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ORIGINAL ARTICLE

Assessment of Bottom Trawl Impacts on the Status of Seabed Communities in European Seas

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ABSTRACT

Bottom trawling affects seabed habitats, but its large-scale impacts remain poorly quantified. Assessment of trawling impacts is essential to support monitoring and achieving sustainability objectives under international conventions, sustainable development goals, and seafood certification programs. We present a Europe-wide quantitative assessment of bottom trawling impacts, accounting for regional seabed-community sensitivity drivers, across the Baltic, Atlantic, Mediterranean and Black Sea continental shelves. Using two risk-based indicators of seabed status—Relative Benthic Status determined as benthic community biomass relative to seabed fauna carrying capacity (RBS_{tot}) and RBS_{sen} (biomass of the 10% most sensitive fauna relative to carrying capacity)—we found substantial regional and habitat differences. The Black, Baltic and Aegean-Levantine Seas showed low trawling intensity and high seabed status across habitats. In contrast, the Western Mediterranean, Ionian and Central Mediterranean and Adriatic Seas were the most severely impacted. Trawling affected the sensitive species biomass fraction more strongly than the total community biomass. RBS_{tot} was in good condition (here chosen as RBS > 75% for epifauna) for over 79% of habitat-ecoregion combinations. In contrast, RBS_{sen} met this threshold in only 46% of these. A strong correlation emerged between the mean trawling intensity and RBS_{tot} and RBS_{sen}, allowing the use of SAR to estimate ecosystem status. This relationship can support decisions on where, and by how much, SAR reductions are needed to achieve good environmental status in regions where no detailed assessment is available. Our approach provides a quantitative framework to balance fishery production with ecosystem sustainability, offering tools for environmental and fisheries management in Europe.

1 | Introduction

Mobile bottom-contacting fishing gears, such as beam trawls, otter trawls, demersal seines and shellfish dredges ('bottom trawls' hereafter), are designed to catch fish and shellfish species that live close to, on, and in the seabed, and provide ~25% of global seafood landings (Amoroso et al. 2018). Bottom trawls are widely considered to have the highest environmental impact of commonly used fishing gears (Steadman et al. 2022), and are the most widespread source of anthropogenic physical disturbance to seabed habitats (Foden et al. 2011). The use of bottom trawls faces growing opposition due to bycatch rates, fuel use, impact on seabed habitats and release of organic carbon from disturbed seabed sediments (Hiddink et al. 2017; Pitcher et al. 2022; Zhang et al. 2024). Concerns about the environmental impacts of trawling have fuelled strong public campaigns, resulting in bottom trawling being restricted (e.g., EU Action Plan, COM 2023), or banned in some countries (e.g., Belize, Hong Kong) and regions and proposals to implement such restrictions elsewhere (McConnaughey et al. 2020; Hilborn et al. 2023). Balancing fishery production and ecosystem sustainability remains a challenging issue, partly because indicators of ecosystem state are often unavailable or practically impossible to acquire at management scales.

Ecosystem-based management requires continuous monitoring and adjustments based on new data and insights, including assessments of the impact of bottom trawling on benthic biota and habitats (e.g., Cyrielle et al. 2020; McLaverty et al. 2020; Serrano et al. 2022). Such assessments are essential to fulfil ecosystem-based management commitments, address trawling impacts, meet certification and policy requirements and guide sustainable fisheries and habitat protection strategies (Rice and Rochet 2005; Jennings et al. 2012; Rice et al. 2012; Rijnsdorp et al. 2016). For example, Descriptor 6 in the EU Marine Strategy Framework Directive (MSFD) requires that the seabed is in Good Environmental State and that ecosystem structure and functions are maintained (EU-MSFD 2008), while the Marine Stewardship Council requires the avoidance of serious or irreversible harm to habitat structure and function on commonly encountered habitats (Marine Stewardship Council 2018).

2 | Methods for the Assessment of Bottom Trawling Impacts

Many different approaches have been developed and applied to evaluate the impact of bottom trawling on seabed ecosystems. This section will discuss the advantages and disadvantages of the different approaches.

State-based indicators that rely on sampling the seabed, for example, the Shannon-Wiener diversity index or the AMBI indicator, comparison of many indicators in Van Denderen et al. (2024) present challenges due to spatially and temporally sparse sampling, limiting their use for assessments over large spatial scales. Field sampling provides a means to assess the benthic condition within a defined area through empirical observations, often based on long-term monitoring data. These sampling-based approaches differ in their underlying assumptions, methodological frameworks and data processing techniques. The indicators derived from such methods target various aspects of the benthic community and ecosystem, and may incorporate species-specific sensitivity metrics to particular pressures, enabling more targeted pressure–impact assessments (ICES 2022). However, this type of monitoring is resource-intensive and is often insufficient to detect habitat-specific impacts or to identify the drivers of observed changes, due to substantial natural variability across spatial and temporal scales—such as fluctuations driven by recruitment dynamics (Bijleveld et al. 2012). Thus, with current sampling efforts, faunal sample data are unlikely to provide a representative regional picture of bottom trawling impacts on seabed habitat status.

Many before-after and/or control impact (BACI) experiments have been undertaken to estimate the local direct impacts of trawling and differences in sensitivity between species and habitats (Sciberras et al. 2018). Such experiments are important to understand the mechanisms driving differences in responses between areas but cannot direct inform the regional scale impacts, while recovery rates estimated from such experiments tend to be much faster than seems realistic for large scale commercial trawling grounds (Collie et al. 2000).

Comparative studies of commercial trawling impacts over gradients of chronic bottom trawling intensity have been used to evaluate the impact of bottom trawling on benthic communities (Hiddink et al. 2020; Van Denderen et al. 2024). Such studies are likely to yield more realistic estimates of the impact of large-scale bottom trawl activities than BACI studies because they capture the actual time and spatial scale at which trawling impacts the seabed. However, it does not seem realistic to carry out comparative studies in all the habitats in a region that would allow scaling up to a regional assessment.

Different types of ecosystem models have been used to evaluate the impact of bottom trawling on different ecosystem components (e.g., ERSEM (Allen and Clarke 2007), StrathE2E (Heath et al. 2015), size-based benthic models (Hiddink et al. 2006)). Such models can be very complex, making them hard to parameterise and difficult to apply consistently over large spatial scales, while sometimes predicting unexpected and unintuitive impacts. This complexity makes such ecosystem models less suitable for application as a management tool.

Risk-based assessment methods that generate pressure-based indicators (Hobday et al. 2011) can predict benthic state from bottom trawling pressure and community/habitat sensitivity information. They are either built on expert judgment and sensitivity/pressure overlap calculations, which produce ordinal outputs (e.g., Elliott et al. 2018)–or alternatively on mechanistic models or statistical predictions of pressure–state relationships, which produce continuous quantitative outputs (with or without uncertainty) (e.g., Pitcher et al. 2017). Such pressure-derived assessments can more easily be applied to large geographic areas, and can be used to predict the impact to unsampled areas (ICES 2022). Since pressure data is more readily available and spatially comprehensive than faunal sampling data, pressure-based indicators offer a pragmatic alternative for assessing seafloor health (ICES 2022). Such models generate continuous quantitative outputs at a regional scale, including unsampled areas. Most pressure-based assessments estimate a single indicator; however, some can estimate multiple indicators within the same model (Hiddink et al. 2019). Risk-based assessment methods, such as the RBS model used in this paper (Hiddink et al. 2019), are therefore the most readily available and practical solution for large-scale assessments of bottom trawling impacts.

