France), introduit l'Indice de Sédiment de Dépôt de Dragage (D^2SI), un outil de gestion multicritères développé pour évaluer et atténuer les impacts de l'élimination des sédiments de dragage en mer. L'outil intègre des variables environnementales et biologiques afin d'évaluer l'étendue des perturbations causées par le dépôt des sédiments. Grâce à son application sur divers sites de dragage, le D^2SI a été affiné pour améliorer sa capacité prédictive, offrant ainsi une ressource précieuse pour les gestionnaires marins afin de garantir la durabilité des habitats à sédiments meubles.

Silvana Birchenough (Environmental Resources Management, ERM, UK) présente quant à elle un défi émergent : le démantèlement des structures emerging challenge: the decommissioning of man-made structures (MMS) in marine environments. While these structures have altered marine landscapes, in some cases they have become integral components of the ecosystem, supporting species such as the cold-water coral *Lophelia pertusa*. The presentation highlights the necessity of an evidence-based approach to decommissioning, balancing environmental protection with the imperative to reduce human-made intrusions in marine habitats.

Technological innovation in fishing gear is another promising avenue for reducing impacts on sedimentary habitats, as explored by **Gwenola de Roton** (OFB, France), **Benoit Vincent** (IFREMER, France) **and Pauline Stephan** (CNPMEM, France). Their presentation details recent advancements in trawl technology, including modifications to trawl doors and real-time monitoring systems that minimize seabed contact and sediment resuspension. The findings suggest that, while new gear designs can significantly reduce environmental impact, additional research is needed to assess their effectiveness across different habitat types and integrate them into broader conservation strategies.

The session concludes with a presentation by **Jean-Luc Solandt** (Blue Marine Foundation, UK) on the UK's approach to managing bottom trawling in offshore sedimentary habitats. Following the designation of Dogger Bank and other MPAs as no-bottom-trawl zones, the UK has implemented a science-based regulatory framework to monitor habitat recovery. This presentation traces the historical and legislative context of these protections, emphasizing their role in fulfilling marine conservation objectives and setting a precedent for similar actions across Europe.

Together, these presentations illustrate the diverse strategies available for better managing sedimentary habitats, combining science, policy, and innovation to mitigate human impacts and foster resilient marine ecosystems.

artificielles dans les environnements marins. Bien que ces structures aient modifié les paysages marins, dans certains cas, elles sont devenues des composantes de l'écosystème, soutenant des espèces telles que le corail d'eau froide Lophelia pertusa. La présentation met en évidence la nécessité d'une approche fondée sur des données probantes pour le démantèlement, en équilibrant la protection de l'environnement avec l'impératif de réduire les intrusions humaines dans les habitats marins.

L'innovation technologique des engins de pêche est une autre voie prometteuse pour réduire les impacts sur les habitats sédimentaires, comme présenté par **Gwenola de Roton** (OFB, France), **Benoit Vincent** (IFREMER, France) **and Pauline Stephan** (CNPMEM, France). Leur présentation met en lumière les récents progrès en matière de chaluts, notamment les portes modifiées et les systèmes de surveillance en temps réel, qui réduisent le contact avec le fond marin et la remise en suspension des sédiments. Les résultats suggèrent que, bien que les nouveaux designs d'engins puissent réduire l'impact environnemental, des recherches supplémentaires sont nécessaires pour évaluer leur efficacité sur différents types d'habitats et les intégrer dans des stratégies de conservation plus larges.

La session se termine par une présentation de **Jean-Luc Solandt** (Blue Marine Foundation, Royaume-Uni) sur l'approche du Royaume-Uni pour la gestion du chalutage de fond dans les habitats sédimentaires en mer. Après la désignation du Dogger Bank et d'autres Aires Marines Protégées (AMP) en tant que zones sans chalutage de fond, un cadre réglementaire fondé sur la science a été mis en place pour surveiller la récupération des habitats. Cette présentation retrace le contexte historique et législatif de ces protections, en mettant l'accent sur leur rôle dans la réalisation des objectifs de conservation et en établissant un précédent pour des actions similaires à travers l'Europe.

Ensemble, ces présentations illustrent les stratégies disponibles pour mieux gérer les habitats sédimentaires, alliant science, politique et innovation pour atténuer les impacts humains et favoriser des écosystèmes marins résilients.

A multicriteria index-based management tool to assess and limit the impact of dredge disposal sediment

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Keywords: D²SI, Multi-criteria index, management tool, dredging disposal, benthic macrofauna, sediment bathymetry

Contextual introduction

The Dredge Disposal Sediment Index (D²SI) was initially developed as part of the INDICLAP project (2015-2017) to objectively assess the impact of dredged sediment deposits at sea. This multi-criteria indicator is based on three categories of variables:

- The morpho-sedimentary environment and hydrodynamics,
- Biological compartments (macrofauna and ichthyofauna),
- Life-history traits of macrofaunal species.

This indicator was tested on three dredge disposal sites in the eastern Bay of Seine. The main impacts on these sites are linked to the deposition of significant amounts of fine silts (< 63 µm) and fine sands (63 < x < 200 µm), which can alter the physico-chemical conditions of the environment and cause disturbances in benthic communities (Baux et al., 2017; Baux, 2018).

Initially inspired by the Roberts et al. (1998) index and later refined in Dauvin et al. (2018), the indicator was significantly reworked into a multi-criteria assessment tool based on 6 criteria. A second phase of the project was launched in 2020 under the LIFE integrated Marha program (LIFE 16 IPE FR001) in order to finalize the development of the D²SI for soft sediment substrates. Additional work was conducted to select criteria, refine the calculation methods for sub-indices, establish impact thresholds, and analyse indirect effects of sediment immersions observed at two experimental and operational sites.

The project sought to provide a diagnostic tool for assessing the impact of dredged sediment disposal on marine habitats. This was achieved by studying the effects of varying levels of sediment deposition pressure (low/high material deposition), measured through bathymetric and sedimentary changes, on the composition and structure of benthic communities. The findings of this study were compiled into a scientific report, justifying the finalized methodology (Chouquet et al., 2021).

In 2022, the D²SI was further consolidated by applying it to a low-volume dredge disposal site, the Port of Caen-Ouistreham. This study allowed for the validation of previously defined thresholds and the adaptation of the indicator to contexts where the volume of sediment immersions is lower (Chouquet et al., 2024).

Methodology

This indicator aims to characterize dredge disposal pressure on marine ecosystems, both qualitatively and quantitatively. It was designed to leverage data typically collected during regulatory environmental monitoring of disposal sites. This approach allows for the use of historical data, avoiding modifications to existing monitoring protocols and preventing additional costs associated with these assessments.

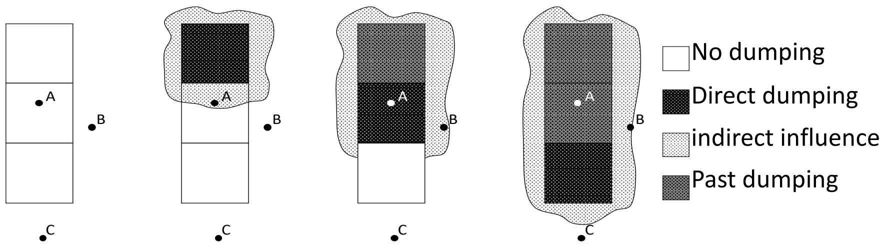
The indicator is based on three sub-indices, each measuring a specific dimension of the impact of dredging activities:

– D²SI-B (Benthos): Evaluates variations in benthic communities,
– D²SI-T (Sediment Thickness): Measures bathymetric changes caused by sediment deposits,
– D²SI-S (Sediment Composition): Analyzes granulometric changes in sediment characteristics.

Definition of stations

The analysis of the **D²SI** relies on a **comparison between stations**, with their initial classification defined prior to calculating the sub-indices:

- **Control station:** A station located **outside the disposal site**, not subjected to **direct sediment immersions**, and outside the **hydro-morpho-sedimentary influence zone** (i.e., no bio-sedimentary variations linked to sediment disposals during the study period).
- **Impacted station:** A station located **within the disposal site** that has experienced **direct sediment immersions** during the study period.
- **Influenced station:** A station located **outside the disposal site** (not directly subjected to immersions) but **within the hydro-morpho-sedimentary influence zone**, thus experiencing **bio-sedimentary variations** caused by sediment disposals during the study period.



Station	Year 0	Year 1	Year 2	Year 3	Final nomenclature
A	Non impacted	Under Influence	Impacted	Impacted	Impacted
B	Non impacted	Non impacted	Under Influence	Under Influence	Under Influence
C	Non impacted	Non impacted	Non impacted	Non impacted	Non impacted

Sub-Index are calculated for every available combination of Control/Impacted or influenced station (as far as they share similar benthic fauna community. nature of sediment and bathymetry before dumping).
To determine whether a control station can be used to study an impacted station, it is necessary to check if the bathymetry, the granulometry composition and the habitat (macrozoobenthic communities) are similar between the two types of stations before the beginning of the dumping.

To achieve this, it is recommended to conduct a Hierarchical Ascending Classification (HAC) on all available data to accurately define the roles of each station during the first application of the indicator to a site.

Calculation of sub-indices

- Benthic sub-index (D²SI-B)

This sub-index evaluates changes in benthic communities due to dredge disposal. It is based on an analysis of species abundances and faunal diversity.

Initially, the abundance ratio is calculated between the impacted station and the control station for each species.

$$Ratio_{taxon\ i} = \frac{Abundancy\ of\ taxon\ i\ on\ impacted\ station\ to\ date\ n}{Abundancy\ of\ taxon\ i\ on\ control\ station\ to\ date\ n}$$

This ratio represents the difference in abundance of a taxon between the impacted station and the control station at a given date (n). Then, a primary score is assigned, ranging from 0 to 10, based on the ratio value for each taxon, according to the adjusted scoring table. (Table 1).

Table 1: Threshold values for primary scores in the calculation of the D²SI-B sub-index

<table>
<tr><th>Ratio I/C</th><th colspan="3">Groups</th><th>Taxa individual score</th></tr>
<tr><td>0</td><td colspan="3">Taxa present only in control station</td><td rowspan="2">10</td></tr>
<tr><td>]0-0.143]</td><td rowspan="11">Abundance in control stations…</td><td>> 7 times higher</td><td rowspan="11">…than in impacted stations</td></tr>
<tr><td>]0.143-0.200]</td><td>5 to 7 time higher</td><td>9</td></tr>
<tr><td>]0.200-0.250]</td><td>4 to 5 time higher</td><td>8</td></tr>
<tr><td>]0.250-0.333]</td><td>3 to 4 time higher</td><td>7</td></tr>
<tr><td>]0.333-0.500]</td><td>2 to 3 time higher</td><td>6</td></tr>
<tr><td>]0.500-2]</td><td>2 time higher to 2 time weaker</td><td>5</td></tr>
<tr><td>]2-3]</td><td>2 to 3 time weaker</td><td>4</td></tr>
<tr><td>]3-4]</td><td>3 to 4 time weaker</td><td>3</td></tr>
<tr><td>]4-5]</td><td>4 to 5 time weaker</td><td>2</td></tr>
<tr><td>]5-7]</td><td>5 to 7 time weaker</td><td>1</td></tr>
<tr><td>>7</td><td>> 7 times weaker</td><td rowspan="2">0</td></tr>
<tr><td>Ø</td><td colspan="3">Taxa present only in impacted station</td></tr>
</table>

The sum of the scores assigned to each taxon is then calculated separately for common taxa (i.e., present in both sampling events) and non-common taxa (i.e., present in only one of the two sampling events) for each date. The resulting values are divided by the taxonomic richness of each list of taxa (common and non-common) present at date n, which is equivalent to calculating the average primary score for each list. These averages are then multiplied by the proportion of the total abundance for the corresponding sampling event (proportion of common individuals and proportion of non-common individuals).

Finally, the two weighted averages are added to obtain the raw sub-index value for the given date. This value (ranging from 0 to 10) is then normalized to a scale of 0 to 1, providing the secondary score (Table 2).

