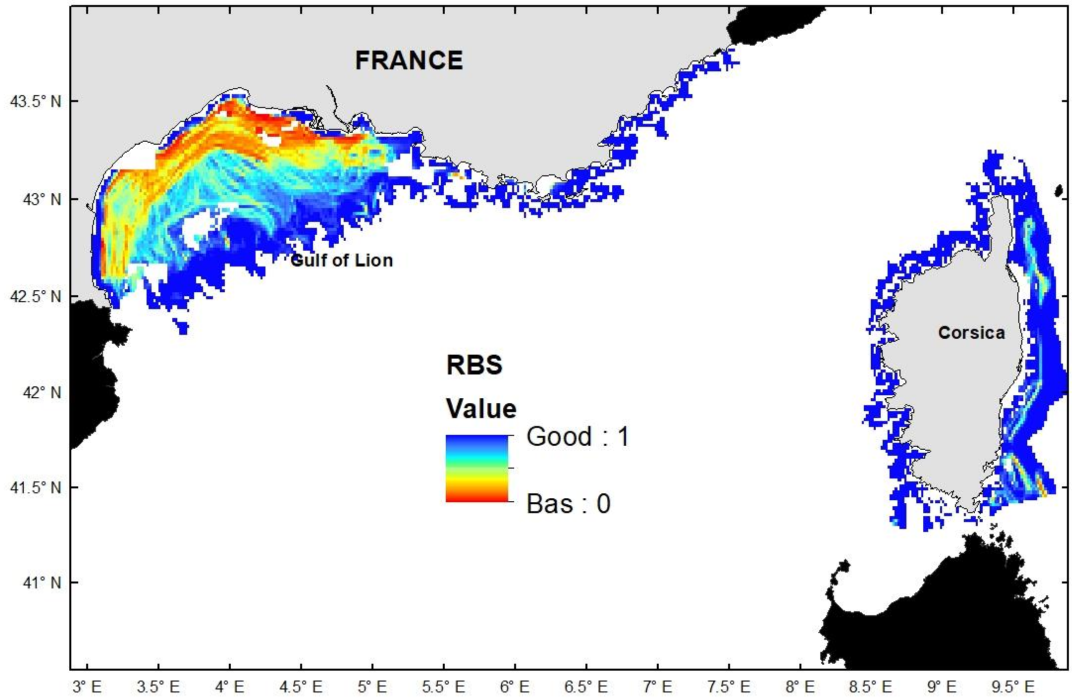
Seabed sensitivity to bottom trawling in the French Mediterranean

Application of ICES WGFBIT assessment framework



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The Mediterranean continental shelf's benthic habitats have been subjected to high-intensity bottom trawling for decades. This has resulted in benthic biodiversity erosion and degraded seabed conditions. The ICES Working Group on Fisheries Benthic Impact and Trade-offs (WGFBIT) has developed an assessment framework, based on the life history trait longevity, to evaluate the benthic impact from fisheries at regional scale. In this study, the framework is applied to the French Mediterranean. First, we collated Mediterranean longevity databases and developed a common database based on fuzzy coding of longevity classes to be applied to the French data (by-catch benthic invertebrates data resulting from scientific bottom trawl monitoring surveys). This database was then used to associate existing benthic biomass data with longevity classes. Then, a multinomial GLMM was fitted, linking biomass per longevity class to environmental predictors. Next, we used this model to predict the average benthic community longevity value under reference conditions as a proxy of benthic sensitivity. We predicted more sensitive habitats in upper/lower bathyal sediment, and less sensitive habitats in the more shallow, muddy sediments. Last, the predicted longevity curve parameters were used to estimate local carrying capacity and benthic vulnerability (expressed as Relative Benthic State) based on known fixed depletion rates, the observed biomass and abrasion rate. In agreement with previous studies, our Relative Benthic State estimate suggested highly impacted area's close to the coast in the Gulf of Lion, and lowest impacted habitats around Corsica. Many uncertainties remain and this first preliminary application will need to be further developed and validated in the future.

Mots-clés/ Key words : benthic sensitivity, trawl impact, Mediterranean, longevity, Relative Benthic State, FBIT

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1 Introduction

The disturbance caused by bottom-trawling is among the most widespread sources of anthropogenic impact on marine ecosystems (Hiddink et al., 2007; Halpern et al., 2008). This impact on seabeds is due to the accumulation of numerous effects (Dounas et al., 2007), for instance, the trawling gear mechanically damages biogenic structures, increasing the mortality of benthic fauna and affecting the structure and functioning of invertebrate communities by changing species compositions (Collie et al., 2000; Rumohr, 2000; Thrush & Dayton, 2002). In addition, benthic communities are impacted indirectly by fishing activity as it releases clouds of suspended sediment (Palanques et al., 2001), resulting in the release of nutrients to the overlying water (Durrieu de Madron et al., 2005) and resuspending biologically recyclable organic material (Mayer et al., 1991).

Also on the Mediterranean continental shelf, benthic habitats have been subjected to high-intensity bottom trawling for decades (Jackson et al., 2001). This has resulted in benthic biodiversity erosion and degraded seabed conditions. In the gulf of Lion, 50% of original benthic communities were replaced by communities adapted to the impact of fishing (Jac et al., 2020b). A maximum of 10% of the area was considered to be in 'good environmental status' (EC, 2008). However, in Corsica, about 40% of the studied area was considered to be in good environmental status and no habitats were classified as lost (Jac et al., 2020b; Figure 1).

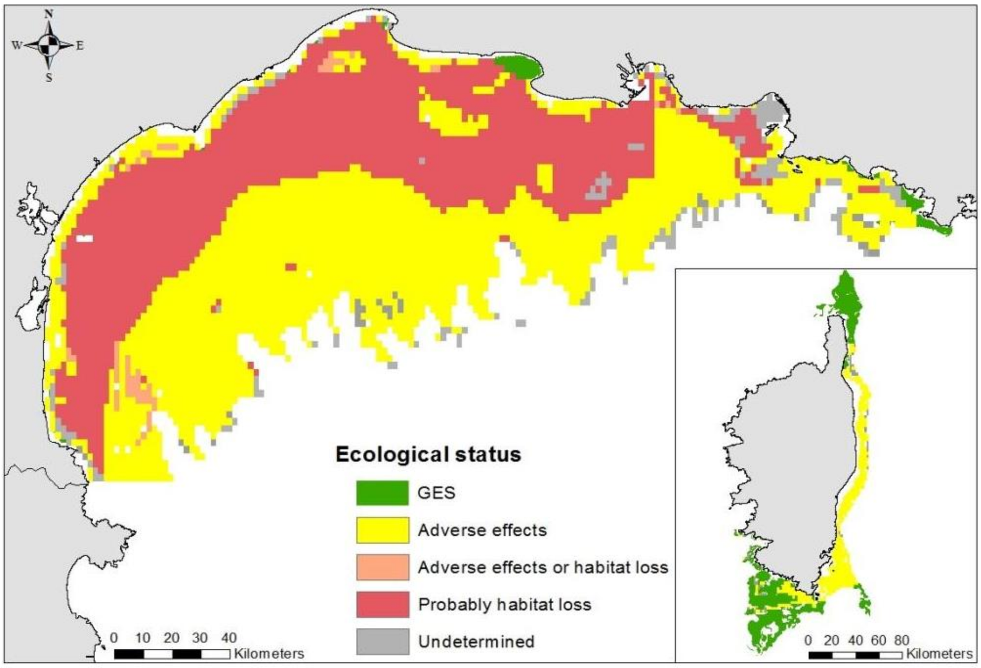

Figure 1. Ecological status of benthic habitats in the French Mediterranean Sea (Jac et al, 2020b).

The impact of bottom trawling on benthic habitats is determined by the frequency of disturbance, which is governed by exposure to fishing activity, and mortality rates of affected species, which is governed by the depletion rate (Hiddink et al., 2017). The latter depends on the penetration depth of the gear into the sediment (Hiddink et al., 2017), the morphology and size of organisms, and their positioning in the sediment surface (Rijnsdorp et al., 2018; Sciberras et al., 2018). In addition, life-history traits determine the capacity to withstand this impact of bottom trawling. Species with a higher intrinsic rate of increase (r), who also have higher recovery rates, are expected to be less sensitive to a certain rate of mortality (Hiddink et al., 2019). These higher intrinsic rates of increase tend to be associated with certain characteristics, such as higher metabolic rates, earlier maturity, higher annual reproductive output, higher natural mortality and lower average life span (Brown et al., 2004; Savage et al., 2004). Therefore, Hiddink et al. (2019), showed that the effect of any given rate of trawl mortality on a population will depend on its life history, whereby populations with low intrinsic rate of population increase, low mortality rates (M) and greater longevity (Tmax) have an increased sensitivity to trawling disturbance.

In 2008, the European Union adopted the Marine strategy Framework Directive (MSFD). The MSFD aimed at achieving good environmental status of the marine environment by 2020 (EC, 2008). Seabed integrity is the sixth of eleven descriptors used for the status of the marine environment. Descriptor 6 of the MSFD ‘reflects the safeguarding of the characteristics (physical, chemical and biological) of the sea-floor, including natural spatial connectivity, upon which a healthy structure and functioning of marine ecosystems depend’ (EC, 2008). This required the development of indicators and assessment tools to monitor the effect of human pressures on the marine environment. Many indices can be used to detect changes in the benthic fauna community under fishing pressure. However, not all of them are sufficient to detect the change caused by physical disturbance, such as trawling impact. Jac et al., (2020a) lists species richness, community biomass, Shannon index (Shannon and Weaver, 1963), Margalef diversity (Margalef, 1958), Pielou evenness (Pielou, 1969) and Simpson index (Simpson, 1949) as univariate indices for assessing the effects of trawls on benthic communities. On top of that, indices based on biological traits like the Trawl Disturbance Indicator (TDI, de Juan & Demestre, 2012) and the vulnerability index (Certain et al., 2015) are proposed (Jac et al., 2020a). Biological traits used in these methods are e.g. mobility, fragility, position on substrata, average body size and feeding mode, all being related to an individual’s sensitivity to trawling. At last, modelling approaches have been developed, such as the Relative Benthic Status method (RBS; Pitcher et al., 2017), based both on the longevity composition of the benthic community (Eigaard et al., 2017; Rijnsdorp et al., 2018) and a biomass reconstruction method (Lambert et al., 2011).

The introduction of a satellite-based vessel monitoring system (VMS, Eigaard et al., 2016) has greatly improved the possibility to investigate the relationship between bottom trawling and benthic community alternation. VMS is a surveillance and enforcement tool developed in the early 2000s that allows for spatial and temporal data collection of fishery efforts (Eigaard et al., 2016). Now, VMS provides high-resolution large-scale data on European fishing activity for the largest vessels (Eigaard et al., 2016). This data informs on the time spent to fish per area and time units (Lee et al., 2010). Before, the assessment of bottom trawling impact on the seabed was limited by the lack of data on trawling effort at the appropriate resolution. Bottom trawling is characterised by its patchy distribution, both in space and time (Lee et al., 2010; A. Rijnsdorp, 1998; van Denderen et al., 2015). On top of that, differences in the gear and boat characteristics cause different benthic impacts. Therefore, the impact on the seabed is better reflected by the total swept area ratio (SAR), per area, and time unit than by the number of fishing hours (Eigaard et al., 2016, 2017).

The Working Group on Fisheries Benthic Impact and Trade-offs (WGFBIT) is an International Council for the Exploration of the Sea (ICES) expert group that 'develops methods and performs assessments to evaluate the benthic impact from fisheries at regional scale, while considering fisheries and seabed impact trade-offs' (ICES, 2022). The current study is part of the working group's objective to implement their MSFD D6 assessment framework to produce (sub-)regional assessments for the North, Celtic, Baltic, Arctic (Icelandic, Norwegian Barents), Mediterranean Seas, the Bay of Biscay and the Iberian Coast. In this study, the approach developed by the WGFBIT is applied to the French Mediterranean. First, we aim at collating Mediterranean longevity databases and developing a common database based on fuzzy coding of longevity classes to be applied to the French data (by-catch benthic invertebrates data resulting from scientific bottom trawl monitoring surveys). This database is used to associate existing benthic biomass data to longevity classes. Then a multinomial GLMM is fitted linking biomass per longevity class to environmental predictors. Next, we aim to use this model to predict the average benthic community longevity value under reference conditions as a proxy of benthic sensitivity. Last, the predicted longevity curve parameters are used to estimate local carrying capacity and benthic vulnerability (expressed as relative benthic state, RBS) based on known fixed depletion rates, the observed biomass and abrasion rate.

