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Original Article

Application of a quantitative framework to estimate trawling impacts on benthic community in Central Mediterranean Sea

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Abstract

The Marine Strategy Framework Directive aims to protect EU marine waters by achieving good environmental status. Descriptor 6 focuses on seafloor integrity, which is threatened by activities like bottom trawling, which disturbs the seafloor, alters marine diversity, and impacts habitat functions. In this study, we assessed the impact of bottom trawling on the benthic community of the Sicilian continental shelf using three model-derived indicators based on community longevity composition: L1, proportion of the community with life spans exceeding the interval between trawling; L2, the decrease in median longevity; PD, population dynamics, decrease in biomass relative to carrying capacity. Biomass~longevity distributions were estimated using epifauna data from trawl survey in conjunction with fishing intensity and environmental variables to compute L1, L2, and PD across the study area. High-intensity trawling occurs in about 75% of the area, with the most intense activity occurring over sandy substrates and near the shelf edge. Median longevity ranged from 8 to 9 years and was generally higher at greater depths. The L1 indicator (0.67 ± 0.43) shows that in 63% of the continental shelf at least 80% of the community has a longevity greater than the interval between trawling events, and helps pinpoint minimally impacted zones that could serve as community baselines. The L2 indicator (lower average impact of 0.01 ± 0.18) suggests minimal reductions in median longevity. The PD indicator (0.16 ± 0.17) shows higher impact zones aligned with the distribution of trawling, particularly along the shelf edge and in muddy sediments. Both PD and L2 reveal significant negative impacts along the shelf edge, especially in nursery zones of European hake and deep-water rose shrimp. PD highlights zones where long-lived species are most affected, such as the eastern Adventure Bank and northwestern Malta Bank. The generated maps can represent a baseline to inform policymakers in identifying sensitive areas and then address more effective spatial planning management and control measures enforcement at a regional scale.

Keywords: bottom trawling; trawling impact; benthic status; seafloor integrity; regional assessment; Mediterranean Sea

Introduction

The regulation of human activities in marine systems has become increasingly important considering recent sustainability policies (Fetting 2020, Hermoso et al. 2022). The Marine Strategy Framework Directive (MSFD) adopted by European countries (Directive 2008) aims to achieve a good environmental status (GES) for the EU's marine waters and ensure the sustainable protection of marine ecosystems. The MSFD outlines specific goals called 'Descriptors', which address essential aspects of marine environments. Descriptor 6 focuses on seafloor integrity, a critical resource facing numerous threats, with 79% of the EU's coastal seabed physically disturbed (European Commission 2020).

Bottom trawling is a major human activity contributing to seafloor disturbance, particularly in European waters like the Northeast Atlantic and Mediterranean Sea, where 50%–90% of soft sediments are trawled annually (Eigaard et al. 2017, Amoroso et al. 2018). Trawling removes sensitive species and alters marine bottom community diversity (Hiddink et al. 2006, Tillin et al. 2006, Howarth et al. 2018). Physical abrasion from trawling causes sediment resuspension and changes in biogeochemical properties (O'Neill and Ivanovic 2016, Oberle et al. 2016, Bradshaw et al. 2021), affecting habitat structure and community function (de Juan et al. 2007, Olsgard et al. 2008, Muntadas et al. 2016). The impact varies based on habitat characteristics, fishing gear, and species resilience (Hiddink et al. 2017, Sciberras et al. 2018). Species with rapid recovery and specific behaviours, such as burrowers and scavengers, are more likely to survive or recover relatively quickly after trawling disturbance (Demestre et al. 2000b, de Juan et al. 2007, Mangano et al. 2014). This pressure can lead to a deterioration of seafloor integrity (Jac et al. 2020). Monitoring is crucial to determine if Descriptor 6 is achieving the threshold for GES. This involves assessing adverse effects on

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habitat type, including biotic and abiotic structure and functions. Developing indices and indicators to assess changes in benthic community state across European shelf habitats is key to implementing the MSFD's goals effectively. Trait-based approaches can help to understand the impact of human pressures like bottom trawling (de Juan and Demestre 2012, Van Denderen et al. 2015, Howarth et al. 2018, Rijnsdorp et al. 2018, Hinz et al. 2021). These methods can be qualitative, assigning scores to community structure and function features, or quantitative, establishing relationships between traits and the resulting impact (Pacifici et al. 2015). While qualitative methods may be easier to developed, quantitative methods offer objectivity and rigorous statistical assessment of response-predictor relationships.

Longevity, the maximum lifespan of a species, can be used as a proxy for sensitivity to community change due to trawling (Rijnsdorp et al. 2018, Hiddink et al. 2019). Species with longer lifespans are less likely to withstand and slower to recover from trawling impacts due to lower metabolic rates, delayed maturity, reduced reproductive output, and lower natural mortality (Duplisea et al. 2002, Hiddink et al. 2019). Consequently, biological-trait methodologies based on longevity have been used in quantitative indices to assess the trawling impact on the seafloor at regional scales (Rijnsdorp et al. 2020). A methodological framework has been developed to assess the relative benthic state in relation to trawling impact at spatial scales (Pitcher et al. 2017, Hiddink et al. 2019, Rijnsdorp et al. 2020). This framework requires the use of indicators that measure of benthic community biomass, longevity composition, and recovery potential—quantified in relation to bottom trawling intensity and frequency. These metrics have previously been used to evaluate seabed sensitivity and trawling footprint in multiple regional case studies, including the North Sea (Rijnsdorp et al. 2020), Atlantic European regions (ICES 2023), parts of the Mediterranean (ICES 2023, Smith et al. 2023), and globally (Pitcher et al. 2022).

Validating these methodologies is essential to assess their generalization capacity, adaptability, consistency, and sensitivity to trawling pressure across different habitats and ecological contexts. Subregional case studies, such as those reported by ICES (2023) and Smith et al. (2023), are critical for testing the robustness and ecological relevance of these approaches. They help determine how well these indicators perform in capturing habitat-specific responses to varying fishing pressures and environmental conditions. Such regional applications serve as benchmarks for evaluating the utility and transferability of these methods. They offer valuable insights into benthic community responses and aid in refining model parametrizations. This is particularly important for improving our understanding of ecosystem functioning under anthropogenic pressure and for supporting sustainable fisheries management strategies. The primary objective of our study was to apply this methodological framework at a subregional scale to evaluate the status of the epibenthic community on the Sicilian continental shelf in response to bottom trawling activities. Bottom trawling, widespread in this region, is regulated through various management plans, notably Recommendation GFCM/45/2022/4, which establishes a multiannual management plan for sustainable demersal stock exploitation in the Strait of Sicily. Additionally, Fishery Restricted Areas (FRAs) protect nursery areas and essential habitats for European hake and deep-water rose shrimp stocks. Despite these regulations, high levels of bottom trawling continue, threatening seabed integrity. This is concerning given the sustained high trawling intensities over decades, which have shaped the composition of demersal and benthic assemblages (Gristina et al. 2006, Dimech et al. 2012, Mangano et al. 2013, Lauria et al. 2020, Good et al. 2022).

We estimated three indicators (L1, proportion of the community with life spans exceeding trawling intervals; L2, median longevity decreases; PD, population dynamics, relative biomass decrease to carrying capacity), each based on the estimation of the longevity-biomass distribution of the benthic community. Our investigation focused on describing the longevity composition of the benthic community inhabiting the Sicilian continental shelf, using accidentally caught non-target epifaunal samples collected during trawl surveys. We aimed to assess various factors that might influence the impact assessment approach, as, for example, different spatial resolutions or the time period over which the community could respond to the historical fishing pattern in the area. These analyses result in the production maps of the relative status of benthic community, which provide a salient and credible tool to evaluate the impact on seafloor integrity for the MSFD D6 assessment and support a more effective dialogue around the existing science-stakeholders-policy interface, helping in informing sustainable spatial management plans and to better address control measures enforcement at regional scale.

Methods

The approach used in this study requires the quantification of the epibenthic community's sensitivity to trawling. This is achieved by utilizing longevity as a proxy for sensitivity and constructing a model to depict the biomass distribution of longevity within the study area based on non-target accidentally caught epifaunal trawl samples. Model outputs were applied to grid cells of 1 × 1 km of the study area. Subsequently, these distribution models are integrated with the spatial distribution of trawling intensity to accurately quantify the impact exerted on the community.

