

ICES ANNUAL SCIENCE CONFERENCE
15-18 September 2026
Theme session H: Human impacts on benthic ecosystems

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Furrows and benthos: linking acoustic trawling signatures to macrofauna

Mayya Gogina

Seafloor disturbance by demersal fishing is a major anthropogenic pressure on marine benthic ecosystems, yet natural environmental gradients and temporal variability mask or interact with fishing effects, and quantifying its ecological impact remains challenging. It requires both precise disturbance metrics and explicit consideration of temporal alignment and environmental variability.

We combine multi-year hydroacoustic mapping with macrozoobenthos sampling to disentangle the ecological signal of bottom trawling fishing from background environmental variability in the Fehmarn Belt (southern Baltic Sea), including muddy habitat plots in marine protected area (MPA) and adjacent reference area. This fine-scale study integrates six years (2020–2025) of multibeam echosounder (MBES) hydroacoustic surveys and biological sampling, combining the derived trawling-induced seafloor furrow volume (Trawling Index TI) with macrofauna (MZB) abundance, biomass, diversity, and functional traits metrics.

The analysis demonstrates that benthic macrofaunal communities respond nonlinearly to cumulative trawling pressure, with stronger impacts on total abundance than biomass. Variance-partitioning models incorporating environmental drivers showed that the unique contribution of TI to changes of these community-level variables was generally negligible to modest. It was slightly higher for bioturbation and bioirrigation potential indices. In line with previous studies, Margalef's richness emerged as the most sensitive diversity metric, showing a consistent statistically significant negative relationship with TI. In contrast, environmental variability, factors such as sediment grain size, salinity, and organic content, explain more variance in macrofauna than trawling in this naturally dynamic system.

Fauna-biogeochemistry relationships under bottom trawling

Amrei Gruender

Sediment biogeochemistry can be influenced by bottom trawling directly, through resuspending and mixing the sediment, or indirectly, by depleting vulnerable fauna. Faunal activity can be an important driver of biogeochemical processes. Biodepositors and bioturbators locally enhance organic matter input, mechanically rework the sediment, and increase oxygen availability around ventilated burrows. Studies on bottom trawling have so far focused on the direct impacts on fauna or on sediment biogeochemistry. In this study, impacts on biogeochemistry as mediated through faunal composition change is addressed. Case studies are analysed to identify relationships between sediment biogeochemistry and the trait composition of benthic macroinvertebrates over a gradient of trawling pressures. Organic carbon and pore water nutrients were explained in the framework of statistical modelling in surface and subsurface depth slices and as fluxes across the sediment-water interface. Relevant environmental factors (like sediment type), fishing pressure, and biomass of functional groups were tested as explanatory variables. Species were assigned to functional groups by combined expression of trait modalities biodeposition, bioirrigation, sediment reworking, and upward conveying. The influence of environment and fishing pressure on the distribution of functional groups was investigated through multivariate analysis. This study aims to establish quantifiable fauna-biogeochemistry relationships and assess the impact of faunal composition change induced by chronic trawling on nutrient cycling and carbon mineralisation.

Risk factors determining the vulnerability of sediment organic carbon to remineralisation in response to physical disturbance.

Samuel Rastrick

The conversion of organic carbon (OC) stored in the seabed to inorganic carbon dissolved in the water column can be affected by mobile bottom fishing and other marine industry. However, some effects of bottom disturbance will tend to increase OC remineralisation, while others will have the opposite effect. Published estimates of OC remineralisation associated with bottom fishing also vary widely, reflecting the great uncertainty and the many assumptions and simplifications associated with such calculations. The vulnerability of sediment OC to remineralisation in response to physical disturbance is dependent on the complex interactions between local sediment (e.g. grain size, OC content, lability and source), local environmental conditions (e.g. temperature) and hydrodynamics (e.g. turbulence, currents), local biological communities (e.g. production and bioturbation), local benthic fishing methods (e.g. gear penetration depth, Swept area, Intensity / history) and climate change (e.g. warming, deoxygenation). Here we discuss work from the ICES FISHCARBON workshops, reviewing local drivers of OC accumulation and remineralisation to develop a list of risk factors that can be used by managers to assess the local vulnerability of sediment OC to remineralisation in response to physical disturbance.

Assessing the vulnerability of marine sedimentary Organic Carbon to anthropogenic pressure in Scotland's coastal waters.

James Johnson

Coastal and shelf sediments store vast quantities of Organic Carbon (OC), supporting benthic ecosystems and wider climate regulation. Recent research has identified these sediments as carbon burial hotspots, a valuable function of marine habitats. However, stored OC is becoming increasingly exposed to anthropogenic disturbance as human interactions with benthic sediments have intensified. Whilst the impacts of physical disturbance (e.g., bottom trawling) on benthic ecosystems have been widely studied, little is known about the vulnerability of

sedimentary OC under increased anthropogenic pressure. Bottom trawling resuspends sedimentary OC, removing it from long-term storage in the seabed. When disturbed, these sediments are vulnerable to remineralisation, causing previously stored carbon to be reemitted as carbon dioxide (CO₂). At a global scale, these potentially avoidable greenhouse gas emissions are likely to be enhancing global warming.