2 Methods

2.1 Study area

Trawling in the French Mediterranean (Figure 2) mainly takes place in two regions: the Gulf of Lion and the east coast of Corsica (longitude from 2.5°E to 10°E and latitude 40°N to 44°N).

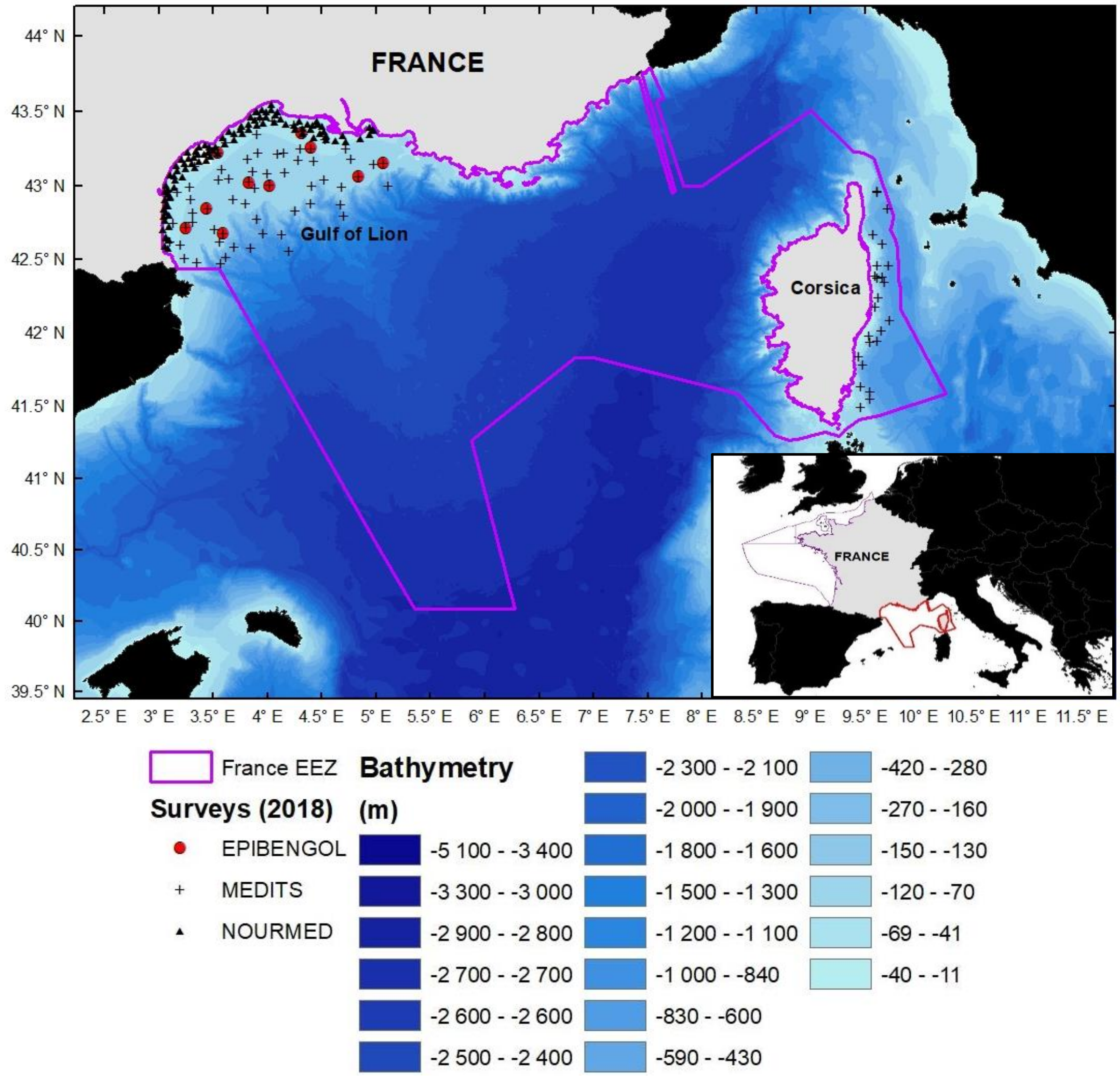

Figure 2. Map of the French waters showing extent of the French Exclusive Economic Zone (EEZ), and, in the Western Mediterranean, the local bathymetry and surveys' positions in 2018.

The Gulf of Lion is located in the North-Western Mediterranean Sea and has an average depth of 90 m (Figure 2). It is a wave-dominated continental shelf, characterised by a micro-tidal regime and incised by numerous submarine canyons (Tesi et al., 2007) down to the abyssal plain at 1000-2000m depth. The granulometric distribution on the shelf consists of a sandy band on the inner shelf, a mud belt in the mid-shelf and a mixture of relict sands and finegrained sediments on the outer shelf (Roussiez et al., 2005). The gulf contains the estuary of the Rhône River, which represents a major freshwater and organic carbon input in the Mediterranean Sea (Tesi et al., 2007).

Corsica is a French island located in the northeast of the Western Mediterranean Sea (Figure 2). The island's east coast is characterised by a relatively narrow continental shelf, with a width varying between 5 km in the north and 25 km in the south (Bellaiche et al., 1994; Jac et al., 2022). The depth increases rapidly with distance from the coast, reaching about 900 m in the area between Corsica and Italy. The area has a current running in the northern direction along the Italian coast with strong seasonal variability (Jac et al., 2022).

2.2 Longevity data

We collated Mediterranean longevity databases and developed a common database based on fuzzy coding of longevity classes to be associated with the benthic biomass data. Fuzzy coding is a method in which the probability of a taxon belonging to a certain age class is determined (Bolam et al., 2017). Seven longevity databases were available (see Appendix A). In order to collate the databases, they were first adjusted to the same format in Rstudio (version 1.4.1106). The general procedure consisted of uploading the taxon lists in WORMS to match them to their accepted scientific names and AphiaID (WoRMS Editorial Board, 2022). Appendix B gives a detailed overview of the decision-making process for matching the taxa to their scientific names in WORMS. Second, the longevity classes were transformed according to the Relative Benthic Status method (RBS; Pitcher et al., 2017) into four classes: <1, 1-3, 3-10 and >10 years. Fuzzy coding was used where three longevity classes were transformed into four longevity classes. The longevity classes were standardised in case their sum did not equal one. The result of this first step was one dataset containing the average longevity (and standard deviation) per taxon, based on fuzzy coding of the seven available databases.

2.3 Benthic biomass data

Biomass data was used from MEDITS (Jadaud, 2018), EPIBENGOL (Vaz, 2018) and NOURMED (Vaz, 2018) trawl surveys on mega-epifaunal benthic invertebrate biomass (expressed in g.km-2, table 1). During these trawl surveys, certain stations were sampled (Figure 3) and data was used from 2012 to 2019. First, the taxon list of the benthic biomass dataset was uploaded to WORMS to match them to their accepted scientific names and to obtain their full taxonomic classification (WoRMS Editorial Board, 2022). Appendix C gives a detailed overview on the decision-making process for matching the taxa from this dataset to their scientific names in WORMS. Then, for each observation, the biomass was divided by the swept surface to obtain biomass in gram per Km². Next, the benthic biomass data was assigned to the fuzzy coding longevity classification, on the lowest taxonomic level possible.

Table 1. Number of stations per year per survey used in this study. The number in brackets shows the number of species per year per survey.

	EPIBENGOL	MEDITS	NOURMED
2012	0	89 (180)	0
2013	0	88 (372)	0
2014	0	89 (394)	0
2015	0	88 (432)	0
2016	0	87 (389)	0
2017	0	90 (400)	0
2018	10 (118)	89 (420)	102 (209)
2019	0	94 (414)	114 (256)

Before matching the biological data to our collated longevity dataset, certain taxa were removed from the analysis (Table 2). According to the WFGBIT framework (ICES, 2022), some species, in particular commercial ones, need to be removed from the dataset as they often dominate the total biomass and their distribution is not independent from effort (risk of circularity in the approach).

Table 2. Overview of taxa that were removed from the benthic biomass data per taxonomic level.

Taxonomic level	Removed taxa
Kingdom	Plantae, Chromista
Phylum	Mega-zooplancton listed by Aubert & Thibault, 2017
Class	Chlorophyta incertae sedis, Actinopterygii, Elasmobranchii, Holocephali, Petromyzonti, Myxini, Scyphozoa, Cephalopoda
Order	Myopsida, Oegopsida

Not all taxa from the benthic biomass data existed in the longevity dataset. Therefore, only part of the benthic biomass dataset could be matched to longevity data at species level. A hierarchical procedure was used to further associate the remaining observations with longevity information. First, these remaining observations were associated based on an exact match of their genus with the genera for which longevity was present in the collated longevity dataset. In addition, a dataset was created with average longevity at genus level, calculated from the collated longevity dataset. Again, the remaining observations were matched to the calculated genus averages. Similarly, longevity was averaged at family, order and class level, and these calculated datasets were used to continue hierarchically associating the unmatched data. A couple of species observations had only a phylum taxon level. For these also a dataset was calculated with average longevity on phylum level.

2.4 Environmental predictors

Three types of spatial information were used for the inclusion as predictors in the model: fishing abrasion data, MSFD habitats and environmental layers.

2.4.1 Abrasion estimates

Abrasion data is expressed as the Swept Area Ratio (SAR). The SAR is used as the unit of abrasion by ICES to assess fishing pressure on the seabed by dragging gear (ICES, 2020). The swept area is calculated by multiplying the linear length of a fishing action by the width of the fishing gear. The linear length of fishing actions is estimated from the information provided by the Vessel Monitoring System (VMS) data. The width of fishing gear is estimated based on vessel and metier characteristics (Eigaard et al., 2016).

The linear distance travelled during a fishing operation is estimated by ALGOPESCA, an algorithm developed by ifremer that processes VMS data from all fishing vessels operating in the French EEZ (including foreign vessels). In France, every hour, the VMS transmits data containing geolocation, instantaneous speed, and heading. Therefore, the ALGOPESCA assumes a straight trajectory of the fishing vessels between two positions. A vessel is considered to be trawling when its average speed is below 4.5 knots. However, in certain situations, e.g., when arriving in a port, the vessel may also reduce its speed to below 4.5 knots. To limit potential biases, data that is retrieved from locations close to ports are excluded (ICES, 2019). The exclusion of data close to ports potentially underestimates the abrasion. On top of that, abrasion will be underestimated because coastal fishing fleets may be dominated by vessels smaller than 12 m, which are not required to and very rarely use VMS tags. The methodology used to derive this metric from vessel size or power is detailed in Georges et al. (2021).

The abrasion data used for this analysis is retrieved from annual maps in GeoTIFF format from 2012 to 2021, including median abrasion, at a 1’ x 1’ grid resolution (about 1.9 x 1.4 km) (Georges et al., 2021; Figure 3).

