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Detecting adverse effect on seabed integrity. Part 2: How much of seabed habitats are left in good environmental status by fisheries?

Jac Cyrielle [1,*], Desroy Nicolas [2], Certain Gregoire [1], Foveau Aurelie [2], Labrune Céline [3], Vaz Sandrine [1]

[1] MARBEC, Univ Montpellier, Ifremer, IRD, CNRS, Sète, France
[2] Ifremer, Laboratoire Environnement et Ressources Bretagne Nord, 38 Rue du Port Blanc, 35800 Dinard, France
[3] Sorbonne Université, CNRS, Laboratoire d'Ecogéochimie des Environnements Benthiques, LECOB UMR 8222, F-66650 Banyuls-sur-Mer, France

* Corresponding author : Cyrielle Jac, email address : cyrielle.jac@ifremer.fr

Abstract :

By relating observed changes to the pressures suffered, the Marine Strategy Framework Directive intends to better control the factors of environmental degradation and to manage their consequences in European waters. Several descriptors are defined within the framework of the MFSD and in particular descriptor 1 relating to the biological diversity of the seabed and descriptor 6 relating to the seabed integrity (i.e. the quality of their structures and functions). For each descriptor, indicators and threshold values must be defined and a novel conceptual approach to define and detect seabed integrity thresholds is proposed here. Bottom trawling being the main source of shelf continental disturbance, it is important to evaluate its impact on benthic habitat. The goal of this study is to propose a methodology to determine "Good Ecological Status" threshold values for each habitat type present in three contrasted MFSD sub-region (North Sea, English Channel and Mediterranean Sea). Trawling impacts are dependent of the spatial and temporal distribution of the fishing effort, fishing gears, intensity of natural disturbances and habitat types. Benthic community structures present in these areas were studied using by-catch non-commercial benthic invertebrates data collected during French scientific bottom trawl surveys. Swept area ratios derived from VMS data were used to quantify the intensity of fishery induced abrasion on the seabed. A modeling approach was used to determine abrasion threshold values on each EUNIS level 4 habitat. The values, beyond which trawling has an adverse effect on benthic communities, have been determined for each habitat. This made it possible to assess and map the ecological status of each of the habitats and to determine the percentage of each habitat impacted by trawling. The method proposed here to evaluate the impact of trawling on benthic communities highlighted that the vast majority of the investigated sub-regions were adversely impacted or lost as a result of seabed impacting trawling.

Highlights

► Propose a general modeling framework to detect thresholds of impact on an increasing anthropogenic disturbance gradient. ► Determine fishing related abrasion thresholds over several contrasted EUNIS level 4 habitats. ► Assess seabed environmental status in response to bottom trawling. ► The vast majority of the investigated sub-regions surfaces' were found to be adversely impacted or lost.

Keywords : GES, Threshold values, Trawling impact, Indices, MFSD

1. Introduction

In 2008, the European Union drew up the Marine Strategy Framework Directive (MSFD) to achieve or to maintain "Good Environmental Status" (GES) in the marine environment (EC 2008). This directive sets out eleven descriptors of human uses of the marine ecosystem, each comprising a number of criteria and methodological standards for determining GES. Each member state must therefore develop quantitative indices and threshold values corresponding to each criteria to assess progress towards the GES (Rice et al., 2012). To measure the evolution of this environmental status, the evaluation of some criteria requires to develop appropriate indices able to detect changes in relation to anthropogenic disturbance (Leonardsson et al. 2009; OSPAR 2012; Rice et al. 2012; van Loon et al. 2018). On the eleven descriptors defined in the MSFD, two of them specifically concern the benthic habitat: the descriptor 1 (biodiversity) and the descriptor 6 (seabed integrity). Criteria 1 and 2 of the descriptor 6 (D6C1, D6C2) are dedicated in evaluating the spatial extent of the physical loss or disturbance of seabed. The criteria D6C3 focuses on establishing pressure thresholds values for the adverse effects of physical disturbance. Finally, D6C4 and D6C5 must allow the assessment of the extent of benthic community “loss” or “alteration” and should set maximum admissible proportion of habitat loss and evaluate the status of each habitat in that respect (EC 2008, 2017).

The information of these criteria requires the development of transparent indices, allowing for a scientifically defensible assessment of the environmental status of the seabed. Since each type of pressure will result in either habitat disturbance or total physical destruction, it is expected that they will affect benthic communities in different ways. It seems therefore more appropriate to address each pressure effect separately and to develop specific indices and thresholds. In Europe, dredging and bottom trawling occur over large surfaces of the continental shelf and are the principal source of the anthropogenic disturbance to seabed habitats (Hiddink et al. 2007; Halpern et al. 2008; CNDCSMM 2019). Based on an extensive assessment methodology, it was possible to identify four indices (Jac et al., submitted) that respond to trawling impact and may probably be used in all European waters. These were computed using benthic community data from scientific bottom trawl surveys which enable to work on a large spatial scale but also to focus on the epifauna, unlike other sampling methods such as grab or box-corer that perform small-scale sampling, mainly of the endofauna (Rumohr 1999; Foveau et al. 2017). The set of indices retained were all based on species biological traits that are known to shape species sensitivity to physical abrasion such as that generated by bottom trawling.