Previous large-scale assessments of bottom trawling impacts in European waters are geographically incomplete and/or driven by globally estimated relationships between seabed sensitivity and sediment type (Eigaard et al. 2017; Pitcher et al. 2022). However, other environmental drivers also affect seabed sensitivity, and the strength and direction of the effects of these drivers vary between regions. For example, although the habitat 'Offshore circalittoral mud' is found in the Baltic, the North East Atlantic, the Mediterranean and the Black Sea (Vasquez et al. 2023), the benthic communities in this habitat differ greatly across the regions (i.e., dominated by small bivalves in the Baltic, by the Norway lobster, *Nephrops norvegicus*, in the NE Atlantic and Mediterranean seas, and by Terebellids in the Black Sea). As a result, a recent assessment of trawling impacts in the Eastern Mediterranean, using regionally developed benthic community sensitivity (Smith et al. 2023) diverged from a large-scale study for the same area (Pitcher et al. 2022).

Relative Benthic Status (RBS) measures the biomass of the benthic community after chronic trawling, relative to its untrawled biomass (the carrying capacity) at regional scales, based on depletion d, intrinsic rate of increase r and fishing intensity estimated as the annual Swept-Area-Ratio SAR (Pitcher et al. 2017). The SAR of an area is calculated by dividing the area swept by trawl gears in 1 year (total distance trawled × trawl width) by the size of the area of a cell. Depletion d is the fraction mortality per trawl pass. The intrinsic rate of population increase (r) of benthic communities is based on their longevity distribution, so that communities with a larger fraction of long-lived biota (e.g., deep-sea communities) have a higher sensitivity (Hiddink et al. 2019). Community-level r estimates are predicted for an untrawled community, including the slower-growing, larger-bodied and longer-lived fauna that are more sensitive to trawling (Rijnsdorp et al. 2018). The RBS method assesses the impacts of trawling on broad-scale, commonly occurring habitats. These sedimentary habitats comprise the majority of the seabed area worldwide (> 99% of shelf and slope areas, Straume et al. 2019), and most bottom trawling occurs in these habitats. Our assessment does not include the impacts of bottom trawling on more sensitive biogenic habitats and hard bottoms (e.g., mussel beds) or Vulnerable Marine Ecosystems (FAO 2009).

3 | Aims

Here, we quantify the impact of bottom trawling in European waters for a contiguous area stretching from the Baltic Sea and the Atlantic seas to the Mediterranean and the Black Sea. Our approach accounts for spatial differences in seabed sensitivity, customised per region. In each region for each habitat type, we estimate two quantitative indicators of biotic status for the sedimentary habitats where most bottom-trawling occurs. This assessment approach supports Ecosystem-Based Management by enabling informed decision-making, adaptive responses and balanced policy development.

4 | Methods

4.1 | Overview

Here we present assessments of bottom trawling impacts on the benthic community in sedimentary habitats for 10 ICES ecoregions (Adriatic, Aegean-Levantine, Baltic, Bay of Biscay and the Iberian Coast, Black, Celtic, Greater North, Ionian and the Central Mediterranean Sea, Western Mediterranean) (ICES 2023).

RBS_{tot} represents the biomass of the whole benthic community and scales from 1 (no impact) to 0 (the original benthic community has been removed or replaced by opportunistic species). The RBS_{sen} impact indicator estimates the decline in biomass of the species that make up the top 10% of carrying capacity by longevity of the benthic community and places more emphasis on declines of sensitive species. Both indicators quantify changes in biomass, which are assumed to be a proxy for the structure and function of benthic ecosystems and are good indicators to detect bottom trawling impacts because they respond strongly to trawling, relate directly to ecosystem functioning and are straightforward to measure (Hiddink et al. 2020; Van Denderen et al. 2024).

Applying the RBS method to estimate the indicators of seabed status involves three steps: (1) mapping the spatial distribution of fishing intensity, (2) predicting the spatial sensitivity of benthic communities using empirical data and (3) estimating the benthic state using the RBS method. It is expected that the drivers of the sensitivity of the benthic ecosystem to bottom trawling vary between ICES ecoregions (ICES 2023) and between infauna (benthic invertebrates that live in the sediment such as clams and polychaetes that are sampled using corers and grabs) and epifauna (benthic invertebrates that live on top of the sediment such as starfish, crabs and sponges that are predominantly sampled using dredges and trawls). Therefore, a unified method is applied separately to each region and faunal component before producing combined outputs (see van Denderen et al. 2025 for all data sources).

4.2 | Mapping the Spatial Distribution of Fishing Intensity

The bottom trawling intensity, represented by SAR, was estimated based on Vessel Monitoring System (VMS), Automatic Identification System and/or fisheries logbook data. To calculate the swept area by fishing gear type, estimates of the gear width and the fishing speed were used (Eigaard et al. 2017). SAR was calculated by dividing the swept area by the area of the grid cell at 0.05° resolution (Eigaard et al. 2017). The estimates of bottom contact for all metiers, including seines, are based on Eigaard et al. (2015) and assume full bottom-contact in the trawl path. In regions where data were available at finer spatial resolutions, SAR was resampled to a 0.05° grid cell resolution. Bottom trawling effort was available for most European countries but was incomplete for Iceland, Norway and Portugal and missing for Russia, Slovenia, Croatia, Montenegro, Bosnia, Albania, Turkey, Romania and north African countries (Table S1). Therefore, SAR was underestimated in areas where these countries fish. The fraction of missing fishing effort within regions varied, with most regions missing the (relatively small contribution of) effort from vessels under (Table S1).

The mean annual SAR over 6 years from 2016 to 2022 was used (where available, Table S1). This time span was considered appropriate because the RBS model assumes an equilibrium between the bottom trawling disturbance and the benthic community, and as the median recovery time for sedimentary benthic invertebrate communities to reach 50%–95% of carrying capacity after trawling ranges between 1.9 and 6.4 years (Hiddink et al. 2017).

The depletion rate *d* varies by gear type and is based on a meta-analysis of all available experimental trawling impact studies (Hiddink et al. 2017). For the Mediterranean and Black Sea, SAR estimates only distinguished between otter and beam trawls, and we applied two different depletion rates. In the Baltic and Atlantic regions, depletion rates for 10 different metier types were used, following Rijnsdorp et al. (2020) (Table S2), and based on the weighted average of the penetration depth of individual gear components weighted by their relative width to the total gear width. They do not differentiate between sediment type and/or species composition.

4.3 | Mapping the Spatial Sensitivity of Benthic Communities Using Empirical Data

The RBS method assumes that the instantaneous population growth rate *r* of benthic communities to trawling is proportional to the reciprocal of the longevity of species and communities. It thus requires estimating the biomass-longevity distribution of untrawled communities over the main environmental gradients using samples of benthic communities. From the datasets of benthic samples available to the authors, we selected datasets with consistent sampling coverage throughout all regions, ensuring coverage of the main environmental gradients. These samples were obtained with grabs, corers, or bottom trawls, which determine what component of the benthic ecosystem is represented by the output of the assessment (i.e., samples using grabs or corers are used for infaunal assessments and samples using trawls for epifauna). Table S3 shows information on the samples used in each region, while Figure S1 shows the distribution of all samples. Commercial, pelagic, fish and cephalopod species were excluded from before analysis, because they were not part of the invertebrate benthic community, were highly mobile and therefore less likely to respond to local environmental and trawling conditions, and because the fishery's targeting of commercial benthos may create confounding effects.

Longevity T_{max} was assigned at the species/genus level to all taxa in each dataset. Higher taxonomic groupings were used when species/genus level information was unavailable. Owing to scarce data and high uncertainty in T_{max} estimates for individual species, longevities were assigned to four T_{max} categories, <1, 1–3, 3–10, >10 years, using fuzzy-coding (Chevenet et al. 1994; Bolam et al. 2017). The categories were chosen to encompass the range of possible attributes of most taxa (Clare et al. 2022) (Table 1).