This study assesses the vulnerability of marine sedimentary OC to the pressures of bottom trawling in Scotland's coastal waters, with focus on the Firth of Clyde. This area has a rich trawling history which has led to the demise of white fish stocks and transition to predominantly *Nephrops* fisheries. Since *Nephrops* habit in muddy sediments which store greater quantities of labile OC, this study examines how carbon is 'lost' when resuspended. Using seabed samples collected from the Clyde, biogeochemical analysis is run in phase one of the study. From the sample set, an incubation experiment is devised in phase two, whereby samples are resuspended, mimicking the effects of disturbance and repeat disturbance on sedimentary OC. The experiment is guided by current fishing pressure using Vessel Monitoring Systems (VMS) and multibeam bathymetric data. This study evaluates benthic ecosystem functioning in a post-trawled environment in order to determine the vulnerability of the Clyde seabed to future disturbance.

Understanding the long-term impacts of bottom trawling in the Firth of Clyde is critical in defining the vulnerability of sedimentary OC to mineralisation. By quantifying the effects of physical disturbance, this study utilises the scientific base necessary to inform the management and protection of the Clyde seabed. The decisions made in future research and policy planning are central to mitigating further ecological impacts in the Clyde, serving as an example which could be applied across British waters.

Vulnerability and biodiversity of cold-water coral ecosystems under anthropogenic pressure: Insights from the Mauritanian margin

Hammoud El Vadhel

While cold-water corals (CWC) are known to be vital biodiversity hotspots, our understanding of their dynamics along the West African margin has long remained fragmented. By synthesizing 40 years of oceanographic and fisheries data (1982-2022) and recent high-resolution ROV observations from 2020–2021, this study provides the first integrated ecological baseline for Mauritanian CWC ecosystems.

Our findings highlight the remarkable resilience of these communities. Between 20°N and 16°N, we identified thriving reefs at depths of 430–650 m, maintaining up to 30% live coral cover despite surviving in an extremely challenging environment—characterized by severe hypoxia (1.24 mL L⁻¹) and temperatures around 10.55°C. These structures are not merely biological curiosities; they are functional engines of diversity. We recorded 120 taxa across 11 faunal groups, with coral mounds supporting 31% more species than the surrounding seabed. Interestingly, even the extensive "dead" coral frameworks, stretching over 400 km, remains a critical habitat, particularly for fish (66% of the megafauna) and crustaceans.

However, this biological richness is now caught in a crossfire of human activities. Our spatial analysis reveals significant overlaps with bottom trawling, hydrocarbon exploration, and an increasing accumulation of marine litter. Given that these corals already function near their physiological limits due to low oxygen, the cumulative impact of these stressors poses a major threat to their long-term survival. By quantifying the spatial overlap between high-density coral habitats and anthropogenic footprints, this work provides the scientific baseline necessary for deep-sea spatial planning. The findings underscore the urgent need for targeted management frameworks to preserve the functional role of CWC in the Mauritanian Exclusive Economic Zone (EEZ).

Ecological trajectories after 30 years of marine aggregates extraction: recovery or regime Shift?

Robert Alexandre

Marine aggregate extraction alters both the physical and biological characteristics of the seabed. Impacts occur directly, through sediment removal and destruction of benthic organisms, and indirectly, via changes in hydrodynamics caused by seabed deepening or the dispersion of turbid plumes during dredging. Beyond quantifying the initial disturbance, assessing the ecosystem's capacity for recovery is essential to understand the medium- and long-term persistence of extraction effects.

This study examines early recovery processes following the cessation of intensive dredging at a French extraction site. Located in the outer Loire estuary (Bay of Biscay), the 8.2 km² Le Pilier concession was exploited for 30 years and closed in 2017. Approximately 40 million m³ of coarse sand were removed, creating a depression up to 8 m below the natural seabed.

A three-year survey (2020–2022) conducted within the RESISTE project, complemented by a 2017 regulatory survey, was used to analyse ecological trajectories of (i) sediment characteristics, (ii) macrobenthic species composition, and (iii) biological trait structure. Five years after dredging ceased, the ecological state of the former extraction site remains markedly different from adjacent undisturbed areas. In the most exploited south-western sector, the deep pit likely traps fine particles from the Loire plume, leading to the temporary development of an *Abra alba* muddy habitat contrasting with surrounding sandy habitats dominated by *Spisula solida*. Species composition followed a diverging trajectory, increasingly differing from reference sites, while functional composition paradoxically appeared more similar. This suggests that the pit has shifted into a new ecological regime with its own dynamics, making full recovery sensu Holling (1973) unlikely.

On the pit slope, sediments remain dominated by mobile sands. Here, species composition converged toward reference conditions within five years, although functional differences persist. The presence of sand dunes near the western boundary of the concession may explain these discrepancies: cross-shore sediment transport from the continental shelf is trapped, generating large sand inputs and dune formation that migrates along the slope. Biological recovery in this area appears constrained by persistent sediment alterations and modified sediment dynamics induced by extraction, even after operations have ceased. Further monitoring will be required to confirm whether these trends persist over the longer term.

Assessing the compatibility of static gear fishing with biogenic reef conservation in a partially protected MPA

Leo Clarke

Marine protected areas (MPAs) are a widely used tool in an ecosystem-based approach to fisheries and marine conservation management, although many are only partially protected. MPA management typically excludes bottom-towed mobile fishing gears and allows the continued use of static gears. These are generally considered to be relatively benign and are expanding. Yet the impacts of static gears to seabed habitats remain understudied and our understanding of their impacts is limited to few studies on temperate rocky reefs, which suggest potential impacts to sensitive taxa through gear movement.