The distribution and composition of benthic assemblages are known to be dependent of environmental conditions such as depth, hydrodynamism and granulometry (Gray and Elliott 2009) or trawling pressure (Eigaard et al. 2017). Therefore, the evaluation of trawling impact on benthic community must be carried out by habitat type. As a great diversity of seabed habitats is present in the continental shelf of European waters, the development of an index that can be used in all European waters requires its evaluation in contrasted habitats, subjected to important gradient of trawling effort. Thus, a pan-european habitat map in a reasonably standardized typology is necessary to evaluate the relevance of each tested index at the scale of each MFSD sub-regions. A generic and hierarchical habitat classification of European Waters was developed by the European Nature Information System (EUNIS; http://www.emodnet.eu) and is currently available. This typology is based on a hierarchical classification of habitats allowing access, for the marine domain, to levels of precision ranging from the type of substrate to the precise identification of benthic stands, defined by the presence of characteristics species, while integrating the exposure level and depth (Galparsoro et al. 2012). Many studies on trawling impact have used EUNIS level 3 (Eigaard et al. 2017; van Loon et al. 2018) which takes into account depth, sediment grain size, light and hydrodynamism.

The characterization of GES, with regard to the impact of trawling, requires the definition of thresholds for each habitat type that may be trawled. Threshold values correspond to values below which no negative effect of the impact source (trawling in this study) can be observed on the community (here the benthic community). Thus, beyond this value, the observed effect results from the abrasion. Existence of these threshold values is linked to the community resistance to trawling. The more a community is resistant to the pressure; the more the pressure threshold value from which a negative effect may be observed will be high. Threshold can also be defined as the point at which small changes in a driver (fishing intensity for example) may produce large responses in the ecosystem (Groffman et al. 2006). It is therefore important to define the threshold at which GES is met as the use of trends-based targets gives no clear indication of the status achieved (EC 2008).

The aims of this study were to propose a methodology based on four functional indices proposed earlier by Jac et al. (submitted) to determine GES threshold values for each habitat type present in three contrasted MFSD sub-regions: Western Mediterranean Sea, North Sea and English Channel. Maps representing the environmental status of these sub-regions were produced as a result of the application of this methodology.

2. Methods

2.1. Fishing impact

Maps of 90th inter-annual (from 2009 to 2017) percentile of swept surface area ratio, based on VMS data (Eigaard et al. 2016; ICES 2019a), were used to determine the abrasion value at each sampled stations of the three studied areas (as detailed in Jac et al., submitted). Resolutions of these maps were different: 3'x3' in the English Channel and North Sea (https://www.ospar.org) and 1'x1' in Mediterranean Sea (Jac and Vaz 2018).