Study area and benthic samples

This study applies the benthic impact assessment framework by Rijnsdorp et al. (2020) to the continental shelf around Sicily in the Central Mediterranean Sea. The continental shelf is characterized by detrital mixed sediments, local volcanic rocky structures, terrigenous nutrient inputs, and seasonal upwelling contribute to high biological productivity, attracting fishing activities (Consoli et al. 2016). This productivity has fostered the growth of the Sicilian fishery sector, especially in the Strait of Sicily. The Sicilian fleet, Italy's largest (Popescu 2010), primarily employs set longlines, purse seines, and bottom otter trawls, the latter targeting soft bottoms for species like European hake, red mullet, and deep-water rose shrimp (FAO 2023). The investigated sub-region (Longitude: 11°36′E–15°36′E, Latitude: 36°24′N–38°24′N) includes three Geographical Subareas (GSA): GSA10,

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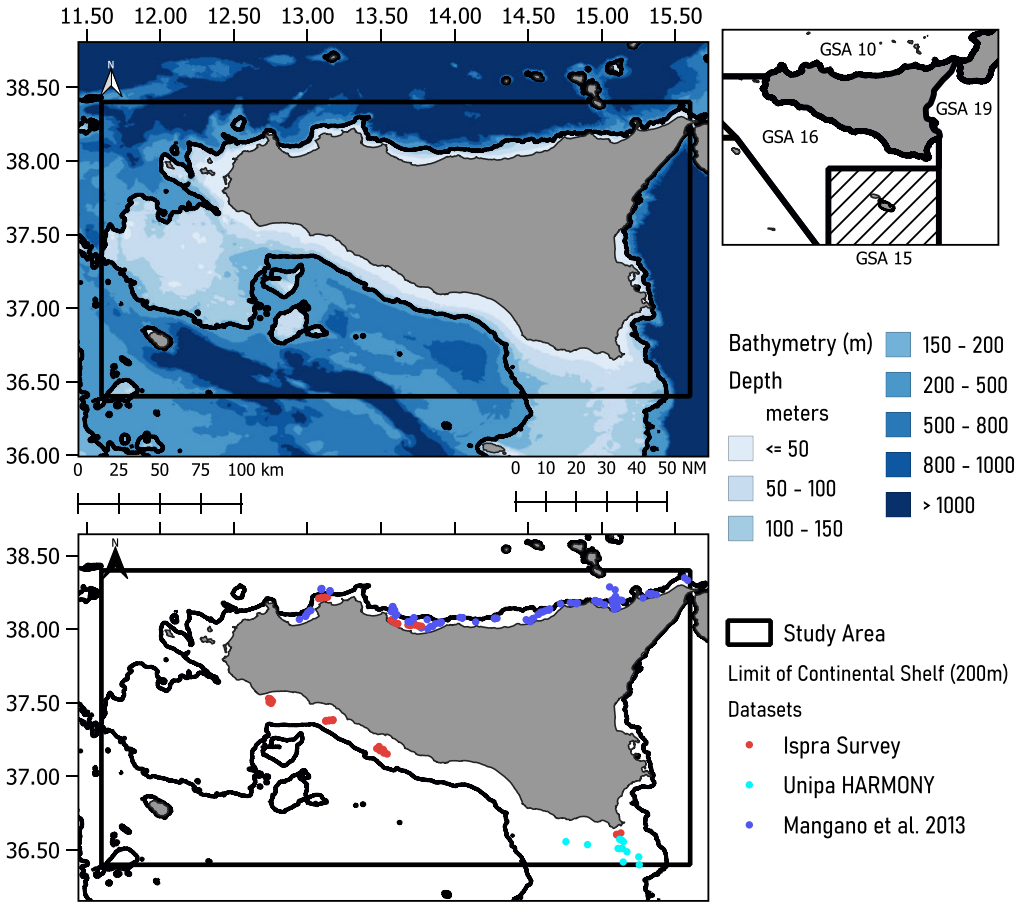


Figure 1. Selected study area and location of the trawl sampling points for each different dataset: Trawl survey campaign from Mangano et al. 2013 (blue points), ISPRA Italian National Monitoring Program campaign (red points), and Interreg Italy Malta HARMONY Project campaign (light blue points).

GSA16, and GSA19, as designated by the General Fisheries Commission for the Mediterranean (GFCM). GSA15 was excluded due to the lack of VMS fishing data (Fig. 1).

To estimate the longevity composition of the benthic community and assess its relative state, trawl samples of benthic epifauna were used. Samples were collected during three fishing campaigns performed along the Sicilian coasts between 2010 and 2020 (Fig. 1): 2010–2013 (Mangano et al. 2013), 2016–2020 (ISPRA, Italian National Monitoring Program), and 2019–2020 (Interreg Italia Malta 'HARMONY' Project). The surveys have been performed by deploying trawlers with similar characteristics of otter door spread and mesh net reflecting the standardized and routinely applied MEDITS protocol (Carpentieri et al. 2020) with a 20 mm cod-end mesh size and the MSFD Italian National Monitoring Protocol for the assessment of D6 (SNPA 2024) with a 25 mm mesh size deployed. The net was towed for 30 min over seabed shallower than 200 m and for 60 min over deeper seabed at a speed of ~3 knots. In the HARMONY survey trawl duration was not fixed, therefore all the biomass data of all three surveys were standardized by swept area and expressed in g/km^2 assuming an average net width of 40 m and trawl distance calculated from the trawl duration in hours multiplied by an average vessel speed of 3 knots (5.56 km/h) in accordance with the average characteristics used in the MEDITS survey. Of the 173 samples collected on mud and sand sediments between 15 and 711 m deep, 82% were from the continental shelf, not exceeding 200 m. Despite covering different time periods, the sampling activities for the three datasets were all conducted with the aim of monitoring the status of the epibenthic community affected by trawling activities on continental shelf habitats. Similar sampling protocols were employed across the studies, and the habitats sampled on the Sicilian continental shelf were relatively homogeneous, ensuring comparable environmental conditions.

For Mangano et al. (2013) and 'HARMONY' Project datasets, both total wet biomass and the number of individuals per species were available. For the ISPRA dataset, only individual counts were recorded and converted to biomass using average biomass per individual from the other two datasets. Biomass was chosen as the primary response variable due to its consistency in responding to fishing activity and its stronger association with community trophic dynamics, as it was initially validated in the published methodology (Pitcher et al. 2017).

Demersal fish species and highly mobile invertebrates like cephalopods and deep-water rose shrimp, were excluded due to their unsuitability for high-resolution grid basis impact assessment compared to low-mobility species (ICES 2022, see Table S1 for a list of all the selected species). These species, often targeted by fisheries, show biomass correlations with swept-area ratios that may not accurately represent broader benthic impacts.

All benthic species were assigned to four longevity classes (<1, 1–3, 3–10, >10 years) through a fuzzy-coding method, as outlined in Chevene et al. (1994). Longevity estimates were extracted at the finest taxonomic level feasible from lists provided

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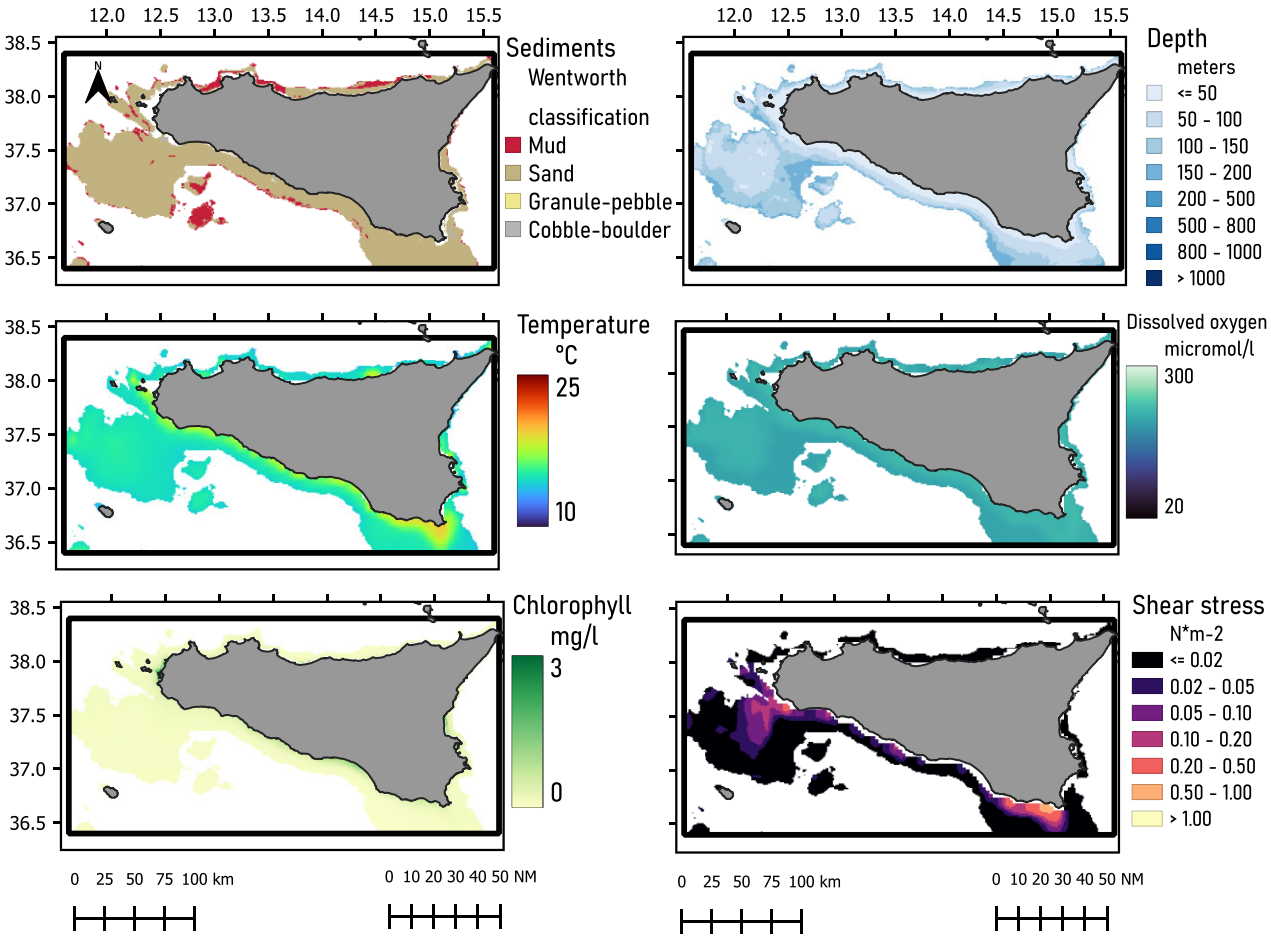