We used a novel application of accelerometry and acoustic telemetry to assess the magnitude and drivers of pot movement in a common whelk fishery operating on biogenic horse mussel (*Modiolus modiolus*) reef. Pot movement was primarily driven by current speed, which strongly

influenced the area of seabed covered by a single pot in a typical 24 h fishing period, particularly in current speeds above ~ 0.5 m/s.

A control-impact study revealed immediate localised depletion of the soft coral *Alcyonium digitatum*, squat lobsters, hermit crabs, the brittle star *Ophiothrix fragilis*, and overall abundance, within the footprint of pot contact with the seabed. We found no similar trend in species densities in relation to chronic potting effort at the reef scale, however, although taxonomic richness and overall abundance were lower in areas of higher potting densities. Our results indicate that environmental factors strongly influence the movement of static whelk fishing gear and that this movement may result in localised depletions of sensitive reef epifauna within the potting footprint. However, we found no detectable impacts of the fishery at the reef scale.

Shifts in Biodiversity in Response to Mussel Bottom Culture in the Wadden Sea

Lotte Bouwman

Wild mussels are key ecosystem engineers, forming complex biogenic habitats that support diverse marine communities. Although mussel culture plots share many structural similarities with natural mussel beds, the extent to which mussel aquaculture influences biodiversity remains largely unknown. Dutch mussel culture, occurring in the Western Wadden Sea and Oosterschelde Estuary, covers 11,500 ha of designated plots alongside wild bivalve beds of similar scale. During the 2021 optimisation of mussel plots, we conducted a unique before-and-after study across six newly designated blocks. A longitudinal sampling campaign monitored changes in infauna and epifauna, providing insights into the facilitative role of mussel plots for (associated) macrozoobenthos. Here, we present findings on benthic community development on the newly established plots. Using biodiversity indices and functional trait approaches, we examine community structure, ecological functioning, and temporal dynamics. This large-scale monitoring illuminates ecological succession and species establishment, offering guidance for sustainable management of aquaculture impacts in Dutch waters.

Methodological and operational approaches to assess the cumulative effects of human activities at sea

Simon POLICE

The English Channel–North Sea (ECNS) facade is one of the most anthropized maritime zones in the world, with diverse human activities such as fishing, marine aggregate extraction, submarine cables, port dredging, disposal of dredged materials, and recently offshore wind farms. This growth of uses raises the question of cumulative effects as several drivers of change can interact with each other with concomitant impacts on ecosystem functioning.

The concept of cumulative effects, linked to the accumulation of multiple drivers of change, is used in many scientific fields and was introduced in ecology in North America in the 1990s. European scientists took up the topic later, particularly in connection with the European Marine Strategy Framework Directive and the recognition of the need for an integrated, ecosystem-based approach. In France, article R122-5 of the Environmental Code specifies that Environmental Impact Assessment (EIA) studies must address the “cumulation of impacts with other existing or approved projects”. Within the context of this legislative framework, all project leaders subject to EIA face the shared challenge of developing a shared methodology to build the “cumulative effects” chapter of EIA studies. On the ECNS facade, marine project leaders have combined their knowledge and expertise with the Universities of Caen, Rouen and Le Havre within the Scientific Interest Group “Cumulative Effects at Sea” ([GIS ECUME](#)), a public-

private consortium, with the development of a methodology for cumulative effect assessment being one of the group's core research lines

This study aims to develop an operational methodology for industrial actors, to assess cumulative effects of human activities in coastal environments. Its first focus consists of mapping the maximum extent of physical effects (e.g. morphology and seabed substrate modification, hydrodynamic change, turbidity, ...) of each activity using EIA data. It subsequently aims to visualize and identify benthic habitats at stake in the eastern part of the Seine Bay using benthic habitats maps and sensitivity matrices (MarESA and MNHN) adapted to local environmental conditions. Overlaying maps of cumulative effects on the physical environment with the spatially distributed sensitivity levels of habitats allows for the qualification and quantification of cumulative effects at the project scale. An application is proposed in the Seine Bay where marine aggregate extraction, disposal of dredged materials, submarine cables and offshore wind farms take place.

From single species distributions to community structure: benthic community modelling to assess the impact of marine sand extraction

Jana Schultz

Adapting to sea level rise and storm surges caused by climate change is one of the most pressing challenges of this century. To mitigate these risks, coastal protection such as beach nourishment increasingly relies on marine sand extraction, leading to alterations of seabed habitats and impacts on benthic communities. Quantifying these ecological effects requires analytical frameworks that link physical habitat change to biological responses.

Previous research demonstrated that sand extraction-induced variation in bathymetry, sedimentation, and near-bed hydrodynamics shapes benthic species abundances. However, focusing on species independently overlooks the role of biotic interactions in shaping species distributions. To address this limitation, we applied a joint species distribution modelling (JSDM) approach using generalized linear latent variable models (GLLVMs). We applied this framework to multivariate benthic abundance data of 25 species across 391 locations, collected from multiple sand extraction pits and corresponding reference areas. This framework identifies key abiotic drivers of community composition and quantifies the contribution of species co-occurrence networks to observed community patterns.

