

Relating benthic sensitivity and status to spatial distribution and intensity of trawling in the Eastern Mediterranean

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ABSTRACT

The ecosystem approach to fisheries management needs information of not just where bottom trawlers operate but also on their impact on the seabed, which is also highly relevant to the EU Marine Strategy Framework Directive (MSFD) Descriptor D6, seafloor integrity. In this study, we assess the benthic impact of bottom trawling in the Eastern Mediterranean in areas primarily fished by the Greek fleet. Seabed habitat sensitivity was modelled using macrofaunal longevity and biomass relationship based on data from more than 800 locations, representing 9 MSFD benthic habitats, and benthic status was assessed using the relative benthic status indicator. The pressure of seabed trawling was higher in circalittoral mud and circalittoral sand habitats showing a heterogeneous distribution pattern with intensive trawling in localized areas mainly coastal. Benthic status was high for all habitats reflecting the low trawling intensity and impact in most of the study area compared to other regions of Mediterranean or European waters. The results constitute the benchmark for benthic status in relation to trawling intensity in Eastern Mediterranean allowing to identify regions that are most at risk, and to prioritize management actions.

1. Introduction

Bottom trawling is globally widespread, accounting for close to 25 % of annual marine wild-capture landings (estimated for 2011–2013, Amoroso et al., 2018). The activity is carried out on sedimentary seabeds from shallow waters to approximately 800 m depth on continental shelves (Puig et al., 2012) but in excess of 1000 m on offshore seamounts (Williams et al., 2010).

As with other bottom contact gears, trawl gears have different components in contact with the seafloor, each with a separate degree of impact (Eigaard et al., 2016). The overall direct impacts on seafloor habitats include loss of natural spatial heterogeneity from destruction of small structures, removal of structures and infilling of burrows and pits (Rijnsdorp et al., 2016; Thrush et al., 2006). Benthic communities are altered through species removal, death and damage to benthic species

(Collie et al., 2000); resulting in functional changes (Beauchard et al., 2021; Rijnsdorp et al., 2016). As well as change in sedimentary integrity, direct effects can also be beyond the contact footprint through resuspension and deposition of sediments elsewhere (Bremann et al., 2022; O'Neill and Ivanović, 2016).

Under European Union guidance and related legislation, Member States have obligations to ensure that their fisheries are sustainably managed (Common Fisheries Policy: EC, 2013) as well as ensuring that their marine waters are in Good Environmental Status (GES) (MSFD - Marine Strategy Framework Directive: EC, 2008). The latter obligations concern the monitoring of typical pressures and impacts and ensuring that where failing, programmes of measures are designed and implemented to ensure recovery and improvement in status (Gorjanc et al., 2022). The basic prerequisites for marine ecosystem management are to know the extent and intensity of pressures as well as their impact.

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The ability to map impacts has progressed significantly in the last decades from small area studies up to global assessments including fishing impacts (Halpern et al., 2008). The impact of fishing has been closely correlated to trawler tracks using monitoring devices (e.g., Vessel Monitoring Systems, Automatic Information Systems) and methods have been developed to precisely define fishing pressure in space and time (e.g., Bastardie et al., 2010; Hintzen et al., 2012; Russo et al., 2014) while the trawling intensity/footprint (including the information about swept area) was introduced with the first major European mapping of trawling impact on the seabed undertaken by Eigaard et al. (2017b) in the BENTHIS project (<https://www.benthis.eu>). This work has been expanded further to cover more global continental shelves by Amoroso et al. (2018). Related work has modelled the impact of trawling on benthic communities at the habitat level, estimating benthic community status and using longevity as a proxy for recovery time of taxa, where short-lived species tolerate higher trawling intensities than long-lived species (Rijnsdorp et al., 2016). Major global analyses have contributed to the understanding of fishing impacts e.g., response/depletion and recovery (Collie et al., 2000; Hiddink et al., 2017; Kaiser et al., 2006; Sciberras et al., 2018). Further indicators have been developed and tested (e.g., (Hiddink et al., 2020, 2006; Piet and Hintzen, 2012)). The work to develop indicators of trawling impact on habitats, and on spatial scales was carried out in parallel to the BENTHIS project in the Trawling Best Practices project (<https://sites.uw.edu/trawlingbp/>) and also latterly within the ICES Working Group on Fisheries Benthic Impact and Trade-offs (<https://www.ices.dk/community/groups/Pages/WGFBIT.aspx>), leading to the development of wide area assessments in the European regional Seas (ICES, 2021), in the Baltic linking impact from trawling and hypoxia (van Denderen et al., 2020) and at the global scale (Mazor et al., 2021; Pitcher et al., 2022).

By having spatial information on impacts, management measures can be applied utilising trade-off scenarios where sustainable exploitation of the targeted stocks (benefiting in employment, income and food security) is measured against minimising habitat impacts or losses of ecosystem services (McConnaughey et al., 2020). This can be used towards general fisheries spatial planning (Jennings et al., 2012) or used, for example, on a credit/coupon system to limit impacts in more sensitive areas (Batsleer et al., 2018; Kraak et al., 2015).

In the Eastern Mediterranean, spatiotemporal patterns of trawling pressure and impact (including high-resolution VMS data) have been previously studied, particularly towards commercial species and unwanted catches (Maina et al., 2021, 2018b, 2018a, 2016), but also as trawling extent and intensity (swept area ratio) on European wide habitats (Eigaard et al., 2017). Whilst trawling impacts on seabed have been assessed in specific areas (Smith et al., 2007, 2003, 2000; Tsikopoulou et al., 2019) the work on geographical coverage has, so far, been preliminary (ICES, 2021a, 2021b) or using general data sources from other areas (Pitcher et al., 2022). The scope of the work presented here was to produce the benchmark in a part of Eastern Mediterranean waters for benthic status in relation to trawling intensity, landings and value, at both the MSFD broad habitat level and for different depth zones. Broad habitat levels are constrained to a common, largely physical habitat classification (categorized according to factors such as light penetration, depth, hydrodynamics and substrate type - Evans et al., 2016) and this habitat use is a mandated approach (European Commission, 2017). The classification does lack higher level species-characteristic categorization but has the advantage of complete coverage of the EU European and adjacent seabed. Information for both habitat type or depth zone is an essential requirement for environmental protection and is explicitly linked to EU and Mediterranean policy implementation. This methodology will be used directly in both National and regional monitoring and reporting allowing overall spatial mapping/distribution of impacts as well as habitat specific reporting, complimenting existing indicator data from physically sampled sites.

2. Materials and methods

The methodology followed for the benthic status assessment in relation to trawling intensity was divided in four steps. First, the area of interest was assigned and divided in grid cells of 0.05x0.05 decimal degrees (dd) using the C-square grid approach (Rees, 2003). Within this area, the distribution of the different MSFD benthic broad habitat types was assessed and mapped. Secondly, fishing pressure in terms of swept area ratio, weight and value of landings was estimated. Thirdly, benthic community sensitivity was assessed, utilizing macrofaunal community data from different habitat types classified into different longevity classes (assuming that benthic community sensitivity to bottom trawling is related to longevity). In the final step, fishing intensity and benthic sensitivity were combined to estimate the relative benthic status in the area of interest. Specific details on the steps are described below. All analyses were carried out in the R software (version 4.1.0). Scripts were developed by adapting the code from van Denderen (2020).