Figure 2. Spatial distribution of the six different environmental variables selected for estimating the longevity composition: sediment typology (Wentworth classification), depth (m), average annual bottom temperature (°C), average annual bottom dissolved oxygen concentration (μmol/l), annual bottom average chlorophyll concentration in the water column (mg/l), and seabed shear stress due to waves and currents (N/m^2).

by Beauchard and Troupin (2018), Clare et al. (2022). No species had missing longevity values. These fuzzy-coded biomasses were then aggregated by longevity classes and divided by the total biomass per trawl sample to determine the proportion of biomass in each longevity class.

Fishing intensity and environmental variables

We used fishing intensity and six environmental variables to develop a model to predict the composition of the benthic community's longevity around the study area. Fishing intensity was estimated using Vessel Monitoring System (VMS) data from bottom otter trawling vessels (with a length >15 m) available from 2007 to 2019 and expressed as the surface swept area ratio (SAR), which represents how many times a specific area is theoretically swept in one year (Eigaard et al. 2017). Satellite data were combined with logbook data to identify fishing tracks. Through the vessel identification number, relationship between gear dimensions and vessel size was used to assign the swept width of the gear to each logbook trip (Eigaard et al. 2016). The swept surface of each track was then calculated and aggregated within 1 km^2 cells to obtain the fishing intensity indicator. No VMS signals were reported for depths shallower than 50 m and areas within 3 nautical miles of the coastline, in compliance with the 2007 ban in the Mediterranean Sea (EU Council Regulation—EC No 1967/2006, 21 December 2006).

Environmental variables describing habitat characteristics and potential sources of natural variation in the benthic community (sediment typology, depth, temperature, dissolved oxygen, primary production, expressed as mean chlorophyll concentration, and shear stress), were selected and investigated in the models. The sediment Wentworth classification was obtained from the EUNIS habitat classification from Vasquez et al. (2021) assigning the substrate characteristics to the respective four increasing grain size categories (mud, sand, granule-pebbles, cobbles-boulders); depth was gathered from the digital terrain model (Thierry et al. 2019). Average temperature, primary production, and dissolved oxygen at the sea bottom were, respectively, extracted from Simoncelli et al. (2014), European Union-Copernicus Marine Service (2022), and Teruzzi et al. (2021). Shear stress due to waves and currents was extracted from Rivier (2010). The spatial distribution of environmental variables is reported in Fig. 2 (see also Fig. S1), while the spatial and temporal variation of SAR is shown in Fig. 3.

To obtain a single value for the environmental variables per trawl sample, the midpoint of the trawl coordinates was used to assign a predictor value to each sample. We used fishing intensity values from an average of the 3 and 5 years before the

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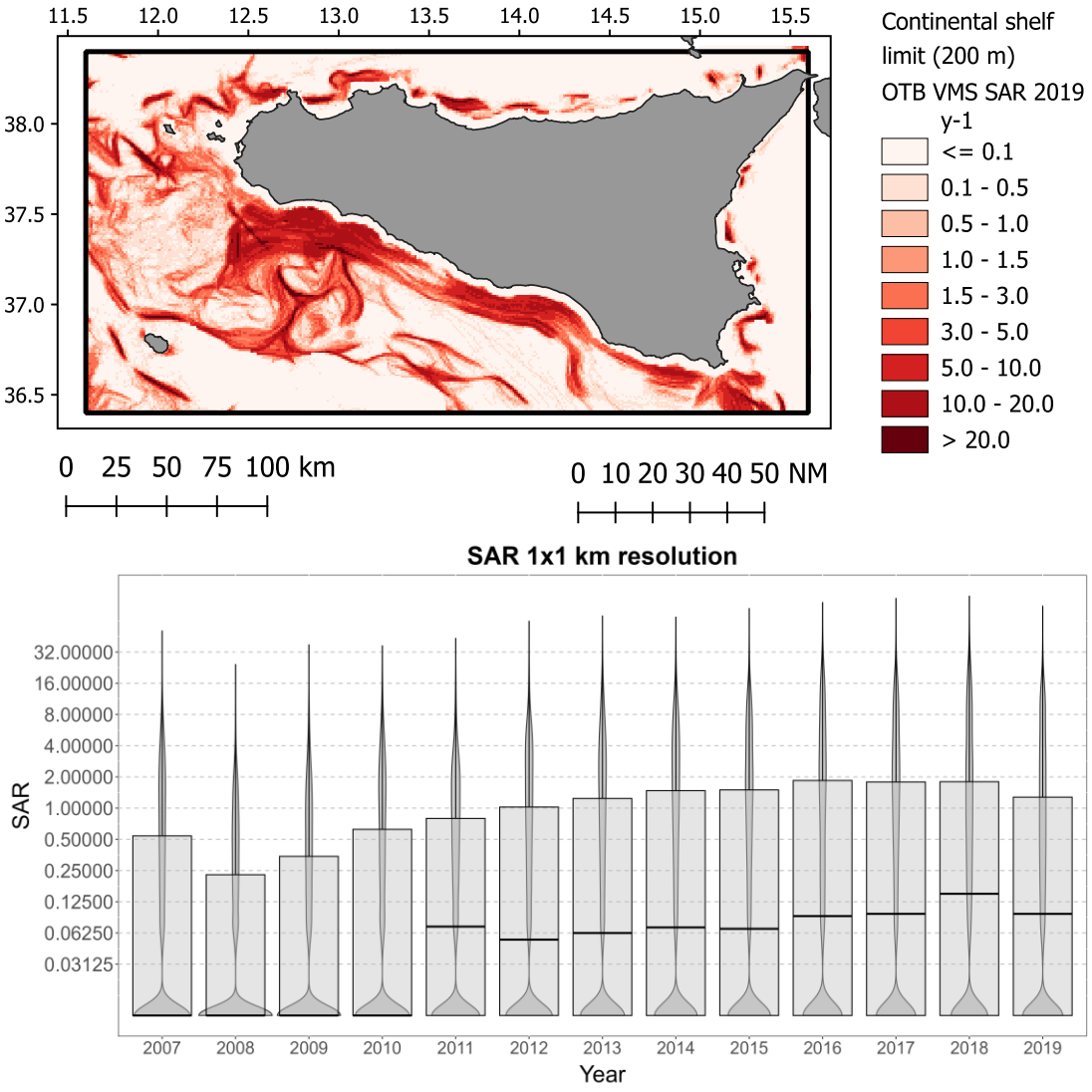


Figure 3. Spatial distribution of otter bottom trawling swept surface ratio (SAR) around the study area obtained from the analysis of VMS data. Below are the temporal distributions of the SAR values for each year starting from 2007 until 2019. SAR values were log-transformed, adding a small value of 0.01 to reduce the positive skewness and better visualize the distribution. The peaks at the bottom of the distribution correspond to values of SAR equal to zero.

sampling year when possible. We considered these two time periods because they can reflect the potential time for the response and/or recovery of the community (Hiddink et al. 2017). Furthermore, we wanted to investigate if different spatial resolutions of fishing intensity would affect the estimation of the longevity composition of the community. To do it, we considered using the original 1 × 1 km resolution of SAR and a downscaled version of 3 × 3 km resolution.