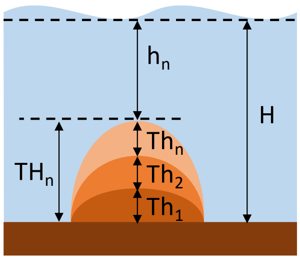
Table 2: Threshold values for secondary score assignment and corresponding impact level assessment for the D²SI-B sub-index

D^2SI-B Valeur brute	Score secondaire	Niveau d'impact
[0,6 - 1[	1	Très fortement impacté
[0,4 – 0,6[	0,75	Fortement impacté
[0,3 – 0,4[	0,5	Moyennement impacté
[0,2 – 0,3[	0,25	Légèrement impacté
[0 – 0,2[	0	Normal

If the abundance frequency of non-common species exceeds the 90% threshold, the D²SI-B value for that monitoring campaign will automatically correspond to a very high impact, with a D²SI-B value of 1 (and therefore a score of 1).This 90% threshold was set because it best matched the level of dissimilarity associated with community replacement, based on data collected between 2000 and 2019 from the two dumping sites of Rouen Port.This threshold may be re-evaluated as regards as additional data from other dredge disposal sites in the English Channel or the Atlantic.

- <u>Sediment Thickness Sub-Index (D²SI-T)</u>

This sub-index measures **sediment accumulation** at the disposal site, based on **bathymetric data**.



$$D^2SI\text{-}T = \underbrace{\left(\frac{(TH_n[I] - TH_n[C])}{(-H[I])}\right)}_{\text{Long term pressure}} + \underbrace{\left(\frac{\left(e^{(Th_n[I]-Th_n[C])} - 1\right)}{\left(e^{3,7\times tempsécoulé(enannée)}\right)}\right)}_{\text{Short term pressure}}$$

The 3.7 factor used in the formula corresponds to the maximum sediment thickness (in meters) deposited over one year at a dredge disposal site along the French coastline under normal operating conditions.

The raw value obtained is clamped between 0 and 1; any value exceeding 1 is set to 1.

This calculation is repeated for every possible combination of impacted (or influenced) stations and control stations, and the raw values are averaged across all combinations. The resulting average represents the raw D²SI-T value, which can be used to interpret the impact measured by this sub-index.

Finally, a secondary score is applied to the average raw value, which contributes to the calculation of the global D²SI indicator. (Table 3).

Table 3: Threshold values for secondary score assignment and corresponding impact level assessment for the D²SI-T sub-index

D²SI-T Valeur brute	Score secondaire	Niveau d'impact
[0,6 - 1[	1	Très fortement impacté
[0,3 – 0,6[	0,75	Fortement impacté
[0,15 – 0,3[	0,5	Moyennement impacté
[0,05 – 0,15[	0,25	Légèrement impacté
[0 – 0,05[	0	Normal

- <u>Sub-index for sediment nature (D²SI-S)</u>

This sub-index is based on the difference between the proportion of the dominant granulometric fraction at the impacted or under-influence station vs. the control station.

$$D^2SI\text{-}S = \left|\frac{\%I - \%C}{\%I + \%C}\right|$$

Where:

- % I: Rate of granulometric fraction f at the impacted (or under influence) station at time n.
- % C: Rate of granulometric fraction f at the control station at time n.

The granulometric fraction f is the dominant granulometric fraction at both stations before clapping. If this fraction is not the same at both stations before clapping, the station pair is invalid.

As with the other sub-indices, the calculation is made by averaging all the usable combinations of impacted and control stations.

The secondary scoring is applied to the average of the combinations of raw values and is used to calculate the overall indicator (Table 4).

Table 4: Threshold values for secondary score assignment and corresponding impact level assessment for the D^2SI-S sub-index

D^2SI-S Valeur brute	Score secondaire	Niveau d'impact
[0,75 - 1[	1	Très fortement impacté
[0,6 – 0,75[	0,75	Fortement impacté
[0,4 – 0,6[	0,5	Moyennement impacté
[0,25 – 0,4[	0,25	Légèrement impacté
[0 – 0,25[	0	Normal

Calculation of the global indicator D^2SI

Once the three sub-indices are calculated, the global indicator D^2SI is obtained by the unweighted average of the three secondary scores.

$$D^2SI = \left(\frac{(ScoreD^2SI\text{-}T) + (ScoreD^2SI\text{-}S) + (ScoreD^2SI\text{-}B)}{3}\right)$$

The scores are then ranked according to an impact scale (Table 5):

Table 5: Impact level evaluation scale for the global D^2SI indicator

D^2SI Valeur brute	Niveau d'impact
[0,8 - 1[	Très fortement impacté
[0,6 – 0,8[	Fortement impacté
[0,4 – 0,6[	Moyennement impacté
[0,2 – 0,4[	Légèrement impacté
[0 – 0,2[	Normal

Discussion & conclusion

Even though the indicator can be calculated as long as there is one impacted station and one control station, it is strongly recommended to increase the number of control stations to better account for natural variability and to more robustly determine whether a station near the immersion site is experiencing indirect impacts or not.

It is essential to have the most accurate data possible regarding the site's conditions before the start of sediment deposition so that the role of each station (impacted, under influence, or control) can be correctly assigned, and also for the calculation of D^2SI-T; however, such data is not always available for older sites.

There are still cases where high values for some sub-indices are observed in the absence of direct impact (sediment deposition): this can be explained by natural variations in the environment; or by indirect effect of the deposits, which can be verified in relation to the location of the station relative to the dumping areas and the timing of the immersions.

The thresholds were defined based on sites subjected to significant sediment deposition, at least a million cubic meters annually. However, they have been tested and appear functional (both in terms of sensitivity and specificity) at two sites with much smaller scales, where sediment volumes are as low as approximately 50,000 m^3 per year. These thresholds should still be tested on other sediment combinations and on sites with even smaller volumes.

This indicator was defined on a small number of sites. In order to verify its robustness, it would be relevant to test it on other sites with environments different from those of the Seine Bay. In any case, and like all indicators, it is meant to synthesize a set of complex data into a single value, and only a thorough study of this data can allow for a correct interpretation of the results.

Finally, it is important to keep in mind that this indicator was designed to respond to the pressure of sediment deposition: it thus provides an indication of the impact on and near the immersion sites. It will not assess impacts on ecosystems at a broader geographical scale, such as changes in hydrodynamics or increased turbidity of surrounding waters. Thus, especially at more dispersive sites, it will necessarily need to be coupled with other approaches/monitoring to evaluate the impact of these other physical pressures, particularly if sensitive habitats are present near the immersion site.

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Q&A

On the potential for reusing dredged sediment in ecological projects: can the sediment dredging methodology be applied to assess the beneficial use of dredged material?

- The indicator presented focuses on the physical and biological aspects of habitats and can help identify potential pressures. It’s mainly used to minimize ecological damage from dredging, helping identify low-impact disposal sites. It’s a conservative tool, not designed (yet) to assess positive/beneficial uses (e.g., beach nourishment, habitat creation for birds). It does not specifically address how dredged sediments could be repurposed or who would benefit from them. However, it could support future planning by ensuring deposited sediment is compatible in nature with the receiving site.

New challenges ahead for sedimentary environments: considering the decommissioning of man-made structures

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Editorial

Man-made marine structures – Agents of marine environmental change or just other bits of the hard stuff?

On paper there has been a very large number of man-made marine structures (MMS) either deliberately or accidently placed in the sea and, while many of these are in coastal, relatively shallow regions, increasingly they are occurring offshore. These cover the huge number of historical wrecks and even submerged cities as well as more recent oil and gas extraction rigs, offshore fixed and floating wind turbine monopiles and tripods, artificial reefs, lighthouses, coastal defences, breakwaters and harbours. With maritime spatial planning, there are now many maps showing an increasingly crowded sea-space. Importantly, we need to be clear about the environmental repercussions of MMS. However, we have to determine whether such maps accurately represent the occupation of sea-space – for example, the thickness of pen-lines on large-scale maps would suggest that cables and pipelines are several km wide and individual rigs cover km^2!

Whether accidentally placed, as with wrecks, or deliberately placed as with all other infrastructure, MMS have a behaviour so we need to determine both the effect of the structure on the marine environment and the effect of the marine environment on the structure. The former may be regarded as a footprint of the activity which in turn leads to a footprint of pressures, as the mechanisms of any effects, and a footprint of effects – a sequence of increasingly-larger footprints (Elliott et al., 2020). Regarding the effects of the marine environment on the MMS, it is necessary to ask a fundamental question – are they acting as just another hard surface, to be treated the same as a rock outcrop, or do they have an identified, quantified and major role in modifying marine ecological structure and functioning? Similarly, we need to ask whether MMS pose another type of hazard and risk or just an increased hazard and risk to the marine environment (see the hazard and risk typology in Elliott et al., 2019).

As all human activities in the sea can be regarded as producing those activity-, pressures- and effects-footprints then here we aim to highlight that while we have a good conceptual understanding of these aspects (Fig. 1), our quantitative knowledge is still poor and requires improving. Taken together, those different types of footprint can be regarded as the cumulative behaviour of our activities and so it is emphasised that for the sustainable management of marine resources, the behaviour and influence of those MMS needs to be determined. In particular, as shown many times in the pages of *Marine Pollution Bulletin*, the signal showing the human-induced causes and effects of changes to the natural system has to be separated from the natural and inherent variability (the so-called signal-noise relationship).

The conceptual basis in Fig. 1 has been derived from many years of assessing the effects of human activities in the marine field although it is not the aim here to give all the supporting literature, that is done elsewhere (e.g. Gray and Elliott, 2009; Dannheim et al., 2019; Birchenough and Degraer, 2020; McLean et al., 2022, and references therein). In particular, conceptually, we consider that MMS can be viewed as a set of decision levels, DL-A to F on Fig. 1. Working through those decision levels then will allow us to objectively consider and quantify the relationship of MMS with their receiving sea area and then use the best-available science to inform marine and maritime decision-making, spatial planning and management. DL-A shows the need to consider several categories of MMS and that there may be similarities and differences in their behaviour. It also indicates the separation between those MMS deliberately placed in the sea, with a defined-purpose, and those MMS such as accidentally-placed wrecks even though such structures have provided some information on colonisation.

DL-B indicates the need to consider a whole life-cycle approach to determining the effects of MMS, from the exploration and planning of where and why an MMS should be in a given place, through the construction and operation to its final total or partial removal or repurposing during decommissioning. This DL again separates wrecks given that it is merely their presence as the source of the changes and although recent wrecks will often be removed, and indeed some wrecks were created for a given purpose such as an artificial reef for recreational diving or coastal protection, older wrecks are left in place, especially if they are designated war-graves.

The third level, DL-C, indicates the main categories of cause and effect: C1 - the interference with and distortion to marine physico-chemical and ecological structure and function (processes); C2 - the creation of a hard surface for colonisation; C3 - the loss of marine habitat or indeed the creation of new habitat, thereby mimicking natural hard substratum such as a rock outcrop; C4 - the introduction of both small and large materials and dissolved compounds and energy (such as electro-magnetic radiation, noise/vibration and heat), and finally C5 - the ability of the MMS to act as a surface for colonisation by non-indigenous species or even species migrating to the area through climate change-induced distributional changes.

The main linkages within and between these main categories (C1-C5) then require to be interrogated (DL-D) to give the spatial and temporal magnitude of marine effects. As with a rock outcrop, placing an MMS will distort physical processes (C1), even by changing current strength and direction, sediment erosion-deposition cycles, water column stratification patterns and even frontal systems. By its presence and role, it will distort animal migrations either by deterring or attracting especially highly mobile animals; for example, as shown by tracking devices of seals visiting offshore wind energy monopiles. This then has resulting effects on faunal connectivity and food-web dynamics.