Preliminary results indicate strong functional structuring of benthic assemblages: sediment mud content primarily affects low-mobility infaunal taxa closely associated with the seafloor, such as burrowing, tube-building, and deposit-feeding taxa. Near-bed hydrodynamics are associated with mobile scavengers and predators, and seabed morphology primarily structures suspension-feeding assemblages. Latent variables revealed clear patterns of species co-occurrence. *Abra alba* showed the strongest positive associations with several deposit-feeding and tube-building species, including *Lanice conchilega* and *Owenia fusiformis*, while also showing negative associations with a smaller group of taxa, including *Philocheras trispinosus* and *Thia scutellata*.

These results demonstrate that JSDMs can inform marine spatial planning and support management strategies aimed at maintaining seabed integrity and ecosystem functioning under the ecological impacts of sand extraction.

A trait-based modelling assessment of bottom fishing impacts and functional recovery in European shelf-sea benthic ecosystems

Marija Sciberras

Growing awareness of the environmental impacts of bottom fishing has led to increasing demand for comprehensive assessments of its spatial extent and ecological consequences. We applied the Benthic Fishing Impact Assessment Tool (Bfiat), a deterministic trait-based modelling framework, to quantify how fishing intensity, sediment type, and species life-history traits interact to shape benthic community state and ecosystem functioning. Using macrofaunal data from 234 stations across seven European shelf-sea case studies, characterized by different fishing intensity and habitat type, we predicted the Relative Benthic State (RBS) and recovery trajectories of benthic communities. Response was assessed across key functional groups (suspension and deposit feeders) and processes, namely bioturbation and bioirrigation, which play central roles in regulating sediment organic matter cycling. Impacts varied strongly among case-studies and habitats. The most degraded benthic states ($RBS < 0.75$) occurred in locations exposed to high fishing intensity (mean SAR 7–14 yr⁻¹) and communities dominated by surface-dwelling or shallow-burrowing (0–5 cm). In contrast, communities dominated by early-maturing or deep-burrowing species exhibited greater resistance and faster recovery, even under moderate fishing pressure. Functional declines mirrored structural changes, with suspension feeders and bioturbation potential showing marked reductions in heavily fished muddy areas, indicating impaired sediment mixing and benthic-pelagic coupling. There are also potential, but yet undetermined implications for nutrient cycling and carbon storage. Recovery times ranged from 3–4 years in lightly impacted systems to 6–8 years in heavily disturbed muddy habitats, with recovery in sand generally faster and less sensitive to fishing intensity. This study demonstrates how functional indicators can be incorporated alongside structural metrics to provide a more comprehensive assessment of faunal seabed condition and supports habitat-specific, risk-based management of demersal fisheries.

From traits to functions: A statistical framework for understanding epifaunal roles in offshore marine ecosystems

Irene Susini

Anthropogenic pressures and natural variability are reshaping marine ecological communities, with consequences for both biodiversity and ecosystem functioning. Because species' biological traits influence their performance under changing conditions, trait-based approaches offer a promising pathway for understanding and predicting ecological responses. These approaches also have the potential to inform marine spatial planning by linking organismal characteristics to ecosystem functions—defined as fluxes of energy and materials—and to the services they support. However, current applications are limited by the difficulty of quantitatively relating specific trait expressions to ecosystem functioning and service provision. Broad asset–service assessments often overlook substantial variation in trait composition within and between habitats, constraining their ability to capture functional differences that affect management outcomes. To address this challenge, we present a statistical framework for identifying and quantifying relationships between biological traits and ecosystem functions in offshore epifaunal communities, a functionally important yet understudied component of benthic systems. Our approach integrates empirical trait–function linkages with literature-derived connections between functions and selected ecosystem services. By clarifying how traits scale to ecological roles and service delivery, this framework strengthens the evidence base for trait-informed marine conservation and supports the development of more ecologically grounded and service-aware spatial management strategies. Crucially, it also provides a transferable tool for monitoring how anthropogenic pressures alter benthic ecosystem functioning over time and space, enabling more adaptive, function-based assessments of

environmental change and more strategically targeted marine spatial management interventions.

Can species distribution models reliably estimate the effects of bottom trawling on benthic species distributions?

Martin Marzloff

Characterising the structure and the distribution of seafloor invertebrate species communities is key to understanding benthic marine ecosystems functioning across continental shelves. Moreover, disentangling the effects of environmental drivers and bottom trawling on benthic communities is critical to predict changes in ecosystem structure and functioning under future scenarios; and to implement effective ecosystem-based management of bottom trawl fisheries. Here, using species distribution models to relate presence/absence of 71 non-rare benthic macrofauna species (sampled across the Bay of Biscay and Celtic Sea over 15 years of fisheries-independent surveys) to a range of environmental covariates (e.g. bottom temperature, sediment types) as well as to proxies of bottom fishing effort, our objectives are two-fold: (i) to investigate the relative effects of climate and trawling intensity on the distribution of macroinvertebrate species; and, (ii) to quantify species-specific effects of bottom trawling using model projections under no-fishing scenarios.