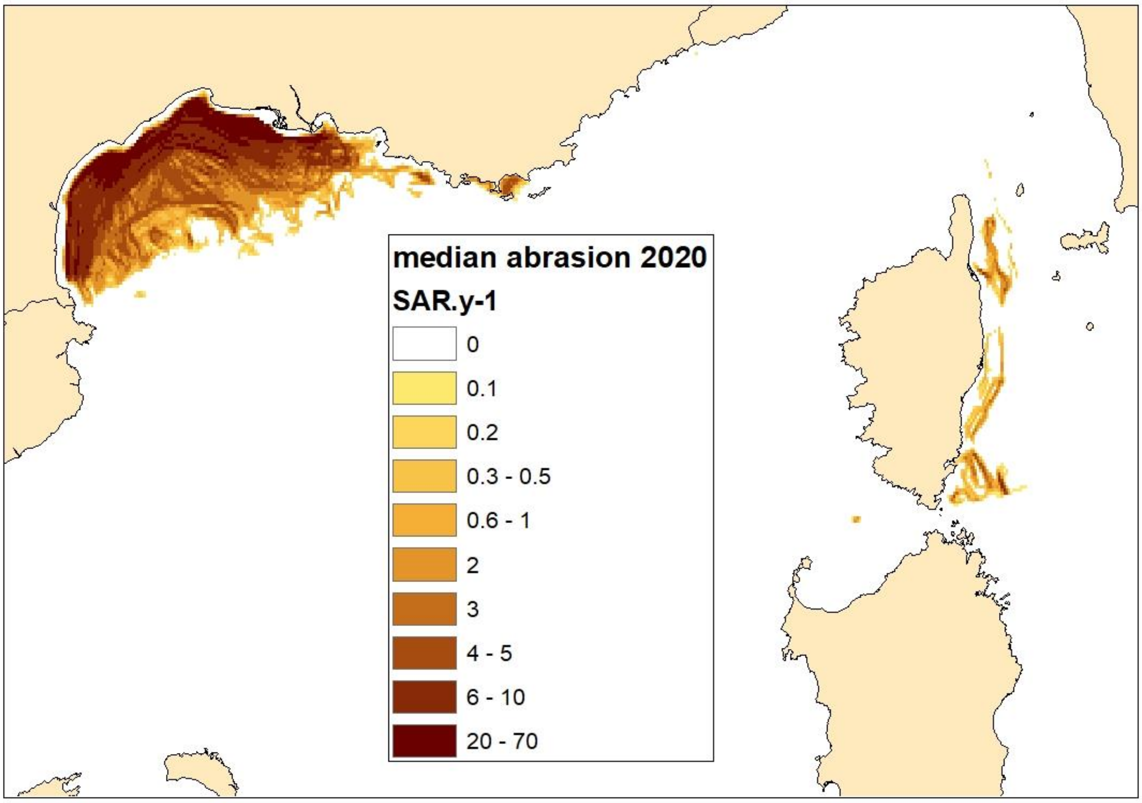

Figure 3: Median abrasion values in 2020 expressed in Surface Area Ration per year (SAR.y-1).

The SAR (Figure 3) may be interpreted as being the percentage of each cell surface that is trawled in one year. A value of 1 means that 100% of the cell surface was swept by bottom-contacting fisheries. In the area of study, values ranged from 0 to 35, meaning that there are areas that have been swept entirely, on average, 35 times within a year.

For this assessment, four metrics were used to estimate abrasion (ICES, 2022). Abrasion was estimated by 1) using the previous year's SAR value, 2) the average of the five previous years' SAR values, 3) the maximum of the five previous years' values, or 4) a weighted average of the five previous years. For the weighted average, an exponentially decreasing weight was given to years that are more distant in time: $w_{n-1} = 0.148$, $w_{n-2} = 0.054$, $w_{n-3} = 0.02$, $w_{n-4} = 0.007$, $w_{n-5} = 0.002$, with n being the observation year. The five-year period used in these metrics is based on literature reporting such recovery duration following trawling impacts (Hiddink et al., 2017).

For this study, we used the second abrasion estimate (the average of the five previous years' SAR values) as a base metric. The whole analysis was rerun using the three other estimates, in order to determine the effect of this decision on the results. Standard deviation maps of the investigated habitats' assessment outputs (sensitivity and relative benthic status) resulting from the use of the four abrasion metrics were produced.

2.4.2 MSFD Broad Habitat Maps

The WGFBIT assessment framework suggests using the MSFD broad habitat classification derived from EMODnet EUSeaMap 2021. This hierarchical habitat classification is developed following The European Nature Information System (EUNIS) and is based on environmental variables such as substrate type, energy level, depth and light penetration (Eigaard et al., 2017). In this study the EMODNET EUSeaMap 2021 for the western Mediterranean basin was used (Vasquez et al., 2021). The stations from the benthic biomass dataset from 2017 to 2019 were overlaid with the MSFD broad habitats from the EMODnet EUSeaMap (Table 3). Next, the number of stations per habitat type was assessed and only habitats covered by a minimum of 5 stations per year were investigated (Figure 4).

Table 3. Number of stations per MSFD Broad Habitat type and year. Only habitats covered by a minimum of 5 stations per year were investigated. Habitats in grey indicate the habitats that were not investigated further in the analysis.

MSFD Broad Habitat type	2017	2018	2019
Circalittoral coarse sediment	3	5	5
Circalittoral mixed sediment	1	0	0
Circalittoral mud	12	75	76
Circalittoral sand	7	35	43
Infralittoral coarse sediment	0	0	1
Infralittoral sand	0	10	9
Offshore circalittoral mud	37	47	46
Offshore circalittoral sand	4	4	5
Upper bathyal sediment or Lower bathyal sediment	26	25	23

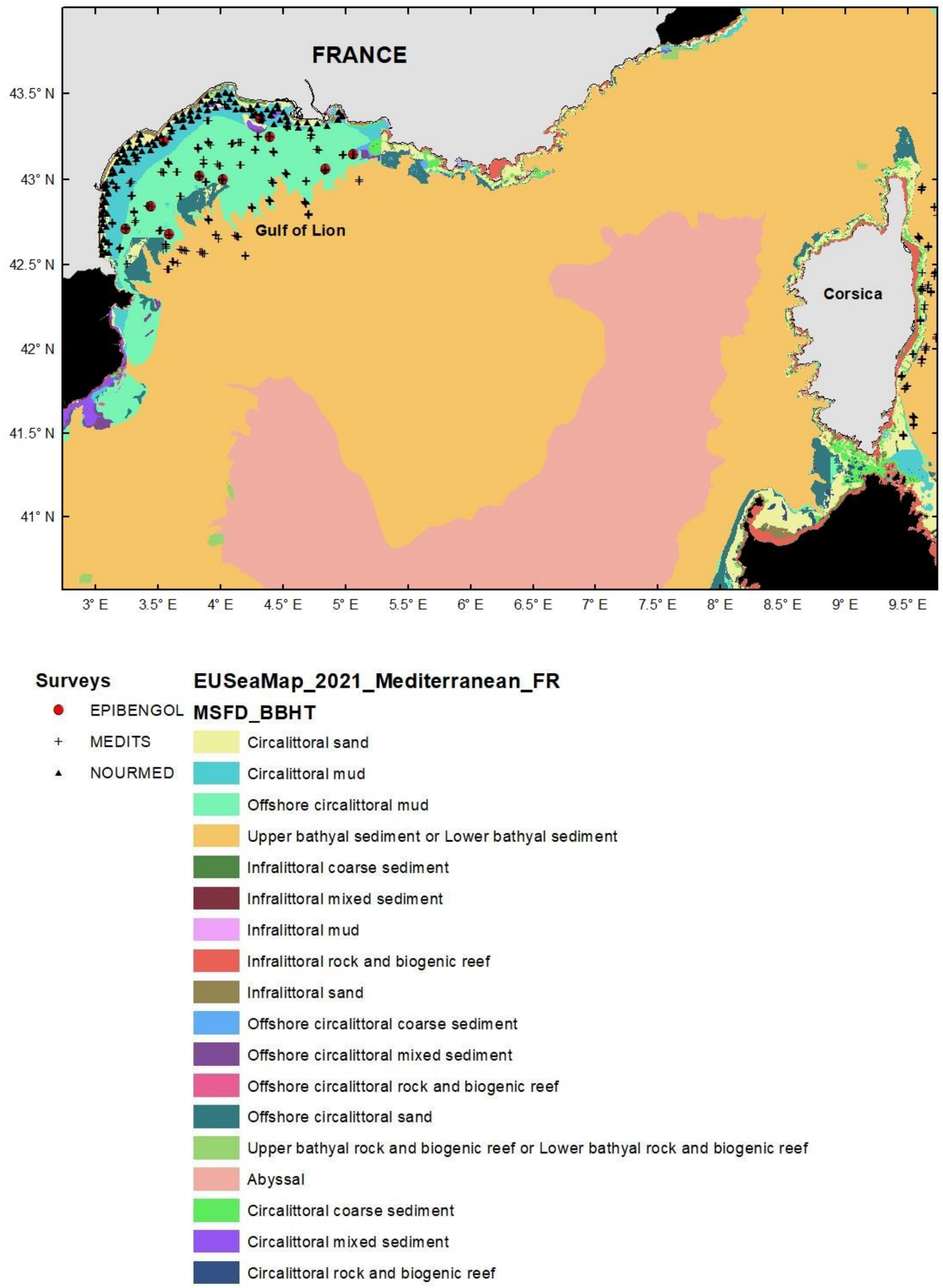

Figure 4. Map of the MFSD broad habitat types and observations used in the assessment after habitat and abrasion filtering.

2.4.3 Environmental layers

For the French Mediterranean, the MSFD broad habitat map lacks validation (Vasquez et al., 2021). As a result, the MSFD typology may not be a sufficient or reliable predictor of local environmental conditions. Instead of using the MFSD broad habitat map as a predictor in the models, several environmental variables were used in our analysis, such as mean bottom temperature, sediment average grain size, depth, seabed stress, mean bottom oxygen concentration, food availability at bottom, maximum chlorophyll, mean chlorophyll-a and stratification. The origin of these environmental predictors is detailed in Appendix D and their layers were sampled at the location of the benthic biomass observations.

The values of these environmental layers, together with abrasion, were tested for correlation (Pearson coefficients, see Appendix E) at the benthic biomass observation locations. The cut-off correlation level to assess redundancy was set to 0.8. For this value, two groups were highly correlated: on one hand, mean bottom oxygen and food availability, and on the other hand, mean and maximum chlorophyll-a concentrations. Based on these correlations and aiming to select the layers with the most complete data coverage, we chose depth, mean bottom temperature, sediment average grain size, seabed stress, mean chlorophyll-a, mean bottom oxygen concentration and stratification to be included in the model (Fig. 5).