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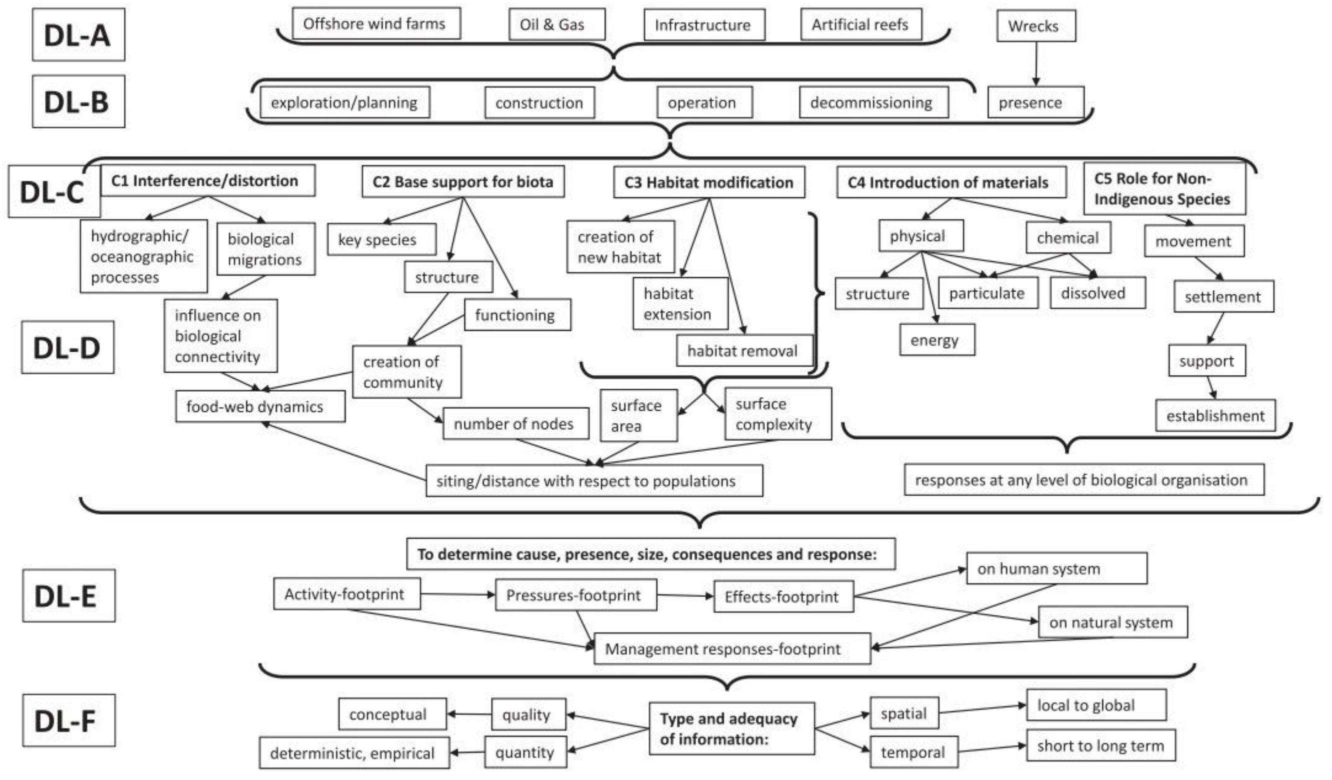

Fig. 1. Cause and consequence conceptual model for man-made marine structures (MMS).

Linked to that interference and distortion is the creation of a support surface for biota (C2), by creating the niche which can then be occupied by colonising organisms to structure the community; that community then modifies itself through functional predator-prey relationships and competition for space and/or food. The ecological community structure and resulting functioning are then established as the result of MMS each acting as an ecological node within the distributional distances and metamorphosis times to ensure or even to enhance connectivity between faunal and floral populations. This degree of connectivity then influences the food-web dynamics seen in C1.

Placing the structure, deliberately or accidentally, thereby not only creates new habitat but also modifies or removes existing habitat (C3). Often it replaces an essentially two-dimensional seabed, such as subtidal sandbanks, with a complex 3-D structure, thereby increasing surface area, surface complexity and number of niches (e.g. Dannheim et al., 2019). The development of such surfaces and their role in connectivity of populations therefore not only depends on the right type of surface being created but also at the right sites and distances from source populations for settlement. However, the surface may only be suitable for colonisation after being suitably 'weathered', i.e. the loss of any surface contaminants, the production of biofilms (biological coatings from yeasts, diatoms, bacteria, slimes, etc.) and the sequence of development of the community after settlement, again similar to a rock outcrop. This requires a better knowledge of species autecology; for example, barnacles settle gregariously and require a smooth surface with fast-flowing conditions whereas mussel spat will settle in lower currents and on more complex surfaces. Errant crustaceans and polychaetes will then settle in the interstices and silt between the sessile organisms.

The most noticeable aspect of MMS is the introduction of materials into the sea and then any resulting biological effects, whether they are large structures, small particles, dissolved compounds or energy (C4). Irrespective of the size or state of the material, placing any material in the sea is regarded as contamination which may mead to pollution per se indicating a biological response on either natural or human biology. As often indicated in the *Marine Pollution Bulletin*, the response can be at any level of biological organisation, from the cell, through individuals, populations of species, and communities up to ecosystems. Those latter levels of biological organisation in turn link to the effects on the habitats described above (C2, C3), especially where the species affected are ecosystem engineers forming the community structure. Where any introduced particulate and dissolved materials are taken up or influence mobile species then this increases the magnitude of the pressures- and effects-footprints. For example, discharges of chemical contaminants directly from the surfaces or the operational aspects of oil and gas exploitation will then be ingested or absorbed from the water column or the surface and transported both by the water currents and the mobile organisms. Hence, in this case, the MMS would not act only as a rock outcrop once those surfaces are weathered or sealed by the epibiota.

As the final major topic, there is the often-mentioned role of structures as settlement surfaces for non-indigenous species (NIS) or for species whose distribution migrates through climate change (C5); where those species rely on a hard-substratum then this allows the suggestion that the structures are stepping-stones. However, this is exactly the same role as any rock-outcrop. Despite this, it is challenging to separate the role of MMS from natural rock outcrops as settlement sites and stepping stones for NIS and invasive species especially given the relative numbers of MMS and outcrops. However, moving the structures, as is increasing the case with disused oil and gas rigs, or repurposing the structures, may transport that fouling fauna and flora, thereby acting as its own vector for non-indigenous species. Furthermore, as with contamination of introduced physical and chemical materials and their polluting effects on any level of biological organisation, the NIS can be regarded as biological contaminants and biological pollutants with potentially similar effects on the above-mentioned levels of biological organisation.

Based on the cause and effect relationships described above, we need to define and assess the spatial extent and duration of the resulting changes to both the natural and human systems (DL-E). As indicated above, this requires determining and quantifying the activity-, pressures- and effects-footprints and, given the highly dynamic nature of marine areas, the cumulative, large-scale and transboundary repercussions. In turn, we need to understand and apply management responses which range from those in a small area (perhaps the area of an Environmental Impact Assessment for a wind turbine monopile and its scour protection), through regional maritime spatial planning areas and up to initiatives in areas beyond national jurisdiction and globally – what may be termed the management response-footprints (Cormier et al., submitted).

The changes identified here may particularly occur once an MMS has been in place for a long time and has thus created a new equilibrium set of conditions and so be regarded as part of the seascape in which the local fauna, flora and habitats have become adapted to its presence. For example, the cold-water coral *Lophelia pertusa* (considered to be a '*Threatened and declining species*') has settled where MMS have been in place for >25 years, hence totally or partially removing the structures will create more disturbance to these systems, species and habitats. Accordingly, further knowledge is needed for the ongoing debate regarding increased decarbonisation and end-of-life decommissioning of oil and gas structures. That knowledge will increase our preparedness to face the future challenges for other structures (e.g. offshore wind farms in the coming decades).

The discussion here has focussed on having an adequate conceptual basis and qualitative approach (DL-F) while emphasising the need for greater data to create deterministic and empirical models showing the role of MMS in our seas. With suitable and adequate spatial and temporal information, respectively covering cumulative effects from local to global space and short to long-term duration (especially given the durability of the MMS), we may then be in a position to determine whether MMS are having a notable wide-scale and long-term effect on our seas or whether they are to be regarded merely in the same way as a rock outcrop.

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Q&A

<u>On project funding sources</u>: who funds the decommissioning of structures?

- In the UK, the projects have a proportion of money allocated for decommissioning, but funds are not enough. A biodiversity action plan is required and must include action towards decommissioning (to make sure projects use the money and don't let the structures in place). The success of decommissioning will be based on collaboration between public authorities and the industry.

Trawl technological innovation to support conservation and management of marine protected areas

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Contextual introduction

Sedimentary habitats are an essential part of the seabed on the continental shelf of the North-West Atlantic, the English Channel and the North Sea. These habitats are exposed to considerable pressure, among which professional fishing is the one affecting the largest areas.

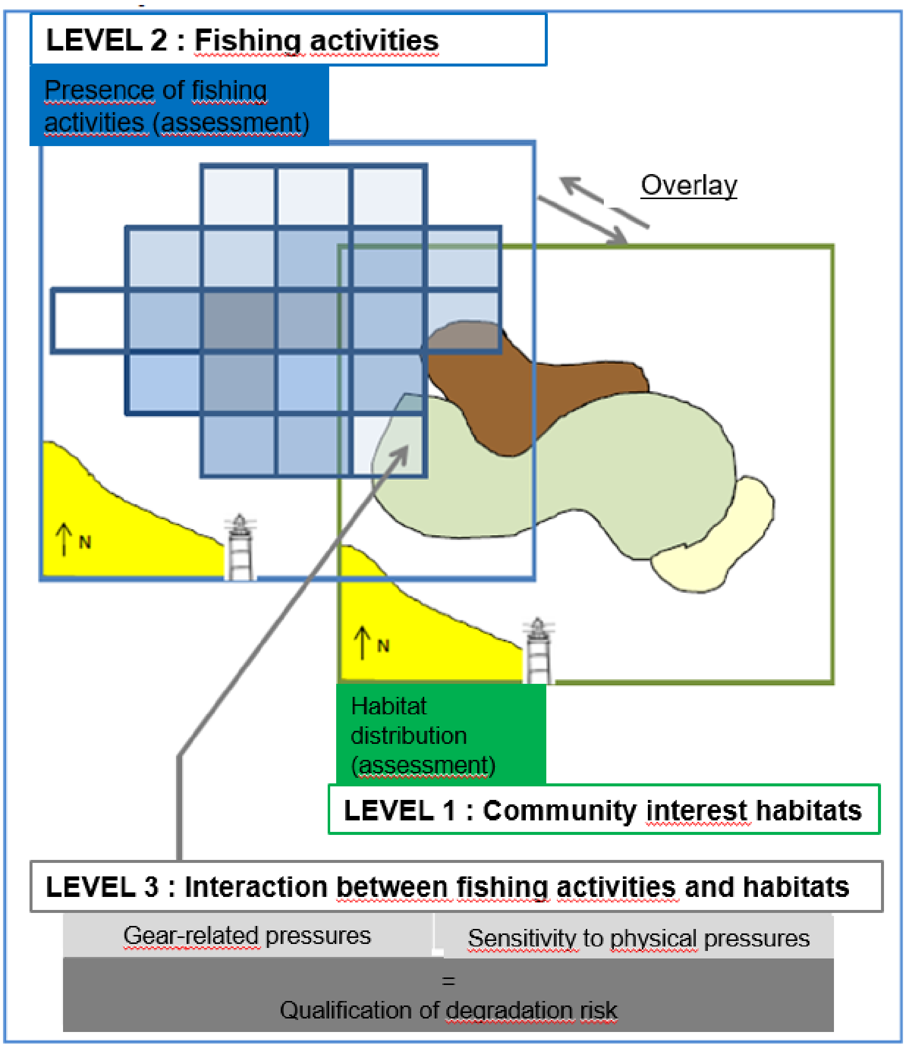
Sustainable development of fishing and effective management of marine protected areas are current topics. These issues are at the heart of the concerns of the French Office for Biodiversity, marine protected area managers, and Committees for Marine Fisheries and Aquaculture.

In accordance with the European directives "Birds" and "Habitats", Article L.414-4 of the Environmental Code provides that professional fishing activities are exempt from Natura 2000 impact assessments, if a risk analysis to assess any potential harm to the conservation objectives of the Natura 2000 site is conducted, due to the specific nature of this activity, which is managed at the fleet level rather than the project holder level (i.e., the shipowner). These analyses are conducted during the development or revision of the Natura 2000 site management plans (DOCOB) where these fishing activities take place.

Fisheries risk analysis in Natura2000 sites (SACs)

The method focusing on the habitats is based on a method developed at the national level under the guidance of the Ministries, which allows for:

- Part 1 : assessing and locating the risk of habitat degradation by cross-referencing the sensitivity level of benthic habitats to physical pressures with the type and level of intensity of the pressures that may be generated by each fishing gear. For this, the map of marine habitats on the site is overlaid with the fishing activity spatialization map (gear or métier, in presence/absence), and risk scores are assessed for each interacting grid cell.
- Part 2 : assessing the risk of compromising the site's conservation objectives based on the risk of habitat degradation and local parameters (level of ecological stakes, environmental characteristics, and specifics of the fishing activity).