2.2. Biological data

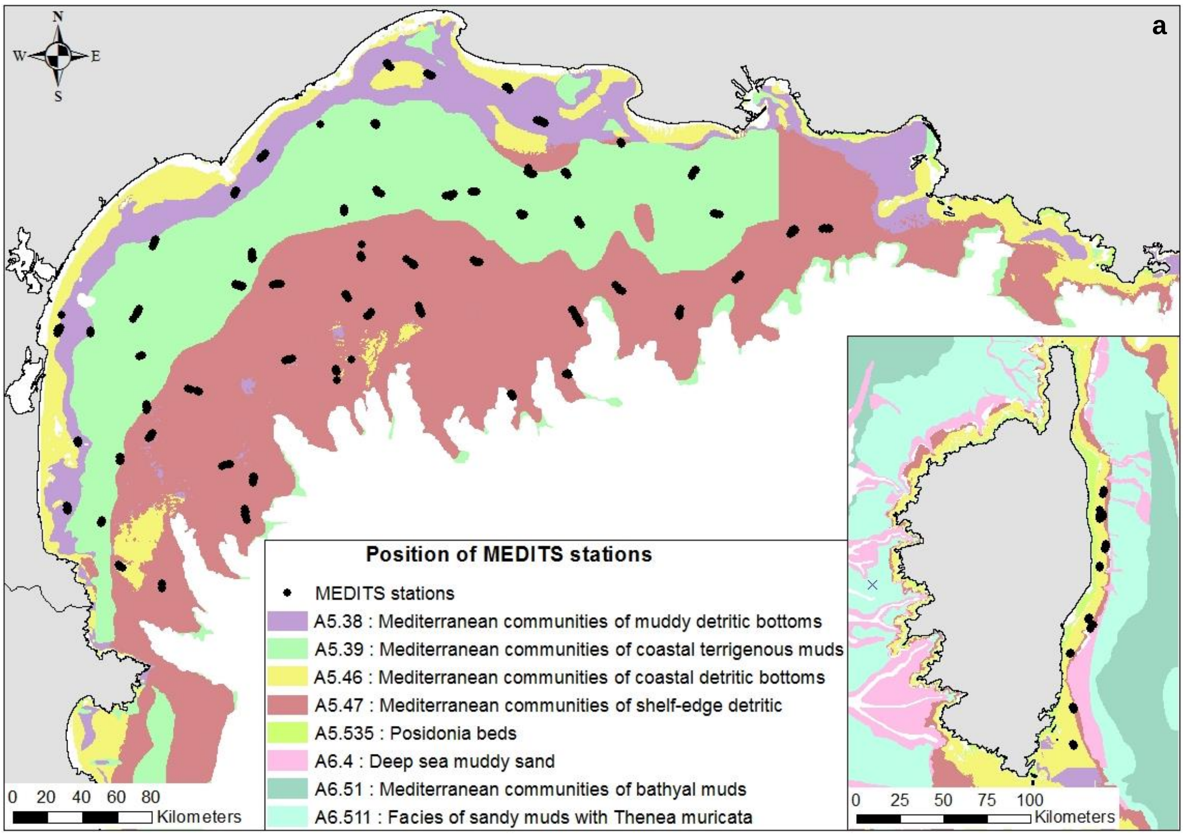
The benthic fauna studied in this work was collected, identified, counted and weighed during four scientific bottom trawling surveys: Mediterranean International Trawl Survey (MEDITS ; Jadaud et al. 1994), International Bottom Trawl Survey (IBTS ; Auber 1992), Channel Ground Fish Survey (CGFS ; Coppin and Travers-trolet 1989), Campagne Manche Occidentale (CAMANOC ; Verin and Travers-Trolet 2014) taking place in our study areas. These surveys are internationally coordinated and use standardized bottom trawls and fishing protocols. Three of these four surveys were performed in the English Channel and the North Sea: IBTS yearly in January/February since 1970, CGFS yearly in October since 1988 and CAMANOC in September 2014. MEDITS has been conducted each year in June since 1994 in the Mediterranean Sea. The data generated are mostly used in the frame of the Data Collection Program to support the implementation of the European Common Fisheries Policy (CFP). Benthic invertebrate species, considered as by-catch species, are either opportunistically or contractually monitored during these surveys since 2008 during CGFS surveys, 2009 during IBTS surveys and 2012 during MEDITS surveys (Callaway et al. 2002; Reiss et al. 2006; Brind'Amour et al. 2009, 2014). As the spatial repartition of abrasion is not independent of the presence of target species, commercial species (*Homarus gammarus*, *Crangon crangon*, *Maja brachydactyla*, *Pecten maximus*, *Aequipecten opercularis*, *Palaemon serratus*, *Nephrops norvegicus*, *Buccinum undatum*, *Cancer pagurus*, *Aristaeomorpha foliacea*, *Aristeus antennatus*, *Parapeneus longisrostris*, *Bolinus brandaris)* and cephalopods were removed from the dataset. Since it is impossible to estimate the number of individuals for colonial species such as sponges or hydrozoans, biomass data was preferred to abundance data. Data were standardized according to trawling swept area and expressed in g.km^{-2}. Finally, to limit identification errors, the procedure proposed by Foveau et al. (2017) to aggregate uncertain taxa at a higher identification level was used (Jac et al., submitted).

2.3. Indices computation

Four indices, all based on species biological traits specifically related to trawling sensitivity, were found to detect trawling impact in benthic community composition (Jac et al, 2020, submitted). These were the Trawling Disturbance Index (TDI; de Juan and Demestre 2012), the modified TDI (mTDI, Foveau et al. 2017), the partial TDI (pTDI, Jac et al. submitted), the modified Sensitivity to Trawling Index (mT; modified by Jac et al. submitted after Certain et al. 2015). Calculation methods of each of these indices were detailed in Jac et al., submitted.

2.4. Habitat data

Spatial repartition of the seabed habitats was obtained from the EUNIS layers level 4 as defined in EUNIS habitats classification of 2019 ; (http://www.emodnet.eu, EUseamap). Habitat classes corresponding to sampled locations were extracted and assigned to each station (Figure 1). Only habitats sampled at least 40 times were retained for analysis. The IBTS survey is carried out in both the English Channel and the southern North Sea. As a result, habitats A5.14 and A5.15 of the English Channel were sampled twice each year (January/February with IBTS and September/October with CGFS). Analyses were therefore performed independently to allow the observation of seasonal differences on these habitats.