Longevity composition and impact assessment

Fishing impact assessments were conducted using three indicators that were based on modelling the longevity composition of the benthic community, as described in Rijnsdorp et al. (2020). To begin, we converted the biomass proportion for each longevity class into a continuous scale by fitting a sigmoidal (logistic) function to the cumulative biomass of the longevity classes, following the method of Rijnsdorp et al. (2018). This was done by applying a binomial generalized linear mixed model to the cumulative biomass proportions adding the upper bound of longevity classes as an explanatory variable. We used the selected environmental variables as predictors, along with fishing intensity. To account for potential spatial dependencies and variability among hauls within the samples, we included Trawl ID as a random effect in the model. Each trawl represents a unique sampling event from which cumulative biomass values were calculated for each longevity class. This structure allowed us to model the repeated measures of biomass across longevity classes within individual hauls, treating Trawl ID as a grouping factor to account for between-haul variability.

For the assessment, it was necessary to establish the longevity biomass relationship under untrawled conditions, so generally a cut-off criterion of SAR $<0.1\ y^{-1}$ is selected to detect reference samples representative of low exposure to fishing intensity (Bolam et al. 2017). The SAR $< 0.1\ y^{-1}$ threshold from Bolam et al. (2017), though based on infauna, is often applied to epifauna as a precautionary and likely conservative measure, given their greater exposure to bottom-contact fishing. In regions

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Table 1. Number of samples and summary of fishing intensity values (SAR mean ± standard deviation) assigned to the samples for all the sixteen different conditions investigated to model the longevity composition of the benthic community.

Condition	Sample size	*N* mud	*N* sand	*N* Granule-pebble	*N* Not assigned	SAR
Incl-1km-3yrs-NoD	173	76	94	0	3	2.65 ± 4.30
Incl-1km-5yrs-NoD	173	76	94	0	3	2.25 ± 3.52
Incl-3km-3yrs-NoD	173	76	94	0	3	2.41 ± 3.82
Incl-3km-5yrs-NoD	173	76	94	0	3	2.06 ± 3.10
Incl-1km-3yrs-D	143	49	91	0	3	2.55 ± 4.45
Incl-1km-5yrs-D	143	49	91	0	3	2.17 ± 3.67
Incl-3km-3yrs-D	143	49	91	0	3	2.41 ± 4.06
Incl-3km-5yrs-D	143	49	91	0	3	2.05 ± 3.29
Excl-1km-3yrs-NoD	87	45	39	0	3	0.06 ± 0.11
Excl-1km-5yrs-NoD	92	45	44	0	3	0.08 ± 0.13
Excl-3km-3yrs-NoD	86	47	36	0	3	0.08 ± 0.12
Excl-3km-5yrs-NoD	88	49	36	0	3	0.08 ± 0.11
Excl-1km-3yrs-D	80	38	39	0	3	0.05 ± 0.10
Excl-1km-5yrs-D	85	38	44	0	3	0.07 ± 0.14
Excl-3km-3yrs-D	79	40	36	0	3	0.08 ± 0.12
Excl-3km-5yrs-D	81	42	36	0	3	0.08 ± 0.12

Incl/Excl = inclusion of SAR in the model or exclusion of samples with SAR ⇒ 0.5 y^{-1}; 1 km/3 km = 1 × 1 km or 3 × 3 km resolution of the SAR layers; 3 yrs/5 yrs = 3 years or 5 years time-period average for assigning fishing intensity to the samples; D/noD = exclusion of samples outside the continental shelf (>200 m) or inclusion of all the samples despite their depth. Unit of measure: Depth (m), Temperature (°C), Dissolved oxygen (μmol/l), Chlorophyll (mg/l), Shear stress (N/m^2), SAR(1/year).

where low fishing intensities are uncommon, a cut-off criterium of 0.5 y^{-1} may be used to enable statistical robustness in models (ICES 2022). It is also possible to extrapolate the predicted longevity composition at an untrawled state when using all samples regardless of the SAR, after adding fishing intensity to the model and predicting the biomass longevity distribution at SAR = 0 (ICES 2022). To not lose information from sampled trawls, we considered it relevant to explore the usage of this higher cut-off point or to directly add fishing intensity in the model equation. Additionally, considering the limited representation of samples beyond the continental shelf, we examined whether excluding samples from depths >200 m would improve the model's fit. In total, we explored sixteen different conditions to model the longevity composition of our benthic community, taking into account the various factors and decisions mentioned above, including spatial resolution and time averaging of fishing intensity layers and cut-off points based on fishing intensity and depth (Table 1).

When applying the SAR cut-off criterion (SAR < 0.5 y^{-1}), fishing intensity was excluded as a predictor, assuming that the sampled communities inherently reflected an untrawled state. Conversely, in models without the cut-off, SAR was included as a predictor in interaction with variables such as longevity, depth, and sediment type to detect its influence on longevity-biomass distribution. Therefore, the null model for the cut-off criterion included only longevity as a predictor, while the null model without the cut-off criterion included both longevity and SAR. This choice was driven by the need to estimate the biomass distribution of longevity classes in an untrawled state when using samples from various fishing intensities. Continuous predictors were natural log transformed to reduce the skewness of their distribution, especially fishing intensity, where a small value of 0.01 was also added to avoid taking the logarithm of zero.

We compared all possible variable formulations by employing the 'dredge' function in the MuMIn R package (Bartoń 2022). For each of the sixteen conditions, the function selected the most parsimonious set of environmental predictors to account in the model after the null model, based on the Bayesian Information Criterion (BIC). BIC was preferred over the Akaike Information Criterion due to its tendency to be more conservative in variable selection.

The sixteen selected models were subsequently used to assess which condition provided the most accurate estimation of community longevity composition. We compared each selected model to its corresponding null model to determine the percentage increase in explained deviation (decrease of deviance of the model) and its significance. The condition with the higher significantly explained deviation was chosen as the final model for inferring the longevity distribution. This approach was selected to allow comparisons of model outputs across different sample sizes, as selection criteria such as BIC or R^2 could be biased.

Application of Precautionary approach L1

To assess trawling impact, we applied three different indicators. The first method, known as the precautionary approach (L1), calculates the proportion of biomass of species of the community with longevity exceeding the reciprocal of trawling intensity in a specific area. It operates under the assumption that species are impacted if exposed to trawling during their lifespan; therefore, only populations of species with a longevity shorter than the average interval between two successive trawling events are likely to include individuals that remain unaffected. The estimation is derived by rearranging the logistic equation, with longevity set as 1/fishing intensity:

$$I_{L1} = \frac{\exp\left(\alpha + \beta_L * lnln\left(\frac{1}{S}\right) + \beta_H * H + \beta_S * lnln\left(S_0\right) + \beta_{LH} * lnln\left(\frac{1}{S}\right) * H + \beta_{HS} * lnln\left(S_0\right) * H + \beta_{LS} * lnln\left(\frac{1}{S}\right) * lnln\left(S_0\right)\right)}{1 + exp\left(\alpha + \beta_L * lnln\left(\frac{1}{S}\right) + \beta_H * H + \beta_S * lnln\left(S_0\right) + \beta_{LH} * lnln\left(\frac{1}{S}\right) * H + \beta_{HS} * lnln\left(S_0\right) * H + \beta_{LS} * lnln\left(\frac{1}{S}\right) * lnln\left(S_0\right)\right)},$$

where α is the intercept of the model and β corresponds to the slopes associated with different predictors, where L stands for longevity, S for fishing intensity, and H for the environmental predictors. We set S_0 to 0.01 to prevent taking the logarithm of zero. It's important to note that the presence of interaction terms in the model may vary depending on the final model selection.

