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Relative benthic status guides sustainable trawl management in the Adriatic–Ionian Seas

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Abstract

Fishing activities with mobile bottom-contacting gears can heavily impact the seafloor, disrupting marine life and potentially leading to a loss of biodiversity. The impact of fishing pressure on benthic habitats depends on their natural sensitivity, the type of fishing gear, and the frequency and intensity of fishing. This study focused on assessing the health of benthic habitats in the Adriatic and Western Ionian Seas (Mediterranean Geographical Sub-Areas 17, 18, and 19), using the relative benthic status indicator, which quantifies the interaction between fishing pressure and habitat sensitivity. Results obtained provide relevant insights to help balance conservation goals with the need for sustainable fishery activities. The results revealed differences between the two studied areas. The Adriatic Sea, with its high concentration of fishing activity in muddy continental shelf habitats, showed significant degradation of the benthic state. In contrast, the Western Ionian Sea, characterized by a higher proportion of deeper waters, appeared to be in better condition due to comparatively lower fishing intensity. These findings highlight the critical need for spatially targeted management to mitigate the fishing impact. Two management scenarios were explored to support sustainable fisheries. The first scenario focused on introducing spatial closures in areas of ecological importance, reallocating banned fishing activities to less sensitive areas. The second scenario implemented a gradual reduction in fishing effort over five years, aligning with the regional management plan in force in the study area. While spatial closures resulted in localized improvements in benthic health, broader effort reductions offered more widespread benefits across the region. These findings underscore the importance of spatial planning and adaptive fishery management to protect marine habitats and their long-term productivity and diversity.

Keywords: relative benthic state; risk assessment; adriatic sea; western ionian sea; trawl fishing impact; ecosystem-based management

Introduction

A great proportion of the marine ecosystems is subject to human disturbance (Halpern et al. 2015, Kenny et al. 2018), and fishing is generally recognized as one of the most pervasive stressors (Harris 2020), especially on the continental shelf (Pitcher et al. 2022, Van Hoey et al. 2023). Fishing with mobile bottom-contacting gears significantly impacts the seafloor and associated ecosystems, causing damage to biogenic structures and mortality among benthic invertebrates, in turn affecting species composition and diversity and disrupting food webs (Beauchard et al. 2023). The amount of impact caused by bottom-contacting gears is determined by their penetration capabilities, the extension of the swept area affected by the fishing activities according to its horizontal spread, and the intensity of use (e.g. towing speed, duration), which vary according to the specific gear type and the characteristics of the sediment (Eigaard et al. 2016, Pitcher et al. 2022), together determining the footprint. The effect of trawling also depends on habitat characteristics, such as the type of sediment and species composition (Hiddink et al. 2019). For example, habitats characterized by coarse and clean sands are known to be less stable and recover more quickly than stable habitats, such as muddy sands and mud (Dernie et al. 2003).

Even environmental factors can influence the composition of benthic habitats (Dutertre et al. 2013). Variability in environmental conditions can either mitigate or exacerbate the impact of fishing activities. On one hand, areas with high natural variability with regular fluctuations in temperature, salinity, hydrodynamics, or nutrient levels may support more resilient communities with species adapted to survive under changing conditions and, thus, more capable of facing additional stressors, like fishing. On the other hand, in more stable environments, benthic communities might be less tolerant of disturbances and more susceptible to fishing (Jennings and Kaiser 1998).

The composition of benthic communities significantly influences their cumulative sensitivity (across all species) to fishing disturbances. Benthic communities are comprised of a variety of species, each with unique life history traits determining their potential vulnerability to external stressors. One of the factors known to influence species sensitivity to bottom contacting gears is longevity (Rijnsdorp et al. 2018, Hiddink et al. 2019). In trawled areas, the abundance of long-living organisms shows a higher relative reduction in comparison to that of short-living species because of their slower growth rates and lower capability to compensate for trawled induced mortality, given their lower reproductive outputs (Hiddink et al. 2019). Indeed, these species often invest substantial energy in individual growth and survival rather than rapid reproduction, making them less resilient to population declines. When such species are affected by fishing activities, their recovery is slow and challenging, as they replenish their populations at a slower rate (Kaiser et al. 2006). Sessile and fragile organisms, such as corals, are clear examples of species characterized by high sensitivity to physical disturbances. Being anchored to the seafloor and displaying reduced capability to avoid harm, these organisms can easily be damaged or destroyed. Sessile benthic species provide essential habitat and refuge for various marine species, representing in many cases biodiversity hot spots (Carbonara et al. 2020, 2022). The destruction of these habitats can, in turn, affect species relying on these structures for their survival (D'Onghia et al. 2010).

The high sensitivity of benthic organisms and habitats reinforces the importance of carefully managing fishing activities. To address marine habitat degradation, the European Union has implemented legislation and policies, including the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC). The MSFD aims at achieving and maintaining good environmental status (GES) in European waters with a particular focus on evaluating the benthic status, though both biodiversity and the seafloor integrity. Several benthic species play a significant role in building vulnerable marine ecosystems (VMEs), which consist of fragile and long-lived species (e.g. corals and sponges) that provide essential structural complexity and support high biodiversity, making them particularly sensitive to bottom-contact fishing (FAO 2009). For this reason, there is growing attention on the conservation and management of these ecosystems with respect to the threats posed by fishing activities, both on the shelf and slope (FAO 2009, 2016).

Fishing effort is, indeed, a useful index of the fishing pressure applied on benthic communities (Pitcher et al. 2022). This data provides insights into the spatial distribution and intensity of fishing activities, allowing the evaluation of the potential impact on seabed habitats. Fishing effort data, particularly VMS (vessel monitoring system) and AIS (automatic identification system) data (Kroodsma et al. 2018, Thoya et al. 2021), are essential for accurately assessing the level of fishing pressure. While both systems provide valuable information on vessel movements, they have distinct characteristics. VMS devices, which are often mandated by the fisheries management authorities of EU member states, are only relevant for vessels over 12 m in length (Council Regulation (EC) No 1224/2009). The analysis of VMS data offers detailed information about the spatial and temporal distribution of fishing activities and can be directly coupled with logbooks to more precisely map the fishing impact on marine resources. However, it typically records positions at set time intervals, which may limit the resolution of movement data. Conversely, AIS devices, primarily designed for vessel tracking and collision avoidance, are mandatory for vessels over 15 m in length (Directive 2009/17/EC). AIS data are more widely available and provide near-continuous location updates. Nevertheless, they cannot be directly integrated with logbooks in the same way as VMS devices, potentially reducing their utility for certain analyses. Despite these differences, AIS data can still complement VMS data, particularly in areas with limited VMS coverage (Thoya et al. 2021) or when VMS data is not accessible due to confidentiality issues.

Different methodological approaches have been developed to assess the environmental risk linked to the fishing activities (Pitcher et al. 2022). Some methods rely on the use of qualitative scores or expert judgement (Stobutzki et al. 2001, Eno et al. 2013) to provide estimates of relative levels of susceptibility or potential risk, with limited ability to effectively assess the level of impact of fishing effort. In contrast, quantitative methods that provide continuous indicators (Pitcher et al. 2022) are also available. Among these, the population dynamic (PD) approach proposed by Rijnsdorp et al. (2020) has been identified as particularly effective in assessing the relative benthic status (RBS) of the seabed. This method estimates the impact of bottom trawling by measuring the reduction in benthic biomass relative to the carrying capacity of the system (Pitcher et al. 2022). This approach was implemented and further developed by the ICES Working Group on Fisheries Benthic Impact and Trade-offs (ICES 2024) and by the SEAwise H2020 project (Shaping ecosystem-based fisheries management) (Van Hoey et al. 2023, 2024).