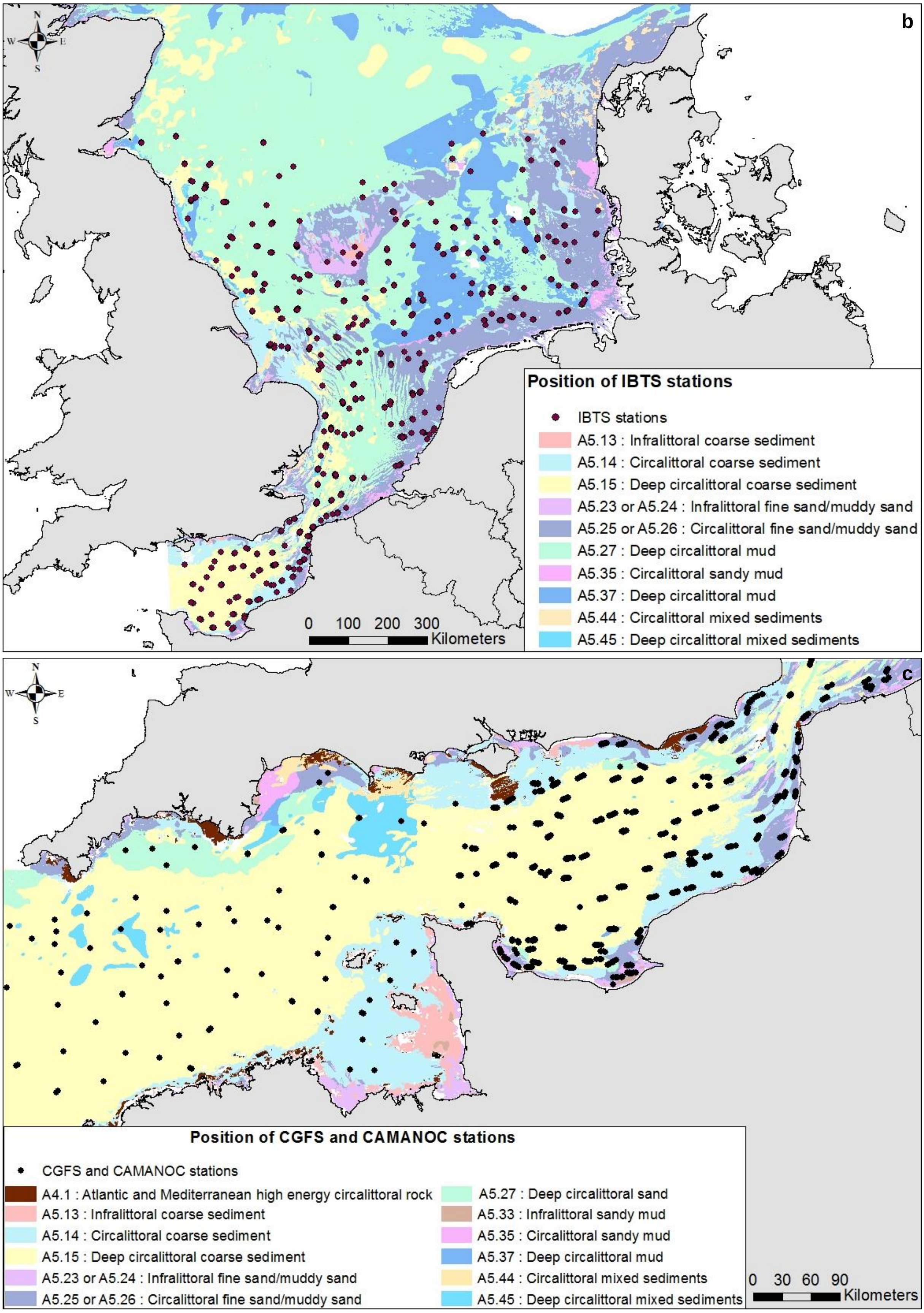


Figure 1 : Location of sampled stations within different benthic habitats a. MEDITS stations in the Gulf of Lion and eastern Corsica b. IBTS stations in the southern North Sea and Eastern English Channel c. CGFS and CAMANOC stations in the English Channel

2.5. Data analysis

2.5.1. Determination of threshold values by habitat and biogeographical area

Depending on habitat types, benthic communities do not respond in the same way to trawling (Kaiser et al. 1998). Thus, based on EUNIS marine habitat description, the relationship between indices and abrasion was studied separately in each habitat type. Indices were centered and standardized (rescaled to have a mean of zero and a standard deviation of one) using the robustHD package 0.5.1 (Alfons 2016) and abrasion values were squared or log-transformed to improve their statistical distribution. However this relationship is not expected to be linear over the entire abrasion range and "abrupt" changes in slope may occur when certain abrasion intensity thresholds are exceeded (Figure 2). The identification of the abrasion values where these changes appeared allows detecting trawling intensity thresholds for each habitat. Thus, below a given abrasion intensity threshold, no significant relationship between the index and fishing induced abrasion may be detected and therefore no significant relationship will be detected. Under this abrasion limit, this seabed habitat may therefore be considered un-impacted or achieving GES in respect to bottom fishing physical impact. Conversely, when the area is severely trawled, one should not expect to observe a significant relationship between the index and fishing induced abrasion because the benthic community has shifted toward an adapted assemblage to this level of disturbance and has stabilized in a trawling induced semi-natural climax. A benthic community withstanding such level of abrasion may be considered as fully altered and therefore lost. Between these two extreme states, modification of species composition is on-going and communities should therefore be considered as adversely impacted. For more resistant communities, the GES would be maintained to a higher pressure value than that of a non-resistant community. Similarly, in that case, the second threshold corresponding to habitat loss may be reached at higher pressure level. The kinetics of change may also be different so that the resulting curve could also have a different slope. For very sensitive communities, the first threshold may not even exist.