Modelled species distributions help characterise how the six distinct benthic community types across the continental shelf are driven by large-scale environmental gradients. Despite relatively low contributions of trawling intensities to modelled species distributions, projections under no-fishing scenarios indicate that trawling can impact realised species range sizes in different species-specific manners (both in terms of sign, i.e. positive or negative, and magnitude of effects). However, discrepancies between expert knowledge about species-specific vulnerability to trawling and model projections reveal that, for certain species, modelled species-trawling relationships confuses the causal effects of trawling on species distribution on the one hand, and spurious effects related to targeted fishing on main commercial fishing grounds, on the other hand. For instance, most of the commercial species (e.g. *Nephrops norvegicus*) display positive estimated trawling-species relationships, which highlight how targeting of commercial species can induce spurious non-causal relationships. Similarly, we found that such spurious effects (positive relationships to bottom trawling) hold for most non-commercial taxa that share similar habitats with *N. norvegicus*. Overall, our study provides novel insights regarding large-scale drivers of benthic community structure in the NE Atlantic continental shelf. Importantly, our results also call for caution when applying scenario-based approaches using species distribution models.

Investigating the future of Eastern Scotian Shelf demersal fish communities using a multispecies projection model

Danielle Baribeau

Marine fish stocks are currently threatened by the cumulative impacts of fishing pressure and climate change. An increasingly prevalent way to assess the effects of these stressors is multispecies modelling, a form of ecosystem-based fisheries management that simultaneously assesses the dynamics of several stocks. We have developed a new multispecies projection model (MPM) that combines descriptions of species-specific population growth with ecological interactions in order to project future fish community structure. We have applied the MPM to a subset of demersal fish stocks on the Eastern Scotian Shelf (ESS), a region that is already experiencing the combined effects of fishing pressure and climate change. Data from Fisheries

and Oceans Canada's Atlantic summer research vessel survey were used as inputs for this application of the MPM. Within the MPM, stocks are categorized by functional group and linked together via predator-prey and competitive dynamics. Historical relationships within/between functional groups inform the strength of these interactions in the future projections of biomass. We applied simulated fisheries management and climate change scenarios to stocks throughout MPM projections, allowing for the exploration of how different management strategies could shape future ESS demersal fish communities under varying levels of climate change. The effects of alternative scenarios were evaluated according to changes in biomass, productivity and fishery yield at the individual stock, functional group and community-wide scales. By investigating the collective impacts of climate change and fishing pressure on future community productivity, this application of the MPM generates valuable insights into the dynamics of ESS demersal fish stocks.

Context-dependent biodiversity state–pressure relationships and impact thresholds across anthropogenic and environmental gradients in European seas

Alicia Gran

Marine biodiversity is increasingly threatened by anthropogenic and environmental pressures, altering the structure and functioning of ecosystems, and ultimately their stability, resilience, and the services they provide. Yet, how cumulative pressures and their potential interactions shape biodiversity responses remains unclear, largely because these relationships are complex and context dependent.

Here, we quantify how biodiversity state–pressure relationships (BPR) of demersal fish communities vary across spatial scales in the Mediterranean Sea and the North-eastern Atlantic under different scenarios of cumulative pressures. Using long-term European scientific bottom trawl surveys, we applied logistic modelling to (i) assess and compare BPR along a pronounced fishing effort gradient under different environmental scenarios (i.e., productivity, temperature) and spatial scales (regional versus subregional), (ii) identify limiting impact thresholds based on cumulative biodiversity response curves, and (iii) spatially classify biodiversity state (low, increasingly or highly impacted) at a local scale.

Preliminary results suggest that BPRs between species richness and fishing pressure are context dependent. While (sub)regional patterns differ markedly, threshold values delimiting transitions between low and highly impacted states are strongly modulated by environmental variability. In particular, productivity highly mediates how biodiversity responds to fishing, with high-productivity scenarios generally associated with greater resistance to fishing disturbance. In contrast, the indirect effect of temperature on BPRs was weak and often spatially heterogeneous. Moreover, differences between the Mediterranean and the North-eastern Atlantic further reflect contrasting productivity regimes, thermal gradients, and historical fishing legacies. These emerging patterns suggest that the effects of fishing–environment interactions on BPRs may differ among European seas, with productivity largely shaping responses in Mediterranean and southern regions, while temperature potentially becoming more relevant in its interaction with fishing under northern latitudes.

Importantly, cross-scale analyses further revealed that regional patterns often mask strong subregional heterogeneity in BPR sensitivity. Some subregions shift to highly impacted states under relatively low fishing pressure, whereas others display higher resistance despite greater fishing intensity, patterns not fully captured by broader regional assessments.

Together, our findings highlight the need for context-specific assessment and management strategies addressing cumulative impacts, adapted to subregional conditions. Such an approach can better anticipate where fishing pressure is most likely to translate into large

biodiversity loss, while allowing management to redirect effort towards more resilient areas, thereby minimising biodiversity impacts across European seas.

Beyond mean responses: using segmented quantile regression to identify trawling pressure thresholds in benthic ecosystems

Sandrine Vaz

Identifying pressure thresholds beyond which marine benthic ecosystems experience rapid degradation is a central challenge for ecosystem-based management. Such thresholds provide operational reference points to inform spatial planning, fisheries management and conservation actions. However, detecting them statistically remains difficult due to high variability in ecological data, incomplete coverage of pressure gradients, and the widespread reliance on central tendency approaches (mean or median) that may obscure ecologically relevant responses. Indeed, unmeasured factors may act as the actual limiting constraints, generating unequal variation in the biological response variable through interactions with measured factors.