The benthic community biomass for each T_{max} category at each sampling location, expressed as a fraction of the total biomass, was converted into a continuous distribution, to estimate the biomass-longevity distribution of untrawled communities as a function of different environmental drivers (Rijnsdorp et al. 2018). This method fits a sigmoidal logistic function to the cumulative biomass fractions per T_{max} category using Generalised Linear Mixed Models for the different regions. The response variable was the cumulative biomass, with log (longevity), the environmental drivers and in some cases, bottom trawling intensity, as the explanatory variables. All regional models had a random intercept per sampling location to account for the dependency of cumulative biomass proportions within a sample. In addition, some regional models also included other random effects, such as year (Table S4).

Each sampling station was assigned a SAR based on the sampling location (Table S3). Two alternative approaches were used to account for the effect of bottom trawling history on the T_{max} composition of the benthic communities in the samples, ensuring that the predicted biomass-longevity distribution reflects untrawled communities. In the first approach, only sampling stations with no or low bottom trawling intensity were used in the analysis (SAR $=0$ or SAR <0.1, indicating trawling less than once in 10 years on average), assuming they are representative of the untrawled state. In the second approach, bottom trawling intensity was included as an explanatory variable in the statistical model, and the longevity distribution was predicted at SAR $=0$ in a second step to obtain the biomass-longevity distribution of untrawled communities. The approach used for each region is detailed in Table S4.

A stepwise selection approach was used to select the most parsimonious model, where alternative model versions were compared using the Akaike Information Criterion (AIC). The starting and final models for each region are given in Table S4. The final model for each region was used to predict the untrawled biomass-longevity distribution for each grid cell, typically based on average environmental conditions within a cell, whereas for habitat categories, the dominant habitat type was used in each grid cell. This distribution was then converted into a biomass-population growth-rate distribution using $r=5.31/T_{max}$ (Hiddink et al. 2019), yielding a measure of sensitivity to trawling for each grid cell. This analysis was done separately for each sample dataset. The environmental explanatory variables included in the statistical models varied between regions because the factors influencing seafloor sensitivity to bottom trawling vary, and the availability of high-resolution environmental data layers also differs between regions. For instance, bed shear stress is unlikely to be an important driver of sensitivity outside macrotidal areas, such as the Baltic and the Black Sea. Separate sensitivity layers were generated for infaunal and epifaunal assessments. Infaunal sensitivity is based on samples taken using grabs and corers,

TABLE 1 | Overview of the sources used for the longevity trait data by region. Longevity classes used are < 1, 1–3, 3–10, > 10 years.

Region	Type of data	Source of trait data
1. Bulgaria EEZ	Grab	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022) (Vaz et al. 2022)
2. Greek EEZ	Grab	HCMR trait database (Smith et al. 2023)
3. North/Central Adriatic	Trawl	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022)
4. Adriatic Sea/Western Ionian Sea	Trawl	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022)
5. Sicily	Trawl	(Beauchard and Troupin 2018; Clare et al. 2022)
6. Italy west coast	Trawl	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022)
7. French Med. EEZ	Trawl	Merged longevity database (Vaz et al. 2022)
8. Spanish Mediterranean	Trawl	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022) as well as an adapted version of the longevity used for BESITO index (González-Irusta et al. 2018; Serrano et al. 2022)
9. Gulf of Cadiz	Trawl	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022) as well as an adapted version of the longevity used for BESITO index (González-Irusta et al. 2018; Serrano et al. 2022)
10. Portugal	Grab	Merged Longevity database (ICES 2022) and submitted as a dataset with this paper (Vaz et al. 2022). Some local additions were made.
11. North Iberia/Bay of Biscay/Celtic Sea	Trawl	Merged longevity trait data from (Clare et al. 2022), few from expert knowledge (BENTHIS EU-project), Beauchard and additional local additions (e.g., for northern Spain longevity used for BESITO index, González-Irusta et al. 2018; Serrano et al. 2022).
12. Irish Sea, Bristol Channel, Celtic Sea North	Grab	(Clare et al. 2022)
13. North Sea & Channel, including Skagerrak and shallow northwest Scotland	Grab/core	Longevity trait data as compiled by (Clare et al. 2022) and updated for new areas with the Merged Longevity database (ICES 2022), and submitted as a dataset with this paper (Vaz et al. 2022)
14. Baltic Sea (including Kattegat)	Grab/core	Longevity trait data as compiled by (Clare et al. 2022) and (Törnroos and Bonsdorff 2012). The trait data is available here: https://github.com/Dvandenderen/Baltic-benthic-status/tree/master/Benthic%20trait%20data
15. North Sea	Trawl	(fuzzy-coded matrix of taxa longevity, built during the European Benthis project in 2021)

while epifaunal sensitivity is based on samples taken using trawls. Although the infaunal sampling gears sample some epifaunal species and vice versa, these species were excluded from further analysis in some regions (see Table S3).

In a few areas, datasets that were collected in different sampling campaigns overlapped spatially. As a result, for a few 100 s of grid cells, more than one sensitivity layer was created for infauna or epifauna. In these grid cells, RBS indicators were estimated for each infauna and epifauna sensitivity layer separately and averaged afterwards. We took this approach rather than a re-analysis of the original benthic sample data because the time and extent of sampling and the sampling gears used differed between the datasets. Table S5 gives the metadata and sources of the environmental data layers used in each region's analysis.

4.4 | Estimating the Benthic State Using the RBS Method

The RBS method is a quantitative approach for assessing the risks to benthic habitats by towed bottom-fishing gears. It uses the logistic growth equation (Schaefer 1954) to describe the dynamics of benthic fauna, as it provides an effective abstraction of the complex recovery dynamics of populations and communities and can be fitted to available data (e.g., McClanahan et al. 2007; Lambert et al. 2014). This model is identical to the Schaefer models commonly used in fisheries management when the data to implement full age or size-structured models are not available (Costello et al. 2016). The method is based on an equation for relative benthic status (RBS, defined as the biomass B relative to the carrying capacity K), derived by solving the logistic population growth equation for the equilibrium state (Pitcher et al. 2017):

$$\mathrm{RBS_{tot}} = \mathrm{B} / \mathrm{K} = 1 - \mathrm{SAR}\, d / r$$

where SAR is the swept area ratio, depletion d is the fraction mortality per trawl pass, and r is the intrinsic rate of population increase. The assessment sums the impacts of all different metiers i by using SAR $d = \Sigma \mathrm{SAR}_i\, d_i$. The sensitivity layer gives a distribution of carrying capacity by $T_{\max}$ for each grid cell, with its associated recovery rate r.

For computational purposes, we discretized $T_{\max}$ into n categories, each representing 0.5-year intervals. Let $j \in$ (Cade et al. 1999) index these categories. For each category j, we assigned a weight K_j such that:

$$\sum_{j=1}^{n} K_j = 1$$

The total biomass score, denoted $\mathrm{RBS_{tot}}$, was computed as the sum of individual category scores RBS_j:

$$\mathrm{RBS_{tot}} = \sum_{j=1}^{n} \mathrm{RBS}_j$$

To calculate $\mathrm{RBS_{sen}}$, and isolate the upper 10% of the most long-lived biomass, we identified the subset of the largest values of $T_{\max}$, such that their cumulative weight accounted for the top 10% of $T_{\max}$-associated biomass. Let n10 denote the index corresponding to the start of this subset (i.e., the first category in the top decile of longevity). The weights for these categories were renormalized such that:

$$\sum_{j=n10}^{n} K_j = K$$

The corresponding sensitivity biomass score, $\mathrm{RBS_{sen}}$, was then calculated as:

$$\mathrm{RBS_{sen}} = \sum_{j=n10}^{n} \mathrm{RBS}_j$$

We estimated model uncertainty for the depletion and recovery parameters following the methodology described in Denderen et al. (2020). The uncertainty was estimated by calculating both indicators 1000 times at each grid cell based on a resampling of the density distributions of the depletion and recovery parameters. We afterwards obtained the 95th and 5th percentiles of both indicators.