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Application of statistical-impact approach L2

The second approach (L2) involves comparing the median longevity between the species of the community at a specific trawling intensity to the value obtained under untrawled conditions. This method operates under the assumption that median longevity reflects the community's sensitivity to trawling. Therefore, an increase in fishing intensity results in a shift within the community towards shorter-lived species, leading to a decrease in median longevity. The equation for this approach is expressed as follows:

$$I_{L2} = 1 - \frac{M_S}{M_0},$$

where M_S and M_0 are, respectively, the median longevity at fishing intensity S and the median longevity of the untrawled community. Those are obtained from re-arranging the logistic equation as:

$$M_S = \exp(-\frac{\alpha + \beta_H * H + \beta_S * lnln\ (S)\ + \beta_{HS} * lnln\ (S)\ * H}{\beta_L + \beta_{HL} * H + \beta_{LS} * ln\,(S)},$$
$$M_0 = \exp(-\frac{\alpha + \beta_H * H + \beta_S * lnln\ (S_0)\ + \beta_{HS} * lnln\ (S_0)\ * H}{\beta_L + \beta_{HL} * H + \beta_{LS} * ln\,(S_0)}.$$

Application of PD approach

Finally, we employed a third approach, the PD approach, as described in Pitcher et al. (2017), which estimates the reduction in the community's biomass to its relative carrying capacity after trawling pressure occurs:

$$I_{\mathrm{PD}} = \sum_{i=1}^{n} 1 - K_{Li} * \left(1 - S * \frac{d}{r}\right),$$

where K_{Li} is the biomass proportion of the longevity class i in the untrawled community, S is the fishing intensity, d is the depletion rate caused by the trawling gear, and r is the recovery rate. Sediment-specific depletion rates resulting from bottom otter trawlers were obtained from Pitcher et al. (2022), while the recovery rate was estimated with longevity using the equations derived from the meta-analysis and the 1° derivative of the logistic model in order to convert the logistic cumulative curve into a continuous Gaussian curve of biomass proportion along longevity values, described in detail in Hiddink et al. (2019). All three impact assessment methods were applied across the entire continental shelf surrounding Sicily using the parameters obtained from the model and the raster of the different predictors on a grid scale of 1 × 1 km. SAR values were extracted from the last year available in the VMS dataset (2019). To enhance the description of the impact assessment, a summary was provided for each sediment typology and GSA in the results of the main text.

Statistical analyses were conducted using the R package, Version R-4.2.0 (R Core Team 2023).

Results

The Sicilian continental shelf primarily comprises sandy sediments (82.42%) in shallower regions, while muddy (15.97%) seabeds are prevalent in areas near the shelf edge. Granule-pebble and cobble-boulder sediments constitute <1% of the area and are located only in proximity of the coast or in specific small areas near the shelf edge (Fig. 2). About 75% of the total area is fished, recording SAR values exceeding 0, with an average SAR of 2.36 ± 3.55 y^{-1}. The fraction with SAR > 0.5 constituted 49%, with values >5 y^{-1} predominantly spread across the shelf area of the Strait of Sicily and in proximity to the shelf edge throughout the region. SAR values equal to zero are predominant below 50 m depth due to the ban, while low SAR values are primarily observed on the western side of the Adventure Bank and Hibleyan plateau (Strait of Sicily; Fig. 3). The different sediment types exhibited similar trawling intensity values, although sandy sediments displayed a higher average (3.19 y^{-1}) compared to muddy (1.67 y^{-1}) sediments.

The sampled community appeared relatively homogeneous, with ∼30% of recorded species always present along the sampled fishing intensity gradient. These persistent species, commonly found in Mediterranean shelf areas, include scavenger starfish (*Astropecten* genera and *Ophiura ophiura*), decapods (*Aegaeon lacazei*, *Calappa granulata*, *Dardanus arrosor*, *Liocarcinus depurator*, *Polycheles typhlops*, *Medorippe lanata*), deposit feeders (sea urchins like *Diadema setosum* and *Echinus melo*, holothurians like *Parastichopus regalis* and *Paraleptopentacta elongata*). We also observed suspension feeders with lifespans exceeding 10 years, including sea pens (*Pennatula phosphorea*, *Pennatula rubra*, and *Pteroeides spinosum*), crinoids (*Antedon mediterranea* and *Leptometra phalangium*), ophiuroids (*Astrospartus mediterraneus*), and soft corals (*Alcyonium* genera). Some of these aforementioned species holds the majority of the community biomass among the samples, especially *Alcyonium palmatum*, *Parastichopus regalis*, and *Astropecten bispinosus*.

Model selection

Null models, only including longevity, were consistently significant, with the lowest BIC, high R^2 values, but with a lower proportion of deviance explained compared to selected models. Depth was the second most important predictor of longevity composition, along with fishing intensity. In only four conditions, the selected model had a lower BIC and significantly increased deviation explained compared to the model with only longevity (Table 2). Coarser resolution models (3 × 3 km) omitted the interaction between depth and fishing intensity and fit worse than finer resolution models. Averaging fishing intensity over 3 or 5 years did not significantly affect model estimates (Table 2 and Table S2).

The final model selected did not use an SAR cut-off criterion and assigned fishing intensity scores based on higher spatial resolution (1 × 1 km) and a three-year average, without limiting the data to those within the continental shelf (model number

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Table 2. Best models obtained through a stepwise selection procedure using the 'dredge' function for each condition. In bold, models that showed a deviance significantly different from their respective null model.

Model No.	Condition	*N* samples	(Intercept)	Depth	ll	SAR	Depth:SAR	df	BIC	R^2	Deviance	Deviation explained	*P*-value
1	**Incl-1km-3yrs-NoD**	**173**	**−6.5391**	**0.2194**	**2.5824*****	**−0.907****	**0.2037****	**6**	**144.959**	**0.778**	**105.76**	**7.71%**	**0.0121**
2	**Incl-1km-5yrs-NoD**	**173**	**−6.5762**	**0.2306**	**2.5802*****	**−0.9085****	**0.2043****	**6**	**145.3**	**0.777**	**106.06**	**7.50%**	**0.0135**
3	Incl-3km-3yrs-NoD	173	−4.2454	−0.1803	2.0678***	−0.0033		5	154.6	0.6761	121.98	0.76%	0.3352
4	Incl-3km-5yrs-NoD	173	−4.2234	−0.1842	2.0678***	−0.0007		5	154.6	0.6761	121.97	0.79%	0.3239
5	Incl-1km-3yrs-D	143	−6.3979	0.1675	2.6031***	−0.8967*	0.2003	6	118.6	0.7794	80.54	5.12%	0.1139
6	Incl-1km-5yrs-D	143	−6.4845	0.1896	2.6021***	−0.9127*	0.2044	6	118.7	0.7792	80.66	5.16%	0.1113
7	Incl-3km-3yrs-D	143	−3.3783	−0.4306	2.1365***	−0.0016		5	122.7	0.6905	90.99	1.84%	0.1913
8	Incl-3km-5yrs-D	143	−3.3541	−0.4352	2.1365***	0.0007		5	122.7	0.6905	90.98	1.89%	0.1858
9	Excl-1km-3yrs-NoD	87	−2.6148	−0.6059	2.5583***			4	80.9	0.7742	57.53	5.35%	0.0714
10	Excl-1km-5yrs-NoD	92	−2.9556	−0.5004	2.5177***			4	87	0.7682	63.40	3.81%	0.1128
11	Excl-3km-3yrs-NoD	88	−3.7751	−0.2988	2.0798***			4	84.6	0.6794	59.64	1.48%	0.3381
12	Excl-3km-5yrs-NoD	88	−3.7751	−0.2988	2.0798***			4	84.6	0.6794	59.64	1.48%	0.3381
13	**Excl-1km-3yrs-D**	**80**	**−0.9896**	**−0.9994***	**2.5515*****			**4**	**73.3**	**0.775**	**50.25**	**9.79%**	**0.0195**
14	**Excl-1km-5yrs-D**	**85**	**−1.9412**	**−0.7358**	**2.4941*****			**4**	**80.3**	**0.766**	**57.07**	**6.15%**	**0.0531**
15	Excl-3km-3yrs-D	80	−2.1173	−0.6972	2.0669***			4	75	0.6778	50.72	5.58%	0.0799
16	Excl-3km-5yrs-D	80	−2.1173	−0.6972	2.0669***			4	75	0.6778	50.72	5.57%	0.0799

Deviation explained is expressed as a percentage decrease in deviance relative to the null model, while the *P*-value represents the significance of the difference between the deviance explained by the null model and the one explained by the selected model. For conditions using the SAR cut-off criteria, the null model considered only longevity as a predictor. In contrast, for the conditions without the cut-off, the null model considered both longevity and fishing intensity. Asterisks indicate the significance of the predictor's slope coefficient inside the logistic function: ∗ for $P < .05$, ∗∗ for $P < .01$, and ∗∗∗ for $P < .001$.

1). Including the SAR in the model was preferred, as models with an SAR cut-off (models' number 13 and 14) halved the sample size. According to the selected model, at greater depths, the proportion of long-lived species increases. The significant interaction term between depth and SAR seemed to influence this relationship, as the results suggest a shift of the community towards shorter-lived species when SAR increases at depths typically exceeding 100 m. In contrast, at depths <100 m, an increase of fishing intensity implies an increase in the proportion of long-lived species, contrary to the common assumption that fishing shifts the community towards lower relative abundance of long-lived fauna (Fig. 4).