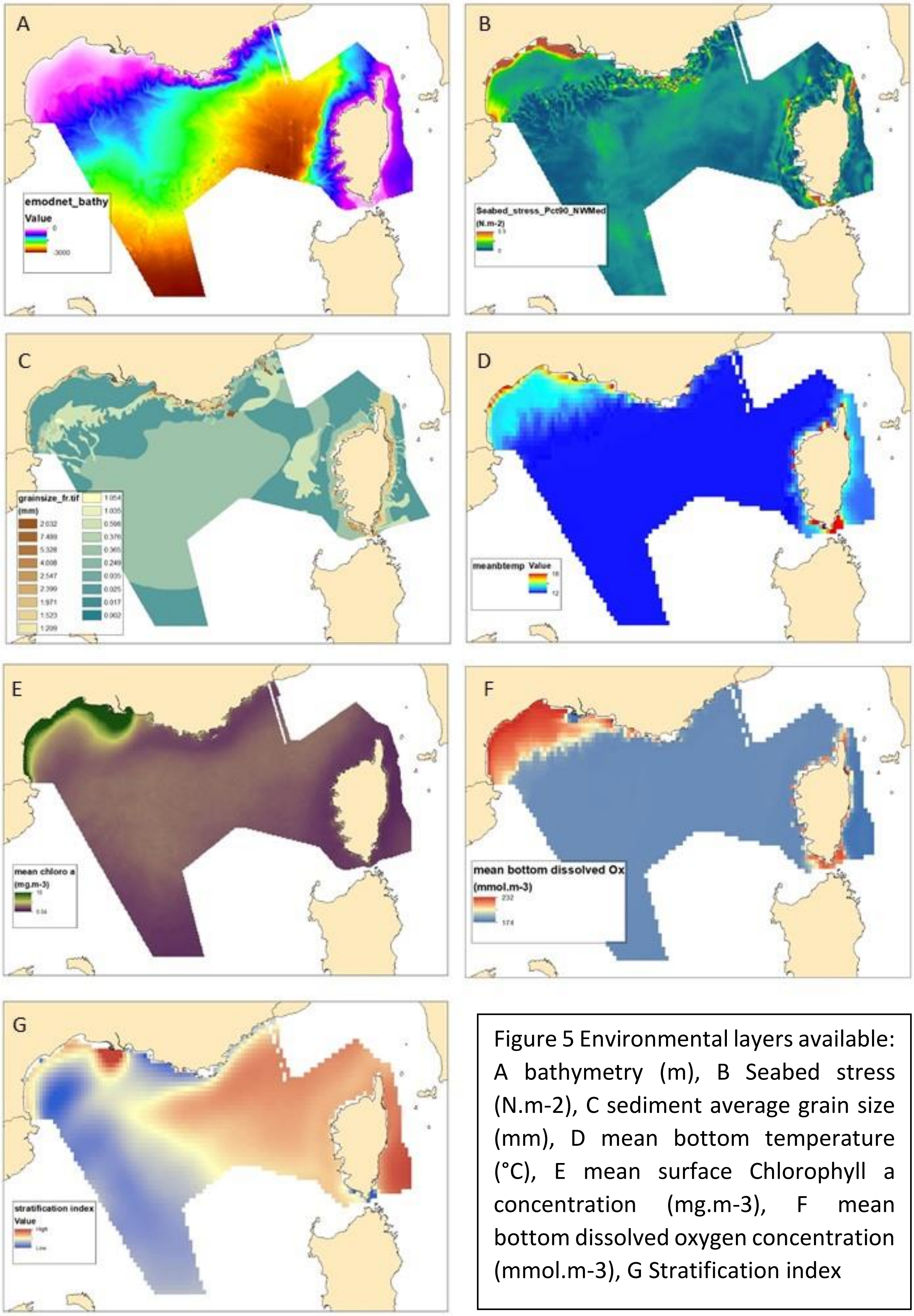

Figure 5 Environmental layers available: A bathymetry (m), B Seabed stress (N.m-2), C sediment average grain size (mm), D mean bottom temperature (°C), E mean surface Chlorophyll a concentration (mg.m-3), F mean bottom dissolved oxygen concentration (mmol.m-3), G Stratification index

2.5 Benthic longevity distribution estimation

The relative biomass of each taxon (expressed proportionally to the total biomass observed in the station) was first multiplied with fuzzy-coded trait data and summed for each station to calculate the biomass fraction of each longevity class. Then two different methods were used to account for the lack of reference stations for certain habitat types. Reference stations were defined as stations in which the abrasion metric was smaller than 0.1. Table 4 shows the number of reference stations for the second abrasion metric: the previous 5 year's average SAR value. 'Upper bathyal sediment or Lower bathyal sediment' and 'circalittoral sand' had enough reference stations and for these habitats, a model based only on the reference stations will be produced. For the other two habitats, 'Circalittoral mud' and 'Offshore circalittoral mud', not enough reference stations were available. For these, all stations will be used and abrasion will be added in the model as a predictor. Figure 4 shows all the stations used in the biomass-longevity model, after both habitat and abrasion filtering. The WGFBIT report suggests using a cut-off criterion of 0.5 as a rule of thumb, instead of 0.1 (ICES, 2022). However, in our data, using SAR<0.5 does not affect whether the habitats can be modelled by using the reference stations or by including abrasion as a predictor. Therefore, in order to be as close as possible to pristine state, we decided to use the stricter criterion (SAR<0.1).

Table 4. The number of reference stations (previous 5 year's average SAR value is lower than 0.1) per MSFD habitat and year. Habitats in grey have not enough observations to be used as reference station.

MSFD Broad Habitat type	2017	2018	2019
Circalittoral mud	0	5	4
Circalittoral sand	3	17	22
Offshore circalittoral mud	1	0	0
Upper bathyal sediment or Lower bathyal sediment	18	15	14

We fitted per habitat type a generalised linear mixed model (GLMM),

$$Cumb \sim \log(ll) + (1 \mid ID) + ENV\ (+\ ABR) \qquad (1)$$

with the cumulative biomass (*Cumb*) as response variable, longevity (*ll*) as explanatory variable and sampling station (*ID*) as random factor to account for the spatiotemporal autocorrelation. For all habitats, the previously selected environmental layers (*ENV*) were added as explanatory variables. For the habitats that did not have enough reference stations, the abrasion estimate (*ABR*) was included as an explanatory variable to the model. This model predicts the cumulative biomass-longevity distribution. It was assumed that the biomass proportion at each station is a logistic function of longevity, which starts at 0 and approaches 1 when longevity becomes large. Therefore, longevity was log-transformed and we used a mixed model with binomial distribution and a logit link function. The dredge-function of the R-package MuMIn was used to evaluate all possible model formulations based on the Bayesian information criterium (BIC). This criterium was preferred over AIC (Akaike Information Criterion) as it is known to be more parsimonious and may better prevent model over-fitting (Brewer et al., 2016).

2.6 Sensitivity estimation

The intercept and predictor coefficients (*coef_env_factor*) obtained from the GLMM (4.5) were used to predict median longevity at a given cumulative biomass (here 50%) in the study area. To do this, we reshuffled the model to get the log-transformed longevity (*coef_ll*) on the left side of the equation 1, resulting in

$$\textit{Predicted sensitivity} = (\exp((\text{logit}(0.5) - \textit{intercept} - \textit{coef\_env\_factor} * \textit{env\_factor}) / \textit{coef\_ll})) \tag{2}$$

in which we used an exponential function to back-transform the log-transformed longevity. Then a reverse logit function was used to back-transform the binomial distribution of the cumulative biomass into its original scale (logit(p) = log(p/(1-p)). For the habitats for which abrasion was included in the model, abrasion was set at 0 during longevity prediction to simulate the absence of trawling pressure on the benthic assemblage longevity. In order to avoid extrapolating the prediction to regions of the study area that were not sampled, we restricted the sensitivity prediction to depths above 800 m.

2.7 Impact calculation

To calculate impact, we multiplied the abrasion estimate for the last year (2020) by depletion rates (fraction of mortality per trawl pass estimated from experimental trawling studies) extracted from literature (0.06; selected based on the dominant type of fishing gear used in this area, namely demersal bottom trawl; Hiddink et al., 2017), resulting in

$$RBS = B/K = 1 - F*d/r \tag{3}$$

where, the relative benthic state (RBS), defined as the biomass (B) relative to the carrying capacity (K) is explained by abrasion estimate (F), the depletion rate (d) and the intrinsic rate of population increase (r), which is calculated based on a constant (Hiddink et al., 2017) and the longevity,

$$r = 5.31/\text{longevity}. \qquad (4)$$

To avoid extrapolating the prediction to regions of the study area that were not sampled, we also restricted the impact calculation to depths above 800 m.

The RBS was compared to the abrasion estimate F using Spearman correlations for each investigated habitat.

2.8 Comparison with other assessment frameworks

In their study Jac et al., 2020a&b carried out an assessment of the Gulf of Lion and Corsica benthic status based on the same biological data as we do here but using other sensibility indices than those linked to longevity. They identified four indices, linked to five biological traits sensitive to trawling (position on the sediment, size, mobility, feeding mode, fragility), that were later used to define abrasion thresholds defining status for each habitat types. These indices were the Trawl Disturbance Index (TDI), the modified Trawl Disturbance Index (mTDI), the partial Trawl Disturbance Index (pTDI), and modified vulnerability (mT).

The median longevity predicted here was therefore compared to each of these indices using Spearman correlations for each investigated habitat. For each habitat status categories that were defined by Jac et al., 2020b (GES, adverse effect, adverse effect or habitat loss, probably habitat loss), the range of RBS values in each habitat types were obtained in an attempt to verify if RBS value threshold could be identified to separate GES from adversely affected.

3 Results

3.1 Longevity merging

The merged longevity data resulted from the averaging of seven longevity databases over 2264 taxa. As a result, the averaged longevity scoring per taxon varied in the number of databases it was based on (Table 5). The standard deviations varied per taxon, from zero (e.g., *Abyssoninoe, Table 5)*, in case all available database had equal longevity values, or to higher values (e.g., *Aeolidia*, Table 5), in case the available databases indicated different longevities.

Table 5. Subset of collated longevity database. Per taxon, the mean longevity is fuzzy coded and standard deviations (sd) are given for each longevity class. “Freq” gives the number of databases available to compute the mean longevity of each taxon.

Taxon	mean <1 year	mean 1-3 years	mean 3-10 years	mean >10 years	sd <1 year	sd 1-3 years	sd 3-10 years	sd >10 years	Freq
Abyssoninoe	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	3.00
Acanthocardia	0.00	0.16	0.18	0.66	0.00	0.35	0.34	0.48	8.00
Adamsia palliata	0.00	0.08	0.68	0.25	0.00	0.15	0.47	0.50	4.00
Aeolidia	0.00	0.50	0.50	0.00	0.00	0.71	0.71	0.00	2.00
Aequipecten	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	4.00

3.2 Longevity matching

After associating the benthic biomass data with longevity data, the majority of the taxa could be associated at species level (Figure 6). This means that most taxa were represented in the collated longevity dataset. As a result, 79 % of all observations were assigned to longevity data at species level and 12.5 % of the observations were assigned to longevity data at genus level. These observations were associated with averaged longevities calculated from the merged seven available datasets. The other observations were associated with taxonomic levels for which no data was available in the original datasets. Using newly calculated longevity estimates for each taxonomic level, 0.016 % of the observations was matched at genus level, 0.042 % at family level, 0.020% at order level, 0.004% at class level and 0.005% at phylum level.

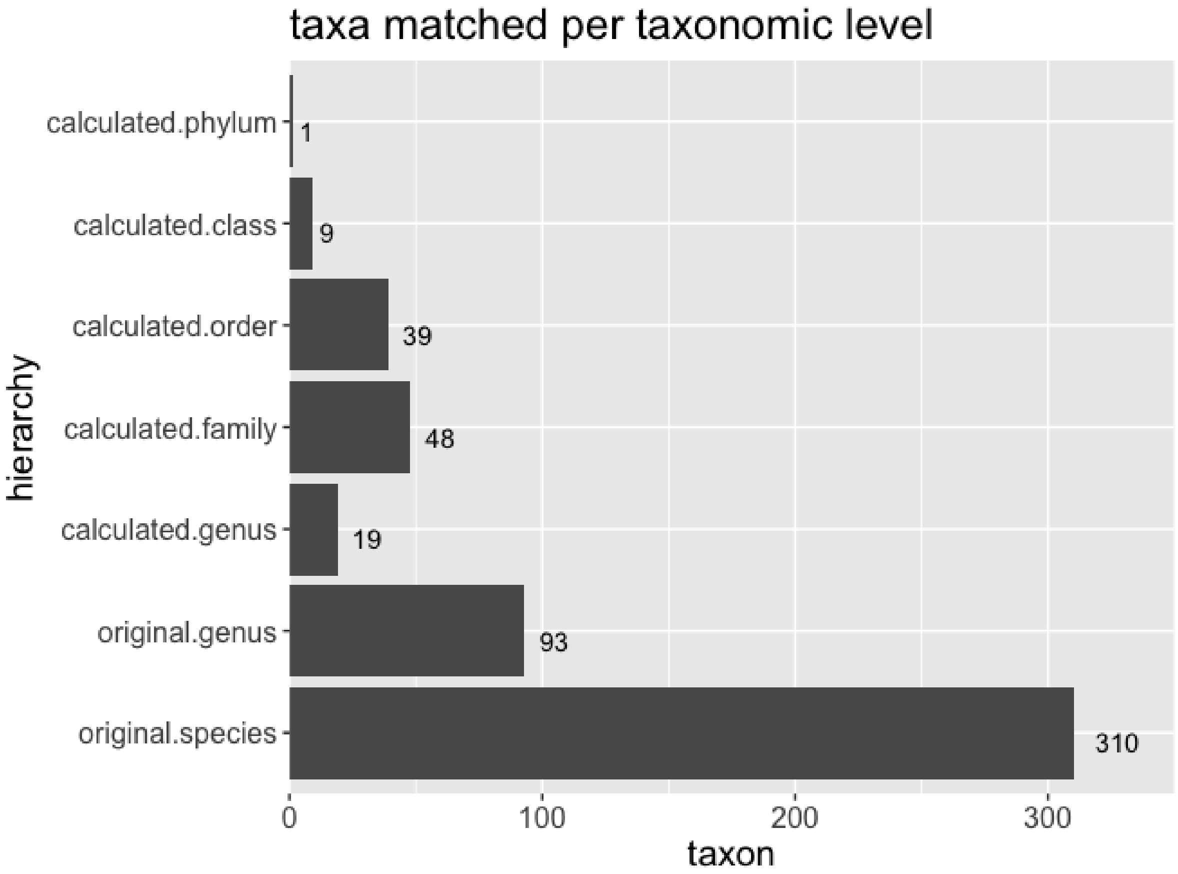

Figure 6. Number of taxa associated by taxonomic level and whether the match is based on original or calculated data. The original dataset was a collation and average of the seven available datasets. The calculated datasets were longevities for higher taxonomic levels based on averages of the original dataset.