4.5 | Analysis

Outputs at the grid cell level were aggregated into habitat types (coarse, mixed, mud, sand), depth zones (< 50, 50–150, > 150 m) and ecoregions, with bathyal (off the continental shelf, generally > 200 m depth) as a separate habitat for the graphical outputs (Text S1). For each ecoregion, the indicators are also reported at the more detailed level of MSFD Benthic Broad Habitat Types (EMODnet 2021) (Table 2). Where multiple habitats are presented within a cell, we used the dominant habitat type. Outputs for habitat-ecoregion combinations containing fewer than 50 grid cells are not reported. The fraction of area covered by assessments is given in Table S6.

Assessments require the estimation of the fraction of the area that is in a good state. Building on preliminary analyses by Hiddink et al. (2023), we propose an RBS threshold of 0.75 to distinguish good from degraded environmental states at the cell scale and to summarise results by ecoregion and habitat type. Additional thresholds (0.5–0.9) are presented in Table S7.

The impacts of bottom trawling were assessed down to the legal depth limit for trawling (800 m in the Baltic and Atlantic, 1000 m in the Mediterranean Sea). In the Black Sea, a 100 m depth limit was used, as the deeper region is permanently anoxic.

5 | Results

5.1 | Spatial Distribution of Fishing Intensity

The total swept area, for all towed mobile bottom gears combined, across the entire region was 3.8 million km^2 per year, which is slightly larger than the assessed area (< 1000 m in Mediterranean, < 100 m Black, < 800 m Atlantic) of 2.5 million km^2. However, no bottom trawl fishing was recorded in 42% of the grid cells (which was 41% of the area). Additionally, in 63% of the grid cells (and corresponding 62% of the area), trawling intensity (SAR) values were < 0.5 per year. This indicates that bottom trawling is highly patchy, with high SAR values concentrated in specific areas within regions and noticeable peaks in Skagerrak, the eastern Channel and around Italy (Figure 1). The highest annual average SAR was recorded in a grid cell in Italy on circalittoral mud at SAR = 70 y^{-1}, which means that this grid cell was trawled on average every 5 days. Even in heavily exploited seas, in most habitats a large fraction of cells remained unfished (fraction of cells unfished, mean by region and habitat, = 0.42, Table S7), but some habitats in certain ecoregions lacked unfished areas. The average SAR was low in the Baltic, Black and Aegean-Levantine seas and in deep (bathyal) and shallow

TABLE 2 | Description of the Marine Strategy Framework Directive (MSFD) Benthic Broad Habitat Types that were used in this study (EMODnet 2021).

Habitat category	Description
Upper bathyal sediment	Sediment habitats on the upper continental slope (approx. 200–750 m depth), typically fine muds and sands, supporting deep-sea infauna and epifauna.
Offshore circalittoral coarse sediment	Offshore gravels and coarse sands in deeper shelf waters, supporting diverse benthic assemblages including filter-feeders and mobile epifauna.
Offshore circalittoral sand	Offshore sandy seabeds. Typically, home to worms, bivalves and echinoderms.
Circalittoral rock and biogenic reef	Rocky seabeds below the kelp zone, often dominated by sponges, bryozoans and reef-forming organisms such as cold-water corals.
Offshore circalittoral mud	Fine sediments in offshore shelf waters, often low-energy, supporting burrowing megafauna (e.g., *Nephrops*)
Circalittoral coarse sediment	Coarse sands and gravels in deeper shelf waters, supporting filter-feeding communities and mobile species like starfish and crabs.
Circalittoral mud	Fine sediments in deeper circalittoral zones, supporting burrowing infauna and sensitive to disturbance.
Circalittoral sand	Sandy seabeds in deeper shelf waters. Important for infauna and demersal fish feeding grounds.
Offshore circalittoral mixed sediment	Dataset-specific category; mixtures of sand, gravel and mud in offshore circalittoral zones, supporting diverse benthic assemblages.
Infralittoral coarse sediment	Shallow subtidal coarse sands and gravels, high-energy environments with diverse benthic fauna.
Infralittoral mud	Fine sediments in shallow subtidal areas, supporting burrowing polychaetes, crustaceans and bivalves.
Offshore circalittoral rock and biogenic reef	Rocky and reef habitats in offshore waters, including cold-water coral reefs and sponge grounds.
Infralittoral rock and biogenic reef	Shallow subtidal rocky habitats dominated by kelp forests, coralline algae and reef-building species.
Circalittoral mixed sediment	Dataset-specific category; mixtures of sand, gravel and mud in circalittoral zones, supporting varied benthic communities.
Infralittoral sand	Shallow sandy seabeds, often home to burrowing worms, bivalves and flatfish nurseries.
Infralittoral mixed sediment	Dataset-specific category; mixtures of sand, gravel, and mud in infralittoral zones, supporting diverse benthic fauna.
Lower bathyal sediment	Sediment habitats on the lower continental slope (approx. 750–2000 m depth), typically fine-grained, supporting deep-sea benthic fauna.
Upper bathyal sediment	Sediment habitats on the upper continental slope (approx. 200–750 m depth). Typically composed of fine muds and sands, these areas support burrowing infauna (polychaetes, bivalves, crustaceans) and epifauna adapted to low light and colder, stable conditions.
Lower bathyal rock and biogenic reef	Rocky outcrops and biogenic reef structures (e.g., cold-water corals, sponge aggregations) on the lower continental slope (approx. 750–2000 m depth). These habitats form biodiversity hotspots, offering complex three-dimensional structure that supports fish, crustaceans and other deep-sea organisms.
Upper bathyal rock and biogenic reef	Hard-bottom and reef habitats on the upper slope (200–750 m). Often colonised by cold-water corals, bryozoans and sponges.