The objective of this study is to investigate the impact of trawl fishing and of environmental factors on the status and sensitivity of benthic communities in the Adriatic Sea and the Western Ionian Sea and how this RBS can be improved through fishery management. Both the Adriatic and Western Ionian Seas were selected due to their ecological significance in hosting important benthic habitats classified as VMEs, such as those associated with the presence of bamboo coral (*Isidella elongata*) (Carbonara et al. 2020, 2022). Additionally, the Western Ionian Sea is distinguished by the presence of biodiversity hotspots on bathyal bottoms, such as the *Lophelia pertusa* coral bank off Capo Santa Maria di Leuca (GFCM/30/2006/3 2006) (Mastrototaro et al. 2010). It is also important to highlight that the Adriatic Sea is one of the most heavily impacted areas by trawling activities in European waters (Eigaard et al. 2017). This is primarily due to its high productivity, particularly in the northern part of the basin, which results from a massive nutrient influx that makes the Adriatic Sea one of the most productive regions in the Mediterranean (Marini and Grilli 2023, Matek and Ljubešić 2024). A secondary objective of the study was to evaluate two different types of management scenarios using the RBS assessment and methodology. The first one is based on spatial closures to protect VMEs, essential fish habitats (EFHs), and areas with low benthic status. The second one, particularly focused on the Adriatic Sea, simulates a progressive reduction in fishing effort in line with the multi annual management plan (MAP) implemented for demersal resources in the study area (Recommendation GFCM/43/2019/5 2019).

Materials and methods

Study area and data sources

The assessment of the benthic status was focused on two areas of the Mediterranean Sea, the Adriatic Sea (GFCM Geographical Sub-Areas, GSAs 17 and GSA 18) and the

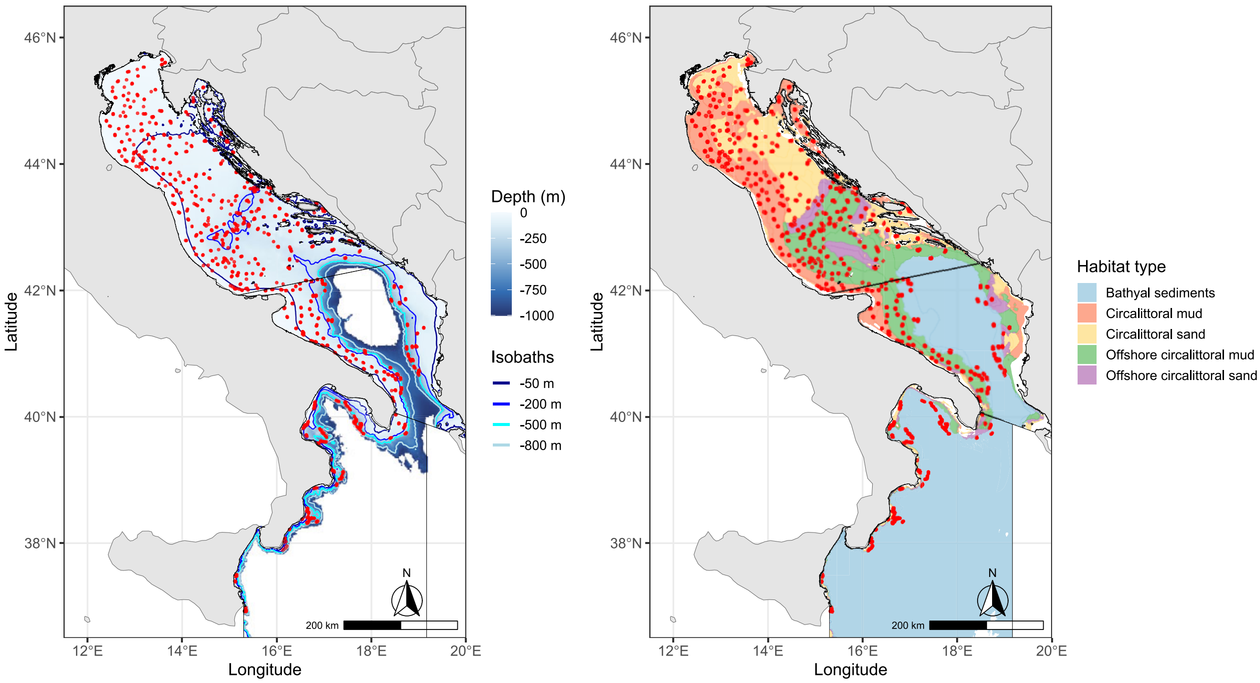

Figure 1. Distribution of MEDITS sampling stations (dots) used in the analysis. Left panel: location of the stations overlaid on bathymetric contours (isobaths at 50, 200, 500, and 800 m), illustrating depth gradients across the study area. Right panel: stations plotted over the main MSFD habitat types.

Western Ionian Sea (GSA 19). The analyses were conducted using biological data collected in the MEDITS scientific trawl survey (Spedicato et al. 2019). The study period encompassed the years from 2017 to 2020, covering a total of 1364 hauls. This number was further reduced to include in the analyses only the benthic habitats that were covered by at least 10 hauls and for which biological information on benthic species was available. To this end, habitat distribution data were derived from the EMODnet EUSeaMap broad-scale seabed habitat map for European waters (Vasquez et al. 2023) (Fig. 1). The final dataset included 1256 hauls: 994 in the Adriatic Sea (GSAs 17 and 18) and 262 in the Western Ionian Sea (GSA 19).

The analyses were conducted using biomass data for epibenthic species, defined as benthic invertebrates that live on the sediment surface (such as starfish, crabs, and sponges). Fish, pelagic species, highly mobile species, cephalopods, and jellyfish were excluded. While the MEDITS survey was not specifically designed for benthos studies, it nevertheless provides crucial information on epibenthic fauna (Farriols et al. 2024). According to the MEDITS survey protocol (Anonymous 2017), the GOC 73 sampling gear was equipped with a codend mesh size of 20 mm (stretched mesh), enabling the capture of small individuals. Upon retrieval on board, all species larger than 1 cm were identified, and data on their total weight and number were systematically recorded, thereby ensuring a robust dataset for subsequent analyses, enabling the estimation of abundance indices standardized over the swept area (N/km^2 and kg/km^2).

Benthic community assessment

The present study utilized the PD method (Ellis et al. 2014, Pitcher et al. 2017, Rijnsdorp et al. 2020) that offered a unique indicator summarizing the overall impact on the benthic community. The PD method calculates the reduction in benthic biomass taking into account the activity of bottom contacting gears (considering the depletion rate accounting for mortality) and the benthic species recovery time, based on the cumulative longevity (recovery rate) and the interval between successive trawling events (Pitcher et al. 2017, Hiddink et al. 2019). The method assumes that the sensitivity of the benthic community to bottom trawling is related to the median longevity of the community (Rijnsdorp et al. 2020), which is defined as the longevity at the 50th percentile of the cumulative biomass. The median longevity was, hence, used as an indicator of community sensitivity to bottom trawling disturbance (Rijnsdorp et al. 2018, van Denderen et al. 2020). Further, this method employs a risk-based approach, estimating the potential impact of a specific fishery footprint on the benthic biomass. It combines community sensitivity and abrasion pressure to produce a community-level index of impact. This index was then used to derive the RBS indicator, which is defined by Pitcher et al. (2017) as the biomass B relative to the carrying capacity K, according to the following formula:

$$\text{RBS} = \frac{B}{K} = 1 - \text{FP} * \frac{d}{r},$$

where FP is the fishing pressure index, d is the depletion index, representing the fraction of benthic fauna biomass removed per trawl, and r is the rate of population growth of the biomass linked to the community median longevity (Hiddink et al. 2017, Pitcher et al. 2017, Rijnsdorp et al. 2018, 2019, 2020, van Denderen et al. 2020).

A detailed spatial reference grid of 0.05° × 0.05° c-squares was created, covering a broad area within the longitudinal range of 12.25°E to 20.0°E and the latitudinal range of 39.7°N to 45.8°N for the Adriatic Sea and from 15.0°E to 19.15°E longitude and 35.0°N to 40.5°N latitude for the Western Ionian Sea. This grid encompassed a bathymetric depth range from 10 to 1000 m, providing a comprehensive spatial framework for the study. Depth data were sourced from the EMODnet digital terrain model (EMODnet 2024).

Longevity data were sourced from a database compiled by the Working Group on Fisheries Benthic Impact and Trade-offs in 2022 (Vaz et al. 2022, ICES 2024), which integrated information from seven distinct longevity datasets covering both the Mediterranean and Atlantic regions. This integrated database provided a comprehensive and reliable basis for assessing benthic species' sensitivity. Species-level longevity was fuzzy-coded into four classes: <1 year, 1–3 years, 3–10 years, and >10 years.