Impact assessment

The median longevity estimates of all models exhibit a high correlation with the observed median longevities (Table S2). While the distribution of these estimates within the continental shelf remains consistent across the models, there are slight variations, as illustrated in Figures S2, S3, S4, and S5. The community is predominantly characterized by species with medium to long lifespans, with a median longevity of ∼8 ± 2.1 S.D. years according to the final selected model (model number 1). Lower median longevities are observed near the coast, with a gradient that increases as it moves towards greater depths, as previously referred to (see Fig. 5).

Precautionary approach L1

Average value for L1 indicator in the study region was 0.67 ± 0.43 S.D. Overall, 63% of the continental shelf exhibited L1 values >0.8. This suggests that in more than half of the area, at least 80% of the community has a longevity that is longer than the interval between trawling events. This situation arises from a community primarily comprised of species with medium to high longevities and fishing intensities exceeding 0.5–1 y^{-1}, resulting in significant impacts on any species with a longevity surpassing 1–2 years (see Fig. 6). This pattern is particularly pronounced in GSA16, where median L1 values are consistently close to 1 for mud and sand sediments, as depicted in Fig. 7 (see also Table S5).

Statistical-impact approach L2

L2 indicator values generally indicate a low impact (average 0.01 ± 0.18 S.D), with only 10% of the total area demonstrating a reduction in median longevity of more than 20%. This is particularly noticeable in the Graham Bank, situated in GSA16 in the central part of the Sicily channel, and in the offshore bottoms south of Capo Passero (Hyblean plateau), as depicted in Fig. 6.

Due to the presence of the interaction term between fishing intensity and depth, the median longevity of the untrawled community was found to be lower within the depth range of 50 to 100 m, resulting in negative L2 values (∼28% of the total area), indicating higher median longevity in comparison to the untrawled state. Higher values are concentrated in muddy sediments of GSA19 and GSA16 (see Fig. 7, Table S5).

PD approach

The average impact estimated for the PD indicator is 0.16 ± 0.17, and, overall, 66% of the shelf has a PD impact of <0.2 but displays a positively skewed distribution (Fig. 6) mirroring the trawling distribution. These values suggest that the continental shelf is in relatively good condition, particularly along the coasts of the north side, except for areas within GSA16 near the mentioned fishing grounds (Fig. 6). High impacts are observed at the very edge of the shelf and the beginning of the continental slope in GSA10, likely due to the increase of proportion of long-lived species in accordance to the steeper increase of depth that

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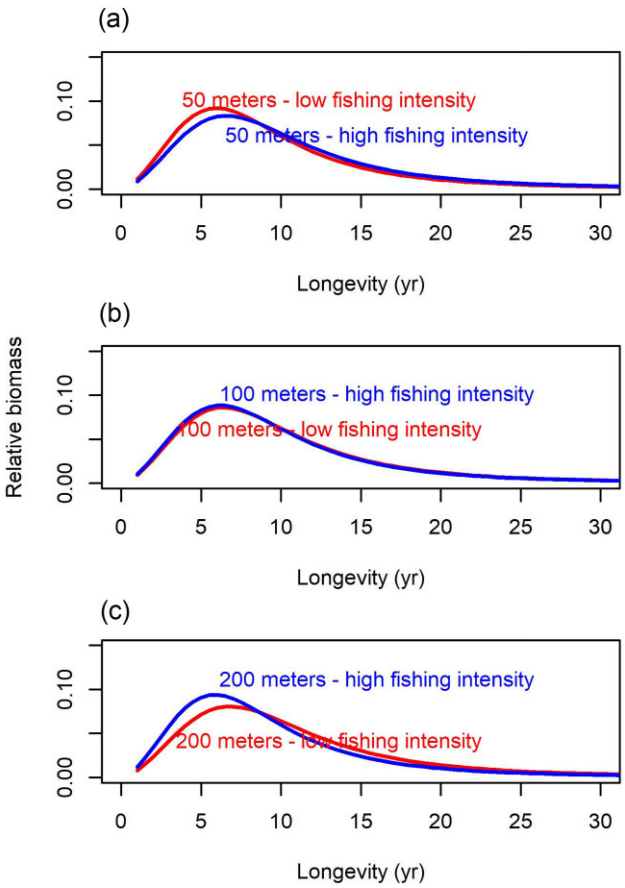


Figure 4. Longevity relative biomass curve distributions obtained from the final selected model (no cut-off SAR criteria, 1 × 1 km SAR resolution, 3 years average with no depth limit) at different depths (A = 50 m, B = 100 m, and C = 200 m) and fishing intensities [low SAR (low fishing intensity) = 0.1 and high SAR (high fishing intensity) = 1].

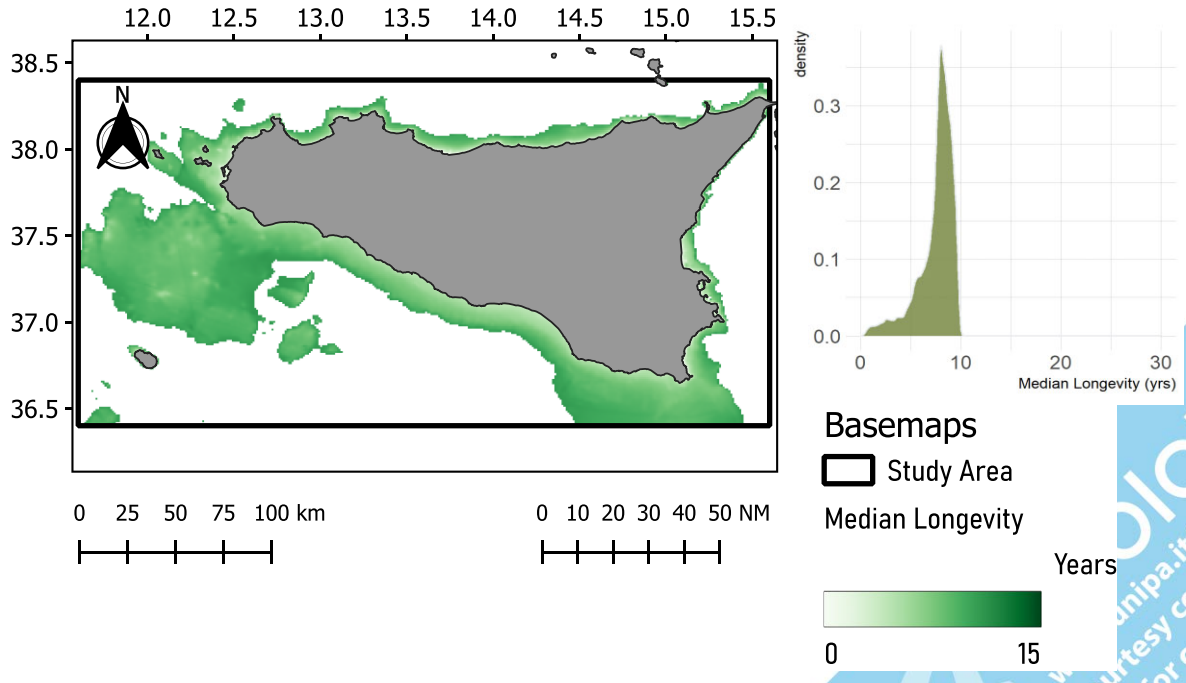


Figure 5. Median longevity distribution across the area based on the selected final model (no cut-off SAR criteria, 1 × 1 km SAR resolution, 3 years average with no depth limit). On the right, a density plot illustrates the distribution of scores across the map.