Here, we explore the potential of segmented quantile regression as a tool to identify pressure thresholds in benthic ecosystems. Unlike conventional segmented regression methods that focus on central responses and assume homoscedasticity, quantile regression allows the examination of different parts of the response distribution. In particular, upper quantiles can better reveal the effect of limiting factors when a given pressure is the active constraint, and where degradation signals may emerge earlier or more clearly than in central trends.

We apply this approach to data collected during scientific trawl surveys to examine the response of benthic megafauna to bottom-trawling pressure, proxied by swept area ratio (SAR). By combining segmented regression with quantile regression across multiple upper quantiles, we identify breakpoints in various ecological indicators that indicate shifts from weak to strong pressure–state relationships. Bootstrapping procedures are used to estimate confidence intervals around breakpoint locations, allowing explicit characterization of uncertainty in threshold estimates. Our results demonstrate that segmented quantile regression can detect pressure thresholds that remain undetected when focusing on central responses alone, and that different quantiles may reveal alternative but ecologically meaningful thresholds. This approach provides a robust and transparent framework for identifying management-relevant pressure limits and contributes to improving the assessment and management of human impacts on marine benthic ecosystem functioning.

Integrating benthic structural and functional indicators into a spatial status/sensitivity map to assess and manage bottom trawling in the Southern North Sea.

Gert Van Hoey

Europe's coastal and continental shelf sediments are increasingly impacted by human disturbances, with mobile bottom-contacting fishing among the dominant pressures. Bottom trawling not only causes extensive physical abrasion but also has significant ecological impacts, reducing benthic biomass, diversity and size structure, and altering functional composition. The severity of these effects varies across habitats and gear types. Consequently, assessing the ecological status and sensitivity of the seafloor has become a central objective of several EU policies, including the EU Action Plan: Protecting and restoring marine ecosystems for sustainable and resilient fisheries, the EU Biodiversity Strategy, and the Marine Strategy Framework Directive.

The Belgian Sea fishery relies heavily on bottom trawling for sole, plaice and shrimp, making the sustainable use of their fishing grounds a key priority to ensure a viable future. Several benthic indicators have been developed to assess seafloor status and sensitivity under trawling pressure. Earlier assessments often relied on single indicators, with the risk of overlooking important ecosystem functions. More recent multi-indicator approaches, such as those proposed in the ICES WKBENTH3 report, address this limitation but introduce new challenges, as different indicators may identify different habitats as sensitive or respond unequally to trawling pressure. Integrating these indicators into a single, coherent assessment therefore remains difficult.

In this contribution, we develop and test an integrative framework to compare and combine multiple structural and functional benthic indicators (FBIAT, SOS, Margalef richness, and the ICES FBIT RBS model). This framework is applied across the Southern North Sea region with the aim of generating a spatially explicit benthic state and/or sensitivity map for the Belgian fishing grounds, based on an integrated indicator score.

This map can be used by policy makers for fisheries management and is also made available to Belgian fishers via the existing onboard platform VISTOOLS, which will enable voluntary adjustments in fishing behavior. VISTOOLS output feeds directly into the VALDUVIS sustainability assessment, where reducing fishing activities in high-state or sensitive areas can improve a vessel's sustainability score, which is visible to consumers. By translating indicator-based assessments into an operational management tool, this work contributes to more sustainable and ecosystem-aware Belgian demersal fisheries.

Introducing MUMARINEX: A multivariate generalist index for assessing anthropogenic impacts and recovery in marine ecosystems

Nathan Chauvel

Marine ecosystems worldwide are increasingly exposed to a growing range of human pressures. To quantify their impacts and to monitor ecosystem recovery, numerous ecological indices have been developed over recent decades. Despite their diversity, most existing indices remain constrained by context-specific limitations, either in terms of the types of pressures they can reliably assess, or by the habitats and biological communities to which they can be applied. Here, we introduce a new multivariate indicator designed to be applicable across a broad range of pressures and marine habitats: the MULTivariate MARine Recovery INdEX (MUMARINEX). This index is based on the assumption that the ecological status of marine communities can be described through the combination of three complementary components: conservation of species (or taxonomic) richness, preservation of community structure, and the absence of shifts in dominance patterns. To evaluate the performance of MUMARINEX, we compared it with two generalist deviation-based indices (the General Purpose Biotic Index, GPBI, and the Ecological Quality Assessment, EQA), as well as with the widely used M-AMBI. All four indices were applied to multiple case studies encompassing diverse marine habitats and anthropogenic pressures. Across all case studies, MUMARINEX consistently exhibited responses aligned with impact intensity and proved sensitive to intermediate recovery stages. Importantly, MUMARINEX was also able to account for situations where moderate disturbance led to local increases in diversity, in line with the Intermediate Disturbance Hypothesis, patterns that are often poorly captured by conventional indices assuming systematic diversity loss under anthropogenic pressure. These results highlight several unique strengths of MUMARINEX, including its continuous response directly proportional to both disturbance intensity and recovery degree, its ability to disentangle the ecological components driving degradation (loss of richness, structural changes, dominance shifts, or their combination), and its capacity to identify the taxa most affected by anthropogenic pressures, features not directly provided by

most commonly used indices. Moreover, owing to its simple underlying assumptions, MUMARINEX is readily applicable by both scientists and environmental managers, with computation facilitated through an R package or an user-friendly online interface. Taken together, its flexibility, interpretability, and broad applicability make MUMARINEX a promising tool for future marine monitoring programs and impact assessments worldwide.