3.3 Modelling cumulative biomass relationship to longevity and other predictors

Four MSFD broad habitat types had enough observations per year to be included in our analysis. For each habitat a distinct model was selected, relating the cumulative biomass to log-transformed longevity and environmental predictors (Table 6). It must be noted that the selected GLMM models did not differ largely in BIC with the next best models (Appendix G). For this analysis, we used the abrasion estimate 'previous 5 year's average'. Depending on availability of sufficient number of reference stations, a model was fitted without abrasion as predictor, otherwise, abrasion had to be included as predictor.

Table 6. Best model selection results per MSFD Broad Habitat type. Cumulative biomass is fitted as a response variable with sample stations (ID) as random factor and log of longevity (ll) as fixed effect. meanBdox = mean bottom oxygen concentration; ABR = abrasion estimate (SAR); meanchl = mean chlorophyll-a concentration; stratif = stratification.

MSFD Broad Habitat type	Model selection	Nber of observations *	BIC	Conditional R^2
Circalittoral sand	~ ll + (1 | ID) + meanBtemp	213	138.9	0.74
Upper bathyal sediment or Lower bathyal sediment	~ stratif + ll + (1 | ID)	132	120.0	0.76
Circalittoral mud	~ ABR + ll + (1 | ID)	258	498	0.80
Offshore circalittoral mud	~ ABR + ll + (1 | ID)	480	360.8	0.63

*After omitting all rows containing NA's

3.4 Sensitivity estimation

The regression coefficients (Appendix F) obtained from the GLMM were used to predict median longevity at a given cumulative biomass (here 50%) in the study area. The predictions were made per habitat type and afterward combined into one map for the French Mediterranean (Figure 8). The prediction was limited to the French EEZ above 800m (deepest observation available). Mean longevity is considered a measurement of the seabed sensitivity to bottom trawling.

The predicted median longevity differs between the four habitats (Figure 9). Upper/lower bathyal sediment appeared to be the most sensitive to trawling disturbance with a median of 12.2 years, in contrast with circalittoral sand with a median of 5.6 years. Circalittoral mud and offshore circalittoral mud are predicted to be constant (as only abrasion entered the model) and to have respectively 6.2 and 8.8 years of median longevity.

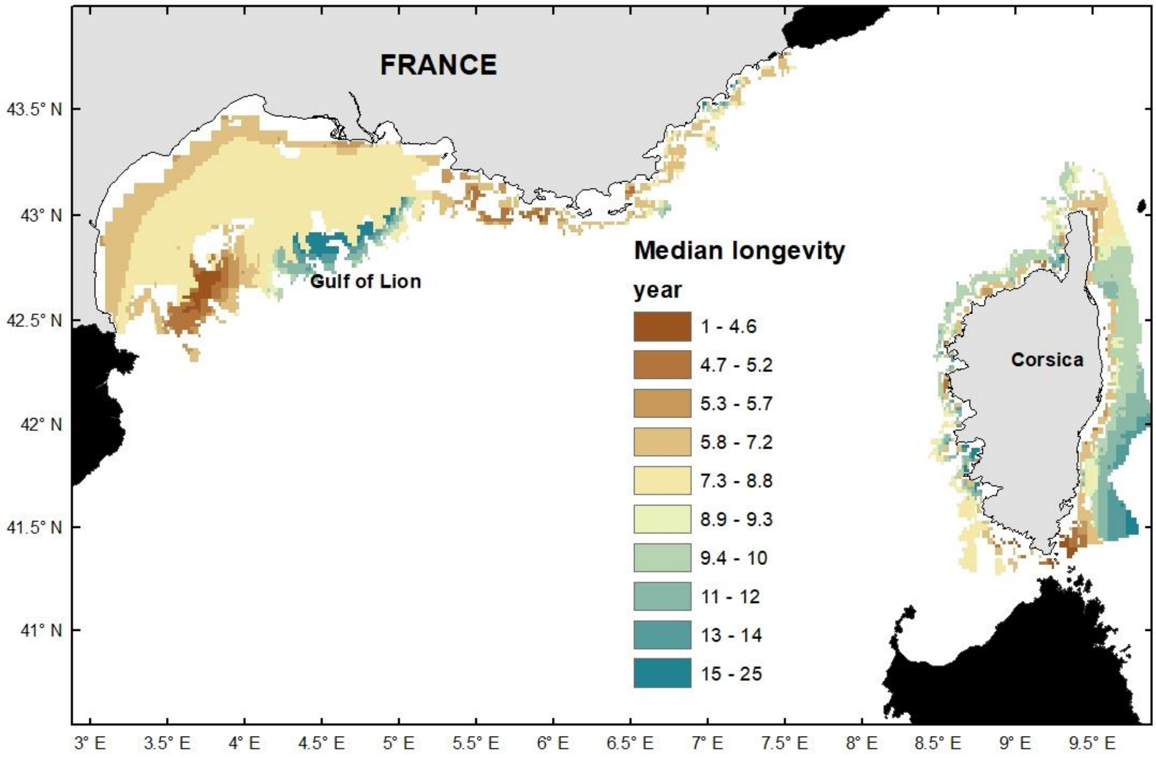

Figure 8. Predicted median longevity for French Mediterranean (Four habitats combined).

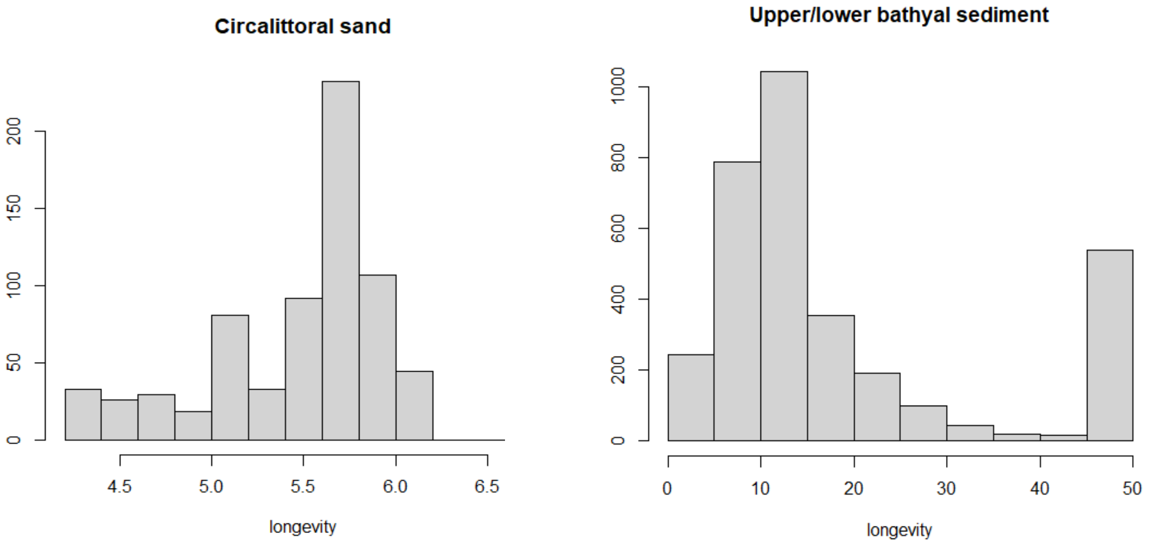

Figure 9. Distribution of median longevity in the investigated MSFD broad habitat types.

3.5 Impact calculation

The distribution of the Relative Benthic State (RBS) indicator across the gulf of lion and Corsica was estimated per habitat and then combined into one map (Figure 10). The prediction was limited to the French EEZ above 800m (deepest observation available). RBS values range between zero and one, with zero indicating a bad state, and one a good state. Combining all habitats, RBS shows a difference between the gulf of lion and the Eastern coast of Corsica, which are both target areas for bottom trawling.

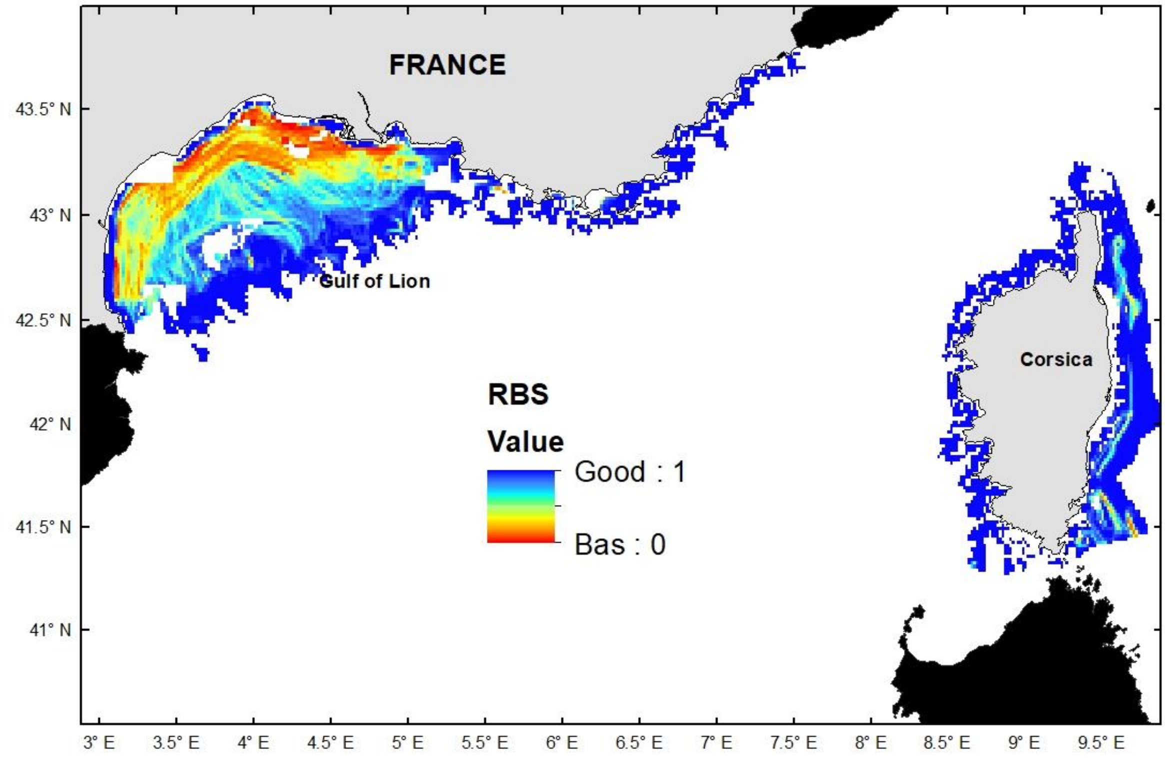

Figure 10. Relative Benthic State for the French Mediterranean (four habitats combined). The scale goes from 0 = bad state, to 1 = good state.

Based on our prediction, the gulf of Lion's seabed is in a worse state than that of Corsica. In the gulf of Lion, the state gets progressively worse when following a gradient towards the coast. Upper/lower bathyal sediment is predicted to be in the best state.

The negative correlation between our RBS prediction and the abrasion in 2020 (the year used for the RBS prediction) was very high, significant and almost constant over the four habitat types investigated (Table 7), highlighting how influential this variable is in this particular instance.

Table 7. Pearson correlation between RBS and 2020 abrasion. All values are significant ($p < 0.001$).