2.1. Study area and habitat information

The study area is a rectangle with minimum and maximum longitudes 18°E and 30°E, and minimum and maximum latitudes 33°N and 42°N (Fig. 1a), which comprises part of the continental shelf in Eastern Mediterranean Sea including the Aegean, Cretan and Ionian Seas and also part of Adriatic and Levantine Seas (Mediterranean FAO – GFCM Geographical Sub-Areas 20, 22, 23). The study area was limited to 1200 m depth, excluding the MSFD lower bathyal sediments and abyssal habitats (Fig. 1b) where no trawling takes place. Trawling activities are prohibited in coastal waters (within 3 nautical miles of the coast or within the 50 m isobath where that depth is reached at a shorter distance from the coast and within 1.5 nm of the coast for any depth) and also in depths greater than 1000 m due to spatial management measures (EC Regulation 1967/2006, Fisheries Restricted Areas, General Fisheries Commission for the Mediterranean and Black Sea, GFCM).

The EMODnet seabed habitat data portal (EUSeamap, 2021) was used to extract the distribution of MSFD broad habitat types within the study area. In order to link habitat information to fishing intensity, habitat types have been transferred into the C-square grid. The MSFD broad habitat type that overlapped the central point of the C-square was assigned to the whole C-square. The coverage of each habitat type in the study area is shown in Supplementary Table S1. It should be noted that for around 8 % of the study area there is no information about the habitat type. This is a known issue with EMODNET data showing usually small amounts of unknown habitat type for each country or subregion.

The study area was also divided into six depth zones adapted from the Maina et al. (2016) strata that are most associated with different trawling activities (Supplementary Table S2). The depth zones were 0–50 m, 50–100 m, 100–200 m, 200–500 m, 500–800 m and 800–1200 m.

2.2. Fishing pressure

2.2.1. Swept area ratio

In the current work, primary VMS data for the years 2015–2018 were provided by the Hellenic Ministry of Mercantile Marine and Island Policy and were analyzed based on the methods and specifications further described in Maina et al. (2021) (and references therein), followed by the estimation of Swept Area Ratio (SAR), an index that is used for describing fishing intensity. The swept area is the cumulative area contacted by a fishing gear within a grid cell (Eigaard et al., 2017, 2016), while the SAR is the swept area divided by the surface area of the grid cell. The SAR values indicate the theoretical number of times the entire grid cell area would have been swept if effort were evenly distributed within each cell (ICES, 2019a). Estimates of total SAR within each grid cell were calculated annually in a regular grid of 0.05 × 0.05 decimal degrees and by métier, which for this analysis is the demersal otter

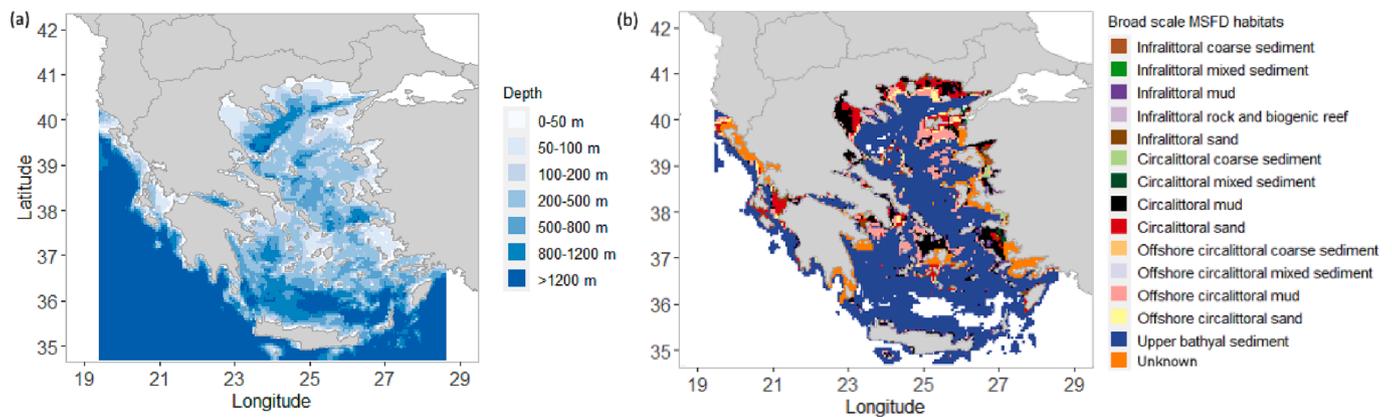


Fig. 1. (a) Bathymetric map of the study area divided in six depth zones and, (b) MSFD Broad habitat type distribution limited to depths up to 1200 m in the study area (source: EUSeamap, 2021).

trawls métier (the only trawling métier in the region). Estimations were derived representing an annual average of the SAR for the years 2015 to 2018.

2.2.2. Landings and value of landings

The spatial estimation of the value and weight of landings for bottom trawl was based on two main datasets: (i) the average landings data (i.e., value in euro and weight in tons by species), for the period 2015–2018, collected in the context of the EU Data Collection Framework (DCF) Fisheries Dependent Information (FDI) data call (<https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/FAD/fdi/>) and (ii) the spatial distribution of bottom trawl fishing grounds by species, based on Maina et al. (2016).

FDI spatial datasets on landings data are disseminated according to the format proposed by the Scientific, Technical and Economic Committee for Fisheries (STECF). The spatial resolution of the FDI datasets is 0.5x0.5 dd. In order to improve the spatial resolution to 0.05x0.05 dd, and given that these data are not available in a disaggregated level, we have combined the FPI estimates and the spatial distribution of trawl fishing grounds by species. The spatial distribution of trawl fishing grounds was based on a methodological approach that combines fishing effort estimations (based on the analysis of VMS data), and species probability of occurrence (based on Generalized Additive Models applied on commercial and survey fishing data) (see details in Maina et al., 2016). The estimation of fishing grounds was performed in a fine spatial resolution for fifteen demersal species; all considered important target-species for bottom trawlers in the Mediterranean. The latter authors have defined fishing grounds as “*crucial areas characterized by both fishing activity and species presence as a result of a strategy to maximize catches and economic gains*”. On that basis, the fine scale spatial outcomes of fishing grounds by species were used as a proxy variable for performing estimations related to the total value and weight of landings. This workaround was necessary for improving the spatial resolution of the FDI datasets. The combination was performed by species and based on the formulas:

$$LVc = FDI_{Lvi} * (proxy_{LVc} / \sum_{n=1}^v (proxy_{LVc}))$$

where LVc is the estimated value of landings for each species in a fine scale 0.05x0.05 dd; FDI_{Lvi} is the value of landings by species in a coarser scale of 0.5x0.5 dd based on FDI; $proxy_{LVc}$ is the proxy value of landings by species in a fine scale of 0.05x0.05 dd based on Maina et al. (2016); v = the number of grid cells of spatial resolution 0.05x0.05 dd that spatially overlapped with the grid cells of spatial resolution of 0.5x0.5 dd.

$$LWc = FDI_{Lwi} * (proxy_{LWc} / \sum_{n=1}^v (proxy_{LWc}))$$

where LWc is the estimated weight of landings for each species in a fine

scale 0.05x0.05 dd; FDI_{Lwi} is the weight of landings by species in a coarser scale of 0.5x0.5 dd based on FDI; $proxy_{LWc}$ is the proxy weight of landings by species in a fine scale of 0.05x0.05 dd based on Maina et al. (2016); v = the number of grid cells of spatial resolution 0.05x0.05 dd that spatially overlapped with the grid cells of spatial resolution of 0.5x0.5 dd.