Assessing bottom-trawling impacts on benthic communities using sensitivity indicators

Natalia Montero

Bottom-contact fishing can cause substantial physical disturbances on the seabed, frequently resulting in the structural degradation of habitats and the loss of key taxa. The magnitude of these impacts is determined by multiple factors, including the type of fishing gear employed, seabed characteristics, and the frequency and intensity of fishing effort. Furthermore, the capacity of benthic communities to recover after trawling operations depends on the intrinsic vulnerability of the resident species, which is largely governed by specific biological traits. Consequently, robust assessments of trawling impacts require the integration of spatial and temporal fishing activity data, seabed geomorphological characteristics and community-level biological information.

Between 2022 and 2025, seven sampling campaigns were conducted on the Basque continental shelf (SE Bay of Biscay) to evaluate the impact of bottom trawling on benthic habitats. Sampling stations were distributed to encompass a broad range of depths, seabed characteristics, fishing intensities (derived from Vessel Monitoring System (VMS) data merged with logbook records¹), and regulatory contexts (i.e., stations located within partial or total fishing closure areas or subject to varying degrees of fishing pressure). Biological and environmental characterization involved 75 beam trawls for megabenthic epifauna and 69 sediment grab samples for macrobenthic infauna, grain size analysis and organic matter content determination. Community metrics, including density, species richness and biomass of both epifaunal and infaunal organisms were examined, and stations were classified through taxonomic similarity analyses. Additionally, the Benthos Sensitivity Index to Trawling Operations (BESITO)² and the Sentinels of Seabed (SoS)³ indicator were applied to assess trawling impacts on megabenthic communities.

Results indicate that macrobenthic community composition is primarily shaped by environmental variables, with fishing effort playing a secondary role. In contrast, while total megabenthic biomass showed no clear spatial correlation with fishing intensity, community structure shifted significantly along the fishing-pressure gradient. Accordingly, high intensity trawling areas were dominated by opportunistic and tolerant taxa, whereas the abundance of sensitive megabenthic organisms decreased consistently with increasing fishing effort. These findings provide valuable insights for assessing seabed integrity and determining the environmental status of benthic habitats subjected to bottom-contact fishing. Moreover, this research offers a solid empirical foundation for the development of targeted management strategies aimed at mitigating the ecological impacts of bottom-trawling activities.

(1) General Secretariat for Fisheries. SGP-AZTI database.

(2) González-Irusta et al., 2018. <https://doi.org/10.1093/icesjms/fsy030>

(3) Serrano et al., 2022. <https://doi.org/10.1016/j.ecolind.2022.108979>

Assessing the impacts of fishing pressure on Tyrrhenian Sea benthic ecosystems: a comparative analysis of the RBS and SoS indicators to support the Italian assessment of Good Environmental Status

Bianca Di Lorenzo

Fishing activities conducted by means of bottom trawling represent one of the most significant anthropogenic pressures affecting Italian marine waters. Despite the substantial national efforts undertaken through the implementation of the Marine Strategy Framework Directive (MSFD), in situ measurements have so far not been sufficient to enable the application of the Relative Benthic Status (RBS) indicator in the Tyrrhenian Sea.

Recently, the Italian Ministry of Agriculture, Food Sovereignty and Forests (MASAF) has made publicly available the extensive long-term dataset of the MEDITS program (International bottom trawl survey in the Mediterranean). Although MEDITS in situ surveys conducted in Italian waters are primarily designed to assess demersal fish stocks and benthic ecosystems in support of sustainable fisheries management and European environmental policies, the data they provide can be effectively exploited within the MSFD Descriptor 6 (seafloor integrity) assessment framework.

Taking advantage of this extensive dataset, we applied both the RBS and the Sentinel of the Seabed (SoS) indicators to evaluate the impacts of fishing activities on Tyrrhenian Sea broad benthic habitat types (BBHTs). The analysis integrates biological data derived from Italian MSFD monitoring programs and MEDITS surveys (covering 2200 sampling stations), 12 Broad Benthic Habitat Types (EUSEMap, 2023), and a depth range of 700 m, together with fishing pressure data based exclusively on Vessel Monitoring System (VMS) information, spanning the period 2015–2023.

Results from the RBS and SoS indicators are compared across habitat types, focusing on the distribution of indicator values, their variability along the depth gradient, and their sensitivity to spatial and temporal patterns of fishing pressure, thereby highlighting differences in benthic status among Tyrrhenian BBHTs.

Implementation of cumulative effects risk analysis in marine protected areas: 4 case studies

Frédéric Quemmerais

Maritime human activities are numerous and overlap in space and time. These activities contribute to generating physical, chemical and biological pressures that interact with marine ecosystems, particularly with benthic habitats.

Since 2017, France has been developing a comprehensive and coordinated approach to all public policies applicable to maritime and coastal areas, with the aim of ensuring their integrated management, both in terms of activities and protection. This framework highlights methods that consider the socio-ecosystem in its entirety, and recommend that impact studies carried out to assess the compatibility of activities with ecological conservation objectives should consider the marine ecosystems and the different economic sectors involved. These recommendations apply to all projects subject to environmental assessment and to Marine Protected Areas (MPAs).