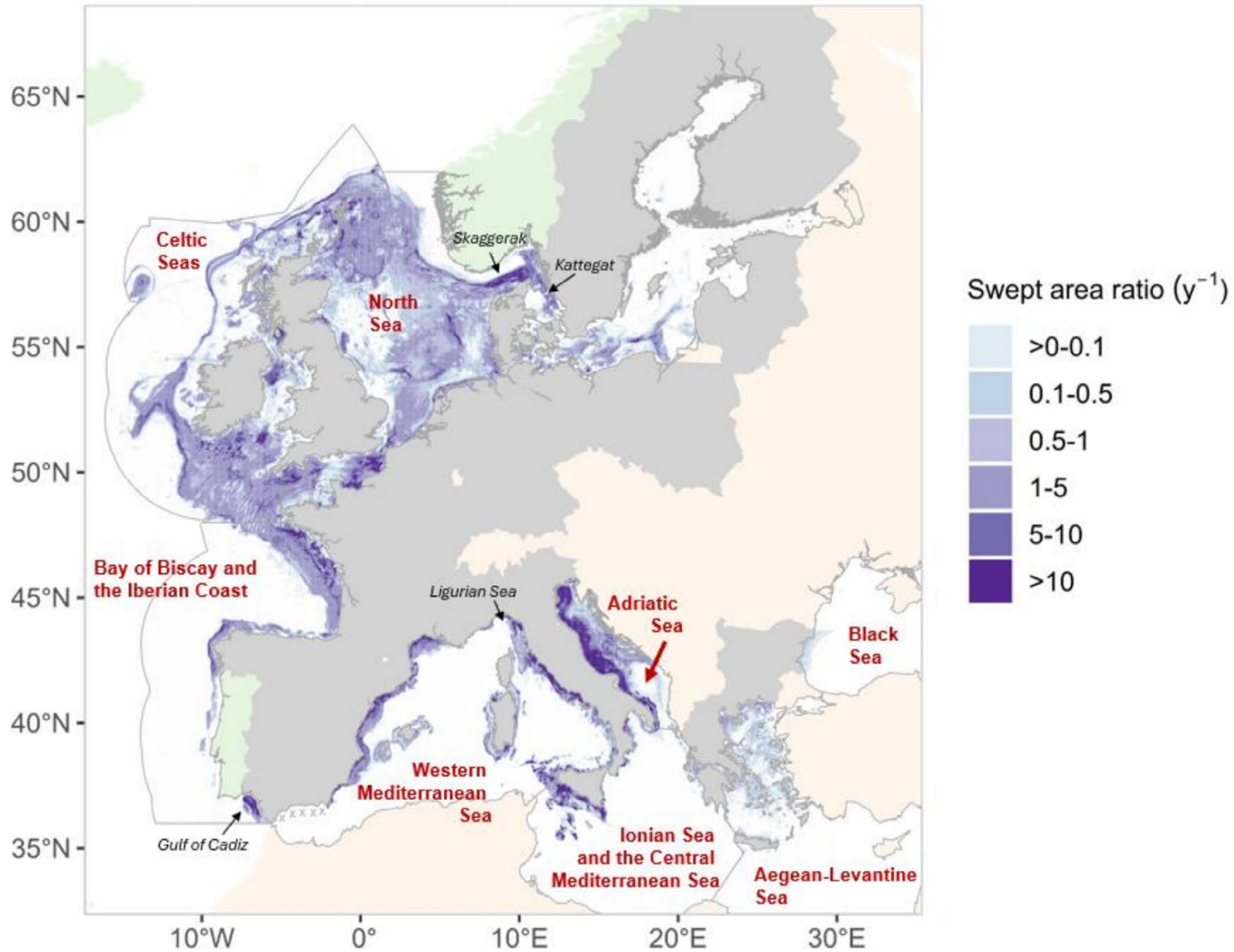

FIGURE 1 | Annual average fishing intensity expressed as swept area ratio (SAR) per year (2016–2022 for most areas, see Table S2). Data are included from countries marked dark grey, supplemented with incomplete data from countries in light green. 'xxx' indicates the unassessed area in the Alboran Sea.

waters (< 50 m, but note the absence of SAR data in many regions for vessels under 12 m, which are particularly concentrated in shallower areas).

5.2 | Sensitivity and State of Sedimentary Habitats

There were distinct spatial patterns in the state of benthic communities that mirrored the distribution of SAR (Figure 2). Ecoregions with large areas where the benthic state was strongly reduced by trawling were characterised by a high SAR and, within those, by the highest sensitivity (Figure S2). Most regions had a mix of more and less impacted areas, but some regions had a uniformly low state, for example, the Western Mediterranean Sea. As expected, RBS_{sen} was more strongly impacted by bottom trawling than RBS_{tot} but there is a tight correlation between the two indicators at the scale of habitats by ecoregion ($RBS_{sen} = -0.6 + 1.58\ RBS_{tot}$, $R^2 = 0.92$, $F_{1,153} = 2018$, $p < 0.001$).

The outputs are derived from a heterogeneous assemblage of infaunal and epifaunal datasets obtained using multiple sampling methodologies and gear types. To evaluate how this may have affected comparability of the results from different regions, we first evaluate infaunal and epifaunal RBS_{tot} and RBS_{sen} only for the cells that had assessment outputs for both groups, and compared the average RBS values by region (North Sea, Celtic Sea, Adriatic Sea), and MFSD habitat (for combinations with $n > 5$ grid cells). We found that there is a very strong correlation between the RBS_{tot} and RBS_{sen} of epifauna and infauna for these overlapping assessments (Figure S4, $r > 0.98$). A linear hypothesis test on the relationship between infauna and epifauna RBS_{sen} showed that the intercept was not significantly different from zero and the slope was not significantly different from one ($p > 0.05$), and assessments from different regions are therefore likely to be directly comparable for RBS_{sen}, regardless of whether the assessment is based on epifauna or infauna. For RBS_{tot}, we found that the state of epifauna was lower than for infauna, with this difference increasing to 0.1 units as the mean RBS_{tot} decreased to 0.6 with SAR increasing to 4.7 y^{-1}. The state of epifauna was lower than for infauna because the average longevity of epifauna was higher than for infauna (e.g., mean 7.58 vs. 5.19 years median longevity in the North Sea, resulting in a mean RBS_{tot} of 0.84 for epifauna and 0.92 for infauna). Assessments from regions with

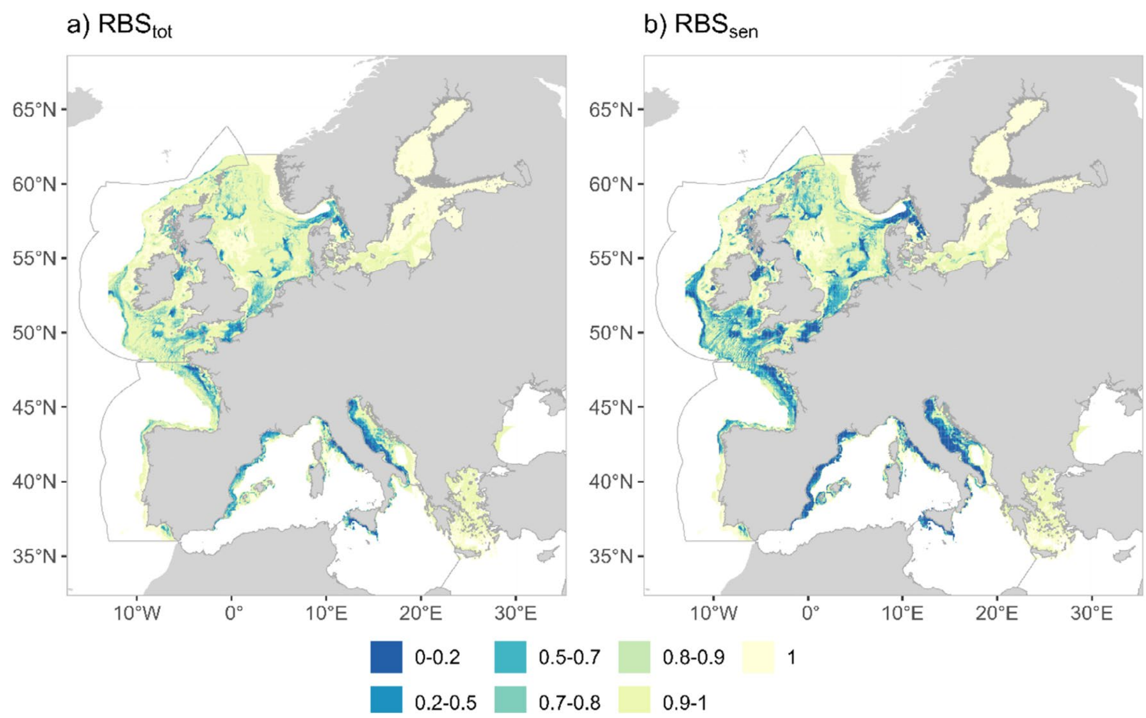

FIGURE 2 | Maps of benthic state for (a) RBS_{tot} (biomass of the benthic community relative to its carrying capacity) and (b) RBS_{sen} (biomass of the 10% most sensitive fauna in the benthic community relative to its carrying capacity) averaging the estimates for both infauna and epifauna where they are overlapping. The individual maps for infauna and epifauna are shown in Figure S3.

a high mean SAR where assessments are limited to epifauna (Western Mediterranean Sea, Adriatic Sea), therefore may yield lower RBS_{tot} estimates than if they were based on both infauna and epifauna. Overall, by coincidence, regions where the impact of trawling on epifauna was assessed had a higher mean SAR (3.22 y^{-1}) than regions where the impact on infauna (0.54 y^{-1}) was assessed, and this will also have resulted in a lower RBS for epifauna overall.