Additionally, for the rest of the species, not included in the study of Maina et al. (2016), fishing effort was used as a proxy variable to estimate the total value and weight of landings. This alternative approximation was performed, since the distribution of certain species has not been studied yet. Based on previous studies the fishing effort patterns in the area are recurring in annual cycles. These patterns are related to a typical fishers' behavior which have translated their experience gathered over time into collective knowledge and are relatively aware of the productive fishing areas (Maina et al., 2018a). Although this is case specific and it depends on species distribution, in most cases the main fishing grounds can be considered as the most profitable (in total values). Finally, the above outcomes were aggregated (summed) to estimate the total value and weight of landings for all species. Estimations were derived in a spatial resolution of 0.05x0.05 dd and representing an annual average for the years 2015–2018.

2.3. Macrofaunal data sources

Macrofaunal data were collated from various scientific projects that took place in the study area from early 90 s to 2020, including seasonal sampling periods and yearly samplings. Studies were only included if the biomass of benthic species or higher taxonomic groups of macro-invertebrates was reported. Benthic samples in all studies were collected using either 0.1 m² Smith-McIntyre or van Veen grab samplers. The outcome was a database containing more than 54,500 records distributed in more than 200 sites and more than 800 sampling locations ranging in depths from 7 to 1200 m. These records are adequate for covering the most widespread benthic habitats and depth zones of the area (Supplementary Table S1 and S2).

For each site, benthic species were linked to a species-by-trait matrix with trait information on longevity (maximum lifespan). Information on the longevity of species was obtained from a variety of sources including primary and secondary literature and databases (<https://www.marlin.ac.uk/biotic>; <https://www.polytraits.lifewatchgreece.eu>). Longevity was subdivided into four trait classes (less than 1 year, 1–3, 3–10, and greater than 10 years). Individual species were coded for each class of the longevity trait using a fuzzy-coding procedure, which allows assessment of the affinity of a species to multiple categories using a discrete score from 0 (no affinity) to 3 (total affinity). The trait scores were standardized for each taxon by re-coding the scores as percentage frequencies. From this species-by-longevity matrix, a table of sites by

biomass-weighted trait longevity classes was calculated by multiplying the total biomass per species by the longevity score. These were then summed by longevity class and divided by the total biomass of the site to produce a proportional biomass-weighted longevity table for all sites.

2.4. Benthic community sensitivity

Median longevity is the longevity of 50 % of the cumulative biomass of macroinvertebrates in a site and was used as an indicator of the benthic community sensitivity to bottom trawling. The sensitivity of benthos is related to the longevity (Rijnsdorp et al., 2018). Long-lived species are usually larger, build biogenic structures and are more susceptible to bottom trawling. On the other hand, long-lived species have longer reproductive cycles and lower population growth rates. In this context, short-lived species are expected to tolerate higher trawling intensities than long-lived species and consequently a community with higher median longevity consists of species more sensitive to bottom trawling disturbance. The distribution of median longevity in the area of interest reflects the benthic community sensitivity (Rijnsdorp et al., 2018; van Denderen et al., 2020) and was selected to evaluate the difference in the longevity composition between benthic habitats.

To estimate median longevity, sampling locations that are largely undisturbed by fishing were selected in order to derive, as far as possible, an undisturbed reference state (Supplementary Fig. S1). For this reason, the disturbed sites located in C-squares with average trawling intensities, i.e., SAR greater than 0.1 were excluded from the analysis. Bolam et al. (2017) have shown that that benthic habitats can tolerate a low level of trawling pressure before trait composition significantly diverges from an untrawled reference level.

To statistically estimate the longevity composition in relation to depth and habitat type, we converted the biomass by longevity to a cumulative biomass by calculating the biomass proportion with longevity that is smaller than or equal to 1, 3 and 10 years in each site. It was assumed that the shape of this cumulative biomass proportion—longevity relationship is a sigmoidal (logistic) function, which starts at 0 and approaches 1 when longevity becomes large (Rijnsdorp et al., 2018; van Denderen et al., 2020). To examine how the cumulative biomass-longevity relationship varies across our area of interest, we have used a logistic mixed effect model using Generalized Linear Mixed Models (GLMMs) and a stepwise forward selection approach, including depth and MSFD habitat type as fixed effects and assuming sites as random effect. Depth was transformed to improve model fit using the natural logarithm $\ln(x + 1)$. Alternative model versions were compared using the Akaike information criterion (AIC).

2.5. Relative benthic status

For the environmental status assessment of the benthic habitats, we have used the relative benthic status (RBS) indicator developed by Pitcher et al. (2017), this is the seabed status, using a mean longevity basis, relative to an untrawled state given as 1 (Pitcher et al., 2022). The method is based on a logistic population growth equation that relates the biomass of the benthic community to its carrying capacity (see details in Pitcher et al., 2017). Estimating RBS requires distribution of fishing intensity and habitat type, and also depletion rate for specific métiers and recovery rate of the benthic community. Depletion rate for demersal otter trawls was adopted from the global meta-analysis of Hiddink et al. (2017). Depletion rate is dependent on the penetration depth of the gear and in our case was 0.06 (Hiddink et al., 2017). Recovery rate r was also derived from a global meta-analysis of recovery after trawling disturbance and is dependent on longevity $r = 5.31 / \text{longevity}$ (Hiddink et al., 2019). We estimated model uncertainty for the depletion and recovery parameters following the methodology described in van Denderen et al. (2020) and afterwards uncertainty in benthic status was expressed as the difference between the 95th and 5th percentile.

3. Results

3.1. Swept area ratio, weight and value of landings

Grid cell trawling intensities (SAR) between 1 and 5 occur along the coasts of Greece and generally decrease away from the coastline (Fig. 2). Hotspots of trawling intensity (SAR greater than 5) are mainly concentrated in the northern part of the North Aegean Sea where shallow waters are more extensive, and in Evoikos and Saronikos Gulfs in the Central Aegean, as well as in the outer Patraikos Gulf in the Ionian Sea. SAR is much lower in the southern Aegean Sea with the exception of certain narrow coastal strips (e.g., Crete). In the areas where the fishing intensity is higher, the landings were also the highest in terms of weight, peaking in northern Aegean waters and gulfs with high discrepancies in values with other areas (few areas with high weight of landings, with large areas of low weight of landings). Values of landings also followed a similar picture but with more equity in value between areas (few areas of low landing value) (Fig. 2).

Several trawling pressure indicators concerning the spread of intensity, landings and value were calculated and presented per MSFD broad habitat type in Table 1 and per depth zone in Table 2. The swept area in terms of extent varies considerably between habitats (also partially reflecting extent of habitat – Supplementary Table S1) and may have a different swept area ratio (SAR) while the Max SAR is the maximum swept area ratio reached in any cell and the Number of untrawled cells is effectively a degree of “pristine” for that habitat from trawling. For example, the habitat upper bathyal sediment has the largest swept area of $10.63 \times 10^3 \text{ km}^2$, but a very low swept area ratio 0.08 (under once every 10 years) at a maximum of 1.85 in any one spot, with 53 % of the habitat untrawled during the period. Overall, the habitats where most of the trawling pressure was concentrated are upper bathyal sediment and circalittoral mud in terms of the swept area (Table 1). Circalittoral sand was the individual habitat that received the most trawling intensity per year (SAR, indicating trawling coverage of 0.63 times per year, with a peak of over 7 times per year in one part of the habitat) in relation to its extent. Offshore circalittoral habitats including mud and sand, were also intensively trawled during the study period – offshore circalittoral had the least amount of untrawled cells by far. The most “productive” habitat in terms of landings was the upper bathyal sediment due to the large extent of this habitat in the study area, but also circalittoral mud and sand as well as offshore circalittoral mud (these 4 habitats dominated (90 %) the landings category). Whilst circalittoral, offshore circalittoral and upper bathyal were overall the habitats with the highest weight and value of landings per swept area, with peak values in the offshore circalittoral mixed sediment (that is a function of its very small swept area). Circalittoral sand was the habitat that offers the highest landings per habitat area. Finally, on average, the total seabed surface needed to be trawled per unit of landings was $2.48 \text{ km}^2/\text{t}$, with the highest value recorded in circalittoral coarse sediment ($10.53 \text{ km}^2/\text{t}$).