Schematic summary of the risk assessment approach for habitat degradation caused by fishing activities within Natura 2000 sites (Method 2019).

If a risk of harm to the site's conservation objectives is identified following the analysis, the relevant fishing activities must be subject to regulatory measures in order to reduce the pressure of the activity on the concerned habitat. These measures may take the form of spatial and/or temporal exclusion measures, technical measures regulating the use of certain high-risk gear on the affected habitats, measures to control fishing effort, the establishment or modification of an existing authorization, or technical measures to adapt practices or promote the use of alternative fishing techniques. Thus the mobilization of reduction devices developed for trawl nets is one way for managers to reduce the pressure generated and, in some cases, the level of risk to habitats.

This risk assessment is carried out in Natura 2000 sites by the OFB and the fisheries stakeholders since 2013. In 2024, this risk assessment is completed for habitats on 56 SACs (i.e., 45% of the sites) ; it is in progress on 58 SACs (i.e., 47%), and remain to be carried out on 9 SACs (i.e., 7%). [This does not include sites and lagoons where the presence of professional fishing has yet to be confirmed.] A European project funded by the EMFAF is underway to finalize these analyses across all sites by 2026, in accordance with France's commitments to the European Commission and the actions planned in the Strategic Facade Documents (MSFD) action plan.

In the medium or long term, if the evolution of activities or improvements in knowledge warrant it, this analysis can be supplemented and/or updated, particularly during the revision of the DOCOB.

Trawl technological innovation

A large number of French fishing vessels use bottom trawling and bottom trawl doors. In 2022 they landed about 25% of the seafood produced by the French fleet.

Otter trawls are designed to rest on the seabed and have sufficient interaction with the sediment to maximize the success of benthic species capture. Depending on operating conditions, this can lead to significant weights, which are mainly concentrated in the doors and in the lower part of the net (lower wings and belly), to prevent the gear from lifting off the bottom due to vessel traction, vessel movements and bathymetric irregularities such as seabed ridges, for example. Even if the effective weight of the various trawl elements is often greatly reduced compared to the "weight in the air", the pressures exerted on the sediments can damage habitats and resuspend part of the sediments, releasing carbon and pollutants and causing the displacement of fine sediments.

To minimize or avoid these negative effects, three options have been developed in recent research projects. Two of these concern the doors, as they exert the most intense pressure, even though they are applied on a narrow track compared to the trawl track, and are responsible for most of the sediment resuspension. The first "radical" option (REVERSE project) is to raise the bottom doors (3-7 m high) to cancel out the pressure they exert on the seabed. The new doors have been designed to increase hydrodynamic performance, reduce drag and fuel consumption. The new doors and their rigging, including a heavy chain to secure the fishing gear to the seabed, can be simply inserted into an existing trawl rig. The height of the door is controlled and adjusted to minimize contact of the chain with the seabed. Sediment resuspension was measured at zero, and fuel consumption was reduced by an average of 10%. This technique requires the attention of a crew member to adjust the doors height. It could be automated on larger ships.

An intermediate option has been developed with Octech (CONNECT project). It consists of a real-time monitoring system for door interaction with the seabed, based on the measurement of door vibrations. If the doors rest heavily on a hard seabed, the vibration level will be high; otherwise, the vibration level will be low. In the case of a soft seabed (such as sand mixed mud sediments), seabed reaction and vibration will be difficult to detect, and the monitoring system will fail to account for the interaction. The system has the advantage of being able to adapt to any type of bottom door without modification to the fishing gear. It also requires the attention of a crew member to adjust the door interaction with the seabed, which could also be automated on larger vessels.

The third option concerns ground gear in particular, but also all chains, cables or lines resting on the seabed. This approach is theoretical and has the advantage of being simple to deploy and control. The physical pressure of an object on the seabed (ratio of the normal component of a force divided by the surface area to which it is applied) can be calculated, more or less easily depending on the complexity of the object's geometry. For example, the pressure of a man's feet is around 500 mbar, the pressure of a 1.5-liter bottle of water placed vertically is around 40 mbar. We can therefore speculate on the pressure threshold that a piece of fishing gear must not exceed. Considering "light" trawl gear (e.g. the sand eel trawl), a pressure threshold has been arbitrarily set at 10 mbar. Taking into account simplification for calculating the surface area, a simple formula that takes into account the technical characteristics of the fishing gear components is used to calculate the pressure indices and check whether or not it is below the 10 mbar threshold. If all components are below the threshold, the trawl can be described as "light", otherwise as "heavy". The CONTRAST project collected technical data on trawls in order to classify their bottom gear.

Issues such as shear effect, sediment resuspension or the pressure and interaction required to herd, lift and fish a benthic species are not addressed by this approach.

Photo 1 : from left to right, off-bottom door, bottom door with adjusted contact intensity, ground gear separated from the net for weighing, ground gear in operation.

These options, particularly with regard to the impact of doors, need to be accompanied by monitoring (based on software used on board to monitor doors behaviour), as there is no guarantee that they will be used in such a way as to minimize impact on the seabed. In the case of limited ground gear pressure, the question of standardization and homologation of fishing gear can be raised. Acceptance, and therefore incentives, are also key issues to helping the fleet towards sustainable fishing.

SOLUPECHE, a platform providing solutions to reduce the interactions between the fishing activity and sensitive species and habitats

Solupêche was born out of a partnership between the French National Fishing Committee (CNPMEM in French) and the French Office for Biodiversity (OFB in French).

Solupêche is a platform that aims to highlight different solutions to reduce the interactions between the fishing activity and sensitive species and habitats.

It presents solutions, or those currently being developed, and good practice recommendations for fishermen.

From the home page, the research for a solution is carried out via different inputs, depending on:

- the type of solution (marketed solutions, good practices, research and development),
- the fishing gear used
- the species (marine mammals, sea birds, sea turtles) or habitats interacting with it

Depending on the categories selected, the research result proposes one or more solutions. There are three types of solutions:

- Marketed solutions : these are products that have proven their effectiveness and are available for purchase for use by fishermen. These pages propose different alternatives available on the market.
- Solutions under research or development: some solutions are currently being researched or developed. Solupêche presents these prototypes currently being tested, as well as a progress report on this work.
- Good practice recommendations: these are virtuous behaviours recommended to limit

interactions between fishing gear and sensitive habitats and species, and in the case of bycatches, recommendations on the release of the species.

The solutions proposed are tried, tested and documented.

This platform is updated as knowledge evolves.

Conclusion

In conclusion, technological innovation in fishing gear is one of the solutions to reduce interactions between fishing and marine biodiversity. Tests still need to be carried out, as well as an assessment of the effectiveness of these devices on the various sedimentary habitats, and in particular on biocenoses; with the prospect of deploying them more widely if they are conclusive. However, this type of solution cannot address all interactions, particularly in highly sensitive habitats, where spatiotemporal exclusion measures are often required.

Q&A

On evaluating the impact of gear modifications: are there assessments or reference methods to evaluate the impact of gear changes?

- All human activities have an impact, and the challenge is determining an acceptable level. Currently, there are no assessments specifically measuring gear impact on species and habitats. There are impact matrices (e.g., levels of abrasion) to describe gear effects, but they do not assess how species are affected. Previous work (e.g. with Jacques Graal) involved testing trawling effects on species at different frequencies, but it is time-consuming. More research is needed to link gear modification to real ecological outcomes.

On the willingness of fishermen to adopt new techniques: how effective is the adoption of new fishing techniques by fishermen?

- Some progress has been made, such as reducing gear weight, but they have seen limited adoption. However, fishing remains physically demanding and hazardous, and fishermen are often resistant to external guidance on their equipment use. External pressures (like COVID-19 and Brexit) have also hindered adoption of new practices.

On financial burdens associated with new equipment: Is cost a major barrier to adoption? Who pays for new gear and innovation?

- Yes, fishing vessels operate as businesses, and financial stability is required for investment in new equipment. Financial uncertainties (quotas, Brexit, etc.) discourages investment.

On the number of fishermen needed to achieve conservation goals in MPAs: how many fishermen need to adopt these measures for them to have a meaningful impact on Marine Protected Areas (MPAs)?

- There is no clear answer yet. The ecological effectiveness of these technologies on habitats still needs to be studied. Adoption alone isn't enough—the key is whether they actually reduce risk to marine habitats based on scientific indicators.

On alternative approaches for managing mobile species in protected area: are alternative legal mechanisms available to protect mobile species?

- Some mechanisms exist, but there is scepticism about using new equipment as a substitute for securing designated protected areas. While trials outside MPAs may be useful, their application inside MPAs remains questionable.

UK Doggerbank Marine Protected Area and other sedimentary habitat bottom towed gear bans – why and how?

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Summary: The UK protected the entire 12,337km2 area of the Dogger Bank Special Area of Conservation (SAC) from bottom trawling and dredging in June 2022 alongside 3 further offshore MPAs. A further 13 offshore Marine Protected Areas (MPAs) with varying levels of sediment/reef habitat were protected in March 2024. UK officials have collated evidence for a further tranche of offshore MPA fisheries management measures to protect sedimentary habitats. Why has the UK come to this position to manage bottom trawling in offshore sediment MPAs? The British Isles and Crown Dependencies has a history of protecting then undertaking science to examine sedimentary habitat recovery since 1989. This started on the Isle of Man where scallop dredging closures resulted in benthic habitat recovery in muddy sands (Bradshaw et al 2001). This moved to the studies of Lyme Bay from 2008-2020, where the University of Plymouth recorded recovery of sediment habitats adjacent to reefs (Sheehan et al, 2014), onto the Isle of Arran where gravel and sediment habitat recovered rich hydroid and bryozoan beds (Allerton, 2020), and finally by a consortium of fisheries regulators, academics and NGOs near Plymouth in 2020 at the Eddystone offshore sediment banks (Pikesley et al, 2020). Here we provide the chronology of this history of science and regulation that meets the requirements of marine conservation laws (national MPAs, Natura and MSFD), and report on how we are meeting the objectives of the EU Marine Action Plan, whilst – ironically – no longer being an EU member state. We call on European partner countries to start protecting large swathes of seabed from bottom towed gear to help to start recovering our contiguous seas, and to meet legal objectives.

Keywords: sediment, MPA, regulation, bottom trawl

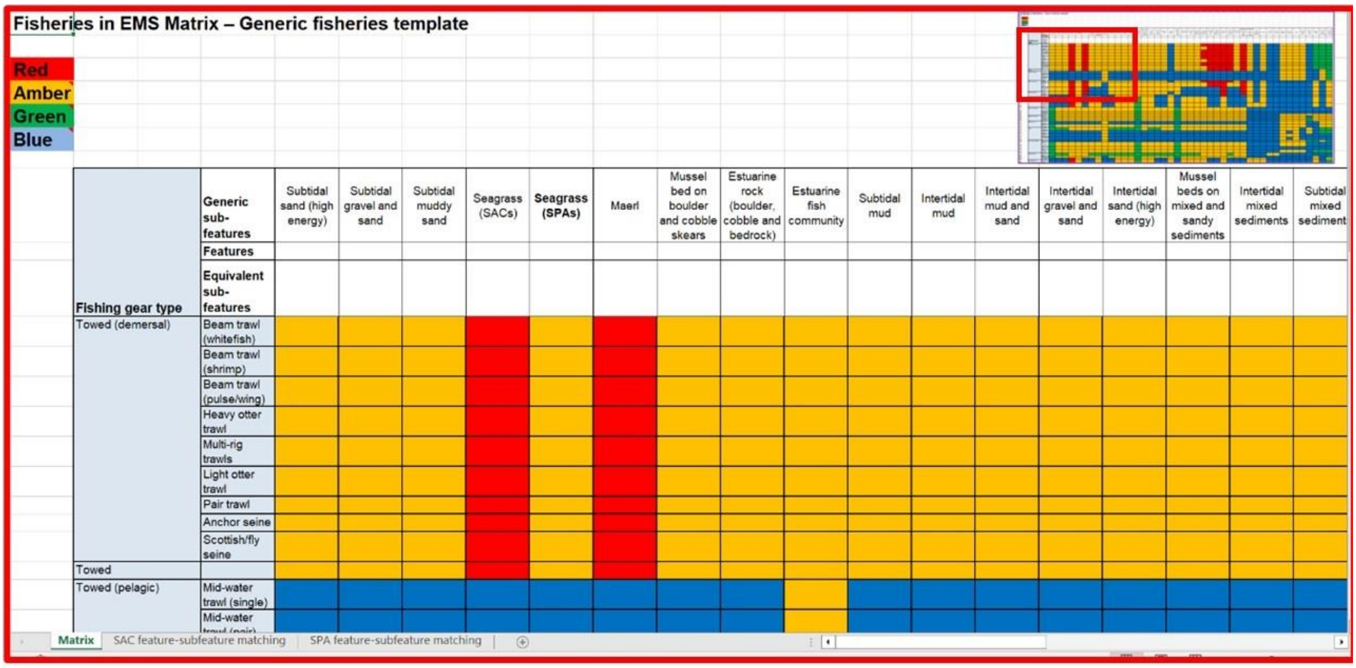

Figure 1. The matrix, developed by UK authorities to help deliver fisheries management in MPAs (2011). [This image is a small subsection of the entire matrix – see inset.]