Fishing effort estimation

For this analysis, fishing pressure was estimated based on automatic identification system (AIS) data obtained from the Global Fishing Watch (GFW) platform using the gfwr R package (Clavelle et al. 2024). The raw AIS data consisted of geolocated vessel positions transmitted at regular intervals, which GFW processes to infer fishing activity through behavioural classification algorithms (Merten et al. 2016). Although vessel monitoring system (VMS) data are widely used in similar analyses, they were not available for all countries involved in this study, preventing their use as a consistent data source across the entire study area. As a result, AIS-based datasets provided by GFW were used as the most suitable alternative. Notwithstanding, the GFW coverage of beam trawlers active in the Northern Adriatic Sea, the rapido trawlers (Ceccacci et al. 2024), was limited, preventing the inclusion of this fleet in the present analysis, likely resulting in an underestimation in the assessment of the risk linked to bottom contacting gears in the Adriatic Sea. Despite known limitations, such as the mandatory use of AIS in vessels above 15 m in length and occasional data transmission gaps, GFW AIS data represent a valuable and consistent source of effort information, especially in comparative studies. The activity patterns of trawler vessels are typically well captured by GFW's algorithms (Shepperson et al. 2018, Hintzen et al. 2025), offering a reliable proxy for estimating fishing pressure at the spatial and temporal scales required for this study. To associate vessel characteristics with the detected fishing activity, a harmonized and cross-validated database was created and included the active vessels in the study area (Adriatic Sea, GSA 17 and 18; Western Ionian Sea, GSA 19), based on the information extracted from GFW. This database merged official sources such as the GFCM fleet register (GFCM 2024a) and the EU fleet register (DG MARE 2024) with supplementary information from public platforms (Marine Traffic, Vessel Finder). This integration allowed inconsistencies to be resolved and missing data to be recovered on key vessel attributes such as main gear type, length overall (LOA), vessel engine power (kW), and port of registration. The final, refined database comprised a total of 1650 active vessels operating in the study area, for which all the required information was accurately identified and AIS data available for the years 2017–2020. Of these, 1082 vessels were registered as bottom otter trawlers (OTB), offering a coverage of almost 81% of the potential fleet operating in the study area. It should be noted that the AIS device is mandatory for vessels with LOA >15 m. For this reason, the analysis did not cover the activity of vessels operating in the area with LOA below 15 m [∼988 vessels, according to the GFCM fleet register (GFCM 2024a)]. Additionally, the analysis was carried out at gear level due to the lack of the metier level information in the GFW data.

To determine fishing intensity levels, some assumptions regarding horizontal gear spread, bottom contact extent, and vessel speed were considered (ICES 2020). Fishing intensity was quantified by the equation:

$$SA = \sum e * (v * 1852) * w,$$

where SA is the swept area over an entire year, e is the time fished (hours, h), v is the average vessel speed in knots (kn), converted into meters per hour using the 1852 conversion factor (1 kn = 1852 m/h), and w is the total gear width (meters, m) of the fishing vessel causing abrasion.

To account for varying cell sizes of the *c*-square grid, swept-area values were additionally divided by the grid cell area:

$$SAR = \sum SA/CA,$$

where SAR is the swept-area ratio (SAR), representing the cumulative area impacted by fishing gear within a grid cell over the span of 1 year (Mazor et al. 2021), SA is the swept area, and CA is the cell area. The gear width (door spread) at vessel level was estimated using the equations reported in Eigaard et al. (2016) for bottom trawlers, while the total trawled distance was estimated assuming an average trawling speed of 2.9 kn (Eigaard et al. 2016). To further describe the fishing effort spatial allocation, the average SAR values for both the slope and the continental shelf areas were statistically compared in each GSA using the Kruskal–Wallis test and the Dunn's post-hoc test (Kruskal and Wallis 1952, Dunn 1964). Furthermore, the relationship between the SAR pressure index and the depth strata considered in the analysis (0–50, 50–100, 100–200, 200–500, 500–800 m) for the three GSAs (17, 18, and 19) was investigated using a linear regression analysis.

Modelling approach

The relationship between cumulative biomass and log-longevity was estimated using a modelling approach proposed by Rijnsdorp et al. (2018), employing Generalized Linear Mixed-Effects Models (GLMM) with a binomial distribution, using the *lme4* package in R (Bates 2015). The null model explored the basic relationship between the two variables. Various pressure and environmental covariates were iteratively incorporated as fixed effects, while grid cell code (ID) was included as a random effect. The fishing pressure effect was included as a SAR, while benthic habitat characteristics were included as a factorial predictor using the EMODnet EUSeaMap habitat layer (Vasquez et al. 2023). Only habitats covered by a minimum of 10 stations between 2017 and 2020 were included in the investigation, to ensure a more robust statistical analysis. The modelling analyses for the Adriatic Sea and the Western Ionian Sea were conducted separately due to their inherent oceanographic and biological differences (Civitarese et al. 2010, Borzelli et al. 2014).

Environmental covariates, extracted from the Copernicus Marine Environment Monitoring Service (Cossarini et al. 2021, Escudier et al. 2021) and depth profiles from EMODnet (EMODnet 2024), were tested for inclusion in the modelling analysis as fixed terms. The tested covariates included: sea

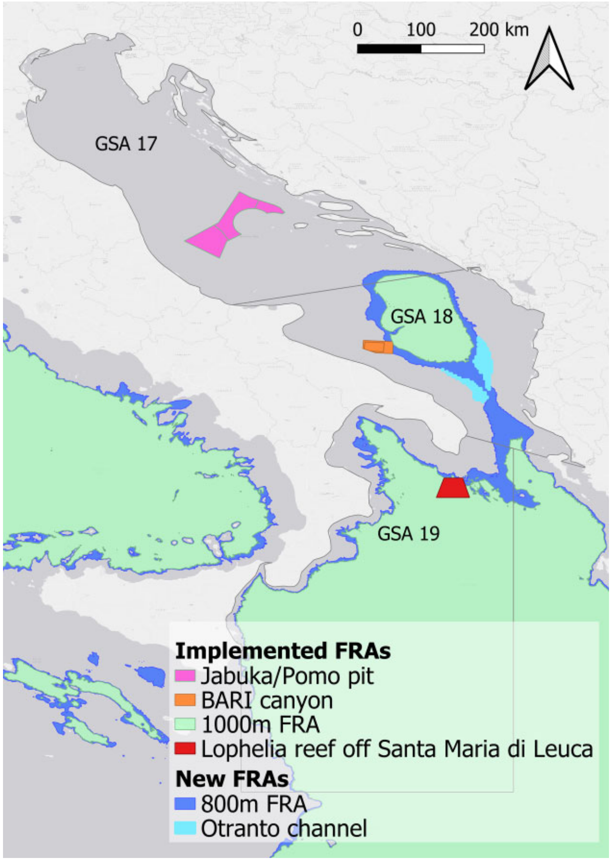

Figure 2. Map of the allocation of the FRAs already implemented (Lophelia reef off Santa Maria di Leuca and the 1000 m FRA) and under implementation FRAs (800 m FRA, Otranto channel) in the study area.

water salinity at the bottom level (botso), sea water temperature at the sea floor (botT), sea water velocity at the bottom level (botcur), mole concentration of dissolved molecular oxygen in sea water at the bottom level (botDox), mole concentration of nitrate in sea water at the bottom level (botNit), mole concentration of phosphate in sea water at the bottom level (botPho), and mass concentration of chlorophyll in sea water (chl).

Models incorporating all possible combinations of fixed terms were generated using the *MuMIn* package (Bartoń 2022), excluding combinations involving correlated variables. Both log-transformed longevity (ll) and SAR were included as mandatory covariates in all candidate models to ensure consistent estimation of median longevity under pristine conditions (i.e. SAR = 0). A train/test procedure with 20 iterations was implemented to evaluate the fitting and predictive performance of the best models. Model selection was based on the Akaike Information Criterion (AIC) (Akaike 2011), which measures the relative quality of statistical models by balancing goodness of fit and model complexity. Models with a $\Delta AIC < 3$, compared to the model with the lowest AIC value, were considered potential best candidates. These selected models were then refitted using 70% of the dataset (training data set) and tested on the remaining 30%, following a train-test cross-validation approach based on the minimization of AIC values. The coefficients and intercept estimated from the best GLMM were used to predict median longevity, extrapolating the binomial model to a cumulative biomass (Cumb) of 0.5 and SAR equal to 0. The estimated coefficients were subsequently utilized to predict the RBS using the PD method described in Pitcher et al. (2017). A clear and agreed threshold for RBS to discriminate when the benthic habitat status can be considered adversely affected has not already been agreed. Hence, for illustrative purposes, we used a threshold value of 0.8 to distinguish more impacted areas (RBS < 0.8) on a 0–1 scale of the index.