The intensity of bottom trawling follows a bathymetric pattern, where the majority of fishing activity takes place at depths from 50 to 500 m (Table 2), accounting for approximately 90 % of landings and weight and value, with many leading indices particularly within the 50–100 m zone (swept area, SAR, proportion of area trawled, total and percentage weight and value of landings, value of landings per swept and habitat area). The depth zone with the lowest proportion of untrawled cells was between 200 and 500 m. This is also reflected by the highest volume of landings per area (either swept area or total area) in the 50–200 m zone. Finally, the total seabed surface needed to be trawled per unit of landings was quite similar between all the depth zones, with the highest in the 0–50 m zone. For the 0–200 m zone SAR averaged 0.33 and for all depths deeper than 200 m, 0.08.

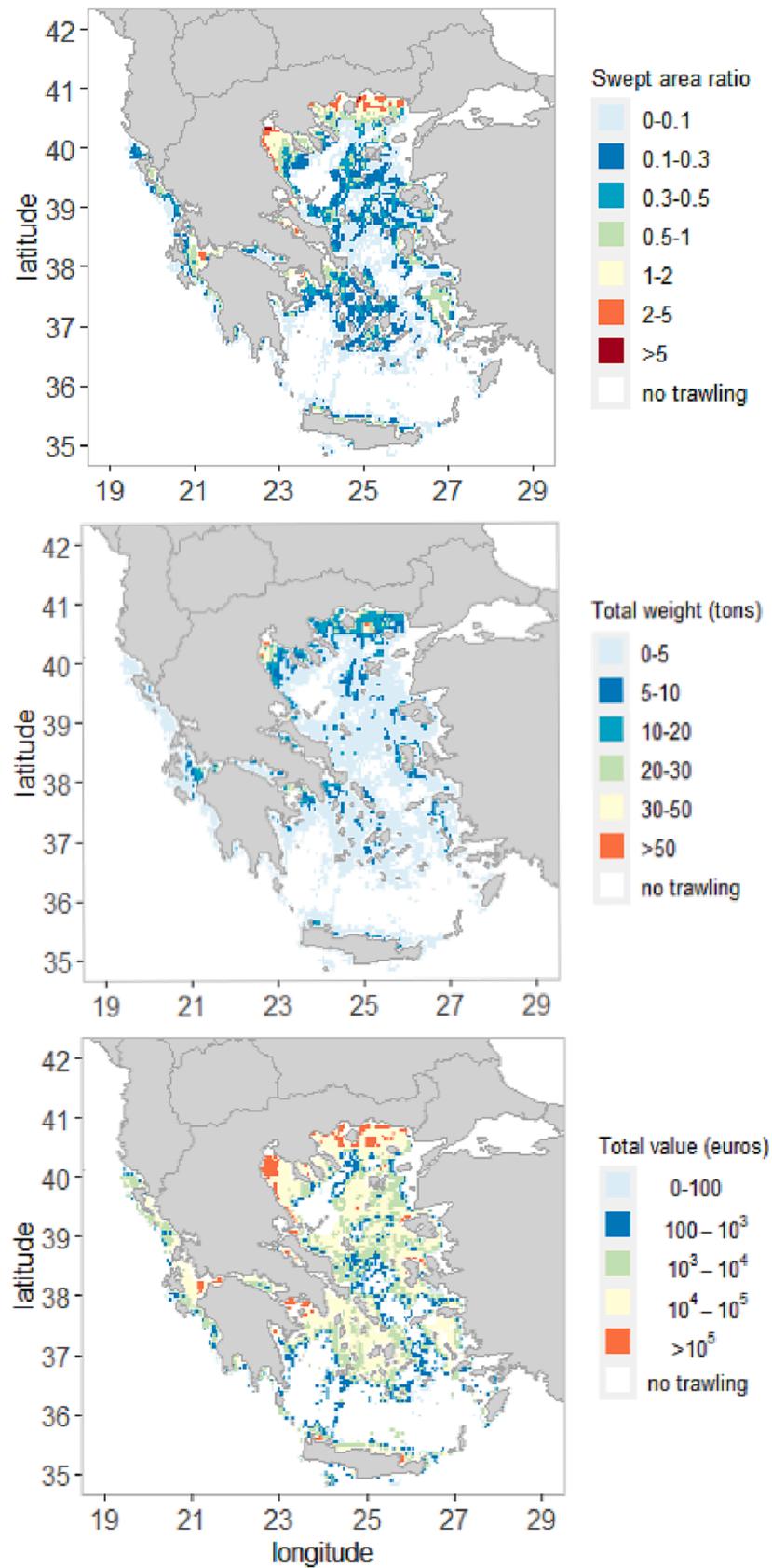


Fig. 2. Map of (a) swept area ratio, (b) total weight of landings in tons and (c) total value of landings in euros averaged for the years 2015 to 2018 in the study area based on VMS data on demersal otter trawls activity.

Table 1

Trawling pressure indicators per MSFD broad habitat type estimated in the study area for the years 2015 to 2018 based on VMS data of demersal otter trawls activity. The columns show the total swept area (10^3 km^2) in the different habitat types, the average swept area ratio (SAR) per grid cell, the maximum value of SAR found in the habitat (max SAR), the proportion of untrawled cells, the proportion of area trawled (10^3 km^2), total weight of landings (tons) and percentage of weight of landings, total value of landings (10^6 euros) and percentage of value of landings, weight of landings divided by the swept area ($\text{tons}/10^3 \text{ km}^2$), weight of landings divided by the habitat area ($\text{tons}/10^3 \text{ km}^2$), value of landings divided by the swept area ($10^3 \text{ euros}/\text{km}^2$), value of landings by the habitat area ($10^3 \text{ euros}/\text{km}^2$) and seabed trawled per unit of landings (km^2/ton). The last row refers to the value of each indicator for the entire study area.