[N.B. Similar matrices have been published by the EU Marine Expert Group and French Natural History Museum for France Biodiversity Department, but have yet to be systematically applied to fisheries management in EU and French seas through appropriate national or regional management.]

Governance process of implementation of systematic fisheries management

The UK initiated a systemic approach to managing damaging fishing in its Natura 2000 network in 2013, before EU exit. To guide management for regulators, scientific advisors developed matrix[2] of fishing gear impacts in relation to MPA species and habitats. Risk of damage from fishing ranged from high (so called 'red risk') to no interaction at all ('blue'), or where the interaction was deemed so limited that there was no discernible impact ('green') (Fig. 1).

The UK central government department responsible for fisheries and conservation (Defra) delegated the process of assigning management of these 'gear–feature' interactions to nearshore regulators in England (10 regional Inshore Fisheries and Conservation Authorities), and to offshore fisheries and conservation regulators (the Marine Management Organisation) at the end of 2011[3]. Targets for delivery set by central government were that by 2014 all MPAs with 'red risk' interactions were legally protected by 2014 and, that all pre-existing amber-risk interactions were assessed by 2017, with protection measures pending. This led to an initial 18 byelaws protecting over 25 Natura sites (over 3300 km^2) throughout England from bottom trawling and dredging over reef, seagrass and rich sediment areas by December 2015[4]. This process was known as the 'revised approach[5] to fisheries management in Natura 2000 sites'.

For offshore MPAs, the Marine Management Organisation at that time had to work through the Joint Recommendation (JR) process of Article 11 of the CFP with other member states. This led to weak draft protection measures for sites before EU exit. For example, draft management of the Dogger Bank sandbank SAC was deemed inappropriate by the Commission after a complaint in 2018 by a consortium of EU NGOs. Further sites offshore of East Anglia were also deemed to receive legally inadequate conservation measures by UK NGOs.

Case work & science to inform IFCA and MMO management

The risk matrix (Fig. 1) was informed by UK marine science. Many references within the background document to the matrix showed damage to reef habitats and rich sedimentary habitats from bottom towed fishing gears. There were also precedents of closures of bottom towed gears from UK and EU case law and application, from sites such as Loch Creran (benthic reefs), Firth of Lorn (benthic bivalve reefs, maerl and rich sediments) that resulted in the threat of infraction from the EU court. A further case from Strangford Lough in Northern Ireland (where horse mussel reefs were damaged by scallop dredging) also incurred infraction measures (fines) from the Commission, that resulted in subsequent closures of the sites to bottom towed fishing gears.

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[2] Fisheries in European marine sites: Matrix - GOV.UK

[3] Delivering effective and equitably governed marine protected area networks in the UK: The role of Inshore Fisheries and Conservation Authorities (IFCAs) - ScienceDirect

[4] Dialectics of nature: The emergence of policy on the management of commercial fisheries in english European Marine Sites - ScienceDirect

[5] Revised approach to the management of commercial fisheries in European Marine Sites: overarching policy and delivery - GOV.UK

The UK government closed the Fal and Helford SAC in Cornwall to all forms of bottom towed gears in 2008 as a result of damage to sandbank, shallow inlet and bay and reef habitats, largely because of concerns of EU infraction (Solandt et al., 2013).

The above sites clearly showed deterioration from the impacts from drop-down camera, sidescan sonar imagery, and diver-recorded evidence. They were all nearshore. Most infractions within marine SACs during this decade were related to scallop dredging impact, with occasional beam trawling.

Science to inform regulators of the need to manage deterioration pressure

Another part of the process of informing the 'revised approach' was the science that was being carried out to discern the impact of recovery since the deterioration from the dredging and trawling: Sites that *had been* scallop dredged and beam trawled prior to protection were recorded for their recovery trajectories in multiple locations since the 1990s. Evidence of subsequent of recovery has informed scientific opinion on pressures that lead to deterioration in Favourable Conservation Status (FCS) of site protected features.

These studies informed managers of legally required management measures for habitats such as reefs, reef-gravelly sediment mosaic, rich sandbanks, and maerl beds. These are typical NE Atlantic continental shelf benthic habitats. Much of the research counted species after bottom trawling restrictions in a number of these habitats (Isle of Man 1989-2000[6]; Lyme Bay 2008-2016[7]; Start Point 1990-2003[8]; Eddystone reef 2013-2019[9]; Arran 2008-2020[10]; Jersey 2010-2020[11]). All sites have shown that protection increased biodiversity and / or the biomass of benthic species in areas that were subject to bottom towed fishing before closures. Increases in slower growing, larger, longer-lived lifeforms dominated these sites after management. In The Isle of Man, scallop dredgers were banned from a small area of mixed sediment grounds, with subsequent increases in scallop numbers, biomass[12] and benthic biodiversity (such as corals and hydroids – essential habitats for 'capturing' scallop spat). A 7-year study carried out in the deeper (50m) depths of the offshore sediment beds surrounding the Eddystone reef revealed that sediment areas inside the no-trawl area showed richer assemblages of sessile epibenthic species (see Appendix) than in areas in controls that were subject to regular scallop dredging (Fig. 2). Lyme Bay has shown increasing benthic biodiversity (Fig. 3) in the assigned reef habitat, but also in adjacent soft-sediment areas – areas with veneers of sediment over reef. Commercial fish populations were also at greater densities within Lyme Bay 12 years after the closures[13] (Fig. 4). In Arran, in western Scotland, the benthic biodiversity on protected mixed sediment has also increased dramatically.

Such science has supported regulators in their assessment process to understand where management activities over protected features is required. Management of activities is needed where features are

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[6] The effect of scallop dredging on Irish Sea benthos: experiments using a closed area | Hydrobiologia
[7] Drawing lines at the sand: evidence for functional vs. visual reef boundaries in temperate Marine Protected Areas - PubMed
[8] Voluntary management in an inshore fishery has conservation benefits | Environmental Conservation | Cambridge Core
[9] Benefits beyond 'features': Cooperative monitoring highlights MPA value for enhanced seabed integrity - ScienceDirect
[10] 2019-Notley-Recovery-of-biodiversity-habitats-Lamlash-NTZ-and-South-Arran-MPA-Msc-thesis.pdf
[11] Removal of bottom-towed fishing from whole-site Marine Protected Areas promotes mobile species biodiversity - ScienceDirect
[12] Inter Research » MEPS » v298 » p189-204
[13] Ecosystem Approach to Fisheries Management works—How switching from mobile to static fishing gear improves populations of fished and non-fished species inside a marine-protected area - Davies - 2021 - Journal of Applied Ecology - Wiley Online Library

deemed to be in unfavourable condition, and there is a strong evidence base of their continued deterioration of state being caused by human activity. Where features are deemed to be at favourable conservation status, no additional management is likely to be required, but ongoing monitoring informs any future decisions.

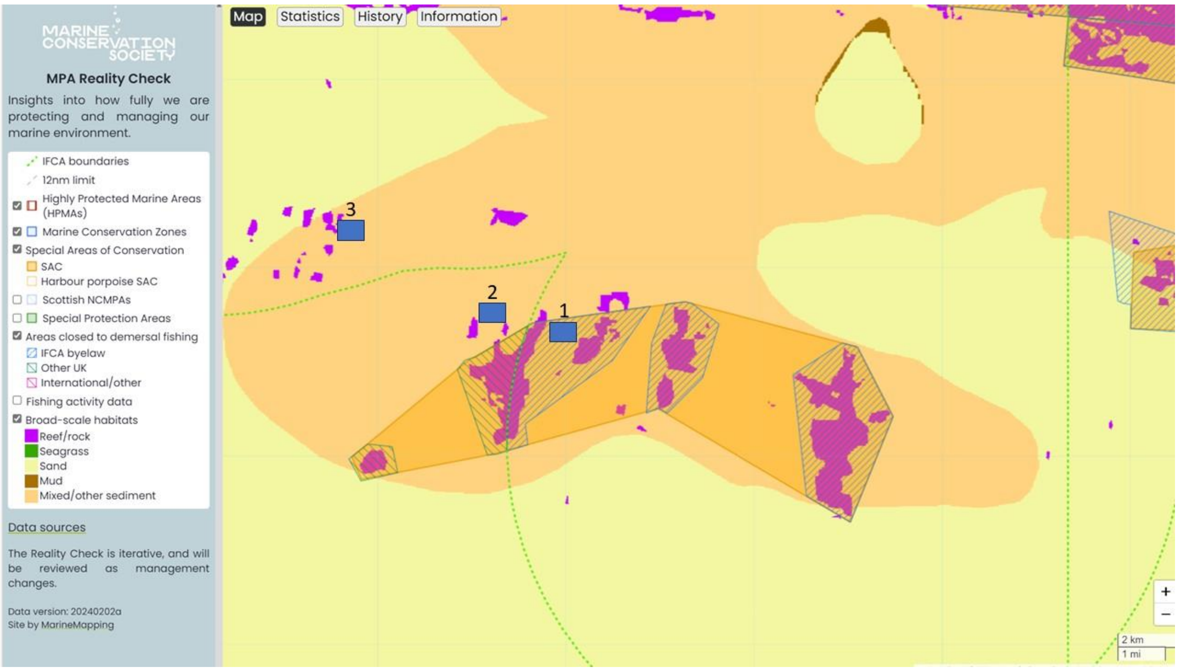

Figure 2: Eddystone reef complex showing the reef areas (pink) and adjacent rich sediment communities (orange) protected within the hatched area bottom towed fishing gear restricted areas. Experimental plots were 1: closed area to bottom towed gear, 2: open ground as 'near' control, 3: open area in 'far' control. Sediment areas are within the closed areas were richer in epibenthic communities (sponges, corals, hydroids and bryozoans) than adjacent fished areas14.

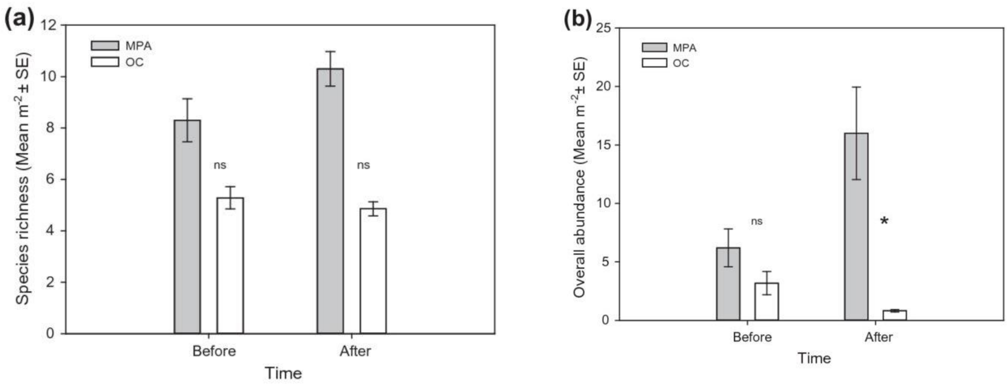

Figure 3. Differences between (a) Species Richness and (b) Overall Abundance of sessile Lyme Bay reef associated species recorded on pebbly-sand habitat between Times 'Before' and 'After' 3 years of protection and between Treatments (MPA = Marine Protected Area; OC = Open Control). (from Sheehan et al., 201315). Habitat in this study was sediment and thin veneers of sediment over reef.