Management scenarios simulation

Simulations of management scenarios were conducted in the two study areas (Adriatic and Western Ionian Seas) to assess the potential effectiveness of protecting and recovering benthic communities in comparison to the actual conditions. The first scenario (Scenario 1) aimed at simulating the effect of the full implementation of the recently established (2021) closure areas, the Bari Canyon Fishery Restricted Area (FRA) (Recommendation GFCM/44/2021/3 2021, MASAF 2023), and the forthcoming implementation of new FRAs, one expanding the current fishing ban from 1000 to 800 m depth (Recommendation GFCM/29/2005/1 2005), and the Otranto Channel FRA to protect the *I. elongata* VME (Resolution GFCM/44/2021/3) and red shrimp EFH (Fig. 2). To estimate the effects of the closures on benthic status, current RBS estimates were used as a baseline for the analysis. The establishment of a FRA implies a ban on fishing activities within its boundaries. Consequently, the fishing effort originally recorded at vessel level within the closed areas was redistributed across the rest of the study area following a static displacement approach. For each vessel, the spatial distribution of fishing activity was first estimated at grid-cell level based on historical data (baseline). The portion of effort displaced from the closure was then redistributed proportionally across the other cells historically exploited by the same vessel, assuming that each vessel would continue to target its preferred fishing grounds while avoiding less productive areas. The re-estimated layer of fishing effort, obtained through this vessel-specific spatial reallocation, was then used to compute a new RBS layer, which was compared to the baseline fishing footprint. Statistical differences in RBS values between reference (baseline) and simulated conditions were detected using the non-parametric Kruskal–Wallis test (Kruskal and Wallis 1952).

The second scenario (scenario 2) aimed at simulating the effect of the implementation of a 5-year (2022–2026) fishing effort regime, as foreseen by the MAP for sustainable demersal fisheries in the Adriatic Sea (Recommendation GFCM/43/2019/5 2019). The fishing footprint in 2021 was used as a reference for the progressive reductions of fishing effort up to 2026, following the scheme reported in Table S1, where a cumulative reduction of up to 27% was reported for EU-flagged vessels operating with bottom trawlers (particularly fleet segments VL1224 and VL2440), while Albanian vessels were subjected to a milder effort reduction (up to 9.0%), and no reductions were imposed in the Montenegrin fleet. Scenario 2 was only implemented in the Adriatic Sea due to the presence of the MAP specifically operating through effort quotas. Indeed, in the Ionian Sea, the deep-water fisheries MAP (GFCM/42/2018/4 2018) operates with catch limits that are not directly linked to effort. Significant trends

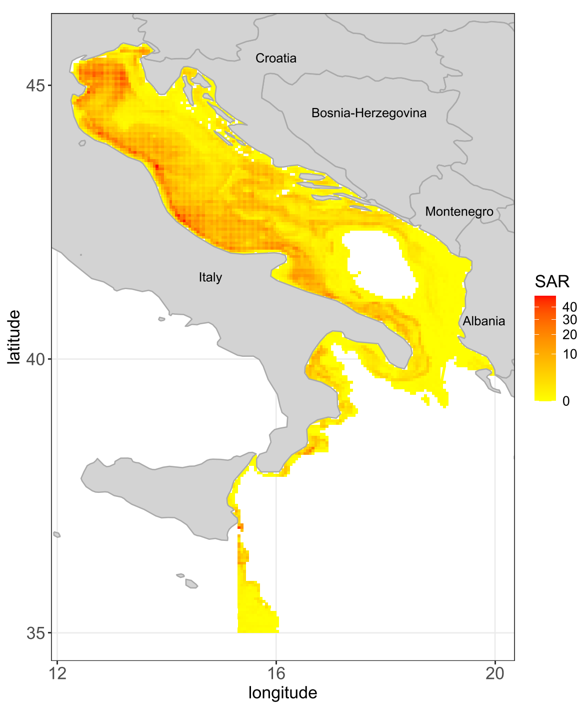

Figure 3. Map of the estimated SAR (swept area ratio) pressure index covering the Adriatic Sea (GSAs 17 and 18) and the Western Ionian Sea (GSA 19).

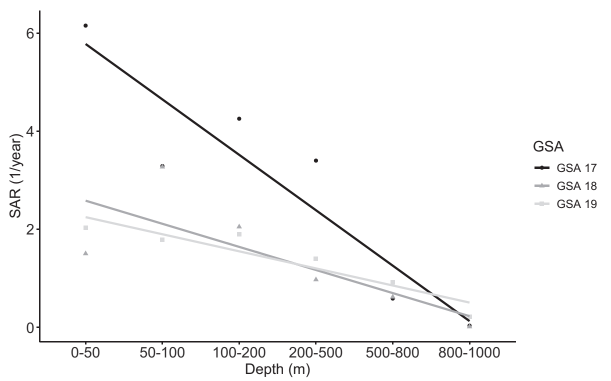

Figure 4. Plot of the relationship between the SAR pressure index (2017–2021) and the depth strata considered in the study area: Adriatic Sea (GSAs 17 and 18) and the Western Ionian Sea (GSA 19).

in the RBS values in the simulated time series were detected using the Spearman trend test (Spearman 1961).

Results

Fishing effort and spatial distribution

The analysis of the AIS effort data confirmed that the Adriatic Sea, particularly its northern part (GSA17) (Kruskal–Wallis, $P < .05$), is intensively exploited by bottom trawl vessels (Table S2). In GSA17, mean SAR values of 5.16 ± 6.14 year^{-1} were estimated, with maximum values of 49.80 year^{-1}. The higher fishing intensities (Fig. 3, Fig. 4) were observed on the continental shelf (10–200 m depth) (Kruskal–Wallis, $P < .05$) along the Italian coasts of GSA 17. The slope (more than 200 m depth) of this area (GSA 17) has a small extent and was characterized by lower mean SAR values: 2.61 ± 2.34 year^{-1} (maximum value: 10.62 year^{-1}). The mean SAR levels recorded in the Southern Adriatic Sea (GSA 18) were lower than in GSA17, on both the continental shelf (2.77 ± 4.17 year^{-1}) and the slope (0.51 ± 1.47 year^{-1}). The GSA 19 (Western Ionian Sea) was characterized by a very low fishing activity, on both the continental shelf and the slope, showing SAR values of 1.89 ± 2.56 year^{-1} and 0.94 ± 2.57 year^{-1}, respectively. The effort data (Fig. 3) highlighted an apparent low activity of the trawling fleet (bottom otter trawl, OTB) on the eastern side of the Southern Adriatic Sea compared to the number of vessels reported in the official GFCM fleet register (almost 5% of the coverage). This under-reported picture of the fishing footprint was likely due to the low number of vessels equipped with AIS devices in this part of GSA 18.

Considering the repartition by habitat of the SAR pressure index reported in Table S2, it was evident that OTB vessels' higher fishing activities were mostly concentrated in the circalittoral mud and offshore circalittoral mud habitats. This was particularly evident in the continental shelf area of GSA 17 and, to lesser extent, in GSA 18. In the Western Ionian Sea, OTB fishing activity was mostly concentrated in the circalittoral sand and offshore circalittoral mud of the continental shelf, while the slope area was less exploited, but consideration should also be given to the extension of those areas. Although fishing activity was also greater on the shelf in GSA 19, the difference with fishing activity on the slope was smaller than in GSA 18 and GSA 17. Figure 4 clearly shows that the fishing intensity exerted in the three GSAs was distributed according to depth strata, following an inverse relationship, higher in GSA 17 and lower in GSA 19.