The cumulative effects assessment provides a conceptual and methodological framework that can help to address these challenges by allowing us to assess the relative contributions of each of the activities and pressures using an intersectoral approach, thus enabling us to identify and prioritize the most appropriate management levers.

However, the implementation of this approach at the national, regional, and MPAs levels faces scientific and technical challenges in developing robust and operational tools, and remains highly variable and dependent on the technical and human resources available to move from theory to practice.

I will present four examples of Cumulative Effects Assessments in French MPAs from recent years (2023-ongoing). Using the same methodology and tool (Carpediem), we evaluated the cumulative effects of human driven physical pressures on benthic habitats.

Two studies were conducted as part of the integrated Life Marha project (LIFE 16 IPE/FR001) and concern the Special Areas of Conservation of the Natura 2000 network in the Seine estuary (English Channel) and the Loire estuary (Bay of Biscay). One study has been underway since 2024 with the Marine Natural Park *Estuaires picards et de la mer d'Opale*, located in the English Channel. One study is being conducted since 2025 with the Marine Natural Park *Cap Corse et Agriate* located in the Mediterranean sea and funded by the European Interreg project Talassa (Italy-France). All these studies were conducted by the French Office for Biodiversity and carried out in close collaboration with the MPAs managers.

This aims to present the different MPAs management issues and needs, the common methodological framework applied, some specific developments that had been carried out, the main results that could inform MPAs managers, the challenges of working with MPAs managers, progress made in implementing this approach, as well as its limitations and constraints.

A bio-economic modelling framework for evaluating the effects of spatial closures on benthic communities and fisheries

Pierre-Yves HERNVANN

Regulating mobile bottom-contacting gears (hereafter 'bottom trawling') epitomizes the challenge of balancing marine conservation and resource exploitation, calling for operational decision-support tools.

Building on recent advances in monitoring and mapping the relative state of benthic communities, the ICES working group on Fisheries Benthic Impact and Trade-offs of ICES (WGFBIT) proposed areas of spatial restrictions on bottom trawling (MPAs) based on a pragmatic strategy that preserves core fishing grounds by closing the least impacted areas first until a target proportion of the surface area of each habitat is closed to bottom trawling.

Although innovative and promising, such an approach does not assess the direct and indirect effects of MPAs on exploited resources, fisheries viability, and cannot account for counter-effects induced by fleet dynamics.

We developed a simulation approach to move beyond MPAs identification and, using the Bay of Biscay as a case study, assess their performance and their consequences on the entire socio-ecosystem. To do so we used the bio-economic multi-species ISIS-Fish model, which simulates stocks' dynamics and technical interactions among the 48 demersal fleets of the BoB mixed fishery and represents fleet responses to management through adaptation of fishing strategies. Our approach consisted of (i) representing MPA under alternative coverage levels, (ii) predicting fleet responses under different assumptions regarding the redistribution of fishing effort in space and among métiers, (iii) assessing the MPA performance in terms of benthic communities' status, (iv) quantifying the socio-economic consequences for fleets and the entire fishery, and (v) predicting indirect effects on main exploited stocks under alternative non-spatial management measures.

WGFBIT strategy to define MPAs appears effective in protecting benthic communities, particularly when more than 30% of habitat surface area is closed, while limiting the proportion of fishing effort lost or redistributed. However, its effectiveness varies among habitats, suggesting differing sensitivities to spatial redistribution of effort. Changes in fleet economic viability reflect MPA-induced shifts in resource accessibility, catchability and target species driven by adaptive fishing strategies. In most configurations, negative impacts are associated with limited diversification within fishing strategies and strong dependence on specific fishing areas. Nevertheless, winners and losers differ across scenarios combinations, underscoring

the sensitivity of outcomes to fishing effort redistribution assumptions and the cascading effects of fleet responses through technical interactions (e.g. choke species dynamics). Overall, this work and the richness of its outcomes represent a major step toward integrated decision-support tools to inform European biodiversity conservation and restoration policies, while enabling sustainable transitions in fisheries.

Taking stock of seabed carbon storage and sequestration (Blue Carbon) – future implications for impact, recovery and management interventions

Ruth Parker

The subtidal seabed sedimentary habitats in the UK's English waters contain between 80 and 100 Mt of organic carbon (OC) and so have a significant climate change mitigation potential (as Blue Carbon).

However, much of this organic carbon stock is under pressure and risk of degradation from physical disturbances by various human activities. Management of human activities, including protection or restoration of seabed areas containing OC, may therefore provide a significant Nature-based Solution (NbS) to climate change itself.

We present a case study focused in English waters to highlight key considerations for seabed OC management:

- • Organic carbon storage and burial across the shelf: what drives variability, and what is the role of OC composition, source and reactivity? What are the trade-offs with biodiversity or nature recovery?
- • Present pressures on seabed carbon: Where is OC storage under pressure and risk? By how much? What is the potential impact?
- • Policy and management: How can this evidence base inform spatial management interventions and measures, including protection and recovery measures which promote the potential of the seabed climate change regulation service? How does this interact with biodiversity, food or energy security sectors?

Within each element, insights into the developing evidence base, confidence level and remaining knowledge gaps and priorities will be presented as well as recommendations for future inclusion of carbon considerations within integrated seabed management approaches.