The state of the epifauna was lowest in three ecoregions of the Mediterranean Sea, and both within and across regions on mud habitats (Figures 3 and 4). For infauna, the state was lowest in the Celtic and North Seas, and again particularly so on mud habitats, while in the other ecoregions and habitats, the impact of trawling on infauna was limited ($RBS_{tot} > 0.95$ for all habitat types). Bathyal habitats were also strongly impacted by trawling in the Celtic Seas but were relatively little impacted in other ecoregions. Overall, the mean RBS_{tot} was > 0.75 for 98% and 79% of the habitat-ecoregion combinations for infauna and epifauna respectively, while the mean RBS_{sen} was > 0.75 for 94% and 46% of the habitat-ecoregion combinations for infauna and epifauna (Table S7). Ecoregion-habitat combinations with the lowest states were characterised by a very high mean SAR (> 3 y^{-1}) and a very low fraction of unfished cells (< 0.2, sometimes even 0.0, Table S7). In all regions (but mostly in the Western Mediterranean Sea and Ionian Sea and Central Mediterranean Sea), and some habitats (mud and mixed) and depth zones (bathyal), RBS_{sen} was predicted to be zero in some grid cells, indicating the predicted absence of any original long-lived fauna (Figure 4).

The five region-MSFD Benthic Broad Habitat Type combinations with the lowest states ($RBS_{tot} < 0.53$ and $RBS_{sen} < 0.34$) were Offshore circalittoral mixed sediment in the Bay of Biscay and the Iberian Coast, Circalittoral mud in the Western Mediterranean Sea, Offshore circalittoral mud in the Ionian Sea and the Central Mediterranean Sea, and Circalittoral mud in the Adriatic Sea (Table S7).

Tight negative correlations were observed between mean RBS_{tot}, mean RBS_{sen} and mean SAR (calculated from means by region and MSFD habitat, Figure 5, $r < -0.85$), and this relationship can be used to approximate the state of the ecosystem for regions and habitats where no sensitivity layer can be estimated but SAR is available. There was also a tight negative correlation between the fraction of the area that can be considered to be in a good state with $RBS_{tot} > 0.75$ and mean SAR for both infauna and epifauna ($r < -0.80$, $p < 0.001$) (Figure 5: common regression for infauna and epifauna calculated from means by region and MSFD habitat: fraction of area with $RBS_{tot} > 0.75 = 1 - 0.080$ SAR, $R^2 = 0.85$). These strong relationships exist because RBS was estimated using SAR, while the variation around the fitted relationships is caused by differences in sensitivity between habitats and regions.

6 | Discussion

We present a Europe-wide quantitative risk assessment of the impacts of bottom trawling on sedimentary habitats on the continental shelves where most trawling occurs. Our assessment considered the regional drivers of habitat sensitivity, covering the Baltic, Atlantic, Mediterranean and Black Seas and is parameterised for each region using faunal samples. We used two quantitative indicators of benthic state, RBS_{tot} and RBS_{sen}, which synthesise recent advances in the understanding of

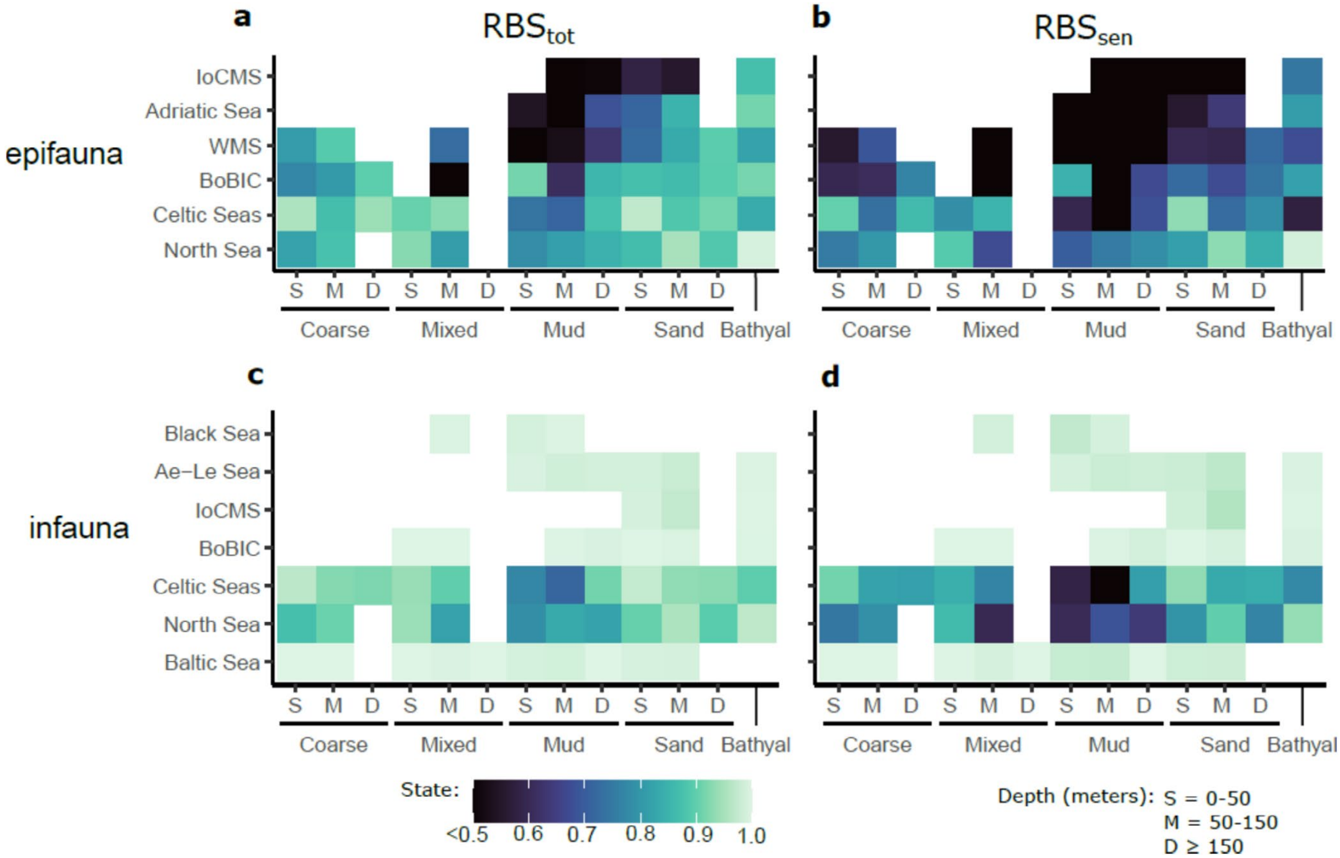

FIGURE 3 | Average benthic state for RBS_{tot} and RBS_{sen} grouped by infauna and epifauna, ecoregion, substrate type and depth class. Variations in benthic state between infauna and epifauna may arise from differences in sensitivity within the area and/or from geographic differences in the regions where sensitivity predictions are made. Uncoloured, white, cells are combinations with fewer than 50 grid cells. BoBIC = Bay of Biscay and the Iberian Coast; WMS = Western Mediterranean Sea; IoCMS = Ionian Sea and the Central Mediterranean Sea; Ae-Le Sea = Aegean-Levantine Sea.

trawling disturbance to the seabed and provide a seascape-scale risk assessment of cumulative trawl impacts on the relative biotic state of sedimentary habitats.