Broad Habitat type	Pearson correlation coefficient
Circalittoral sand	- 0.86
Upper/lower bathyal sediment	- 0.99
Circalittoral mud	- 0.96
Offshore circalittoral mud	- 0.97

3.6 Uncertainty resulting from chosen abrasion metric

To determine the effects of the abrasion metric used on the assessment framework results, we reran the whole analysis, including model selection (Appendix H), with the other three abrasion metrics. The standard deviation between the four resulting sensitivity and RBS prediction maps were then computed and are presented in figures 11 and 12 respectively. The results show that large uncertainty levels, of up to 21 years, in estimated longevity are present in upper bathyal sediment and offshore circalittoral mud. It was however very low in circalittoral habitats. This did not result in high uncertainty in RBS which was generally low or moderate but could reach up to 31% in some areas.

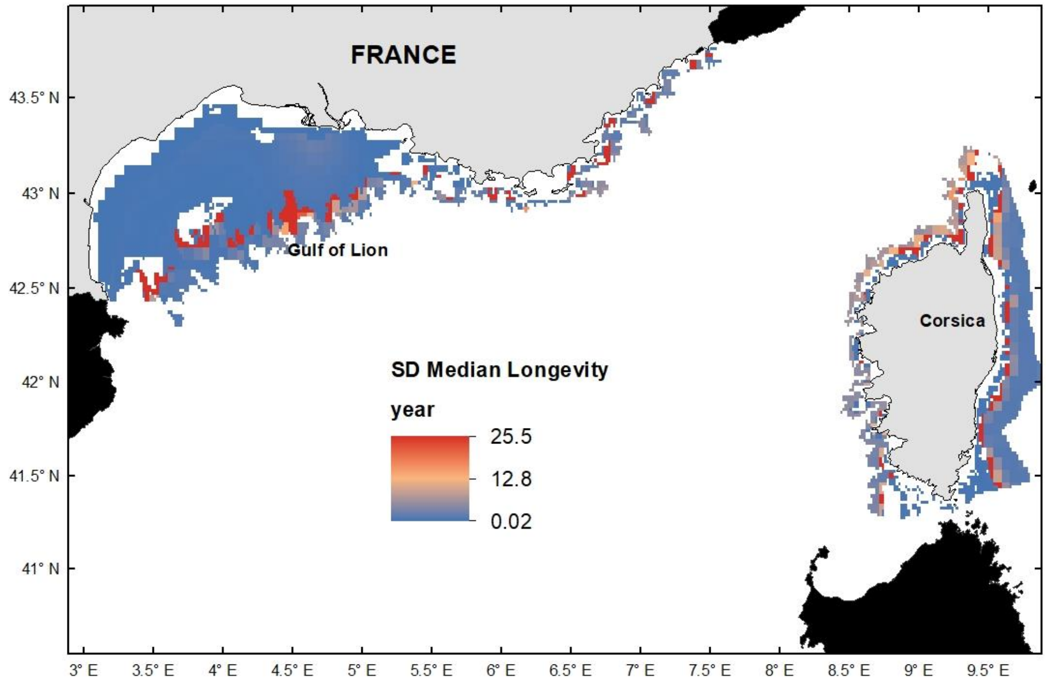

Figure 11. Standard deviation of the predicted median longevities based on four alternative abrasion metrics.

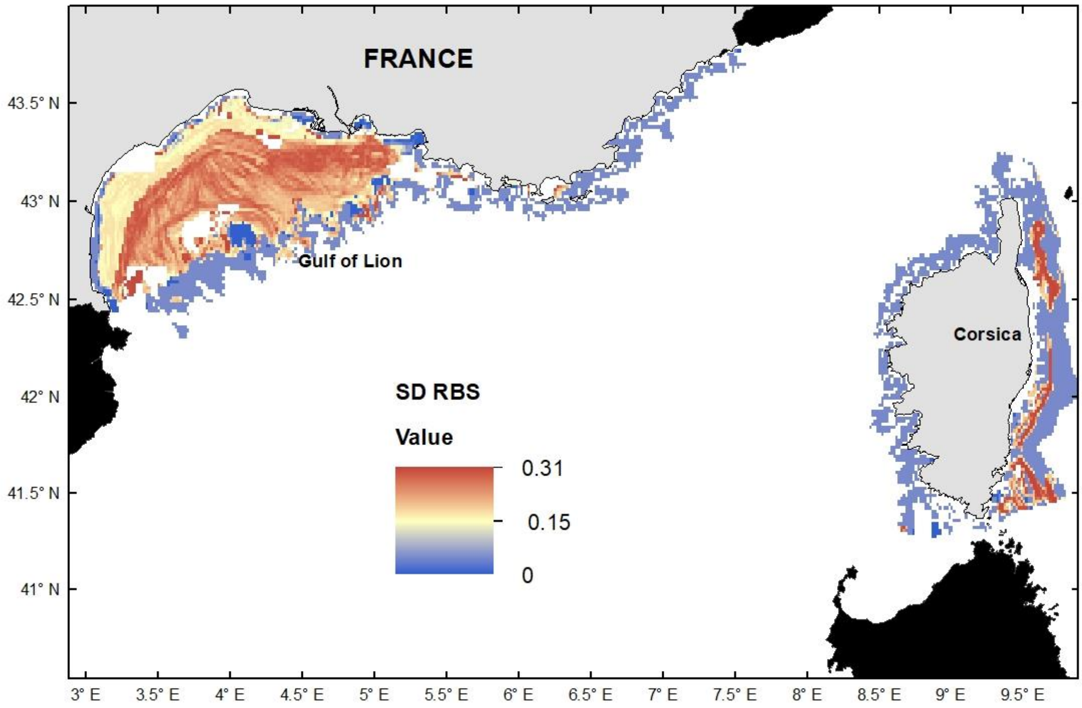

Figure 12. Standard deviation on the predicted RBS based on four alternative abrasion metrics.

3.7 Comparison with other assessment framework

Jac et al. (2020a) selected four indices linked to alternative biological traits other than longevity to describe sensitivity. These indices were mapped by interpolation in the Gulf of Lion and their interpolated values were compared to those of the median longevity map obtained here (Table 8). Since the median longevity of circalittoral and offshore circalittoral mud habitats were constant, these could not be compared to the values obtained in this previous study. These results highlighted moderate correlation levels at regional scale but also revealed that the sign of the correlation could be reversed depending on the habitat type, showing a lack of coherence between the two frameworks.

Table 8. Pearson correlation values between median longevity and four indices used by Jac et al. (2020b) per habitat and for all habitats. All values are significant ($p < 0.001$).

Broad habitat type	TDI	mTDI	pTDI	mT
All habitats	0.29	0.33	0.31	-0.33
Circalittoral sand	0.84	0.85	0.89	-0.80
Upper/lower habythal sediment	-0.16	-0.46	-0.29	0.50

Based on these indices, Jac et al. (2020b) identified abrasion thresholds by habitat and defined benthic status as a result of this reclassification. The range of the RBS status obtained in the present study were studied within each status class obtained in the Gulf of Lion and in Corsica in this former study (Tables 9 and 10). The dispersion of the RBS values by status categories is illustrated in Appendix I. The average RBS value seems to generally decrease with deteriorating status in the Gulf of Lion with the exception of circalittoral mud where a reversed trend could be observed. The pattern was similar for most habitats in Corsica but for Upper/lower bathyal sediment where it was reversed again.

Table 9. Mean RBS value (and minimum- maximum range) per Jac et al. (2020b) predicted status per habitat type in the Gulf of Lion.

Broad habitat type	adverse effects	adverse effects or possible habitat loss	probably habitat loss
Circalittoral sand	0.071 (0 - 0.999)	0.043 (0 - 0.632)	0.003 (0 - 0.999)
Upper/lower habythal sediment	0.029 (0 - 0.999)	0 (0 - 0)	0.002 (0 - 0.854)
Circalittoral mud	0.024 (0 - 0.999)	0.072 (0 - 0.773	0.1465 (0 - 0.999)
Offshore circalittoral mud	0.613 (0 - 0.999)	0.289 (0 - 0.849)	0.234 (0 - 0.999)

Table 10. Mean RBS value (and minimum- maximum range) per Jac et al. (2020b) predicted status per habitat type in Corsica.

Broad habitat type	GES	adverse effects
Circalittoral sand	0.688 (0 - 0.999)	0.675 (0 - 0.999)
Upper/lower bathyal sediment	0.149 (0 - 0.999)	0.204 (0 - 0.999)
Circalittoral mud	0.057 (0 - 0.999)	0.029 (0 - 0.999)
Offshore circalittoral mud	0.105 (0 - 0.999)	0.0172 (0 - 0.999)

GES : Good Environmental Status relative to abrasion

4 Discussion

This preliminary assessment of the French Mediterranean, according to the WFGBIT framework, has shown how biomass and longevity can be used as predictors for the seabed's sensitivity to bottom trawling and its current environmental state. The seabed's sensitivity to trawling disturbance was estimated by the median longevity and differed from the four investigated MSFD broad habitat types. Upper/lower bathyal sediment was predicted to be more sensitive than the other three habitats. De la Torriente Diez et al. (2022) showed that in the Southern coast of Spain, Western Mediterranean, circalittoral soft bottom habitats are non-sensitive to bottom trawling. In their sensitivity prediction, based on Biological Traits Analysis (Bremner et al., 2003), bathyal soft and hard bottoms were both more sensitive than the circalittoral habitats (De la Torriente Diez et al., 2022). In addition, Rijnsdorp et al., 2018 showed that in the North Sea, the biomass proportion of long-lived species is highest in coarse sediments and lowest in muddy sediments while sandy sediments have an intermediate longevity distribution. Besides that, a higher shear stress has been shown to shift the longevity composition toward shorter-lived taxa (Rijnsdorp et al., 2018). This may explain why the median longevity decreases in the circalittoral habitats. However, shear seabed stress was not selected in our model selection even though it is the environmental factor that best represents a source of natural disturbance. The absence of this factor in the selected model is remarkable as the reason to use longevity as a predictor is because of its relation to disturbance. In environments with a high frequency of disturbance (e.g., shear seabed stress), being short-lived is adaptive as it minimizses the chance for an individual to die due to a disturbance before having the chance to reproduce (Rijnsdorp et al., 2018). Instead, bottom temperature in the warmest and shallowest waters (circalittoral sand) and stratification index in the deepest habitat (upper bathyal sediments) were selected. This result is in line with those found by Jac et al. (2022) that revealed that in the French Mediterranean waters, environmental parameters linked to growth potential and resilience were more structuring and probably more limiting than in the Atlantic.

Other biological traits than longevity may be used to compute sensitivity indices such as Trawl Disturbance related indices proposed by Jac et al., (2020a). These were compared to the predicted median longevity and revealed contrasted and not always coherent relationships at the scale of each broad habitat types. It is likely that each biological trait has a different relation to abrasion depending on both assemblages' composition and environment and more work is needed in investigating each trait separately and possibly combining them.

Jac et al., (2020b) estimated the ecological state of the French Mediterranean seabed in respect to bottom fishery pressure. According to their study, all investigated habitats around Corsica were either in Good Environmental State (GES), or had suffered adverse effects. This is in line with our results that show an RBS close to one around Corsica. The gulf of lion on the other hand barely had any areas in GES and was mostly either in the categories 'adverse effects' or 'probably habitat loss' (Jac et al., 2020b). The latter category was predicted for areas closer to the coast which coherent with our predicted RBS lowest values. The MSFD descriptor 6 requires the evaluation of the percentage of surfaces where benthic communities were altered or lost by trawling. In order for the RBS to be useful for this evaluation, thresholds should be set on its scale so that we can classify the regions according to their susceptibility to fishing-induced abrasion. In the areas for which abrasion is zero (mostly Upper/lower bathyal sediments), the RBS is one (best state), so they can be considered as GES regarding fishing physical impact. However, for each habitat is it necessary to determine the RBS threshold above which the trawling pressure can be considered to have adverse effects on the benthic communities and even possibly when the original communities have been replaced by communities adapted to fishing (Jac et al., 2020b). When comparing the RBS values per broad habitat type to the states defined by Jac et al. (2020b), it was not possible to distinguish a possible RBS threshold that would separate GES from adverse effect. A next step in the development of this assessment would be to identify thresholds based on the RBS prediction in reference areas and contrast them with those in impacted areas. However, the very high correlation between RBS and abrasion indicates that it might be equivalent as to setting pressure thresholds directly.