[14] Benefits beyond 'features': Cooperative monitoring highlights MPA value for enhanced seabed integrity - ScienceDirect
[15] Drawing lines at the sand: Evidence for functional vs. visual reef boundaries in temperate Marine Protected Areas - ScienceDirect

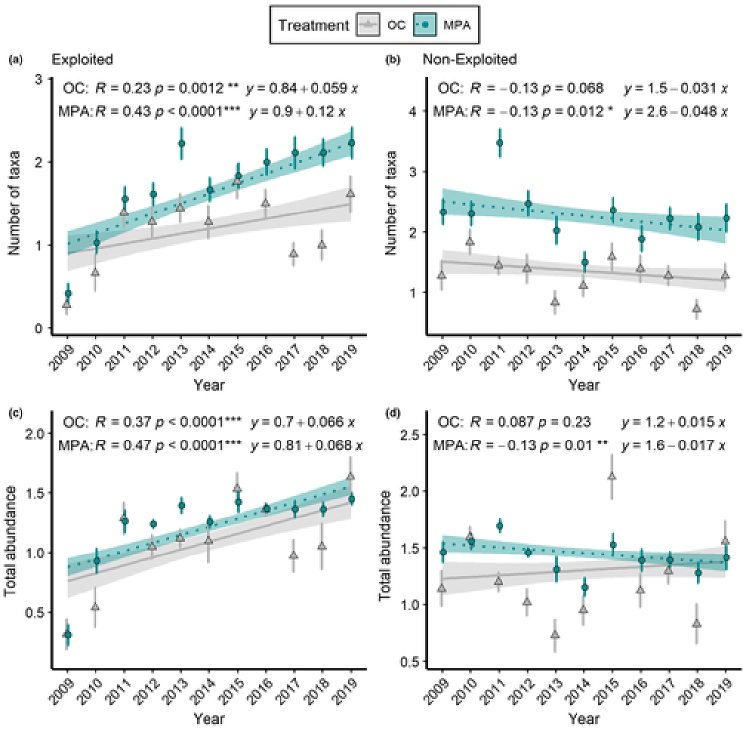

Figure 4. Number of taxa (a) and total abundance (c) of Exploited fish by year and treatments, and number of taxa (b) and total abundance (fourth root transformed: d) of Non-Exploited fish by year and treatments (marine-protected area [MPA]: blue circles, open controls [OC]: grey triangles). Lines and equations show linear regression equation coefficients. Points with errors bars show mean values and standard errors. From Davies et al (2021)16.

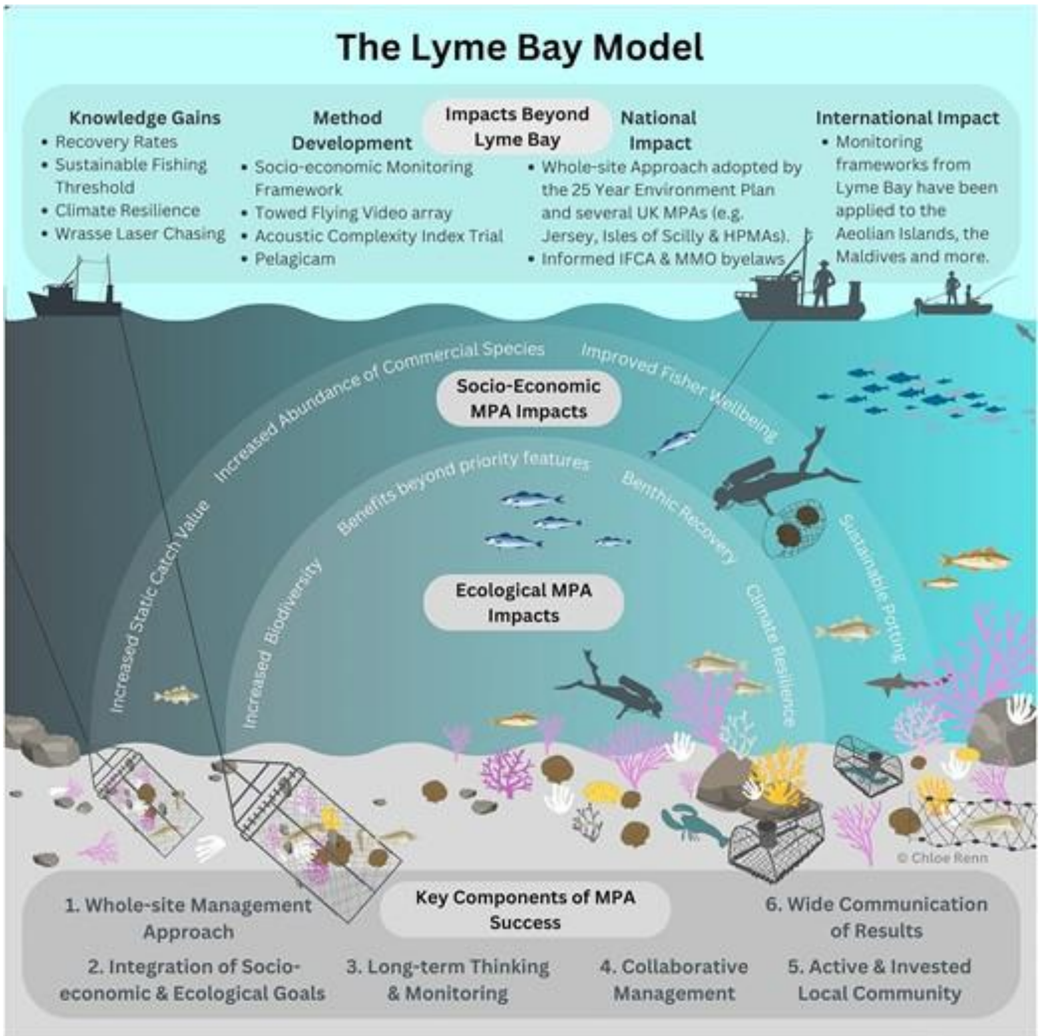

Figure 5. Summary of Lyme Bay research and impact (from Renn et al., 2024. Lessons from Lyme Bay (UK) to inform policy, management, and monitoring of Marine Protected Areas. ICES j Mar Sci 81(2)).

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[16] [Ecosystem Approach to Fisheries Management works—How switching from mobile to static fishing gear improves populations of fished and non-fished species inside a marine-protected area - Davies - 2021 - Journal of Applied Ecology - Wiley Online Library]

Offshore MPA sediment protection

In 2016, the UK voted to leave the EU. In Jan 2021, that process was enshrined in law with the EU (Withdrawal) Act, 2018. This has allowed UK to unilaterally set up fisheries management measures for its offshore MPAs, as long as measures aren't discriminatory (apply equally to EU and UK boats) and meet legal objectives (are proportionate) to the relevant area of MPAs. Measures taken to date incorporate legal and policy targets of the Nature Directives, domestic MPA provisions, and Marine Strategy Framework Directive targets – incorporated into UK legislation through the UKMS Regs 2010. This has since led to 17 offshore MPAs receiving fisheries management measures within 5 byelaws preventing access for bottom towed gears to over 18,000 Km^2 of sea area within a combination of Marine Conservation Zones (MPAs set up under domestic legislation: The Marine and Coastal Access Act 2009) and Natura 2000 sites. The biggest single area protected is the 12,337 km^2 Dogger Bank sandbank SAC that was closed in June 2022[17]. This large area of sand and gravel has since been released from mobile seabed trawling[18] and is showing signs of recovery[19]. It is the largest area of sediment within an MPA closed to mobile bottom contacting fishing. In June 2023, a further 13 MPA closures to bottom towed in 13 offshore N2k and domestic MPAs were implemented. Further sites are currently being considered for significant fisheries management measures in the southwest approaches, English Channel and southern North Sea, such expansive measures allows understanding of the response of 'typical species' to being released from bottom towed fishing gears, such as demersal finfish, sharks, and even cetaceans and seals. The above coastal research from Lyme Bay, Eddystone, Arran and other international locations also provides information on both the benthos and the species that benthos supports, increased population densities and biomass of mobile species that are supported by such measures (e.g. at Lyme, Isle of Man) within the fish, lobster and scallop populations. Research outlined in this paper has informed the MMO of measures required to meet conservation objectives and relevant articles in law[20].

Text from the evidence document for fisheries management for offshore N2k sites under EU law:

'…the management measures have been developed solely in relation to the MMO's legal duties relating to Dogger Bank SAC and its designated features, MMO agrees that the proposed management is likely to have a wide range of ancillary environmental benefits, from protecting fish stocks and benthic ecology to increasing prey availability for marine top predators. As detailed in the Dogger Bank SAC RTA, the proposed management will allow the site to continue to provide carbon storage and reduce carbon released from the seabed (Luisetti et al., 2019). Critically, the MMO MPA fisheries assessment concluded that an adverse effect on site integrity from bottom towed fishing activity could not be ruled out and thus prohibiting these gears will allow for a restoration of the habitat to favourable conservation status.' (Dogger Bank Decision Document, April 2022).

Northeast Atlantic seas have suffered significant declines in biodiversity biomass, density and productivity since industrial fishing developed over 100 years ago[21] - these are 'typical species'. A collapse in the native oyster reefs over the North Sea has mirrored the decline in commercial fish biomass[22]. Regulators in England (MMO) alongside scientific advice from JNCC and NE have determined that management of bottom towed gear impacts on sediment habitats where it is a designated feature

[17] How to 'flip' a paper park: Success in the North Sea carries lessons
[18] Decrease in bottom-towed fishing in Dogger Bank MPA - Oceanographic
[19] A tale of two crises: Diary of an expedition to Dogger Bank | Blue Marine Foundation
[20] Dogger_Bank_SAC_Decision_Document.pdf
[21] The effects of 118 years of industrial fishing on UK bottom trawl fisheries | Nature Communications
[22] The Society for Conservation Biology

in those MPAs assessed is necessary to meet conservation objectives of those MPAs. This in turn will support the achievement of GES – particularly D1, D4 and D6.

Conclusions: what is a reasonable application of the law and our 30 by 30 targets?

Society and fishers understandably want to know when we'll have restored our seas inside MPAs. The evidence from the science above shows important *restoration trajectories* for our inshore sediment habitats after the cessation of bottom towed fishing over a variety of sediment-reef habitats. The UK has 38% of its seas inside on or another form of MPA. Many of the MPAs are designated to protect seabed habitats, and mostly in sediment areas. Many MPAs are still without necessary regulation appropriate to the legal mechanisms needed to prevent continued deterioration (e.g Article 6(2) of the Nature Directives). Furthermore, when MPAs are meant to be the outstanding measure under the UK Marine Strategy to prevent deterioration of Good Environmental Status, states are legally obliged to introduce management measures to prevent deterioration and significant impacts to site integrity. This includes - most urgently mobile bottom towed gears, and excessive ecosystem-scale fishing that our seas have been subjected to since the late 19th century. The MSFD assessment on seafloor integrity and trade-offs (ongoing fishing vs biodiversity) carried out by ICES in 2021 illustrates that the mobile bottom fishing gear sector intensively fish some areas, and less intensively fishes others[23] in the North Sea. This work illustrates that our whole continental shelf has likely been compromised, and that favourable conservation status will require cessation of exploitation methods that are indiscriminate, take out entire swathes of the ecosystem, have changed the function of marine ecosystems, and left very little value in seabed habitat systems[24].

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[24] (PDF) A Global Map of Human Impact on Marine Ecosystems

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Appendix 1: Sediment area richness inside and outside no trawl zones in Eddystone reef. (from Pikesley et al. 2020. Benefits beyond features: Cooperative monitoring highlights MPA value for enhanced seabed integrity. *Marine Policy* 134.)