MSFD Broad habitat type	Swept area	SAR	max SAR	Proportion of untrawled cells	Proportion of area trawled	Total weight of landings	Percentage of weight of landings	Total value of landings	Percentage of value of landings	Weight of landings per swept area	Weight of landings per habitat area	Value of landings per swept area	Value of landings per habitat area	Seabed trawled per unit landings
Infralittoral mud	0.1	0.01	2.12	0.98	0.01	25.2	0.17 %	0.18	0.18 %	242.68	3.45	1.72	0.02	4.12
Infralittoral mixed sediment	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0
Infralittoral sand	0.26	0.05	2.35	0.93	0.03	69.27	0.46 %	0.52	0.51 %	262.85	11.79	1.96	0.09	3.80
Infralittoral coarse sediment	0.01	0.02	0.24	0.82	0.02	2.54	0.02 %	0.02	0.02 %	235.75	4.78	1.61	0.03	4.24
Infralittoral rock and biogenic reef	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0
Circolittoral mud	9.91	0.48	6.67	0.46	0.33	3927.78	26.09 %	26.9	26.60 %	396.16	190.14	2.71	1.30	2.52
Circolittoral mixed sediment	0.16	0.26	2.36	0.54	0.18	51.00	0.34 %	0.39	0.39 %	314.59	81.29	2.40	0.62	3.18
Circolittoral sand	7.16	0.63	7.18	0.43	0.37	2323.04	15.43 %	15.53	15.36 %	324.60	204.44	2.17	1.37	3.08
Circolittoral coarse sediment	0.07	0.09	0.52	0.52	0.09	6.18	0.04 %	0.04	0.04 %	95.00	8.22	0.67	0.06	10.53
Offshore circolittoral mud	5.55	0.39	3.17	0.12	0.31	2771.32	18.41 %	17.8	17.60 %	499.52	194.60	3.21	1.25	2.00
Offshore circolittoral mixed sediment	0.00	0.01	0.09	0.86	0.01	1.22	0.01 %	0.01	0.01 %	580.45	7.30	3.33	0.04	1.72
Offshore circolittoral sand	1.83	0.4	3.88	0.24	0.31	797.42	5.30 %	4.75	4.70 %	436.76	175.32	2.60	1.05	2.29
Offshore circolittoral coarse sediment	0.02	0.06	0.39	0.67	0.06	4.73	0.03 %	0.03	0.03 %	275.69	16.17	1.79	0.10	3.63
Upper bathyal sediment	10.63	0.08	1.85	0.53	0.08	4535.16	30.13 %	31.12	30.78 %	426.44	33.93	2.93	0.23	2.34
Unknown	1.69	0.09	2.43	0.71	0.09	538.47	3.58 %	3.83	3.79 %	317.28	30.09	2.25	0.21	3.15
Total/max/average	37.40	0.17	7.18	0.53	0.13	15053.34	-	101.11	-	402.48	68.88	2.70	0.46	2.48

Table 2
 Trawling pressure indicators per depth zones estimated in the study area for the years 2015 to 2018 based on VMS data on demersal otter trawls activity. The columns show the total swept area (10^3 km^2) in the different depth zones, the average swept area ratio (SAR) per grid cell, the maximum value of SAR found in the habitat (max SAR), the proportion of untrawled cells, the proportion of area trawled (10^3 km^2), total weight of landings (tons) and percentage of weight of landings, total value of landings (10^6 euros) and percentage of value of landings, weight of landings divided by the swept area ($\text{tons}/10^3 \text{ km}^2$), weight of landings divided by the total area ($\text{tons}/10^3 \text{ km}^2$), value of landings divided by the swept area ($10^3 \text{ euros}/\text{km}^2$) and seabed trawled per unit of landings (km^2/ton). The last row refers to the value of each indicator for the entire study area.

Depth zone	Swept area	SAR	max SAR	Proportion of untrawled cells	Proportion of area trawled	Total weight of landings	Percentage of weight of landings	Total value of landings	Percentage of value of landings	Weight of landings per swept area	Weight of landings per habitat area	Value of landings per swept area	Value of landings per habitat area	Seabed trawled per unit landings
0-50	4.01	0.16	7.18	0.88	0.07	1228.62	0.08	8.30	0.08	306.38	2.07	48.16	0.33	3.26
50-100	14.84	0.53	5.43	0.45	0.35	5465.93	0.36	36.82	0.36	368.36	2.48	192.73	1.30	2.71
100-200	7.74	0.27	2.56	0.33	0.24	3650.25	0.24	23.75	0.23	471.67	3.07	127.46	0.83	2.12
200-500	9.85	0.16	1.85	0.28	0.15	4392.15	0.29	29.89	0.30	446.06	3.04	70.01	0.48	2.24
500-800	0.84	0.02	1.28	0.61	0.02	269.57	0.02	2.09	0.02	319.40	2.47	6.69	0.05	3.13
800-1200	0.12	0.00	0.52	0.85	0.00	46.81	0.00	0.27	0.00	378.78	2.16	1.42	0.01	2.64
Total/ max/ average	37.40	0.17	7.18	0.53	0.13	15053.34	-	101.11	-	402.48	66.88	2.70	0.46	2.48

3.2. Benthic sensitivity

Representative infaunal data were only available for analysis of benthic sensitivity in 9 of the 14 MSFD broad habitat classes. In Fig. 3, the average biomass distribution over the longevity classes for the different habitat types and depth zones are presented. The highest biomass proportion was recorded in the 1–3 years age class in all habitats with the exception of one (infralittoral mixed sediment). The biomass proportion of long-lived taxa (more than 10 years), one of the categories with the least proportion, was largest in the offshore circalittoral mud. Lower proportions of long-lived taxa were found in the circalittoral habitats (Fig. 3a). Regarding the longevity distribution in the depth zones, again the 1–3 years class dominated in all zones, with the largest proportion of long-lived taxa recorded at depths between 100 and 200 m (Fig. 3b).

Table 3 shows the statistical models tested to best fit the data for the predictions of the longevity distribution in the benthic community (best fit indicated by low AIC value). The cumulative biomass proportions across longevity classes are best described by longevity as well as the interaction of habitat type with depth. Using the statistical model outcome (Supplementary Table S3), the longevity composition of the benthic community was predicted in the study area. Predicted sensitivity (median longevity) of the benthic community extent-wise was between 2 and 3 in most of the study area (Fig. 4). Nevertheless, there were patches with sensitivity values less than 1, located mainly in specific coastal/shallow habitats (Table 4, 5 and Fig. 4). In terms of specific habitats, mean sensitivity was around 2 in most habitats, with very high values for infralittoral mixed sediment (Table 4). Sensitivity was higher in the shallowest and deepest zone, nevertheless the differences between the depth zones were very small (Table 5).

3.3. Relative benthic status

Combining trawling intensity (SAR) with benthic sensitivity, the predicted status of the benthic community for Greek waters is shown in Fig. 5 and the uncertainty of the model in Supplementary Fig. S2. Status values of 1 indicate unimpacted areas where no trawling occurred ($\text{SAR} = 0$), while lower values indicate increasing impact. Across most of the sea area, values for the status of benthic habitats are over 0.9 and from analysis of the mapped data, values are below 0.95 in only 2.1 % of the study area, and below 0.8 in only 0.03 % of the area (only 2 out of the 8000 cells total were in the lowest category of Fig. 5). The cells with the lower benthic status coincide with the areas where most of the fishing intensity occurs and also in the most sensitive habitats (Fig. 5, Table 4) in some spots to the east and west of the central belt. Benthic status is summarized in Table 4 for each habitat type (entire habitat based on its total extent) in the study area and as a worst-case scenario based on partial extent i.e., on the part of the habitat that is trawled only (highlighting the most sensitive habitats). For individual entire habitat, all values were over 0.97, with the highest values seen in circalittoral sand (0.976) followed by offshore circalittoral mud (0.987). When taking into account only the area within the habitat where trawling occurs, infralittoral sand is the habitat at most risk showing the highest decrease in benthic status reflecting its high sensitivity (Table 4). For the different depth zones (Table 5), benthic status for the entire zones (based on their total extent) was lowest in the 50–100 m depth zone at 0.982 and increasing with depth. This gradient pattern was repeated when considering partial extents i.e., only the areas trawled within each depth zone, with a larger impact in the shallowest zone (0.947). Impacts in the shallowest zone were however very localized as the proportion of untrawled cells is very high (Table 2).