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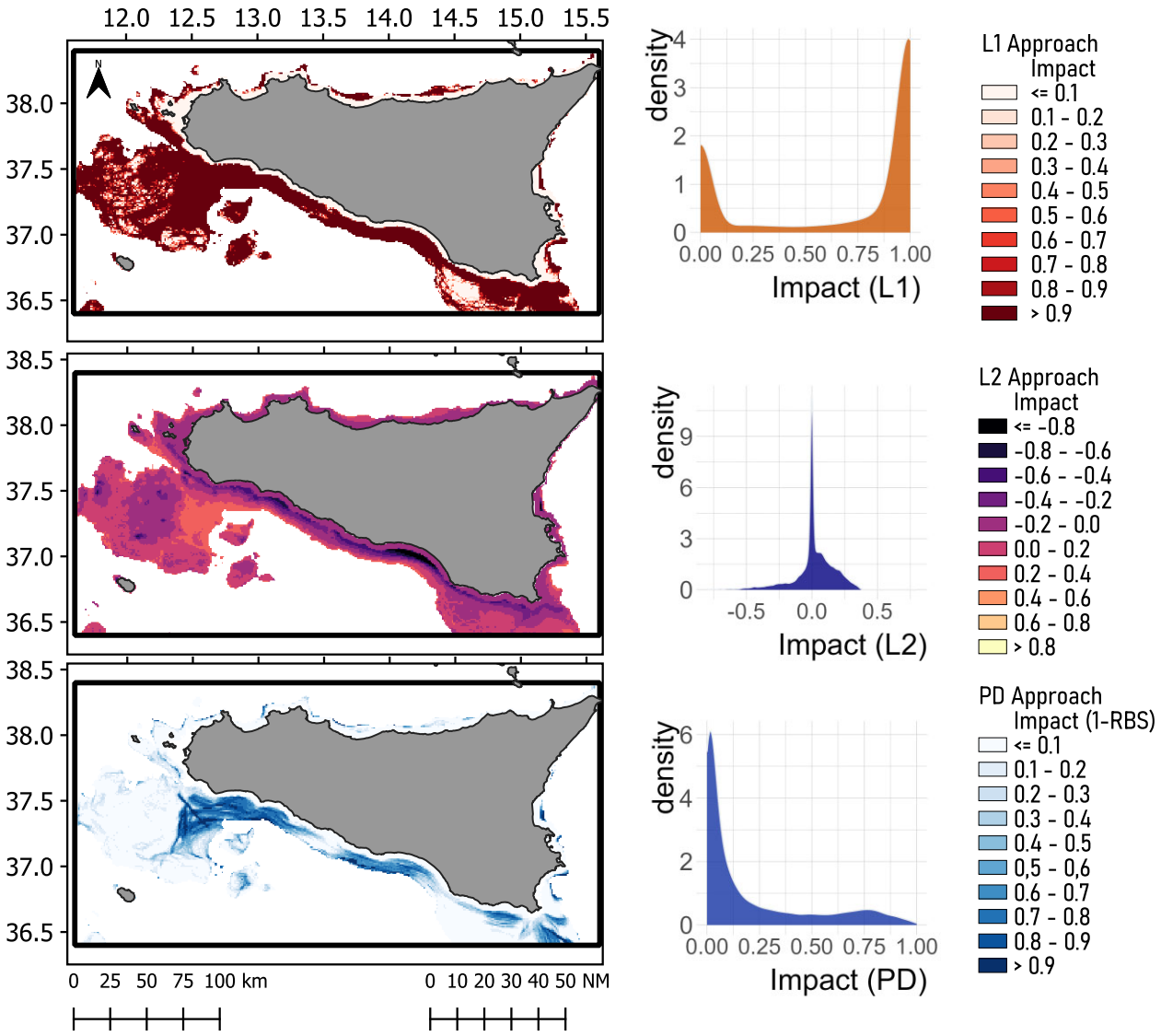


Figure 6. L1 (up), L2 (middle), and PD (bottom) impact assessments across the area based on the selected final model (no cut-off SAR criteria, 1 × 1 km SAR resolution, 3 years average with no depth limit). On the right, density plots illustrate the distribution of scores across the map.

adds up to the presence of higher fishing intensities. GSA16 appears to have a relatively higher impact compared to the other two subareas, with muddy sediments being more adversely affected than sandy ones, owing to the different depletion exerted by bottom trawl gear (see Fig. 7, Fig. S6, Table S5).

Discussion

The outcomes from the three selected impact indicators—L1, L2, and PD—allowed us to assess the spatial distribution and magnitude of trawling impacts on the benthic community along the Sicilian continental shelf. The investigated seabed was primarily sandy, with muddy sediments concentrated near the shelf edge and granule-pebble or cobble-boulder substrates limited to small coastal zones. High trawling intensity spans about 75% of the area, with the most intense activity occurring over sandy substrates and near the shelf edge. The L1 indicator detected that 63% of the shelf has at least 80% of its community with a longevity greater than the trawling interval, implying significant impact for species with lifespans exceeding one year. Integrating this information, the L2 indicator suggests minimal reductions in median longevity overall, with higher impacts localized at the Graham Bank and the offshore bottoms of the Hyblean plateau. Lastly, the PD indicator highlighted a generally low impact across the shelf but identifies high-impact areas that closely align with trawling activity, particularly along the shelf edge and over muddy sediments. Among the three selected indicators, the PD exhibits the broadest sensitivity to varying trawling intensities, effectively highlighting zones with long-lived species near the shelf edge, in muddy areas, and in high-intensity fishing grounds. Overall, it suggests a relatively healthy condition across much of the continental shelf, though specific high-impact zones require further management attention.

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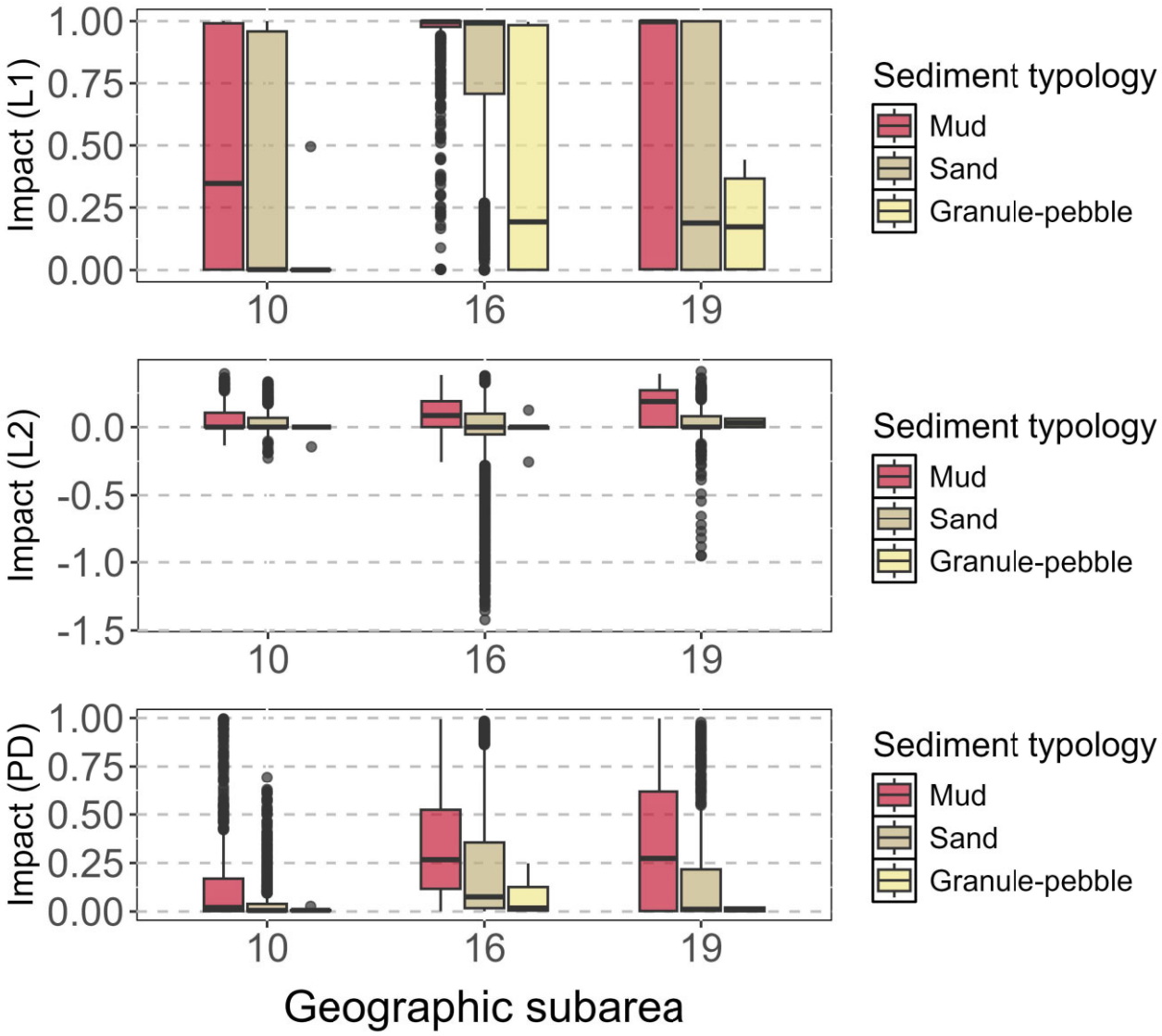


Figure 7. Summary boxplots of the three different impact assessment approaches for each GFCM Geographic Subarea and sediment typology inside the continental shelf of the study area.