Modelling analyses

Regarding the modelling analysis conducted for the Adriatic Sea, the correlation analysis allowed to identify high levels of correlation between the following pairs of covariates: Depth-botPho, chl-botNit, chl-botso, and botNit-botso. Among the possible combinations of covariates (excluding those that included these pairs simultaneously in the formula), a total of 384 models were tested, but the use of a threshold value of 3 as a cut-off for the ΔAIC allowed the identification of 20 possible best models, reported in Table 1. The train-test analysis conducted on the 20 best models did not highlight any significant difference in the average fitting and predictive performances of the models. Hence, the null model (number 1 in Table 1), reporting the lowest AIC value ($\Delta AIC = 0$) was selected as the best model. The final model included log-longevity (ll), SAR, botT, botcur, botDox, and the MSFD benthic broad habitat types as environmental covariates. The inclusion of these variables allowed an increase in the adjR^2 value by about 1.14%. It is relevant to highlight that all of the 20 best-performing models shared with the selected one both botcur and botT as covariates, underlining the importance of these environmental factors in shaping benthic sensitivity. In the Western Ionian Sea, the correlation analysis allowed the identification of high levels of correlation between the following pairs of covariates, not included in the complete set of possible combinations of covariates tested: Depth-botT, Depth-botDox, Depth-botNit, Depth-botPho, botT-botNit, botT-botPho, botDox-botNit, botDox-botPho, botNit-botPho, and botNit-botso. A total of 105 models were tested, and the 5 best models selected are reported in Table 2, according to the ΔAIC threshold

Table 1. Summary of the 20 best models selected for the Adriatic Sea by means of the ΔAICc threshold of 3.

n	Models	Intercept	botcur	botDox	botNit	botPho	botso	botT	chl	Depth	ll	MSFD	SAR	adjR^2	df	AICc	ΔAICc
0	Cumb ~ ll + (1 | ID)	+	-	-	-	-	-	-	-	-	+	-	-	0.846	3	1136.20	54.40
1	Cumb ~ botcur + botDox + botT + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	-	+	-	-	+	+	+	0.857	11.00	1081.79	0.00
2	Cumb ~ botcur + botDox + botNit + botT + ll + MSFD + SAR + (1 | ID)	+	+	+	+	-	-	+	-	-	+	+	+	0.858	12.00	1082.41	0.62
3	Cumb ~ botcur + botDox + botT + Depth + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	-	+	-	+	+	+	+	0.858	12.00	1082.83	1.03
4	Cumb ~ botcur + botDox + botso + botT + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	+	+	-	-	+	+	+	0.858	12.00	1083.04	1.25
5	Cumb ~ botcur + botDox + botT + ll + SAR + (1 | ID)	+	+	+	-	-	-	+	-	-	+	-	+	0.856	7.00	1083.08	1.28
6	Cumb ~ botcur + botDox + botT + Depth + ll + SAR + (1 | ID)	+	+	+	-	-	-	+	-	+	+	-	+	0.856	8.00	1083.25	1.46
7	Cumb ~ botcur + botDox + botNit + botT + Depth + ll + MSFD + SAR + (1 | ID)	+	+	+	+	-	-	+	-	+	+	+	+	0.858	13.00	1083.36	1.57
8	Cumb ~ botcur + botDox + botT + chl + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	-	+	+	-	+	+	+	0.858	12.00	1083.42	1.63
9	Cumb ~ botcur + botT + ll + MSFD + SAR + (1 | ID)	+	+	-	-	-	-	+	-	-	+	+	+	0.857	10.00	1083.52	1.73
10	Cumb ~ botcur + botDox + botPho + botT + ll + MSFD + SAR + (1 | ID)	+	+	+	-	+	-	+	-	-	+	+	+	0.857	12.00	1083.58	1.78
11	Cumb ~ botcur + botDox + botNit + botT + ll + SAR + (1 | ID)	+	+	+	+	-	-	+	-	-	+	-	+	0.856	8.00	1083.73	1.94
12	Cumb ~ botcur + botDox + botNit + botT + Depth + ll + SAR + (1 | ID)	+	+	+	+	-	-	+	-	+	+	-	+	0.856	9.00	1083.99	2.20
13	Cumb ~ botcur + botDox + botso + botT + Depth + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	+	+	-	+	+	+	+	0.858	13.00	1084.00	2.20
14	Cumb ~ botcur + botso + botT + ll + MSFD + SAR + (1 | ID)	+	+	-	-	-	+	+	-	-	+	+	+	0.857	11.00	1084.06	2.27
15	Cumb ~ botcur + botDox + botNit + botPho + botT + ll + MSFD + SAR + (1 | ID)	+	+	+	+	+	-	+	-	-	+	+	+	0.858	13.00	1084.31	2.51

Table 1. Continued

n	Models	Intercept	botcur	botDox	botNit	botPho	botso	botT	chl	Depth	ll	MSFD	SAR	adjR^2	df	AICc	ΔAICc
16	Cumb ∼ botcur + botDox + botT + chl + Depth + ll + MSFD + SAR + (1 | ID)	+	+	+	-	-	-	+	+	+	+	+	+	0.858	13.00	1084.37	2.58
17	Cumb ∼ botcur + botDox + botso + botT + Depth + ll + SAR + (1 | ID)	+	+	+	-	-	+	+	-	+	+	-	+	0.856	9.00	1084.59	2.80
18	Cumb ∼ botcur + botNit + botT + ll + MSFD + SAR + (1 | ID)	+	+	-	+	-	-	+	-	-	+	+	+	0.857	11.00	1084.59	2.80
19	Cumb ∼ botcur + botT + Depth + ll + MSFD + SAR + (1 | ID)	+	+	-	-	-	-	+	-	+	+	+	+	0.857	11.00	1084.77	2.98
20	Cumb ∼ botcur + botDox + botso + botT + ll + SAR + (1 | ID)	+	+	+	-	-	+	+	-	-	+	-	+	0.856	8.00	1084.78	2.98

The + symbol indicates the inclusion of a variable in the model, and the − symbol indicates its exclusion. The column ‘models’ reports the implemented formula of the tested models, where Cumb refers to the response variable ‘cumulative biomass’; (1|ID) denotes a random effect for sampling unit (ID), accounting for spatial structure in the data. The other columns refer to the fixed effect implemented in each model. Environmental predictors include botCur (bottom current speed), botDOx (bottom dissolved oxygen), botNit (bottom nitrate concentration), botPho (bottom phosphate concentration), botso (bottom salinity), botT (bottom temperature), and chl (chlorophyll a concentration). Other covariates include Depth, ll (log-longevity, i.e. community-level trait-based sensitivity), MSFD (benthic broad habitat type as defined in the MSFD), and SAR (swept area ratio, i.e. fishing pressure indicator). The last columns report the adjusted R^2, the degrees of freedom (df) for each model, the AICc (Akaike Information Criterion corrected), and ΔAIC, the difference from the best model (ΔAICc = 0).

Table 2. Summary of the 5 best models selected for the Adriatic Sea by means of the ΔAICc threshold of 3.

n	Models	Intercept	botcur	botDox	botNit	botPho	botso	botT	chl	Depth	ll	MSFD	SAR	adjR^2	df	AICc	ΔAICc
0	Cumb ~ ll + (1 | ID)	+	-	-	-	-	-	-	-	-	+	-	-	0.90	7	219.69	3.22
1	Cumb ~ botDox + botso + botT + ll + SAR + (1 | ID)	+	-	+	-	-	+	+	-	-	+	-	+	0.90	7	216.47	0.00
2	Cumb ~ botDox + botso + ll + MSFD + SAR + (1 | ID)	+	-	+	-	-	+	-	-	-	+	+	+	0.90	9	217.59	1.12
3	Cumb ~ botDox + botso + botT + chl + ll + SAR + (1 | ID)	+	-	+	-	-	+	+	+	-	+	-	+	0.90	8	218.23	1.76
4	Cumb ~ botcur + botDox + botso + botT + ll + SAR + (1 | ID)	+	+	+	-	-	+	+	-	-	+	-	+	0.90	8	218.50	2.03
5	Cumb ~ botDox + botso + botT + ll + MSFD + SAR + (1 | ID)	+	-	+	-	-	+	+	-	-	+	+	+	0.90	10	218.83	2.36

The + symbol indicates the inclusion of a variable in the model, and the − symbol indicates its exclusion. The column 'models' reports the implemented formula of the tested models, where Cumb refers to the response variable 'cumulative biomass'; (1|ID) denotes a random effect for sampling unit (ID), accounting for spatial structure in the data. The other columns refer to the fixed effect implemented in each model. Environmental predictors include botCur (bottom current speed), botDOx (bottom dissolved oxygen), botNit (bottom nitrate concentration), botPho (bottom phosphate concentration), botso (bottom salinity), botT (bottom temperature), and chl (chlorophyll a concentration). Other covariates include Depth, ll (log-longevity, i.e. community-level trait-based sensitivity), MSFD (benthic broad habitat type as defined in the MSFD), and SAR (swept area ratio, i.e. fishing pressure indicator). The last columns report the adjusted R^2, the degrees of freedom (df) for each model, the AICc (Akaike Information Criterion corrected), and ΔAIC, the difference from the best model (ΔAICc = 0).