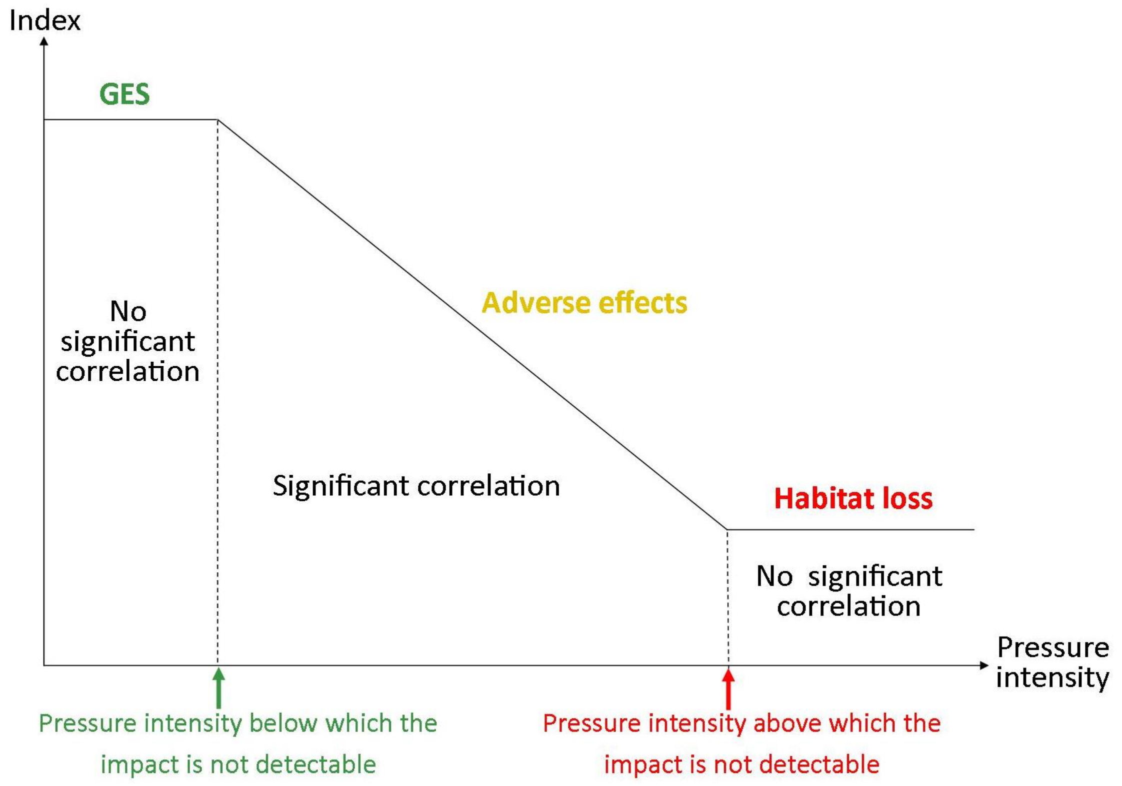


Figure 2 : Schematic relationship between any given index and pressure intensity and its corresponding ecological status

For each habitat, the detection of breakpoints and the determination of the corresponding abrasion threshold values required several steps. Thus, the type of relationship using statistical linear regressions (generalized linear models with Gaussian link function or segmented linear regression) between transformed abrasion values and standardized indices was studied, on each habitat, with a modelling approach consisting into fitting five models: two “simple” models (linear and null models) and three segmented models corresponding to a part (only one breakpoint) or all (two break points) of the theoretical relationship (Figure 3). The first step in selecting the “best model” was to check if the slope was negative or null, any other models being excluded. The presence of breakpoints was then evaluated using a specific statistical test (Davies 2002). In case of significant presence of breakpoints, “simple” models (linear and null) were excluded. Finally, the adjusted R squared (Yin and Fan 2001) was used to evaluate which model has the best explanatory power in each habitat as it penalizes more broken-line models than would the R-squared. All of these analyses were carried out with the Segmented R package 0.5-3.0 (Muggeo 2019) using R version 3.4.2 (R Core Team 2017). For each EUNIS habitat category, these models were therefore fitted to predict indices values from abrasion in the Western Mediterranean Sea, the English Channel and the southern North Sea and, when they could be detected, compute their associated thresholds.