4. Discussion

Among the recent most important requirements of the environmental policy in the European Union is to achieve GES in the European seas. To

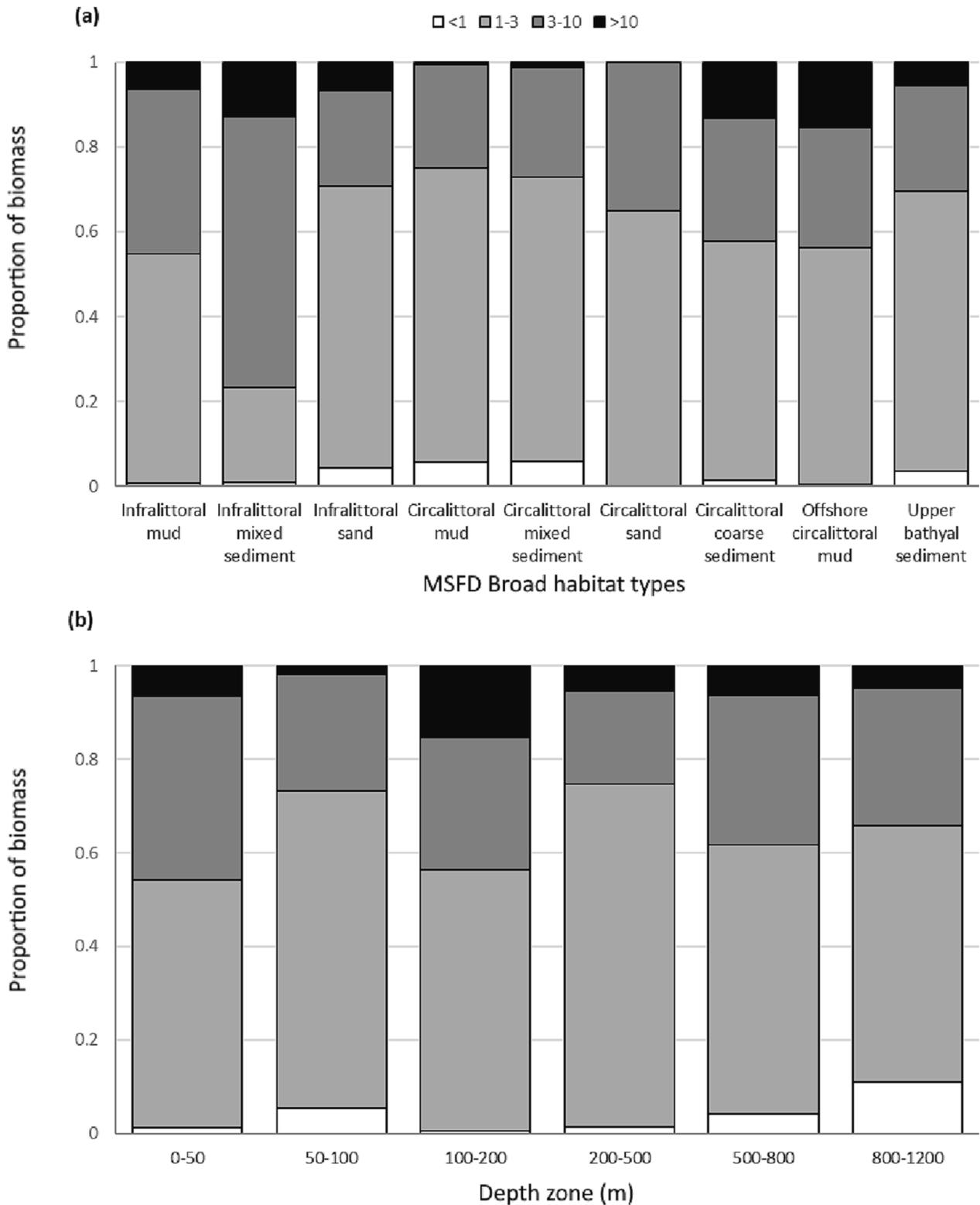


Fig. 3. The proportion of biomass of longevity classes (less than 1, 1–3, 3–10, and greater than 10 years) of the benthic community (a) in different MSFD Broad habitat types and (b) depth zones.

accomplish this, the Member States should firstly determine the pressure that a human activity exerts on the marine environment and then assess the current status of the marine ecosystem due to this activity. The present study attempts to present the trawling impacts on the benthic ecosystem on a geographical coverage and to produce the benchmark for benthic status in relation to trawling activity indicators, at both the

MSFD habitat level and for different depth zones in the Eastern Mediterranean.

Towards this goal, maps indicating the level of trawling activity were produced using three indicators i.e., SAR, weight and value of landings. Trawling pressure showed a heterogeneous distribution pattern with intensive trawling in localized areas mainly coastal, inside the major

Table 3
Model selection for the cumulative biomass proportions in relation to longevity, depth and habitat type.

Model	df	AIC
Longevity + Habitat	11	1078
Longevity + Depth	4	1088
Longevity + Habitat + Depth	12	1075
Longevity + Habitat + Longevity*Habitat	19	1070
Longevity + Depth + Longevity*Depth	5	1084
Longevity + Habitat + Longevity*Habitat + Depth	20	1068
Longevity + Habitat + Longevity*Depth	13	1073
Longevity + Habitat*Depth	18	1065

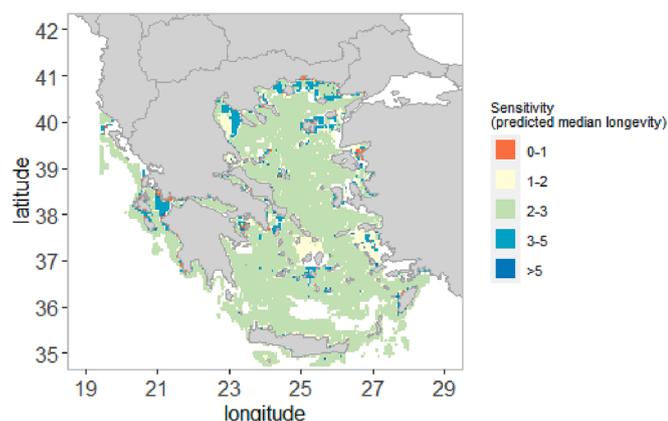


Fig. 4. Map of benthic sensitivity in the study area presented as predicted median longevity of the benthic community i.e., the longevity in years where the cumulative biomass proportion is 0.5.

Table 4
Benthic community sensitivity and status estimated per MSFD broad habitat type in the study area. Status is shown for both total area of the habitat and for those parts of the habitat that are trawled. Note that trawled parts vary in extent between habitats (for details and proportion of untrawled cells see Table 1).

MSFD Broad habitat type	Sensitivity	Benthic status - total habitat	Benthic status in trawled parts
Infralittoral mud	3.13	0.999	0.979
Infralittoral mixed sediment	14.72	1.000	-
Infralittoral sand	4.26	0.997	0.963
Infralittoral coarse sediment	-	-	-
Infralittoral rock and biogenic reef	-	-	-
Circalittoral mud	1.97	0.987	0.977
Circalittoral mixed sediment	1.73	0.993	0.985
Circalittoral sand	3.19	0.976	0.958
Circalittoral coarse sediment	2.79	0.997	0.994
Offshore circalittoral mud	2.72	0.987	0.985
Offshore circalittoral mixed sediment	-	-	-
Offshore circalittoral sand	-	-	-
Offshore circalittoral coarse sediment	-	-	-
Upper bathyal sediment	2.60	0.997	0.994
Unknown	-	-	-

*Median longevity and benthic status were only estimated for the habitats in which there were macrofaunal community data available.