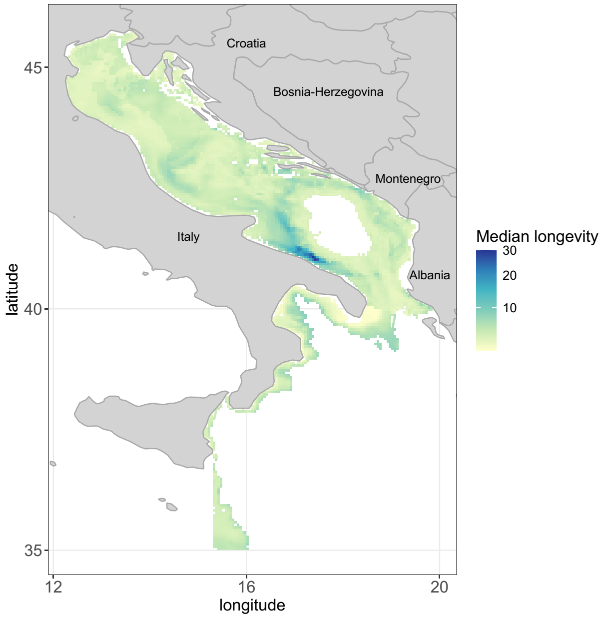

Figure 5. Map of the median longevity sensitivity layer created pooling together the results of the models created, respectively, for the Adriatic Sea and the Western Ionian Sea.

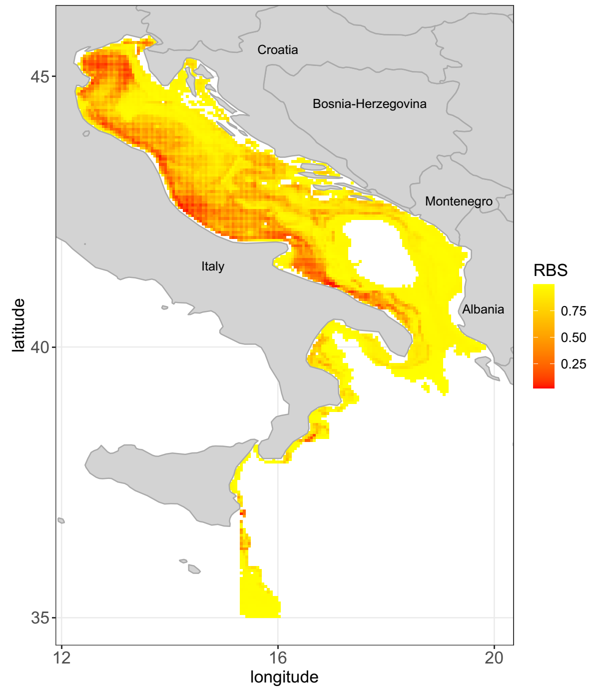

Figure 6. Map of the estimated RBS layer created pooling together the results of the models created, respectively, for the Adriatic Sea and the Western Ionian Sea.

selected. The train/test analysis also did not highlight any significant differences among the 5 best models. Thus, the model showing the lowest AIC value ($\Delta AIC = 0$) was selected as the best one. It included the log-longevity (ll), SAR, botDox, botso, and botT as predictors. Notably, all five top-ranked models shared botDox, and botso as explanatory variables, further confirming their relevance. The contribution of the environmental variables to the improvement of adjR^2 was minimal (about 1.8%).

Finally, the fitted models for both the Adriatic Sea and the Western Ionian Sea were used to extrapolate the median longevity maps, resolving the logistic models for the 0.5 probability value. Figure 5 reports the final longevity distribution for both the Adriatic and the Ionian Sea, while Table S3 shows the mean values of the sensitivity layer by stratum and benthic broad habitat type. The higher median longevity values observed in the Adriatic Sea were mostly located in the continental shelf stratum, in particular in the offshore circalittoral mud (5.81 ± 3.10 years) and bathyal sediment (5.98 ± 1.4 years) habitats, with peaks mainly occurring on the western side of the Southern Adriatic Sea, in correspondence to areas that are less exploited by trawlers. The lowest value of the sensitivity layer for the Adriatic Sea occurred in the circalittoral mud habitat (3.99 ± 0.87 years) on the shelf area, where the highest SAR values were observed, with an average of 7.16 ± 7.51 year^{-1} and peaks of 49.80 year^{-1}. In the Western Ionian Sea, higher median longevity values (5.11 ± 1.35 years) were observed in the bathyal sediment habitat of the slope stratum, where SAR values were globally lower than 1, while lower longevity values were generally estimated in habitats characterized by higher fishing pressure, such as the circalittoral sand (2.92 ± 0.52 years), offshore circalittoral mud (2.99 ± 0.68 years) and the bathyal sediment (3.00 ± 0.23 years) habitats on the continental shelf.

Estimated RBS

The estimated average RBS value for the whole Adriatic Sea (Table S3) was 0.75 ± 0.24, which is slightly lower than the 0.8 threshold value (ICES 2025) used to distinguish habitats in good status to meet EU marine targets (D6C5 Adverse Effects on Habitats). The most impacted areas in the Adriatic Sea (Fig. 6) were located in GSA 17 in the muddy habitats of the circalittoral (0.613 ± 0.254) and the offshore circalittoral mud (0.657 ± 0.198) on the continental shelf, and in GSA 18, in the circalittoral mud (0.759 ± 0.276) and offshore circalittoral mud (0.686 ± 0.286) of the continental shelf. In contrast, the Adriatic habitats characterized by higher RBS were the bathyal habitats on the slope of GSA 17, and all the remaining habitats of the GSA 18 on both the slope and the continental shelf. All of the habitats explored in the Western Ionian Sea, except for the circalittoral sand of the deeper stratum, were characterized by RBS values higher than 0.8, on both the continental shelf (0.875 ± 0.109) and the slope (0.936 ± 0.117), in accordance with the lower fishing pressure observed in GSA 19 in comparison to the Adriatic Sea (Table S1). Indeed, the average RBS value estimated for the whole Western Ionian Sea (Table S3) was 0.93 ± 0.12.

Effects of management scenarios

Regarding the management scenarios, simulations under Scenario 1 indicated no significant differences in RBS compared to the baseline when assessed at the level of individual benthic broad habitat types across the entire Adriatic Sea, as determined by the Kruskal–Wallis test ($P < .05$). However, when analysing the results by GSA and depth stratum (10–200 and 200–1000 m), a significant difference was only observed in the 200–1000 m depth stratum of GSA 18. The implementation of closures benefits the bathyal habitats in GSA 18 (Table S4),

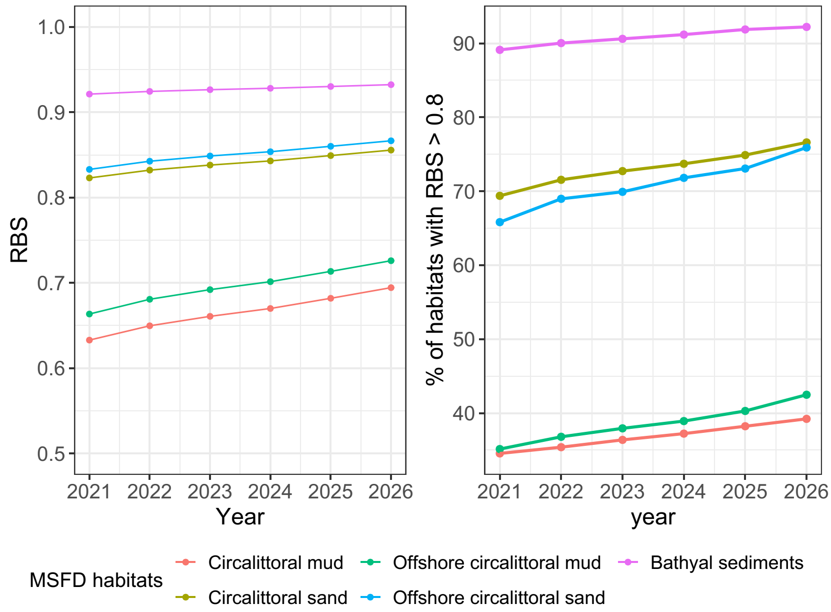

Figure 7. Plots reporting the RBS temporal trends by habitat type (circalittoral mud, circalittoral sand, offshore circalittoral mud, offshore circalittoral sand, upper bathyal sediment, or lower bathyal sediment) in the Adriatic Sea (on the left) and of the percentage of habitats characterized by RBS values higher than 0.8.

resulting in an increase in areas with an RBS greater than 0.8 (+1.17%). In contrast, a reduction in RBS was predicted for the offshore circalittoral sand (−1.64%) and bathyal sediments in the southernmost part of GSA 17 (−3.66%), as well as in the offshore circalittoral mud of GSA 18 (−0.89%) due to effort reallocation. The same simulation applied to the Western Ionian Sea (GSA 19) and focusing on the 800 m FRA as the closure area revealed that the closures primarily benefit the bathyal habitats (+1.36%), leading to an increase in areas with an RBS greater than 0.8. In contrast, for all the other habitats (Table S4) differences were not found.