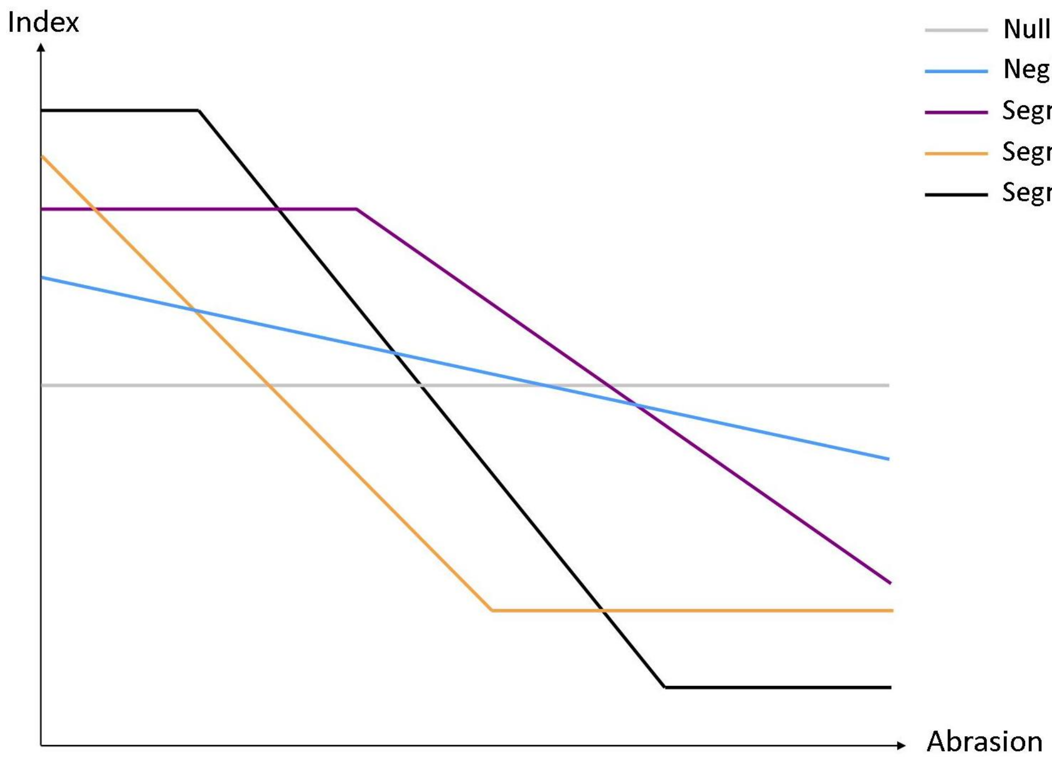


Figure 3 : Schematic representation of different models tested

2.5.2. Assessment approach for determining habitat disturbance and loss

MFSD criteria D6C3 and D6C4 require evaluating the percentage of surface where benthic communities were altered or lost by trawling. Depending on the respective responses of the four chosen indices, a composite indicator is proposed here. Based on a precautionary approach, and in case different threshold values were detected by different indices, this indicator will select the most conservative abrasion thresholds to classify habitat status based on specific EUNIS habitat susceptibility to fishing induced abrasion. This indicator is computed as follow:

For any given habitat, null abrasion values over the available period resulted in these areas being automatically considered in GES in respect to fishing physical impact (ICES 2018). The GES can be assessed until a pressure threshold from which a significant negative relationship between any selected indices and abrasion is detected (Segment 1 and 2, Figure 3). Above this threshold value or when the relationship is negative and significant over an entire non-null abrasion range (Neglinear, Figure 3), it is considered that the trawling pressure has adverse effects on the benthic communities. If the habitat abrasion gradient exceeds that of the observed range, habitat ecological status would be “adverse effect” or “habitat loss” for the highest values outside the observed range. In contrast, the detection of a negative significant relationship below a given pressure threshold value and followed by an absence of significant relationship (Segment 2 and 3, Figure 3) would indicate that the habitat is lost. Indeed, the absence of relationship indicates that original communities were replaced by communities fully adapted to fishing. Moreover, in that case, if the existing abrasion values exceed that of the observed range, habitat ecological status is also defined as “habitat loss” for the highest values even if unobserved. The failure to detect any relationship between any index and non-null abrasion values when the observed abrasion range is very high (>1) indicates that the habitat is “probably habitat loss”.

Any other un-sampled abrasion value for a given habitat or any unstudied habitats were labelled as “undetermined” status. If sampling occurs in different seasons, precautionary approach requires to keep the most “robust” season (with the higher number of observations per habitat) and, when quality and quantity of the available data were similar between seasons, the most sensitive season (with the lowest threshold value per habitat) was considered.

The conversion of habitat distribution and abrasion maps into ecological status categories (“GES”, “adverse effect”, “adverse effect or habitat loss”, “probably habitat loss”, “habitat loss”, “undetermined”) following the proposed assessment approach was conducted and proportion of habitat falling in each category was computed.