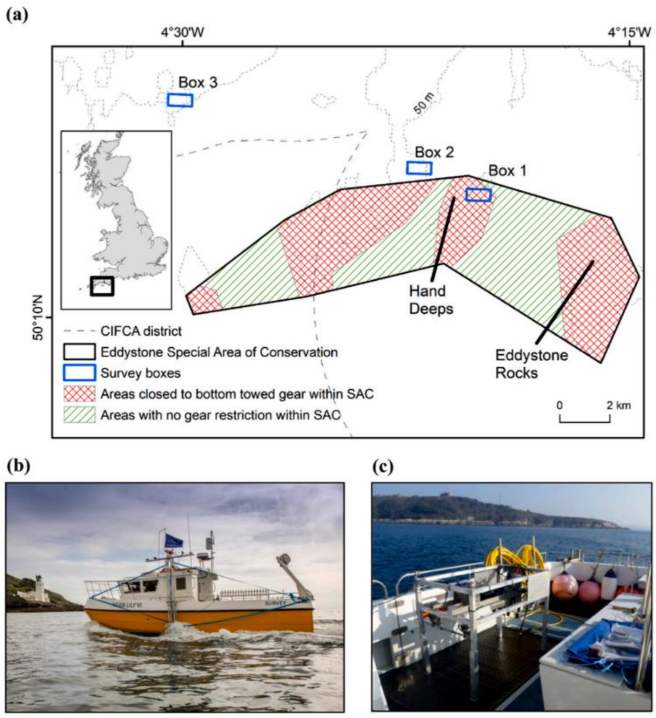

Fig. 1. Eddystone Special Area of Conservation (SAC) study area, CIFCA research vessel and drop-down camera frame. (a) Eddystone SAC (black polygon) in relation to Cornwall Inshore Fisheries and Conservation Authority (CIFCA) district boundary (broken line polygon) in south eastern Cornwall. Areas closed to bottom-towed gear (red hatched polygon) and areas with no gear restrictions (green hatched polygon). 50 m isobath is drawn and labelled; survey boxes are drawn as blue polygons and labelled. Map drawn to Projected Coordinate System: British National Grid Transverse Mercator. (b) CIFCA research vessel used for 2015–2019 surveys. (c) STR SeaSpyder drop-down camera system contained in a custom-built frame. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(b) Community assemblage dissimilarities on circalittoral coarse sediments between survey box 1 and 3

Species	Average abundance		Contribution (%)	Cumulative contribution (%)
	Box 1	Box 3		
crab	2.81	4.62	17.14	17.14
anemone (tube)	6.30	4.23	13.68	30.82
sponge (encrusting/cushion)	2.79	1.61	8.38	39.20
hermit crab	2.39	2.85	8.15	47.35
bryozoa (foliose)	2.63	1.46	7.19	54.54
nudibranch	2.97	2.17	7.17	61.71
pink sea fan	2.41	1.48	6.89	68.61
anemone (symbiotic)	1.91	2.21	5.33	73.93
sponge (branched)	2.05	1.53	4.28	78.22
feather star	1.60	1.00	3.44	81.65
scallop	3.06	2.68	2.96	84.61
dead men's fingers	1.57	1.31	2.25	86.86
sea cucumber	1.40	1.00	2.25	89.10
bryozoa (branched)	2.15	1.86	2.21	91.31
starfish	1.70	1.56	2.03	93.34
brittlestar	1.73	1.70	1.65	94.99

Appendix 2: Species richness and commercial fish species counts from a long-term (>10 year) closed area to bottom towed gear at Lyme Bay (Davies et al., 2021. Ecosystem approach to fisheries management works – How switching from mobile to static fishing gear improves populations of fished and non-fished species inside a marine protected area. *J Applied Ecology* 58.

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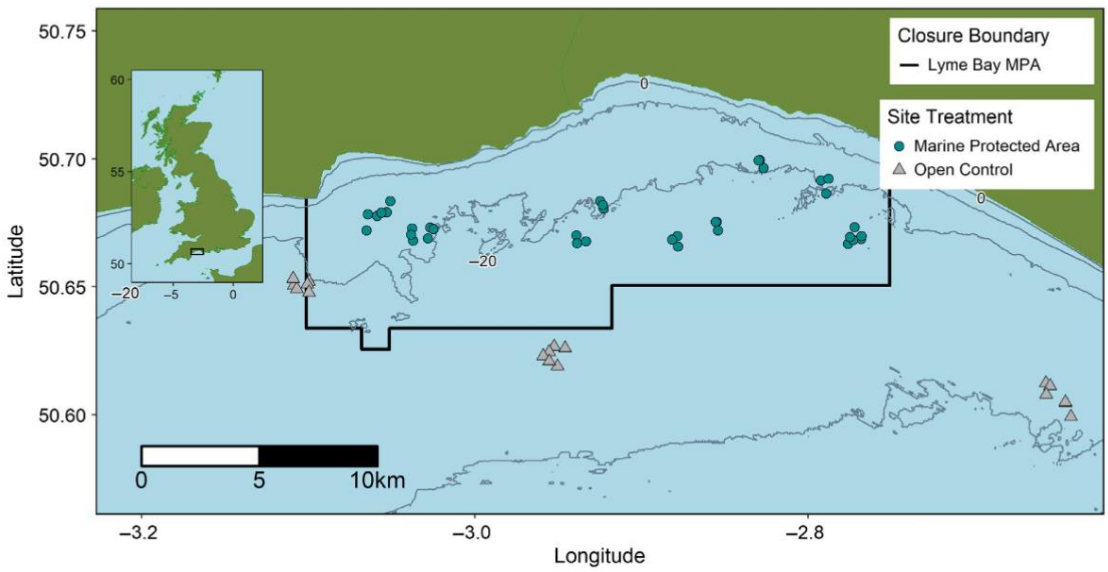

FIGURE 1 Baited Remote Underwater Video system locations within Lyme Bay marine-protected area (blue circles) and open controls (grey triangles)

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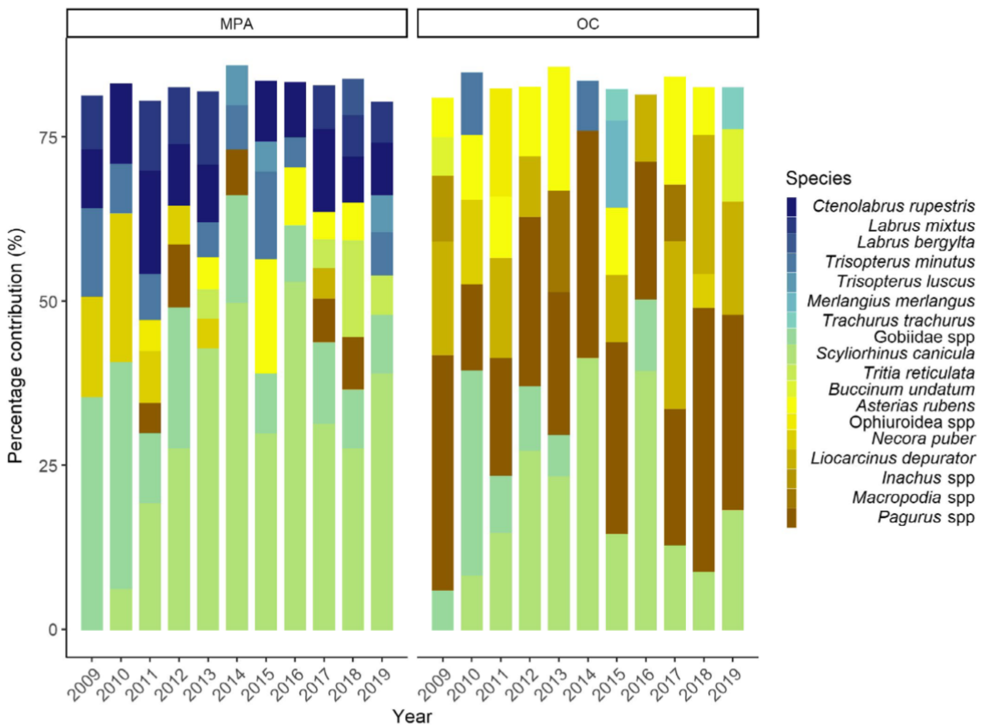

FIGURE 4 Similarity percentages results for the top 80% contributions of species driving the similarities of assemblage compositions of sites within year and treatment

Q&A

On key factors in the success of fisheries regulations over 15 years: after 15 years and multiple initiatives, what has been the most crucial factor in implementing measures?

- The role of IFCAs (Inshore Fisheries and Conservation Authorities) has been key in ensuring fair and effective measures. They represent local fishers (many small-scale, day-boat operators), they are legally empowered to make decisions and measures are developed democratically and equitably. Despite a decline in fleet size, inshore fishermen have understood the reasoning behind these regulations.

On the relationship between small-scale and industrial fisheries: do small-scale and industrial fisheries compete or collaborate?

- Fishermen often complement each other rather than compete. Fisheries committees, particularly in France, represent all fishermen and can propose management measures such as seasonal closures.

CONCLUSION

Better Understanding, Monitoring, and Anticipating the Functioning of Marine Sedimentary Habitats

The discussions and insights shared during the Life Marha seminar highlighted significant progress in the knowledge, monitoring, and management of marine sedimentary habitats, while also underscoring the remaining challenges to achieving their full recognition and effective protection. The key takeaways from these sessions are summarised below and outline the priorities for ensuring the resilience of these vital marine ecosystems.

Sedimentary habitats show both marked spatial and functional complexity and strong temporal variability. **These observations call for integrated approaches, scientific, technical, and operational, based on knowledge sharing, scientific collaboration, and methodological innovation.** Building on these foundations will enable the development of more sustainable practices, based on robust indicators and monitoring tools that are commensurate with the challenges.

The presentations emphasized the importance of strengthening **functional indicators**, alongside traditional taxonomic approaches. Analysing biological traits, considering functional diversity, and understanding ecological processes (recruitment, resilience, trophic flows) provide better assessments of the state of benthic communities and their ability to respond to disturbances. These tools pave the way for more predictive and adaptive diagnostics in changing contexts.

Monitoring methods are evolving towards greater precision, frequency, and automation. Traditional approaches based on physical sampling remain relevant but must be complemented, particularly in high-stakes or hard-to-reach areas. Recent advancements, particularly in **remote sensing** (mapping), **environmental genomics** (eDNA, metabarcoding), the use of **bioindicator species** (e.g., foraminifera), and **automated benthic analysis**, represent promising progress and mark

Mieux connaître, suivre et anticiper le fonctionnement des habitats sédimentaires marins

Les discussions et les idées partagées lors du séminaire Life Marha ont mis en lumière les avancées notables en matière de connaissance, de surveillance et de gestion des habitats sédimentaires marins, tout en rappelant les défis qui subsistent pour assurer leur reconnaissance et leur protection effective. Les principaux enseignements de ces sessions sont résumés ci-dessous et définissent les priorités pour garantir la résilience de ces habitats marins vitaux.

Les habitats sédimentaires présentent à la fois une complexité spatiale et fonctionnelle marquée, et une forte variabilité temporelle. **Ces constats appellent des approches intégrées, à la fois scientifiques, techniques et opérationnelles, basées sur le partage de savoirs, la collaboration scientifique et l'innovation méthodologique**. C'est sur ces bases que pourront se construire des pratiques de gestion plus durables, fondées sur des indicateurs robustes et des outils de suivi à la hauteur des enjeux.

Les interventions ont souligné l'importance de renforcer les **indicateurs fonctionnels**, en complément des approches taxonomiques classiques. L'analyse des traits biologiques, la prise en compte de la diversité fonctionnelle et la compréhension des processus écologiques (recrutement, résilience, flux trophiques) permettent de mieux évaluer l'état des communautés benthiques et leur capacité à répondre aux perturbations. Ces outils ouvrent la voie à des diagnostics plus prédictifs et mieux adaptés aux contextes changeants.

Les **méthodes de surveillance évoluent** vers plus de précision, de fréquence et d'automatisation. Les approches traditionnelles fondées sur l'échantillonnage physique restent pertinentes mais doivent être complétées, notamment dans les zones à forts enjeux ou difficilement accessibles. En ce sens, les progrès récents, notamment en **télédétection** (cartographie), en a turning point toward more sensitive, rapid, and potentially scalable indicators. Provided they are standardized, these methods could meet the need for harmonized monitoring at the scale of European policies.

Establishing **ecological reference states** remains a major challenge. The scarcity of minimally impacted sites, the cumulative effects of human activities, and the natural heterogeneity of habitats make it difficult to define robust thresholds for assessments (particularly under the MSFD). This calls for long-term time series, harmonized protocols, and better coordination among managers, scientists, and institutions at both national and European levels.