We found that the status of sedimentary habitats differs greatly among regions and habitats. The Black, Baltic and Aegean-Levantine Seas had low trawling intensities (SAR $< 0.25\ y^{-1}$) and high RBS_{tot} and RBS_{sen} values across all assessed habitats (> 0.95). In contrast, the most severely impacted regions were the eastern and southern North Sea, the Western Mediterranean Sea, the Ionian and Central Mediterranean Seas, and the Adriatic Sea. However, even in regions where overall mean RBS was not strongly impacted by bottom trawling, certain habitats were found to have a low state. Muddy substrates were notably impacted across different regions. This was especially evident in areas trawled for species like the Norway lobster *Nephrops norvegicus*, large shrimps and demersal fish, which showed high SAR values and very low fractions of untrawled habitat. Trawling had a greater impact on surface-dwelling animals (epifauna, like starfish, crabs and anemones) than on those living within the sediment (infauna, like worms and clams). This is mainly because epifauna tend to live longer and are therefore more sensitive to disturbance, but also because trawling intensity was on average higher in the areas where epifaunal impacts were measured.

The fraction of seabed considered to be in a good state was highly variable across regions and habitats. We found a very strong relationship between the fraction of the seabed with a $RBS_{tot} > 0.75$ and the mean SAR. Hence, trawling intensity estimates by region and habitat (which rely on the availability of vessel tracking data and habitat maps) can be used to approximate the state of the ecosystem for areas where only SAR is available by using the general relationship with mean state and fraction in a good state. This can, in turn, help guide decisions on whether, to which extent and in which habitats reductions in SAR are needed to improve ecosystem state. The EU Directorate-General for Environment (2023) has set a target for at least 75% of the extent of the seabed to be in 'good environmental status' (here operationalised as $RBS_{tot} > 0.75$ within the cells in this 75%). Our results show that to achieve this mean SAR needs to be $< 2.9\ y^{-1}$ in a habitat with average sensitivity, and lower in habitats that are more sensitive.

These assessments are tailored to regional and habitat-specific drivers of seabed sensitivity and, as such, offer more refinement than previous assessments that were based on global relationships between sensitivity and sediment type alone (Pitcher et al. 2022). Although these assessments are model predictions, they can provide important information that can be used to compare bottom trawling impacts on seabed state across multiple habitats and ecoregions. The confidence of our model outputs is lower in relatively data-poor areas, generally in deeper water and areas where data coverage of the bottom trawling effort is not complete, such as Portugal and the southern Mediterranean

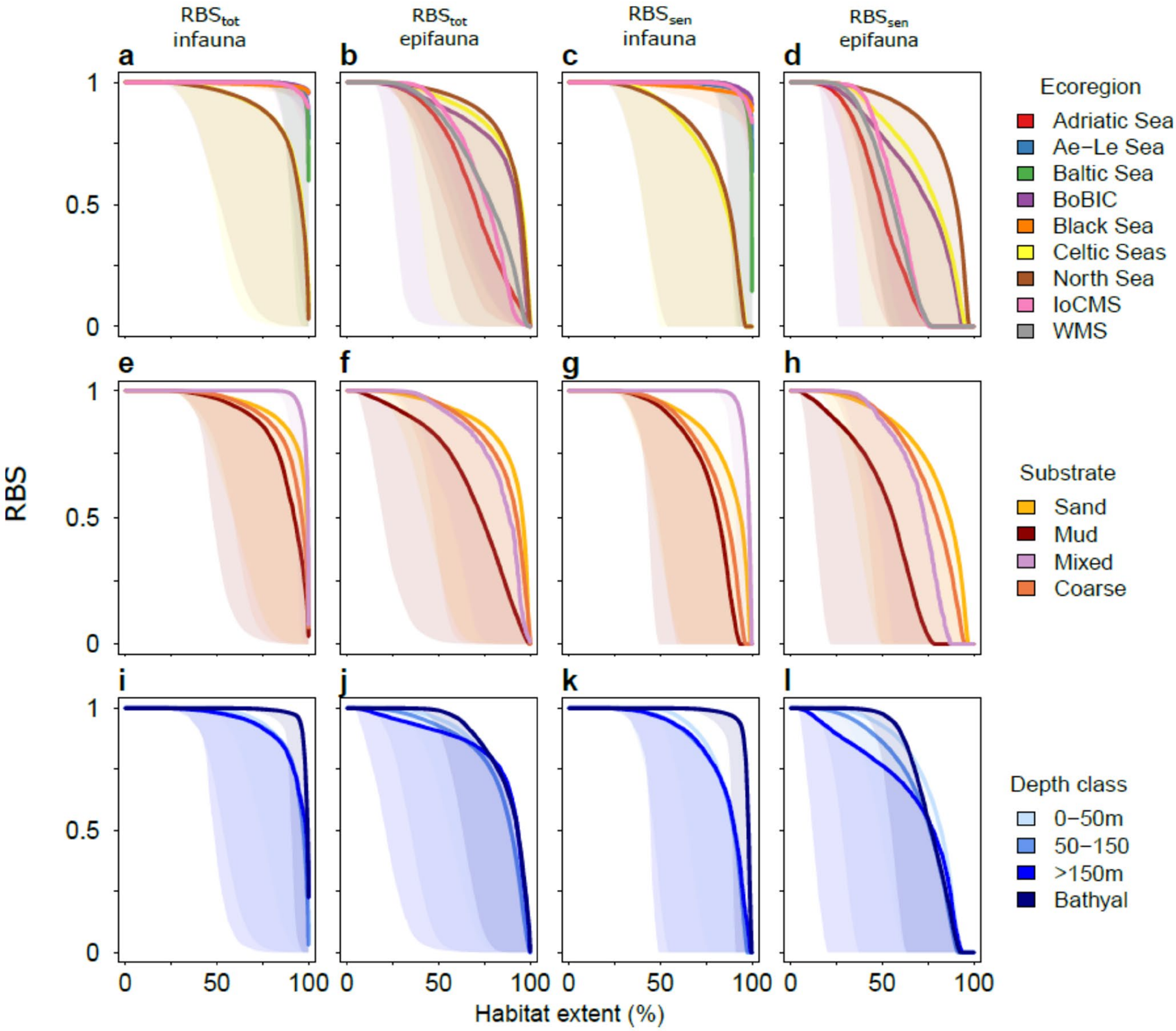

FIGURE 4 | Distributions of grid cell values of Relative Benthic Status indicators (RBS$_{tot}$ and RBS$_{sen}$) ordered from 1 to 0 for infauna and epifauna versus the cumulative percentage of the area per ecoregion (a–d), substrate type (e–h) and depth class (i–l). The lower uncertainty interval is indicated by the band between the mean and the lower 95% confidence interval and is estimated by 1000× resampling of the depletion and recovery parameters. Bathyal includes all grid cells categorised as part of the bathyal zone. These grid cells are excluded from panels e-h and are not part of the depth class > 150 m. BoBIC = Bay of Biscay and the Iberian Coast; WMS = Western Mediterranean Sea; IoCMS = Ionian Sea and the Central Mediterranean Sea; Ae-Le Sea = Aegean-Levantine Sea.

(particularly off the northern coast of Africa and the eastern Adriatic Sea) (Paolo et al. 2024).

The estimates of benthic status are based on the assumption that the state is in equilibrium with bottom trawling distribution. If historical patterns of bottom trawling activity before this period would have been very different, this equilibrium assumption might lead to underestimates of the bottom trawling impacts. However, because the distribution of bottom trawling is known to be relatively stable over time (e.g., Stelzenmüller et al. 2008) and variations in effort distribution further back in time will have less of an effect on the current seabed state, we do not expect such variations to create a significant bias in our outputs.