2.6. Uncertainty maps

To evaluate the degree of uncertainty of the approach developed in this work, the relative mean absolute model error (RMAE) was calculated by habitat as:

$$RMAE = \frac{MAE}{|\max(a) - \min(a)|}$$

Where max(a) is the maximum observed value of the “best” index in the studied habitat, min(a) the minimum observed value of the “best” index in the studied habitat and the mean absolute error (MAE) is calculated as:

$$MAE = \frac{\sum_{i=1}^{n} |p_i - a_i|}{n}$$

With p_i the i^{th} predicted value of the index, a_i the i^{th} observed value of the index and n the number of index value in the studied habitat

The spatial distribution of the RMAE was mapped for each habitat investigated and for the indices used, a value of 1 corresponding to the maximum possible prediction error. The RMAE can therefore be interpreted as a percentile of model uncertainty. Based on a precautionary approach and when several indices were significantly correlated with abrasion, the maximal uncertainty (higher RMAE) by habitat was conserved. For illustration purpose, the value of the RMAE was classified into very low uncertainty (0-0.1), low uncertainty (0.1-0.2), moderate uncertainty (0.2-0.5), high uncertainty (0.5-0.75) and very high uncertainty (0.75-1).

3. Results

3.1. Representativeness of available observation

Four habitats in the western Mediterranean, four in the southern North Sea and four in the English Channel were sufficiently sampled and investigated here.

In the Mediterranean area, two habitat types were sampled only in the Gulf of Lion (Table 1): A5.38 (Mediterranean communities of muddy detritic bottoms), A5.39 (Mediterranean communities of coastal terrigenous muds). Two other habitats were sampled in both the Gulf of Lion and in Corsica (Table A.1): A5.46 (Mediterranean communities of coastal detritic bottoms) and A5.47 (Mediterranean communities of shelf-edge detritic). Although no observations were made in areas of low abrasion value in habitats A5.38 and A5.39, the abrasion range sampled seems very similar to the abrasion range experienced by each of these two habitats.

In the southern North Sea, IBTS observations covered eight habitats (Table A.2) but only four were found sufficiently sampled to be taken into account (Table 1). These were A5.15 (Deep circalittoral coarse sediment), A5.25/26 (Circalittoral fine sand/muddy sand), A5.27 (Deep circalittoral sand) and A5.37 (Deep circalittoral mud). Even if very high abrasion values were not sampled for all habitats, the abrasion range sampled seemed representative to that experienced by each habitat in the North Sea.

In the English Channel, observations were available for two seasons which were kept separated in the following analyses. In autumn, CGFS and CAMANOC surveys' data were used and covered twelve different habitat types. Seven habitats were re-sampled in winter during the IBTS survey (Table A.3).

A great diversity of habitats has been sampled in the Channel but only five habitats in autumn and two in winter were found sufficiently sampled to be studied in more detailed (Table 1). These were A5.14 (Circalittoral coarse sediment) and A5.15 (Deep circalittoral coarse sediment) for the two seasons and A5.23/24 (Infralittoral fine sand/muddy sand), A5.25/26 (Circalittoral fine sand/muddy sand) and A5.27 (Deep circalittoral sand) for the autumn. Despite higher sampling effort in areas of high abrasion values than that of low abrasion, the abrasion range sampled seemed representative of the abrasion withstood by each habitat in the English Channel for the two sampled seasons.

Table 1: Abrasion ranges of the main habitats sampled in the different areas studied and the number of survey carried out in these habitats.
The three abrasion values represent the minimum value, the median and the maximum value. GoL = Gulf of Lion

Area	Habitats	Number of observations	Number of station with null abrasion	Abrasion range ($SAR.y^{-1}$)	Sampled abrasion range ($SAR.y^{-1}$)
GoL	A5.38	49	0	0 – 10.79 – 38.18	2.70 – 17.22 – 29.15
	A5.39	129	0	0 – 5.59 – 29.66	2.06 – 5.25 – 13.79
GoL & Corsica	A5.46	80	9	0 – 3.35 – 28.49	0 – 1.00 – 20.77
	A5.47	182	0	0 – 2.14 – 20.22	0.08 – 3.62 – 11.07
Southern North Sea	A5.15	108	11	0 – 1.15 – 32.70	0 – 3.43 – 16.51
	A5.25/26	121	0	0 – 1.61 – 51.27	0.11 – 2.02 – 11.14
	A5.27	226	10	0 – 0.98 – 62.76	0 – 1.17 – 16.15
	A5.37	84	0	0.004 – 1.30 – 26.47	0.60 – 1.74 – 13.41
English Channel (Autumn)	A5.14	264	3	0 – 0.86 – 36.72	0 – 4.60 – 29.58
	A5.15	495	0	0 – 3.40 – 78.71	0.03 – 14.00 – 74.15
	A5.25/26	140	0	0 – 1.51 – 33.40	0.03 – 3.75 – 21.42
	A5.27	42	0	0.05 – 2.98 – 35.67	1.29 – 11.98 – 26.14
English Channel (Winter)	A5.14	60	1	0 – 0.86 – 36.72	0 – 5.29 – 29.58
	A5.15	71	0	0 – 3.40 – 78.71	1.55 – 10.41 – 72.34

3.2. Mediterranean habitats

The multi-indices and multi-model approach proposed to identify threshold values was applied to each of the four habitats in the French part of the Mediterranean Sea (Gulf of Lion and Corsica ; Table 2).