Effect of depth and fishing intensity on longevity

Our models suggest that in upper-outer shelf areas (more than 100 m depth) increased fishing intensity shifts the community towards species with shorter lifespans, consistently with the existing scientific literature and supporting the promotion of longevity as an indicator of trawl sensitivity. Areas with high and constant fishing intensity from our selected case study have clearly progressively selected species with shorter lifespans that can grow and reproduce between trawl passages or quickly recolonize trawled areas. Instead, on shallower shelves (<100 m depth) an increase in fishing intensity appears to slightly increase the average lifespan of the community. This unexpected response may be explained by the local occurrence of medium to high longevity species that, supporting high biomasses in the samples, influence the model predictions. Specifically, soft corals, such as *A. palmatum*, despite having a medium-long lifespan, could be more resilient than sessile hard corals due to their higher reproduction capacity, linked to planktonic larvae stages that disperse over long distances and a relatively faster settlement period (Kaiser et al. 2018). Additionally, behaviour such as that of the commonly patchy-found pennatulaceans, which can retract beneath the sediment in response to physical pressure from towing activities (Chimienti et al. 2018), jointly to the presence of other epifaunal suspension feeders, can support the explanation of a trawling shifted community towards longer-lived taxa (Rijnsdorp et al. 2018). Interestingly, and more in detail, in the collected samples, *A. palmatum* relative biomasses showed a negative trend to an increase of fishing intensity in deeper, muddy environments, a not observable trend in shallower, sandy environments. Environmental conditions around Sicily, including upwelling, terrigenous nutrient input, and favorable local seabed features (e.g. canyons and steady shelves' slopes) can create suitable habitats that facilitate the settlement and growth of new individuals, showing a new community's pattern generated by trawling (Pinazo et al. 1996, Beranger et al. 2004, Dominguez-Carrio et al. 2022). All this suggests that these species, although highly vulnerable, may be found in trawled areas, chronic trawling has reduced their

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biomasses, but their distribution is likely shaped by environmental constraints or the turnover of species distribution along the depth gradient (Ambroso et al. 2013, Pierdomenico et al. 2018). As a result, intermediate depths in our study showed an increase in the median longevity of the community, further supported by the presence of scavenger or deposit feeder species belonging to intermediate-long lifespan categories (3–10 years) like starfish of genera *Astropecten* and holoturians, commonly found in the collected samples all over the fishing intensity gradient. These species' opportunistic behaviour and trophic plasticity allow them to feed on both live and dead organic matter, enabling rapid growth rates to compensate for the removal effects caused by trawling (Tillin et al. 2006, Hinz et al. 2009, Mangano et al. 2013).

Sediment composition may also influence species' responses to trawling; sandy sediments, prevalent in shallower parts of the study area, create greater resistance to fishing gear penetration compared to muddy sediments, reducing biomass extraction in a single pass (Pitcher et al. 2022). Our findings suggest that muddy sediments are more impacted than sandy ones (Bolam et al. 2014, Handley et al. 2014, Rijnsdorp et al. 2018, Rijnsdorp et al. 2020). A lower depletion rate in shallower areas could thus improve the survival chances of populations, including those of more vulnerable species. Therefore, under favourable environmental conditions, these species may be able to maintain stable biomass levels along the fishing gradient. These local conditions subsequently altered the influence of depth and fishing intensity in determining the longevity distribution in our models. Variations in community responses to depth and fishing disturbance are nonetheless consistent with findings from other Mediterranean regions (Labropoulou and Papaconstantinou 2000, Demestre et al. 2000a, Dimech et al. 2008, Dominguez-Carrìo et al. 2022, Jac et al. 2022). Depth affects species distribution through gradients in temperature, primary production, nutrient concentration, sediment characteristics, and current patterns, potentially making it a primary driver of community distribution. Even though other environmental predictors were not selected in the final model, increasing depth is associated with decreasing levels of dissolved oxygen, chlorophyll concentration, and temperature—factors that shape the ecological niches of species within the community. Lower temperature, reduced chlorophyll, and low oxygen can favour the selection of long-lived benthic species by creating conditions of slower metabolic rates, limited food availability, and physiological stress. This is consistent with the observed general trend of increasing median longevity with depth. Such environments often support stable, low-turnover communities dominated by slow-growing, resilient taxa (Reznick et al. 2000, Levin et al. 2001, Healy et al. 2014, McClain et al. 2015).

Management implications and conclusions

Mapping regional trawling impacts and benthic status represents a valuable tool for informing policymakers in identifying sensitive or high-risk areas, thereby facilitating effective spatial management. The use of multiple indicators can help identify the most sensitive components of the ecosystem to specific types of disturbances, as well as those most effective at describing the overall state of the benthic community.

The L1 indicator, which is expected to be sensitive primarily at low fishing intensities (Rijnsdorp et al. 2020), proved less effective in the selected study areas due to the widespread, high-intensity, chronic trawling pressure. Although the assumptions underpinning this indicator are restrictive, L1 still offers meaningful insights into how trawling pressure aligns with species' life-history traits. Notably, it allowed for the identification of areas where trawling occurs at frequencies that do not significantly impact the benthic community. In our case study, such areas were very limited, occurring primarily below 50 m—where trawling is prohibited—and on the western side of the Malta Bank. These zones could serve as reference points for characterizing the community's near-pristine state.

PD and L2 indicators revealed significant negative impacts, particularly near shelf-edge areas such as the eastern Adventure Bank and northwestern Malta Bank—crucial nursery grounds for various commercial species (Farrugio and Soldo 2014). However, the L2 metric was less effective at shallower depths, where fishing intensity drives the longevity distribution of the community towards higher values. In ∼28% of the study area, L2 values were negative, suggesting a higher median longevity than in untrawled reference states. This can complicate interpretation and obscure clear distinctions between impacted and unimpacted areas. Furthermore, only 10% of the area exhibited a significant reduction in median longevity (>20%), indicating that L2 may be less sensitive to structural community impacts unless fishing pressure is concentrated in deeper regions.

The PD indicator, on the other hand, offers several advantages in assessing trawling impacts. As highlighted by Rijnsdorp et al. (2020), PD is sensitive to a broader range of trawling intensities (up to 10–30 y^{-1}) and is thus well suited for regions with high fishing pressure. By incorporating globally derived depletion and recovery parameters (Hiddink et al. 2017, Sciberras et al. 2018), PD provides a standardized and robust approach to estimating impacts. It includes total biomass and the relative abundance of longevity classes, capturing both community structure and biodiversity. Spatially, PD reflects trawling distribution patterns across the shelf with greater accuracy and is less influenced by model assumptions regarding community longevity distributions. However, its broad coverage may overlook fine-scale impacts, particularly in areas where detailed sediment information would provide more precise insights than general habitat maps. Despite this limitation, the PD indicator effectively identifies high-impact zones, especially along the shelf edge in GSA16 and within the muddy sediments of GSA10. These areas host long-lived species that are especially vulnerable to intensive trawling. Notably, even though these are not designated as primary trawling grounds, SAR values exceeding 10 y^{-1} have been recorded, leading to estimated reductions in benthic biomass of up to 80%–100%, severely limiting community recovery. This is particularly concerning within the FRA of the Adventure Bank, where trawling has been prohibited since 2016 (REC.CM-GFCM/40/2016/4), yet illegal fishing activities persist (Alvarez et al. 2021).

The methodologies and findings presented here, while focused on the Sicilian continental shelf, have wider applicability. This study is based on well-established frameworks adopted in other European marine environments (ICES 2022), making it suitable

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for broader application in regions subject to chronic trawling. The combination of L1, L2, and PD indicators offers a nuanced view of benthic community responses across environmental gradients and fishing pressures, presenting a scalable framework adaptable to different ecological and management contexts. For example, regions experiencing intermediate to high trawling pressure may benefit most from the PD indicator, while relatively undisturbed areas could utilize L1 as a sensitive early-warning tool. Furthermore, this multi-indicator approach can serve as a model for prioritizing monitoring activities and identifying candidate sites for restoration or additional protection. Future research could enhance this framework by incorporating finer-scale habitat data such as high-resolution sediment maps, species-trait databases, or acoustic seabed characterization to improve spatial precision. Applying this model in diverse marine ecosystems would also help validate the indicators' performance across contexts, contributing to the development of a generalized, transferable methodology for trawling impact assessment.

Author contributions

Conceptualization: G.D.B., M.C.M., J.G.H. ; Methodology: G.D.B., M.C.M., J.G.H.; Data curation: All authors; Formal analysis: G.D.B.; Writing - original draft: G.D.B.; Writing - review & editing: All authors; Funding acquisition: M.C.M., G.S.

Supplementary data

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

Conflict of interest: None declared.

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Data availability

Data will be shared on request to the corresponding author with permission of the University of Palermo and the Italian Institute for Environmental Protection and Research (ISPRA).

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