The results presented here may appear to give a more positive assessment of the state of the seabed than other regional scale studies using other state or impact indicators, and using other assessment approaches. Many different indicators of seabed state have been proposed, and a comparison of these indicators has shown that the importance of selecting diversity and trait-based indicators to capture the broader signals of change in benthic communities due to bottom trawling activities (Van Denderen et al. 2024). Other studies using a similar approach found a similar magnitude of bottom trawling impacts in Europe (Pitcher et al. 2022), while an assessment of trawling impacts on Vulnerable Marine Ecosystem indicator taxa in New Zealand indicates more severe impacts of bottom trawling on some taxa in some bioregions (Stephenson et al. 2025). Qualitative or

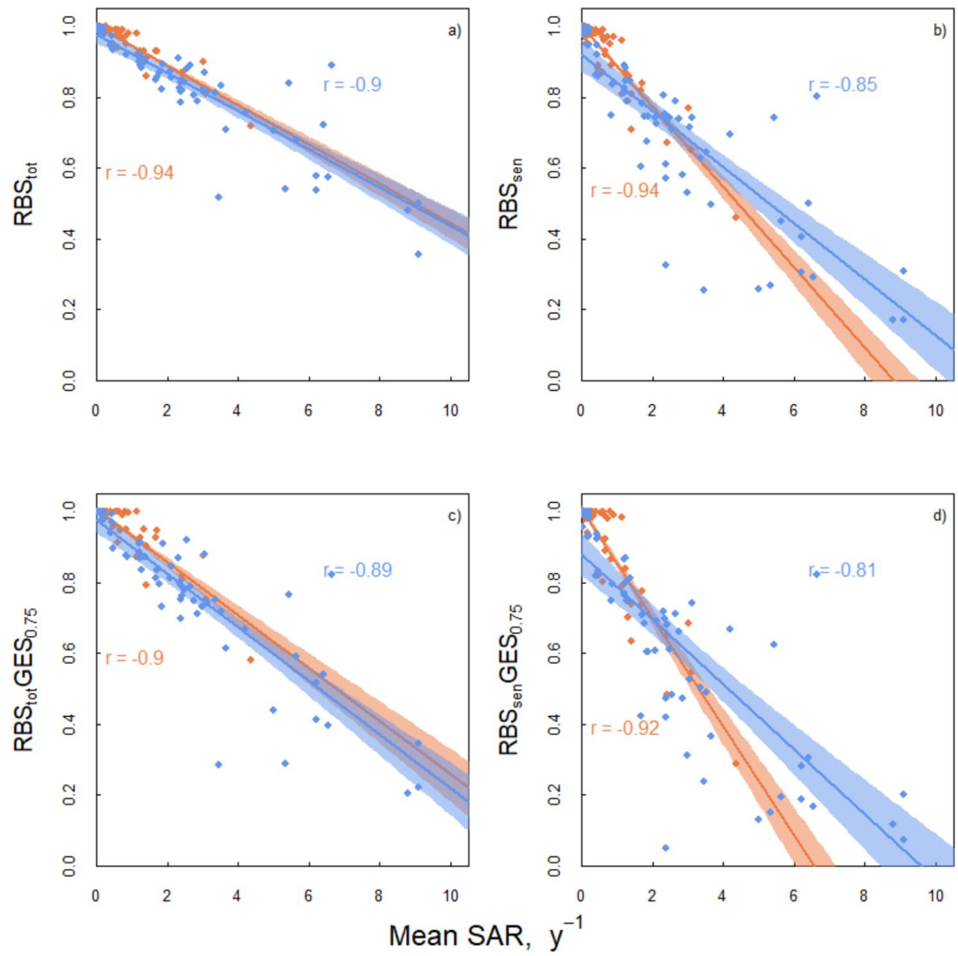

FIGURE 5 | Correlations between the state of the seabed and the intensity of bottom trawling. For (a) and (b) data points are the mean RBS_{tot} and RBS_{sen} per ecoregion and MSFD Benthic Broad Habitat Type, (c) $RBS_{tot}GES_{0.75}$ is the fraction of the area of each MSFD Benthic Broad Habitat Type for each ecoregion that is assumed to be in Good Environmental State (GES) and has a $RBS_{tot} > 0.75$ and hence can be considered in a good state. (d) $RBS_{sen}GES_{0.75}$ is the fraction of each Marine Strategy Framework Directive (MSFD) Benthic Broad Habitat Type for each ecoregion that has a $RBS_{sen} > 0.75$ and hence can be considered in a good state. Orange = epifauna, blue infauna.

categorical approaches have yielded very different assessment outcomes for the same regions in the North-East Atlantic. For example, McQuatters-Gollop et al. (2022) reported that the BH3 indicator of the extent of physical damage to predominant special seabed habitats, which is based on an expert-judgement-derived spatial analysis of habitat distribution and sensitivity, versus pressure extent and intensity (Elliott et al. 2018), showed 58% of the Greater North Sea and the Celtic Seas were assessed as highly disturbed and thus in poor status as a result of bottom trawling. Similarly, (Nikolaou et al. 2025) indicates that most European regions are far from demonstrating a good state because they are suffering from intense pressures and impacts, but again this assessment is based on a qualitative expert-driven evaluation. Differences between the assessment in this paper and other overlapping assessments are therefore likely driven by differences in the assessment approach (quantitative and data-driven vs. qualitative and expert-judgement driven) and differences in the state or impact indicators reported.

The method reported here predicts the relative community biomass, which is the biomass as a fraction of what it would be without bottom trawling. This has the advantage that it is easy to compare the states of different habitats and the data demands of the approach are low. However, it also means that in final products, all cells are equally weighted regardless of the amount of biomass they can support, and areas that can support a high biomass are not given more importance. If a data layer predicting biomass carrying capacity can be provided, absolute biomass can be predicted using this approach.

Although we show here that the impact of bottom trawling on the state of benthic communities is limited in a large fraction of European seas, with larger impacts in some regions, reconciling fishery production with ecosystem conservation remains a challenge. Bottom trawling provides a substantial share of global seafood landings and is economically important and supports coastal livelihoods (e.g., Amoroso et al. 2018; Suuronen et al. 2020). However, the impacts of bottom trawling beyond those documented in this paper include issues such as bycatch, carbon release from the sediment, overexploitation and high fuel use CO_2 emissions (Hilborn et al. 2023). Mounting scientific evidence on the impacts of bottom trawling, including high-profile contributions such as Sala et al. (2021), which explicitly framed scientific findings in support of specific global policy targets, has been accompanied by advocacy campaigns that have amplified public opposition and, in turn, influenced fisheries governance and policy, and the boundary between objective evidence and policy-oriented framing can become blurred (Rice 2011). In Europe, the EU Action Plan (COM 2023) outlines measures to phase out bottom trawling in sensitive habitats, particularly within Marine Protected Areas (MPAs).

Our approach provides a quantitative framework to support management decisions that aim to balance fishery production with the maintenance of healthy ecosystems and long-term sustainability. Our outputs are of great utility for environmental and fisheries management. Integrating indicators such as these into policy frameworks is essential to achieve long-term ecosystem resilience and ensure long-term sustainable use of fisheries resources. This approach provides outputs and methods to address and monitor progress towards the EU's Marine Strategy Framework Directive (MSFD) (EU-MSFD 2008) and the UK's Marine Strategy (UKMS) (DEFRA 2019), which state that Good Environmental Status must be achieved by 2030. It also supports sustainability objectives for trawl fisheries driven by international conventions, sustainable development goals and sustainable seafood certification requirements for individual fisheries.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available on Zenodo (van Denderen et al. 2025) except for data of Spain in the Mediterranean EEZ and parts of the Italian EEZ. The methodology to run the assessment is available on https://github.com/ices-eg/FBIT. All sources for the biological trait information can be found in Table 1. All sources to obtain the fractional biomass by longevity class for each sample as well as the original benthic sampling data are provided in the 'Data availability' section in the supplement (Text S2). Seafloor habitat and depth information for each grid cell are provided in van Denderen et al. (2025).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** faf70054-sup-0001-Supinfo. docx.