In Scenario 2, the yearly linear reduction in fishing pressure exerted by the OTB fleet resulted in a progressive improvement in the RBS across all habitats of GSA 18 included in the analysis. Trend analysis, using the Spearman test ($P < .05$) at the habitat level, reported positive trends in the RBS for each habitat (Fig. 7, left panel). This management measure appeared particularly effective for habitats characterized by the highest average impact, such as circalittoral mud and offshore circalittoral mud. Specifically, the RBS for circalittoral mud would increase from 0.63 ± 0.26 to 0.69 ± 0.23, and for the offshore circalittoral mud, from 0.68 ± 0.23 to 0.73 ± 0.20. Consistent with the positive trend in RBS, the proportion of habitat cells exceeding the GES threshold (RBS > 0.8) also showed a significant and steady increase over time (Fig. 7, right panel). This trend was observed across all benthic habitat types included in the analysis. The bathyal habitat showed the lowest rate of increase, likely due to the already high initial proportion of area in good status.

Discussion

This study provides an assessment of the impact of trawling on benthic communities in fishing grounds located in the Adriatic-Ionian region, focusing on significant spatial and depth-related variations in fishing intensity in the Adriatic Sea (GSA 17 and 18) and the Western Ionian Sea (GSA 19). The trawling intensity in the Adriatic Sea, especially in the northern-central part (GSA17), is one of the highest in the Mediterranean (Amoroso et al. 2018) and in the North-East Atlantic (Eigaard et al. 2016). The high fishing intensities observed on the continental shelf (10–200 m depth) along the western coasts of the Adriatic Sea, underscore, particularly in the northern part, the extensive exploitation by bottom trawl vessels (OTB), mainly in the circalittoral mud habitat. In GSA 17, and to a lesser extent in GSA 18, the distribution of fishing activities, with heightened efforts concentrated in circalittoral mud and offshore circalittoral mud habitats, underscores the vulnerability of these habitats to trawling impacts. The intense exploitation of the Northern Adriatic Sea can be attributed to several factors, including the wide continental shelf and the presence of eutrophic shallow waters (Colloca et al. 2017, Grati et al. 2018), which have led to higher productivity in this basin and, consequently, to the greater number of vessels operating in GSA 17 compared to GSA 18 and 19 (GFCM 2024a, DG MARE 2024). The cumulative impact of this fishing effort is manifold, contributing to the overexploitation of crucial commercial stocks (GFCM 2024b), including by-catches (Maioli et al. 2024), as well as causing significant disturbance to the bottom sediments (Pranovi et al. 2000). It should be noted that our analysis did not include the fishing effort of beam trawlers (rapido, TBB), which are particularly active in the Northern Adriatic Sea and known to cause significant seabed impacts. The rapido trawl is a metal–framed beam trawl with iron teeth that disturb the seabed more deeply than otter trawls (Armelloni et al. 2021). For instance, Pranovi et al. (2000) and subsequent experimental studies reported how rapido trawling flattens seabed features and notably impacts macro- and meio–benthic communities (Petović et al. 2016, Ezgeta-Balić et al. 2021). Moreover, beam trawls in general have been shown to cause ∼14% direct mortality of benthic organisms per pass, about twice the amount caused by otter trawls (Vinther et al. 2024). Consequently, the absence of rapido effort in our model likely led to an underestimation of the total benthic impact, particularly in habitats where rapido trawling is intensive, such as the western side of the Northern Adriatic Sea (Armelloni et al. 2021). Future investigations should aim at integrating rapido trawl effort data, potentially from specific AIS or VMS tracking, to provide a more complete and accurate assessment of fishing pressure in the Adriatic Sea.

A significant relationship was also observed between trawling intensity and bathymetry (Fig. 4), which is consistent with the findings of Eigaard et al. (2017). In particular, trawling activity, expressed as the mean SAR, tended to be concentrated on the continental shelf, where values were notably higher than along the slope. This pattern was evident across all GSAs considered, as shown in Table S2 and Figs. 3 and 4. The contrast between shelf and slope was especially pronounced in the Adriatic Sea, where fishing activity in deeper waters is generally limited. These deeper zones tend to be less profitable and therefore are less frequently targeted by bottom trawling fleets. Conversely, the Ionian Sea, predominantly characterized by deep habitats, is a significant fishing ground for a substantial portion of the Mediterranean's deep-sea fisheries (Maiorano et al. 2022), leading to peaks of SAR values in specific portions of the area, which can reach values up to 40.56 year^{-1} (Table S2).

The results reported here provide useful model-based estimations of the sensitivity distribution of median community longevity, supported by environmental conditions relating to habitat suitability and species spatial distribution. In this study, median longevity was utilized as a cumulative community index of sensitivity, based on the hypothesis that short-lived organisms are less vulnerable to fishing-related mortality (Rijnsdorp et al. 2018, van Denderen et al. 2020, Smith et al. 2023). This reduced vulnerability is attributed to both their enhanced adaptive capacity in frequently disturbed environments and their decreased likelihood of encountering a fishing event within their shorter lifespan.

Incorporating environmental covariates into the models allowed for the consideration of local environmental conditions, which can play a pivotal role in the ability of benthic communities to cope with and to adapt to climate change. This is particularly important given that benthic species are sessile or have limited mobility, and are, thus, unable to migrate in response to changing environmental conditions (Dutertre et al. 2013). Longevity, which is closely related to individual body size, is a key trait influencing species sensitivity and resilience (Hiddink et al. 2019, van Denderen et al. 2024), although other biological traits (e.g. reproductive strategy, dispersal, growth rate) also play a role in determining a species' recovery potential (Hinz et al. 2021, Polo et al. 2025).

The median longevity maps extrapolated from the models indicated higher sensitivity values on the western side of the southern Adriatic Sea, particularly in the offshore circalittoral mud. This is likely due to favourable environmental conditions, such as stronger bottom currents, which can enhance physico-chemical conditions and nutrient availability (Dutertre et al. 2013). However, in areas of intense fishing activity, even characterized by the same muddy habitats, the estimated lifespan was significantly lower. A crucial aspect to consider is that median longevity tends to increase in less disturbed habitats, and this stability benefits species with longer lifespans and makes the habitat more vulnerable to severe physical impacts (Hiddink et al. 2019). This suggests that fishing pressure can override the positive effects of favourable environmental conditions. It is widely agreed that the fishing footprint, resulting from the combination of gear type, trawling intensity, and seabed characteristics, alters the structure and function of benthic communities (Eigaard et al. 2016, Pitcher et al. 2022). These impacts can shift the cumulative composition of benthic communities towards short-lived organisms, especially when disturbance frequency is higher than recovery time (Thrush et al. 2005). Indeed, disturbance caused by fishing activities can produce immediate reductions in species density, leading to a decline in the abundance of macrofaunal species and overall biodiversity. These changes highlight how stable habitats, despite fostering longer-lived organisms, can face more severe ecological consequences when disturbed (Auster and Langton 1999, D'Onghia et al. 2017).