Table 5
Benthic community sensitivity and status estimated per depth zone in the study area. Status is shown for both total area of the depth zone and for the part within the zone that is trawled.

Depth zone	Sensitivity	Benthic status - total area	Benthic status in trawled parts
0–50	2.78	0.993	0.947
50–100	2.65	0.982	0.968
100–200	2.76	0.991	0.987
200–500	2.55	0.995	0.993
500–800	2.65	0.999	0.998
800–1200	2.74	0.999	0.999

gulfs of Aegean and Ionian Seas and also around the islands of the Central Aegean Sea (Chios and Lesbos Islands). The same patchiness was also observed in all habitat types, leading to the conclusion that trawling hotspots may reflect certain morphological features, such as bathymetry, changes in bottom type, distance from the shore, primary productivity or the presence of target species (Eigaard et al., 2017; Maina et al., 2018a, 2016). In contrast to the localized trawling hotspots, low-intensity trawling was widespread in the study area, constrained by the deeper part of the distribution of the deepest species that is targeted (maximum approximately 800 m for red shrimp, Kapiris et al., 2022), unsuitable seabeds or legislation. On the basis of the international legislation (EU and GFCM), trawling is prohibited in coastal waters (within 3 nautical miles of the coast or within the 50 m isobath where that depth is reached at a shorter distance from the coast and within 1.5 nm of the coast for any depth, EC Regulation 1967/2006) and at depths greater than 1000 m (GFCM Recommendation 29/2005/1). The small proportion of the swept area in the 0–50 m depth zone reflects these regulation restrictions. In addition, the “efficiency” of the trawling in shallow habitats (as indicated by the last three columns in Table 2) is relatively low and economically less profitable. This is because adult fish tend to use deeper feeding grounds and therefore fishing in the shallow shelf waters has more discards than deeper trawling lanes. According to the national legislation, there is also a 4-month cessation period (the cessation is currently from the end of May to the end of September). Additional temporal restrictions exist in certain areas of the Aegean Sea, where fishing is banned for particular periods usually from the beginning of April until the end of October. Overall, trawling pressure was much lighter compared to other regions such as the Western Mediterranean, Adriatic Sea and North Sea (Church et al., 2016; Eigaard et al., 2017; Ferrà et al., 2018; Russo et al., 2020). Trawling pressure estimated as SAR in this study was much lower than that estimated in Eigaard et al. (2017) and slightly lower than Amoroso et al. (2018) in the same general area based on trawling data from 2010 to 2012, with differences probably due to differentiations in methodological processing (e.g., grid cell size) or due to annual variation. Generally, fishing effort patterns (hotspots) remain similar over the years (northern coasts and bays) although slight annual changes have been observed in some periods (Maina et al., 2018b, investigating 2010–2015).

Muddy sediments were the most common habitat type in the study area, nevertheless the coarser - but not rocky - sediments were the most profitable, always in relation to the swept or total area, meaning that these habitats regardless of their extent were preferred for trawling probably due to their diversity in fish species or presence of high-value species (e.g., *Mullus* spp. or sparids). To the best of our knowledge this is the first record of specific sedimentary habitat preference of bottom trawling in the Mediterranean, although in line with another study from the North Sea (Hintzen et al., 2021). However, this preference may lead to higher targeting and consequent impact on this habitat and eventually turn it from sustainable habitat to a habitat at risk.

Trawling takes place in the most part on flat unobstructed seabeds. These seabeds have tended to be overlooked when compared to important/vulnerable habitats characterized by sensitive, structural or keystone species. They might not obviously provide important functions

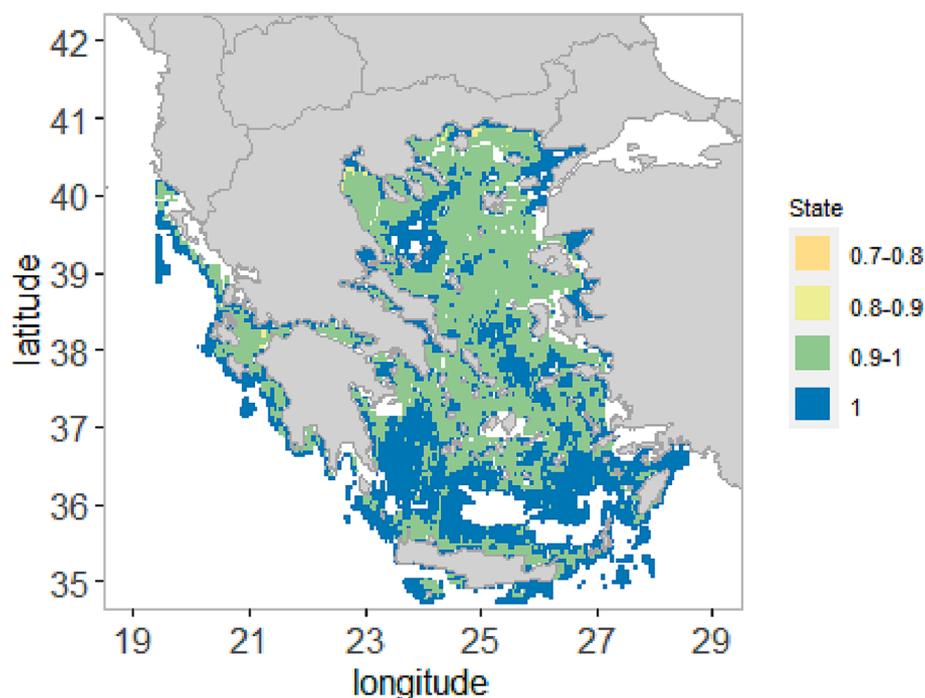


Fig. 5. Map of the benthic community status impacted by trawling in the study area.

per unit area that these other habitats provide (e.g., rich biodiversity, high production, shelter or specialized feeding area), but they still remain important as habitats supporting commercial fish populations (based on normal functioning) and importantly they are beginning to be understood as absorbing and containing significant blue carbon stocks based on massive areal extents from coastal to deep seabeds (Bulmer et al., 2020; Graves et al., 2022; Hilmi et al., 2021) and where trawling disturbance is a high level threat to this storage (Black et al., 2022; Epstein et al., 2022; Luisetti et al., 2019).