As the development of the framework is still a work in progress, several sources of uncertainty need to be addressed in the continuation of this study. First, regarding the data, the collated longevity database can be improved with more species-specific data. Missing longevity data should be assessed for the species that are currently matched to longevity data that is calculated as an average of their higher taxonomic level. The benthic biomass data lacks a sufficient number of stations per MSFD broad habitat type. Only four out of nine habitat types had enough observations per year. On top of that only two habitats over the selected four had enough reference stations. Our sensitivity prediction heavily relies on the representativeness of the reference stations and calls for increasing the number of stations, in particular reference stations, per habitat by the trawl surveys.

The abrasion data used in this study may be underestimated, in particular in coastal areas. Indeed, to limit potential biases, data that is retrieved from locations close to ports are excluded (ICES, 2019) and coastal fishing fleets are dominated by over a thousand vessels smaller than 12 m, which very rarely use VMS tags. If most of these vessels are not using bottom-impacting gears, a few are still using dredges to collect bivalves in the near shore areas and are not accounted for here. The study of the uncertainty resulting from the choice of abrasion metric revealed that it had an important impact on the selected model formulation. It firstly highlighted the instability of the model selection based on information criteria (here BIC) with the data available. This called for further investigation of the model error impact on the assessment or developing ensemble model approaches instead of using a single best model. This may also illustrate how the temporal integration period used to compute the abrasion may be important to model the relationship between accumulated biomass and longevity on impacted habitats for which no reference observations were available. A five-year average was used as the preferred abrasion metric based on literature reporting such recovery duration following trawling impacts (Hiddink et al., 2017) and WGFBIT standard practice. However, Jac et al. (2022a) recommend the use of the highest (90th percentile) abrasion value over the entire available time series at each location to avoid overlooking past impacts and to reflect the probably long recovery time needed for sensitive species. In contrast, abrasion data on a shorter period, e.g., monthly or quarterly, may be more closely related to the benthic biomass observations. Improvement of the knowledge on benthic community resilience is needed in order to better understand the best time scale for abrasion data integration. Ultimately, the choice of abrasion metric used was shown here to have a high impact on the predicted sensitivity in some habitats where long-lived species were expected to occur (here up to 25 years median longevity variability in upper bathyal sediment). Nevertheless, the longevity regression coefficients used as a proxy of recovery rates in the prediction of the relative benthic status remained reasonably stable over the four tested abrasion metrics. As a result, the variability of the RBS outputs was not as high as expected although it could reach up to 30% in some instances.

For two out of four habitats, not enough reference stations were available to fit the GLMM. To solve this, we included abrasion as a predictor and then simulated reference stations in the median longevity prediction by using a value of zero for abrasion. This method is not ideal as it may lead to an underestimation of median longevity since the relationship between cumulative biomass and longevity is based on present, already impacted communities. Therefore, setting abrasion to zero does not simply represent an unimpacted state. The RBS on the other hand, can be expected to be overestimated. Moreover, the calculations used for this indicator relies on constant estimates (depletion rate, carrying capacity) that were developed elsewhere. The framework itself is robust enough to be applied under different environmental conditions, but these constant values need to be reviewed and possibly adapted to the often less productive waters of the Mediterranean.

Due to the large uncertainty linked to the data (in particular longevity assessment and choice of abrasion metric), methodological framework (in particular, model selection and uncertainty and the use of set depletion rates and carrying capacity constant developed elsewhere), the continuation of this study will consist of developing an assessment of the framework’s uncertainty (ICES, 2022). Uncertainty can be assessed based on bootstrapped simulations that will account for uncertainty propagation over the whole assessment framework. This will allow for the identification of the main sources of uncertainty and the potential steps needed to reduce it. Each step of data preparation creates a potential source of uncertainty and should therefore be included as a variable in the bootstrapping simulations. The collated longevity dataset used for the analysis was the result of merging and averaging seven available datasets. The standard deviations on the calculated averages can be used to simulate small variations in the longevity fuzzy coding and observe their impact on the assessment result. Next, we used the previous year’s SAR value as an estimate of abrasion. Uncertainty can be accounted for by constructing the model with the three other abrasion estimates (the five previous year average SAR value, the five previous years’ maximum values and a weighted average of the five previous years). This change of metric was shown here to alter the longevity model formulation and error which will impact the following steps of the assessment framework. Finally, the RBS assessment relies on fixed depletion and carrying capacity rates which effect on the final result is unknown.

5 Conclusion

It is possible to apply the WGFBIT assessment framework to the French Mediterranean EEZ using existing bottom trawl and beam trawl biological data. Collating existing longevity databases allowed us to match 91.5 % of the biomass data from trawl surveys to longevity categories. The leftover biomass could be entirely matched on higher taxonomic levels. Four out of nine of the MSFD broad habitat types occurring in the area had enough observations to be used in our analysis. For each of these habitats, a generalised linear mixed model was fitted with the sampling station as a random factor, and using environmental variables and abrasion as predictive terms. These models' coefficients were used to predict the median longevity over the sampled area. Our study predicts more sensitive habitats in upper/lower bathyal sediment, and less sensitive habitats in circalittoral sediments. In agreement with previous studies, the estimated Relative Benthic State suggests highly impacted area's close to the coast in the Gulf of Lion, and little impacted habitats around Corsica. Many uncertainties remain and this first preliminary application will need to be further developed and validated in the future.

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7 Appendices

7.1 Appendix A. Overview of available databases for collating Mediterranean longevity.

Name	Number of taxa	Data source	Methods used for longevity estimates	Reference area
1. BTA_EMODNET_LifeSpan-OBeauchard	616	Unknown	Unknown	Atlantic
2. full_list	323	Italian National monitoring programme - Medits	Expert judgment; SIBM ISPRA Experts Literature	Italian coasts
3. Lista delle specie con score_	323	Medits survey 2015-19	Expert judgment; SIBM ISPRA ICES experts literature	GSA 18
4. longevity data	219	Solemon Rapido Trawl survey 2014-16 and GAP 2 epibentic data	Expert judgment; SIBM ISPRA experts literature	GSA 17 Italian Northern Central Adriatic Sea
5. LongevityDatabaseMega&Macrofauna241121	164 (mega) + 889 (macro)	HCMR	Allocations by fraction fuzzy logic , Other databases Literature Expert Judgement	GSA 20, 22, 23 Greek waters: Aegean Sea, Cretan Sea, Eastern Ionian Sea
6. Cefas traits data from Clare et al 2022	1025	CEFAS database	Clare et al 2022	Atlantic
7. *Glandiceps talaboti*	1	WGFBIT22	expert judgment Chris Smith	Mediterranean

7.2 Appendix B. List of taxa per longevity dataset that resulted in NA when matched in WORMS

Databases 6 and 7 had both already had been matched in WORMS prior to this analysis.

Database	WORMS status	Changed to
1. BTA_EMODNET_LifeSpan-OBeauchard		
No NA's	/	/
2. full_list		
Hoplostetus mediterraneus mediterraneus	Misspelling	*Hoplostethus mediterraneus mediterraneus*
3. Lista delle specie con score_		
Hoplostetus mediterraneus mediterraneus	Misspelling	*Hoplostethus mediterraneus mediterraneus*
4. longevity data		
Hydorids	Misspelling	*Hydroides*
Holoturoidea	Misspelling	*Holothuroidea*
Flexopecten glaber proteus	Unaccepted subspecies	*Flexopecten glaber*
Polinices nitida	Unaccepted name	*Euspira nitida*
5. LongevityDatabaseMega&Macrofauna241121		
Aphroditoidea	Uncertain > nomen dubium (superfluous name, no longer required as nominal superfamily)	Not changed
Turbellaria	Unaccepted (not longer used; is a paraphyletic group)	Not changed
Terebellomorpha	Unrecognised	Not changed
Flabellifera	Unaccepted (now replaced by *Cymothoida* (including former suborders *Anthuridea*, *Gnathiidea* and *Epicaridea*) and *Sphaeromatidea*)	*Cymothoida*

7.3 Appendix C. List of taxa from benthic biomass dataset that resulted in NA when matched in WORMS.

Taxon	WORMS status	Changed to
Hadriana carinatella	Unaccepted + superseded combination	*Gracilipurpura craticulata*
Inachus tenuirostris	Unrecognized species	Completed to genus level
Pilumnus hirtellus forma spinifer	Unrecognized subspecies	*Pilumnus hirtellus*
Pisidia longicornis longicornis	Unrecognized subspecies	*Pisidia longicornis*
Stenorhynchus tenuicornis	Unrecognized species	Completed to genus level
Ampullotrochus granulatum	alternate representation	*Calliostoma granulatum*
Pleurobranchea meckely	Misspelling	*Pleurobranchaea meckeli* was already included so this row was deleted
Moschites cirrosa	Unrecognized species	*Eledone cirrhosa*
Octopus aldrovandi	Unrecognized species	Completed to genus level
Rudicardium tuberculata	Alternate representation	*Acanthocardia tuberculata*
Aequipecten audouini	Unaccepted (synonym)	*Aequipecten opercularis*
Aequipecten lineatus	Unrecognized species	Completed to genus level
Galeoda tyrrhena	Misspelling + unaccepted	*Galeodea rugosa*
Polybius tuberculatus	Unrecognized species	Completed to genus level
Ophiurides	Unrecognized	*Ophiuroidea*
Astacea rugosa	Unaccepted	*Bolma rugosa*
Eotichopus regalis	Misspelling + unaccepted	*Parastichopus regalis*
Morio rugosa	Unaccepted	*Galeodea rugosa*
Ceratostoma erinaceum	Unrecognized species	Completed to genus level

7.4 Appendix D. Information on environmental variables used

Variable	Metadata
Sea bottom temperature	Bottom temperatures (in °C) from 1994 à 2014 from monthly model predictions were used to compute average bottom temperature (BT), inter- and intra-annual bottom temperature standard deviations (Ti and Ta respectively) [1].
Sediment average grain size	A sediment map in the French Mediterranean waters [2] was used to obtain sediment grain size range (mm), per sediment group (rock, pebble, pebble and gravel, gravel, sand, sand and fine sand, fine sand, mud, silt and clay). Römkens et al. equation[3] enabling the estimation of average grain size from sediment typology and fraction, was applied to obtain modelled seabed sediment average grain size.
Depth	Bathymetry is expressed as average water depth (m) on a 1/16 * 1/16 arc minute of longitude and latitude (ca 115 * 115 meters) resolution [4].
Seabed shear stress	Expressed in N.m-2. Estimated from current and wave hydrodynamic models in the north-west Mediterranean. The 90th percentile was computed over the available period [5].
Oxygen saturation	Average bottom dissolved oxygen concentration (O; mmol.m-3) from 1999 to 2014, from monthly model predictions [6] over a 0.042x0.042° spatial resolution. This was further transformed in % dissolved oxygen using the equation of dissolved oxygen concentration in the water [7].
Food availability at sea bottom	Computed as: Fa = log(Chl.a/bathymetry) − stratification. Then centered, standardized. The resolution is 0.042°x0.042° and the resulting values have no units and are scaled between 0 and 1. The maximum concentration of surface chlorophyll was obtained from monthly satellite observations from 1998 to 2014 [8]. Stratification was considered as the average absolute difference between surface and 30 (± 5) m depth density over 20 years. Salinity and temperature data used to compute density cover the 1994–2014 period and were from monthly model predictions [1]. High Pressure International Equation of State of Seawater (1980) was used to compute Sea water Density [9,10].
Chlorophyll-a concentration	Computed as the maximum and mean concentration of surface chlorophyll-*a* obtained from monthly satellite observations from 1998 to 2014, expressed in mg.m-3 over a 1x1km spatial resolution [8].
Stratification	Considered as the average absolute difference between surface and 30 (± 5) m depth density over 20 years. Salinity and temperature data used to compute density cover the 1994-2014 period and were from monthly model [1]. High Pressure International Equation of State of Seawater (1980) was used to compute Sea water Density [9,10].