A similar pattern was observed in the Western Ionian Sea, where longer lifespan estimates were associated with deeper and less disturbed habitats, while shorter lifespans were found in areas with higher fishing pressure. It is important to acknowledge that using epifaunal data from trawl surveys may introduce a bias (Jørgensen et al. 2011) towards larger and longer-lived species, potentially leading to an overestimation of benthic sensitivity. This is particularly relevant when comparing with assessments based on macrofaunal grab samples, which tend to capture smaller, short-lived taxa. For example, Smith et al. (2023) reported lower sensitivity values in the Eastern Ionian Sea in comparison to the Western side of the same basin, possibly reflecting the dominance of short-lived infaunal species. However, the tendency of trawler epifauna data to overestimate sensitivity may enhance the precautionary value of sensitivity assessments, supporting more robust and conservative decisions in ecosystem-based fisheries management, particularly when fishing pressure is likely to be underestimated. In any case, these differences highlight the importance of integrating multiple sampling approaches to achieve robust and balanced assessments.

The estimated RBS maps clearly delineated the spatial variation of fishing effort across the study area. The Adriatic Sea, characterized by high fishing pressure index (SAR) values, predominantly exhibited RBS values below 0.8, indicative of deteriorated ecological status. In contrast, in the Western Ionian Sea, experiencing lower fishing pressure, generally RBS values exceeded the 0.8 threshold, suggesting a better ecological condition. These findings align with observations from the eastern Ionian Sea (Smith et al. 2023), where fishing intensity is even lower.

While there are limited assessments available for the specific study areas, Pitcher et al. (2022) estimated RBS for the Italian portion of the Northern Adriatic Sea, reporting a value of 0.25, in comparison to the 0.71 ± 0.23 average value estimated in this work for GSA 17. These differences between our results and those of Pitcher et al. (2022) may be attributed to several factors, including the model used to estimate the sensitivity layer, the type of data employed to assess fishing pressure, and the spatial extent of the analysis. While Pitcher et al. applied a generic sensitivity framework based on depletion and recovery rates assigned per habitat and gear type, our method relied on biologically informed assessment based on longevity of benthic organisms derived from empirical survey data. This trait-based modelling enables a more ecologically grounded and spatially resolved assessment of sensitivity, capturing community-level differences in recovery potential that are not explicitly represented in more generalized approaches. Further differences between the two studies arise from the inclusion of environmental variables in the present study, which aimed at better explaining the variability in community sensitivity to fishing effort at the habitat level. Notably, while the present study covered the entire Adriatic Sea, Pitcher et al. (2022) focused only on the western side of the Northern Adriatic Sea, limiting their analysis to Italian waters. The broader spatial scope of our study, which encompassed the entire Adriatic basin, including areas with lower fishing pressure, particularly on the eastern side, may have influenced the overall RBS estimates. Another key difference lies in the fishing effort data used in the two studies. Specifically, the AIS data used in this study may have slightly underestimated fishing activity, as AIS devices are only mandatory for vessels longer than 15 m in length, whereas the VMS data used by Pitcher et al. (2022) included vessels starting from 12 m. It should also be stressed that the present study focused exclusively on the bottom trawl fishing activity, without taking into account the impact of other bottom-contacting gears, such as beam trawls, which are particularly prevalent in the western side of the Northern Adriatic Sea. This limitation could result in a potential underestimation of the overall fishing impact in the area.

The estimation of the RBS index is particularly important in the current European management strategy, as RBS serves as a valuable tool to assess the actual risk of benthic status impairment at both community and benthic broad habitat type levels (ICES 2022). This is particularly relevant within the framework of the EU Biodiversity Strategy for 2030 (European Commission 2020), which aims to halt biodiversity loss and restore natural ecosystems by the end of the current decade. Furthermore, the RBS index aligns with the objectives of the Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC), which requires the assessment of seabed integrity to ensure that the structure and functions of benthic ecosystems are not adversely affected by human activities, thereby maintaining GES. To ensure the sustainability and resilience of these benthic habitats, conservation and management efforts must consider the current state of benthic communities but also the possibility to assess the effects of the implementation of management measures. The RBS approach is an excellent informative tool for predicting the consequences of the implementation of fishing effort management areas and fishing effort regimes. As it is risk-based, it predicts the reduced risk of altering the benthic state under given management scenarios. In particular, the simulated scenarios involving targeted fishing closures in both the Adriatic Sea and the Western Ionian Sea (Scenario 1) showed that displacement of fishing activities from closure areas does not significantly alter RBS at the whole study area level. However, there was a slight improvement in the benthic status, which particularly benefited the bathyal habitats within the 200–1000 m depth. These findings suggest that, although targeted closures can effectively enhance the RBS level and improve the benthic condition of the specific habitats they are designed to protect, displacement of fishing effort to other areas could lead to a reduction in RBS in those regions. These results are complementary to those reported for the same areas by Sbrana et al. (2025), who evaluated the economic effects of similar management closures. Their simulations revealed that effort displacement caused significant changes in catch composition and revenue losses, particularly in the Ionian sector. Slight catch reductions were also observed for the Croatian fleet targeting Norway lobster. This underscores the complex trade-offs of spatial management, where localized benefits may come at the expense of unintended ecological and economic consequences elsewhere within the system. Conversely, the management scenario simulating a progressive reduction in fishing pressure (Scenario 2), based on the fishing effort regime measures in place for the demersal fishery in the Adriatic Sea (GFCM/43/2019/5 2019), demonstrated broader and more consistent enhancements in RBS across all habitats in the area. The effectiveness of these scenarios, particularly in habitats with the highest initial impacts, underscores the potential for long-term improvements through sustained reductions in fishing effort. It is important to note that this management scenario, based on an annual fishing effort regime, could likely achieve significant improvement in benthic status over a short number of years, as it has been previously reported for other GES indicators by Engelhard et al. (2015). The reduction of fishing pressure generates significant positive effects on all benthic broad habitats, with higher effectiveness in habitats previously showing lower RBS levels. These findings suggest that management measures combining closure areas and fishing effort reductions could be particularly effective in protecting valuable and sensitive habitats while mitigating potential displacement effects in other areas exploited by fleets. It is also important to emphasize that the implementation of closure areas, such as the FRAs established in the study region (Jabuka Pomo Pit, GSA 17; Bari Canyon, GSA 18; and *Lophelia* Reef, GSA 19, see Fig. 2), contributes not only to the conservation of benthic communities but also to the replenishment of fisheries resources that depend on these habitats during critical phases of their life cycle (Maiorano et al. 2022).

Building on these ecological insights, future assessments could further benefit from the integration of socio-economic dimensions. In particular, modelling the trade-offs between ecological benefits and economic costs, including potential income losses or gains, as well as potential changes in fuel consumption, and associated carbon emissions, would provide a more comprehensive basis for decision-making.

In conclusion, the RBS approach is a valuable and powerful tool for estimating the potential benefits of management measures on benthic habitats. It provides valuable guidance for the development of effective fisheries management policies that aim at sustaining marine biodiversity and ecosystem health in these regions. Given its capacity to inform spatial planning and management strategies, this approach can serve as a valuable reference for the implementation of ecosystem-based fisheries management beyond the Mediterranean, thus ensuring its broader relevance to global fisheries sustainability efforts.

This study presents a novel approach to assess trawling impacts on benthic communities by integrating habitat-specific environmental conditions into the estimation of community sensitivity and RBS. The incorporation of the effects of key environmental covariates allows for a more ecologically meaningful interpretation of benthic community responses to fishing pressure.

Author contributions

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Casini (Data curation [equal], Writing – review & editing [equal]), Porzia Maiorano (Data curation [equal], Writing – review & editing [equal]), Gianfranco D'Onghia (Data curation [equal], Writing – review & editing [equal]), Igor Isajlovic (Data curation [equal], Writing – review & editing [equal]), Maria Teresa Spedicato (Conceptualization [equal], Project administration [equal], Supervision [equal], Writing – review & editing [equal]), Gert Van Hoey (Methodology [equal], Supervision [equal], Writing – review & editing [equal]), and Anna Rindorf (Funding acquisition [equal], Project administration [equal], Writing – review & editing [equal])

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflict of interest: The authors have no conflicts of interest to declare.

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Data availability

The MEDITS data underlying this article are available in the Joint Research Centre Data Catalogue, at https://doi.org/10.2905/f25092c4-3f0f-449f-ba60-5fbfe385defc

The fishing effort data underlying this article are available in Global Fishing Watch, at https://globalfishingwatch.org/

The environmental drivers data underlying this article are available in Copernicus Marine Service, at https://data.marine.copernicus.eu/products

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