Before assessing the benthic status due to trawling, it is essential to estimate the benthic sensitivity to trawling. Recent studies have proposed several indicators (González-Irusta et al., 2018; Hiddink et al., 2019; Rijnsdorp et al., 2018; Serrano et al., 2022) and/or compared which of them best reflect trawling impacts on the benthic community (Cyrielle et al., 2020; Gislason et al., 2017). Some of the indicators are based on macrofaunal data, others on megafaunal data (trawl caught), some are oriented towards species richness while others are oriented towards species functionality, depending on the data availability in the geographical area that are applied (Cyrielle et al., 2020; Hiddink et al., 2020). Longevity distribution as an indicator of the benthic sensitivity to trawling is one of the approaches that are commonly used in different parts of European waters (ICES, 2022; Kaiser, 2019; van Denderen et al., 2020). This method is based on the observation of previous studies that there is a shift towards shorter-lived species in response to trawling (Hiddink et al., 2019; Tillin et al., 2006). Our results showed that in general, the sensitivity of the benthic community in the study area was between a median longevity of 2 to 3 with higher sensitivity in infralittoral habitats. Moreover, in the shallower depth zone (0–50 m, particularly infralittoral mixed sediment) a high range of sensitivity values (cells with predicted sensitivity less than 1 and others with more than 10) was recorded. A factor that probably caused this wider range in sensitivity values in the shallower depth zone, was the fewer sampling locations used to predict the longevity in this depth zone. On the other hand, the infralittoral zone receives the higher number of human-induced pressures and this wider range in predicted longevity could reflect real-world variation. In this zone, factors other than longevity may contribute to faunal responses to bottom trawling explaining why these diverse responses could be reasonable (Hiddink et al., 2019).

The RBS method to assess the status of the benthic ecosystem due to trawling has been promoted as one of the best performing methods to assess trawling impacts in benthic habitats (Pitcher et al., 2017; Rijnsdorp et al., 2020). In our study area, benthic status had values in almost all cases higher than 0.9 reflecting the low trawling intensity and impact in most of the study area compared to other regions of Mediterranean or European waters (Amoroso et al., 2018; Mazor et al., 2021; van Denderen et al., 2020). The recent worldwide study by Pitcher et al. (2022) gives an average RBS estimate in the Aegean Sea of approximately 0.8–0.9, a lower average status value than found in this study (Table 5), which may be attributed to the higher SAR used in their estimates (from Amoroso et al., 2017 for the years 2010–2012) and/or applying fixed benthic sensitivity values applied to the world analysis rather than based on localized values. When taking into account only the areas that are trawled within a habitat or a zone (worst case scenario), a decline in benthic status was observed, specifically, in the 0–50 m zone within the infralittoral sand habitat. The decrease in benthic status estimated in this habitat indicates how susceptible could be a sensitive habitat to trawling (Hiddink et al., 2019).

4.1. Caveats

The sensitivity of the benthic community is derived from the biomass longevity distribution of the community. Standard macrofaunal sampling may not fully reflect the presence of species that have sparse or low-density distribution, nor species that are distributed below the sampling gear penetration depth, both of which might be collected in wider area megafaunal survey or using more specialized deeper sediment sampling equipment. These groups may include longer-lived individuals that have larger biomass (e.g., surface or burrowing molluscs, echinoderms and crustaceans). It was assumed that if they were not collected using the replicate sampling in the benthic surveys included, then the biomass of the sparser distributed individuals would not contribute significantly to the overall habitat modelled longevity biomass. For the deeper dwelling biomass, absolute area longevity may be underestimated, but this will not be important within the study where the same sampling methodologies are used to establish longevity estimates in a comparative analysis. The deeper dwelling individuals may

tend towards classification of megafauna and they may be less likely to be directly impacted by trawling, living below the mean penetration depth of the trawling gear.

The methodology used for assessing the effects of trawling on benthic communities has been previously applied in both smaller (van Denderen et al., 2020) and wider (Pitcher et al., 2022) regional scales. Nevertheless, it contains a degree of uncertainty due to assumptions in the analysis. Initially, information on habitat distribution was derived from the EMODnet seabed habitat data portal which relies on predictive mapping methods since habitat maps are very costly and time consuming to produce from survey (Vasquez et al., 2021). Although this source of habitat information is valuable and unique (Vassallo et al., 2018), it leaves out 8 % of our study area due to missing data for the determination of habitat. The accuracy of the impact method is also affected by the parameterization of depletion and recovery rates which are currently derived from worldwide meta-analyses (Hiddink et al., 2017), although we have incorporated an uncertainty measure (van Denderen et al., 2020). In addition, regarding trawling pressure, only the Greek fleet fishing intensity was estimated, although this is the principal fleet operating in the regions, there are other nation vessels that trawl in peripheral parts of the area and could potentially affect the trawling pressure on these (mostly deeper) benthic habitats. Thus, acquiring and updating depletion rates for more habitat types, along with validation and incorporation on non-Greek fleets are needed.

4.2. Management implications and further suggestions

Mapping the trawling impact as well as the benthic status at a regional scale enables managers and policy makers to detect which areas, habitats or depth zones are either sensitive or at greatest risk from unsustainable trawling regimes. Therefore, within the European environmental policy context, findings of this study are of importance as they indicate how bottom trawling affects seafloor integrity over certain habitats and over time (following the MSFD cycles of assessments and management actions implemented between cycles). Assessing the benthic status distribution in different habitats and depth zones provides useful guidance for implementing sustainable management strategies and assists in the assessment of trade-offs between human activities and their environmental impact on the seabed and informs the discussions between stakeholders for spatial zoning of activities and of spatial protection measures (McConnaughey et al., 2020). Scenarios can be gamed for spatial or temporal closures. In the Mediterranean since 2005, there has been a ban on trawling greater than 1000 m depth (in the Atlantic a similar ban was introduced in 2016 for 800 m depth). There are currently on-going discussions concerning the Mediterranean limit and it can be seen from our data that effort, landings and catch values deeper than 800 m are all very low, but the sensitivity is still high making a good argument to reduce the limit for protection of deeper waters whilst having a low-level effect on the fisheries. This is an example of where this work can be used for screening management scenarios before more detailed exploration using bio-economic and displacement models (ICES, 2019b).

Our findings showed that 98 % of the study area had benthic status above the threshold of 0.95, and only 0.03 % of the area had benthic status below 0.8. Ideally, the assessment will need to be accompanied with thresholds that indicate the quality, extent and the spatial coherence of the benthic status. It should be clarified not only where to set the threshold for GES regionally, for example, which benthic status values are acceptable to stakeholders, the wider community and sustainable for the environment, but also what fraction of the area needs to be in GES and how this fraction is distributed over the habitats in order to avoid adverse effects (Lambert et al., 2017; Mazor et al., 2021; McConnaughey et al., 2020; Rijnsdorp et al., 2020). Setting thresholds, however, comes with several considerations related to the effect of assessment scales. In line with MSFD requirements currently TG Seabed and other European Commission expert groups, are working at defining 'thresholds for the

maximum allowable extent of habitat disturbance and loss as a proportion of the total natural extent of the habitat type, taking into account regional or subregional specificities while also addressing the scales issues (European Commission, 2022).

In our case, both the assessment of pressure and benthic status has been done at a fine scale and consequently, values were aggregated and reported for larger management units, allowing to identify regions that are most at risk, and to prioritize management actions.

CRediT authorship contribution statement

Christopher J. Smith: Conceptualization, Project administration, Investigation, Resources, Methodology, Writing – original draft, Writing – review & editing. **Nadia K. Papadopoulou:** Conceptualization, Project administration, Investigation, Resources, Methodology, Writing – original draft, Writing – review & editing. **Irida Maina:** Investigation, Resources, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Stefanos Kavadas:** Investigation, Resources, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **P. Daniel van Denderen:** Methodology, Writing – review & editing. **Nikolaos Katsiaras:** Investigation, Resources, Writing – review & editing. **Sofia Reizopoulou:** Investigation, Resources, Writing – review & editing. **Ioannis Karakassis:** Investigation, Resources, Writing – review & editing. **Anastasios Tselepidis:** Investigation, Resources, Writing – review & editing. **Irini Tsikopoulou:** Conceptualization, Project administration, Investigation, Resources, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2023.110286>.

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