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7.5 Appendix E. Correlation matrix between environmental variables (Pearson coefficients)

	mean bottom temperature	grainsize fraction	bathymetry	seabed stress	mean bottom oxygen	food availability	max chlorophyl-a	mean chlorophyl-a	stratification
mean bottom temperature	-	-	-	-	-	-	-	-	-
grainsize fraction	0.04	-	-	-	-	-	-	-	-
bathymetry	0.65	0.16	-	-	-	-	-	-	-
seabed stress	0.59	0.04	0.30	-	-	-	-	-	-
mean bottom oxygen	0.50	-0.04	0.70	-0.02	-	-	-	-	-
food availability	0.56	0.04	0.74	0.23	0.83	-	-	-	-
max chlorophyll-a	0.67	-0.02	0.47	0.52	0.41	0.68	-	-	-
mean chlorophyll-a	0.72	-0.07	0.49	0.56	0.35	0.60	0.90	-	-
stratification	0.46	0.03	0.11	0.54	-0.31	-0.24	0.31	0.40	-
abrasion	0.50	-0.05	0.42	0.32	0.50	0.50	0.48	0.46	0.17

7.6 Appendix F. Fixed effects summary

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

	Estimate	Std. Error	z value	Pr(>|z|)
Circalitorral sand				
intercept	-9.216	3.9356	-2.342	0.0192*
ll	3.1254	0.3863	8.091	5.92E-16***
meanBtemp	0.2731	0.2463	1.109	0.2675
Upper bathyal sediment or Lower bathyal sediment				
intercept	387.813	99.9574	3.88	0.000105***
ll	3.795	0.754	5.033	4.83E-07***
meanchl	-78.7192	17.675	-4.454	8.44E-06***
stratif	-1.9163	0.4901	-3.91	9.24E-05***
seabed stress	57.3555	24.342	2.356	0.018461*
Circalittoral mud				
intercept	-7.84514	0.8034	-9.765	< 2e-16***
ABR	4.31335	0.38172	11.3	< 2e-16***
ll	0.06407	0.02336	2.743	0.00608**
Offshore circalittoral mud				
intercept	-8.21411	1.05539	-7.783	7.08E-15***
ll	3.77577	0.43915	8.598	< 2e-16***
ABR	0.14613	0.05919	2.469	0.0136**

7.7 Appendix G. Forward model selection results (first 10 best models) per MSFD broad habitat type

a. Model selection table "Circalittoral sand"

model	Intercept	depth	ll	mean bottom oxygen	mean bottom temperature	mean chlorophyl-a	shear seabed stress	stratification	df	BIC	delta
1	-42.86		4.747		2.413				4	51.5	0
2	-5.735	-0.03444	4.54						4	52.5	0.95
3	-6.397		3.756						3	53.1	1.6
4	-53.91		5.199	0.05072	2.367				5	54	2.47
5	-70.12		5.17		4.312		-14.75		5	54.2	2.72
6	-41.81		4.908		2.45			-6.752	5	54.4	2.85
7	-3.73	-0.04107	5.033					-8.835	5	54.5	2.94
8	-30.16		5.151	0.09428		1.615			5	54.6	3.07
9	-16.45	-0.0328	4.909	0.04642					5	55.1	3.52
10	-16.5		4.072	0.0447					4	55.1	3.53

b. Model selection table “Upper/lower bathyal sediments

model	Intercept	depth	grainsize	ll	mean bottom oxygen	mean bottom temperature	mean chlorophyll-a	shear seabed stress	stratification	df	BIC	delta
1	387.8			3.795	-1.916			57.36	-78.72	6	89.3	0
2	241.1			3.453	-1.196				-53.07	5	90.5	1.24
3	-3.267			3.082					-14.92	4	91	1.72
4	34.42			3.01		-3.084				4	92.6	3.35
5	313		3.037	3.684	-1.546				-68.71	6	93.6	4.28
6	442.6			3.798	-2.199		9.725	65.69	-81.61	7	93.7	4.38
7	400.9			3.776	-1.903	-1.277		61.87	-73.64	7	93.9	4.62
8	402.1	-9.02E-04		3.876	-1.984			55.65	-81.36	7	94	4.71
9	381.1		-1.265	3.753	-1.884			66	-76.42	7	94	4.74
10	103			3.174		-7.91	-28.91			5	94.1	4.8

c. Model selection table "Circalittoral mud"

model	Intercept	ABR	depth	grainsize	ll	mean bottom oxygen	mean bottom temperature	mean chlorophyll-a	shear seabed stress	stratification	df	BIC	delta
1	-7.69	0.05614			4.473						4	105.9	0
2	-7.832	0.06509		-1.31	4.613						5	109.2	3.3
3	-6.627	0.03879	-0.0252		4.579						5	110.2	4.28
4	-8.474	0.05799			4.512					2.723	5	110.7	4.84
5	-3.356	0.06333			4.499	-0.01971					5	110.9	5.01
6	-7.746	0.0559			4.476				1.075		5	111.3	5.45
7	-7.58	0.05651			4.473			-0.1485			5	111.3	5.47
8	-6.919	0.05646			4.473		-0.05333				5	111.4	5.47
9	-6.331	0.04258	-0.0373	-1.768	4.846						6	112.2	6.32
10	-2.521	0.01698	-0.06743		4.722			-3.082			6	113.3	7.47

d. Model selection table “Offshore circalittoral mud”

model	Intercept	ABR	depth	grainsize	ll	mean bottom oxygen	mean chlorophyll-a	shear seabed stress	stratification	df	BIC	delta
1	-8.214	0.1461			3.776					4	207.5	0
2	-9.738	0.07276			3.965				6.489	5	208.1	0.52
3	-10.48	0.2063			4.119		-2.307		10.43	6	209.3	1.73
4	-36.78	0.3465	0.06909		4.061	0.07792			16.5	7	210.6	3.04
5	-14.26	0.2439	0.03528		4.005				8.578	6	211.2	3.71
6	-10.86	0.3124			4.086		-3.325	-43.73	16.13	7	212.1	4.6
7	-17.44	0.0435			3.964	0.03314			9.013	6	212.3	4.76
8	-15.07	0.3778	0.03568		4.161		-2.359		12.75	7	212.4	4.84
9	-7.964	0.1222		-0.5721	3.772					5	212.6	5.11
10	-8.457	0.1177			3.815			15.78		5	212.7	5.21

7.8 Appendix H. Selected models depending on abrasion metrics used

Abrasion metric used were : a = previous year sar value, b = previous 5 year average, c = previous 5 year maximum, d = previous 5 year weighted average

Significance level of selected parameters is indicates as : *** p<0.001, ** p< 0.01, * p< 0.05

circalittoral sand

abrasion metric	intercept	ll	meanBtemp	R2c
a	-9.61707*	3.18349***	0.28154	0.736
b	-9.216*	3.1254***	0.2731	0.743
c	-5.49003***	3.26862***		0.745
d	-9.5565*	3.18132***	0.27788	0.736

upper/lower bathyal sediments

abrasion metric	intercept	ll	stratif	meanBdox	seabed_stress	R2c
a	-3.7808**	3.0758***	-11.7936*			0.733
b	387.813***	3.795***	-78.7192***	-1.9163***	57.3555*	0.826
c	-4.575**	3.264***	-10.377*			0.751
d	239.0730**	3.3768***	-49.8153***	-1.1882**		0.779

circalittoral mud

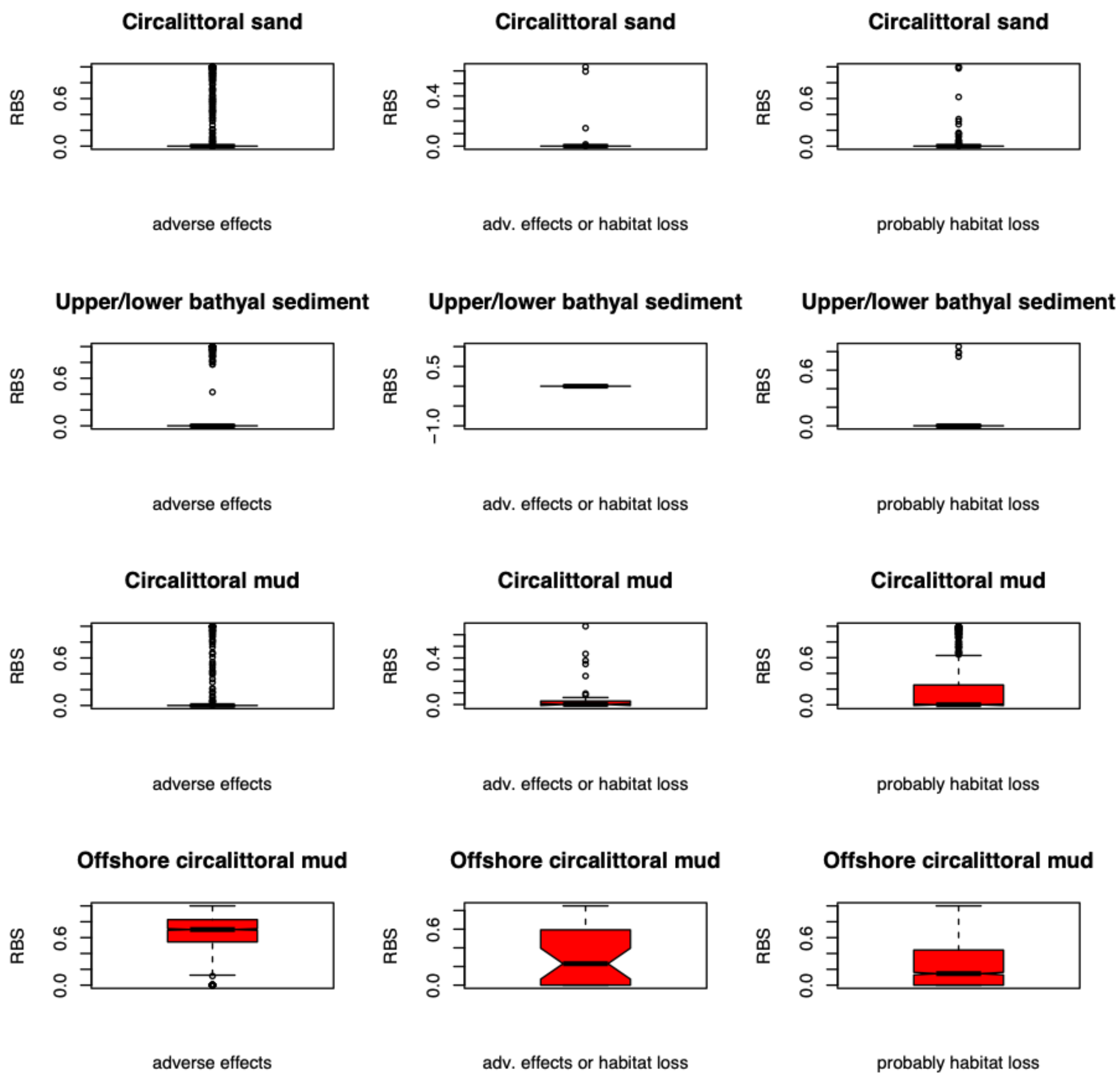
abrasion metric	intercept	ll	ABR	R2c
a	-7.87345***	4.32993***	0.05950**	0.837
b	-7.84514***	4.31335***	0.06407**	0.837
c	-8.05536***	4.35470***	0.05884**	0.839
d	-7.85324***	4.31845***	0.06004**	0.837

offshore circalittoral mud

abrasion metric	intercept	ll	ABR	stratif	R2c
a	-7.9563***	3.7102***	0.1119*		0.789
b	-8.21411***	3.7757***	0.13613*		0.797
c	-9.71069***	3.93817***	0.03121	7.24630*	0.812
d	-9.73434***	3.94879***	0.05260	6.94871*	0.813

7.9 Appendix I. RBS values dispersion within each status categories per broad habitat type

Boxplot showing the dispersion of the RBS values within each status categories defined by Jac et al., 2020b in the Gulf of Lion



Boxplot showing the dispersion of the RBS values within each status categories defined by Jac et al., 2020b in Eastern Corsica