Research on carbon flux dynamics in intertidal zones (e.g., Canche estuary) reminds us that soft-bottom habitats play an ambivalent role in the carbon cycle: acting as sinks under certain conditions and as net sources at other times. Better spatial and temporal quantification of these fluxes is needed to integrate these environments into climate policies (Blue Carbon).

Finally, these methodological advances are taking place within an evolving regulatory framework. Numerous reporting obligations exist in Europe, such as the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD), which impose requirements for efficiency and results. The new EU regulation on nature restoration now complements this framework. However, the European habitat classification system (EUNIS) still does not fully reflect the diversity of sedimentary habitats. National initiatives, such as those led by PatriNat, are essential to improving these classifications towards a more harmonized system.

génomique environnementale (eDNA, métabarcoding), via l'utilisation **d'espèces comme bioindicateurs** (ex. foraminifères), en **automatisation de l'analyse benthique** constituent une avancée prometteuse et témoignent d'un tournant vers des indicateurs plus sensibles, rapides et potentiellement uniformisables à large échelle. Ces méthodes, à condition d'être standardisées, pourraient répondre à la nécessité d'un suivi harmonisé à l'échelle des politiques européennes.

L'établissement d'états écologiques de référence reste un enjeu majeur. La rareté de sites peu ou non impactés, les effets cumulés des usages et l'hétérogénéité naturelle des habitats rendent difficile l'établissement de seuils robustes pour les évaluations (notamment dans le cadre de la DCSMM). Cela plaide pour des séries temporelles longues, des protocoles harmonisés, et une meilleure coordination entre gestionnaires, scientifiques et institutions (échelle nationale et européenne).

Les travaux sur les dynamiques de flux de carbone dans les zones intertidales (ex : estuaire de la Canche) rappellent que les habitats meubles jouent un rôle ambivalent dans le cycle du carbone : à la fois puits sous certaines conditions et sources nettes à d'autres périodes. Une meilleure quantification spatio-temporelle des flux est nécessaire pour intégrer ces milieux dans les politiques climatiques (Blue Carbon).

Enfin, ces travaux méthodologiques s'inscrivent dans un contexte réglementaire en évolution. De nombreuses obligations de rapportage existent en Europe, telles que la Directive Cadre sur l'Eau (DCE) et la Directive-cadre Stratégie pour le Milieu Marin (DCSMM), qui imposent des exigences d'efficacité et de résultats. Le nouveau règlement européen sur la restauration de la nature complète désormais cet ensemble. Toutefois, le système de classification des habitats (EUNIS) ne reflète pas encore pleinement la diversité des habitats sédimentaires. Les initiatives nationales, comme celles de PatriNat, sont essentielles pour faire évoluer ces classifications vers un système plus harmonisé.

Taking Action Against the Pressures Threatening Sedimentary Habitats

The contributions and discussions over these two days once again highlighted the high ecological value of soft-bottom habitats, their essential role in biodiversity and ecosystem services, and the methodological advances in monitoring. However, they also highlighted the extreme sensitivity of these habitats, the intensity of pressures they face, and their insufficient recognition in conservation policies.

This tragedy of the commons unfolds out of sight. And that was indeed the goal of this conference: to share knowledge and findings about habitats that are too little studied, too rarely observed, and still poorly understood. The limited knowledge we have of these complex habitats, as revealed through key insights shared over these two days, makes it clear that the sedimentary marine habitats of the Atlantic biogeographical region are rich but in very poor condition. They have been enduring pressures far beyond their resilience capacity for centuries (starting with deforestation and continental erosion, followed by the advent of mechanical ship propulsion), endangering, among other things, the key provisioning and regulatory services they provide to our societies.

Sedimentary habitats are commonly perceived as having little ecological interest—vast sandy or muddy plains supposedly resilient to pressures. Yet the work presented over these two days demonstrated that not only are these habitats biologically rich, but also extremely sensitive to changes in sediment grain size and burial (dumping), to physical disturbances of varying penetration depths (trawling and dredging), and of course to substrate transformations (infrastructure development, artificial reefs, foundations, dikes, etc.). Furthermore, the pressures they endure are far too intense.

The work conducted in the Bay of Seine clearly illustrated the impact of grain size modifications from sediment dumping on benthic communities. However, it is the British studies from the Isle of Man, Lyme Bay, Arran Island, and more recently the Dogger Bank in the North Sea that provide the most relevant and comprehensive insights into

Agir face aux pressions qui menacent les habitats sédimentaires

Les contributions et échanges de ces deux journées de travaux ont souligné à nouveau la grande valeur écologique des habitats meubles et leur rôle essentiel en termes de biodiversité et de services écosystémiques, et les avancées méthodologiques en termes de suivi. Cependant, ils ont parallèlement mis en lumière la très grande sensibilité de ces habitats, l'importance des pressions qui s'y exercent et leur manque de prise en compte dans les politiques de conservation.

Cette tragédie des biens communs se déroule à l'abri des regards. Et c'était bien là l'objectif de cette conférence, que de partager les connaissances et constats concernant des habitats trop peu étudiés, trop peu observés, et encore très mal compris. Le peu que nous connaissons sur ces habitats complexes à étudier, et dont les éléments majeurs auront été partagés durant ces deux jours, permet de comprendre que les habitats sédimentaires marins de la bio-région Atlantique sont riches mais en très mauvais état car ils supportent depuis plusieurs siècles (déforestation et érosion continentale, puis émergence de la propulsion mécanique des navires notamment) des pressions qui dépassent largement leur capacité de résilience, mettant ainsi en danger, entre autres, l'ensemble des services de fourniture et de régulation qu'ils assurent pour nos sociétés.

Les habitats sédimentaires sont communément considérés comme de peu d'intérêt écologique, vastes plaines sablo-vaseuses peu sensibles aux pressions. Or, les travaux de ces deux jours ont montré que non seulement ces habitats marins sont d'une grande richesse biologique, qu'ils sont très sensibles aux modifications granulométriques et à l'enfouissement (clapages), aux perturbations physiques plus ou moins pénétrantes (chalutage et dragage) et bien sûr aux transformations de substrats (aménagements, récifs, fondations, digues, …), mais aussi que les pressions qu'ils supportent sont beaucoup trop importantes.

Les travaux menés en Baie de Seine ont de manière claire illustré l'impact des modifications granulométriques liées aux clapages sur les communautés benthiques. Mais ce sont bien les habitat dynamics under different pressure regimes.

There is now no doubt that the pressures exerted by mobile bottom-contact gear (bottom trawls and shellfish dredges) are completely incompatible with the sensitivity of these habitats, which can lose up to 95% of their biodiversity and most of their functional roles (such as fishery-related functions and carbon sequestration). Modern monitoring tools show that all European sedimentary habitats are impacted by these pressures. Current reflections on managing these pressures are thus essential for restoring what can still be restored, relying on the extraordinary resilience of marine ecosystems. The new European regulation on nature restoration makes this conservation and restoration imperative, and the work shared during these two days provides full legitimacy for it.

Finally, it would be difficult to conclude these exchanges without mentioning artificial reefs. Although the impact of offshore wind farm structures was briefly touched upon, there was a notable lack of robust references concerning the effects of artificial reefs on benthic communities. Indeed, while there is a wealth of publications on the colonisation of artificial marine structures, very few scientifically robust studies illustrate the positive or negative interactions of artificial structures with sedimentary habitats, a surprising gap. This seminar therefore also serves as a call for caution even restraint, regarding the artificialisation of soft substrates and the deployment of reefs or wrecks under the pretext of restoring sedimentary habitats.

This conference thus calls for strengthening the scientific and technical toolbox so that soft-bottom marine habitats finally find their rightful place in European conservation and sustainable management strategies.

Alain PIBOT

LIFE Marha Coordinator

travaux britanniques de l'île de Man, de la baie de Lyme, de l'île d'Arran et plus récemment des Dogger banks en Mer du Nord qui apportent les éléments les plus pertinents et complets sur la dynamique de ces habitats avec et sans pressions.

Il ne fait ainsi plus aucun doute aujourd'hui que les pressions exercées par les engins trainants (chalut benthique et drague coquillière) sont incompatibles avec la sensibilité de ces habitats qui peuvent perdent jusqu'à 95 % de leur biodiversité et l'essentiel de leurs fonctions lorsqu'ils sont soumis à ces pressions. Les outils modernes de suivi permettent de montrer que l'ensemble des habitats sédimentaires européens sont impactés par ces pressions. Les réflexions en cours sur la gestion de ces pressions s'imposent donc aujourd'hui pour restaurer ce qui peut encore l'être, en comptant sur l'extraordinaire résilience des écosystèmes marins. Le nouveau règlement européen sur la restauration de la nature nous impose cet exercice de conservation et de restauration, les travaux échangés durant ces deux jours en apportent toute la légitimité.

Enfin, il est difficile de clore ces échanges sans évoquer les récifs artificiels. Si le sujet a bien été effleuré sur l'impact des structures des champs éoliens en mer, nous aurons eu du mal à trouver des références sur l'impact des récifs artificiels sur les communautés benthiques. Et pour cause, s'il existe pléthore de publications sur la colonisation des structures artificielles immergées en mer, très peu de références scientifiquement robustes illustrent les interactions positives ou négatives des structures artificielles avec les habitats sédimentaires. On peut s'en étonner. Ce séminaire sera donc aussi l'occasion d'inciter à la plus grande prudence, voire réserve quant à l'artificialisation des substrats meubles et à l'immersion de récifs et autres épaves en vue de restaurer les habitats sédimentaires.

Cette conférence appelle donc à consolider la boite à outils scientifique et technique pour que les habitats marins meubles prennent enfin leur juste place dans les stratégies de conservation et de gestion durable des mers européennes.

Alain PIBOT

Coordinateur du LIFE Marha

TAKE HOME MESSAGES – MESSAGES CLÉS

Marine sedimentary habitats are rich and sensitive, but still very poorly understood (distribution, ecological functioning, etc.).

Les habitats sédimentaires marins sont riches et sensibles, mais encore mal connus (répartition, fonctionnement écologique, …).

The pressures exerted on them exceed their resilience capacity, resulting in their very poor condition.

Les pressions qui s'y exercent sont supérieures à leur capacité de résistance d'où leur très mauvais état.

New methods (eDNA, foraminiferal diversity, remote sensing) enhance monitoring but must be incorporated into clear operational frameworks.

Les nouvelles méthodes (eDNA, diversité des foraminifères, télédétection) enrichissent la surveillance, mais doivent être intégrées dans des cadres opérationnels clairs.

Soft-bottom habitats require indicators that integrate structure, function, and dynamics: functional diversity, biogeochemical fluxes, and biological traits.

Les habitats meubles nécessitent des indicateurs intégrant structure, fonction et dynamique : diversité fonctionnelle flux biogéochimiques, traits biologiques.

There is an urgent need to invest in effective and transferable monitoring tools to objectively assess ecosystem health, anticipate impacts, and guide management actions.

Il est urgent d'investir dans des outils de suivi efficaces et transférables pour objectiver l'état de santé de ces milieux, anticiper les impacts, et guider les actions de gestion.

Robust reference systems, based on long-term data series and detailed habitat knowledge, are essential to objectively assess ecological status.

Des référentiels robustes, fondés sur des séries longues et une connaissance fine des habitats, sont indispensables pour objectiver l'état écologique.

Management measures must focus on removing physical disturbances to allow for the resilience necessary to restore the ecosystem services provided by these habitats.

Les mesures de gestion doivent porter sur le retrait des interactions physiques afin de permettre une résilience nécessaire au recouvrement des services écosystémiques rendus par ces habitats.

Artificial reefs do not contribute to the restoration of marine sedimentary habitats.

Les récifs artificiels ne contribuent pas à la restauration des habitats sédimentaires marins.

These ecosystems must be better integrated into public policies, both for biodiversity conservation and for their role in climate regulation.

Ces milieux doivent être mieux intégrés dans les politiques publiques, tant pour la conservation de la biodiversité que pour leur rôle dans la régulation du climat.

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Marha aims to restore and maintain the good conservation status of the 9 marine habitats of Community interest in mainland France. It mobilizes all players involved in the management of Natura 2000 marine or coastal sites designated under the Habitat Fauna Flora Directive (Mediterranean Sea and lagoons).

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