No significant correlation between indices and abrasion was detected on habitats A5.38 and A5.39 in the Gulf of Lion (Figure B.1 & B.2 ; Table B.1 & B.2). On these habitats, the observed range of abrasion was high, an abrasion value above 2 meaning that the surface of the habitat was entirely swept by trawling at least twice a year. In contrast, negative impacts of the trawling on the benthic community were detected on the two other sampled habitats although no threshold value could be highlighted. On the habitat A5.47, two indices detected a negative significant correlation over all the sampled abrasion range (Figure B.4 ; Table B.4) while a single index (mT) detected such relationship on habitat A5.46 (Figure S3 ; Table S3). On these four habitats, the variance explained by all models for each index seemed very low with a maximal value of adjusted R-squared of 0.05 (Table B.1, B.2, B.3 & B.4).

Table 2: Correlation between indices and abrasion, and the type of model selected for each Mediterranean habitats. * indicates that P< 0.05 ; ** indicates that P< 0.01 ; *** indicates that P<0.001 ; - indicates that there is no negative significant correlation. The lack of value next to an asterisk means that the correlation is significant and negative on the entire abrasion range and that no breakpoint could be found. GoL = Gulf of Lion. Grey shading indicates the index choose for this habitat.

Habitats	TDI	mTDI	pTDI	mT	Selected model	AdjR²
A5.38 (GoL)	-	-	-	-	Null	0
A5.39 (GoL)	-	-	-	-	Null	0
A5.46 (Corsica+GoL)	-	-	-	*	Neglinear	0.04
A5.47 (Corsica+GoL)	-	**	-	**	Neglinear	0.05

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3.3. North Sea habitats

Significant negative relationship between the values of the index and abrasion was detected on all observed habitats (Table 3). Threshold values of 5.90 to 6.52 above which the fishing impact was no longer detectable were determined in habitat A5.15 for most indices (Figure B.5 ; Table B.5). For the three other habitats, the relationship between indices and abrasion was negative and significant over the entire sampled abrasion range even though the observed range of habitat A5.27 included ten apparently un-impacted stations (Figure B.6). On habitats A5.25/26, a significant relationship to abrasion was detected with all indices, except the mT index but no threshold could be found (Figure B.7 ; Table B.7). In contrast, on habitat A5.37, only the mT index detected an impact over the entire abrasion range (Figure B.8 ; Table B.8). On two habitats (A5.25/26 and A5.37), the variance explained by all models for each indices was very low, with a maximal value of adjusted R-squared of 0.07 for the model neglinear on the relationship between the TDI and the abrasion on the habitat A5.25/26 (Table B.6 & B.8). For the two others habitats, the variance explained by all models were relatively higher with a maximum adjusted R-squared of 0.18 for the neglinear model on the habitat A5.27 (Table B.5 & B.7).

Table 3: Correlation between indices and abrasion, and the type of model selected for each habitats in the southern North Sea. * indicates that P< 0.05 ; ** indicates that P< 0.01 ; *** indicates that P<0.001 ; - indicates that there is no negative significant correlation. Values in red represent the trawl intensity above which impact of fishing is not detectable. The lack of value next to an asterisk means that the correlation is significant and negative on the entire abrasion range but no breakpoints could be found. Grey shading indicates the index choose for this habitat.

Habitats	TDI	mTDI	pTDI	mT	Selected model	AdjR²
A5.15	***	6.52**	5.91**	5.90*	Segmented2	0.09
A5.25/26	**	*	**	-	Neglinear	0.07
A5.27	***	***	***	***	Neglinear	0.18
A5.37	-	-	-	*	Neglinear	0.06

3.4. English Channel habitats

The impact of trawling has been detected on all studied habitats (Table 4). On habitat A5.14 and A5.25/26, most indices detected an impact over all the sampled abrasion range but no threshold values were found even though very high abrasion values were also sampled in both cases and three un-impacted observation were available in the A5.14 (Figure B.9 & B.11; Table B.9 & B.11). Threshold values beyond which the fishing impact was no longer detectable were determined for two indices (mTDI and TDI) for the habitat A5.15 (Figure B.10; Table B.10). On habitat A5.27, over which sampled abrasion was quite high, only pTDI and mTDI were able to detect a negative effect of trawling over the entire range of abrasion (Figure B.11; Table B.11). Variance explained by all models were relatively low at three of the four habitats (Table B.9, B.11, B.12) with a maximum adjusted R-squared of 0.10 for the neglinear model on the habitat A5.25/26. But for the habitat A5.15, models seemed to better explain the variance (maximum adjusted R-squared of 0.29 for neglinear models and 0.28 for Segment2 models; Table B.10).

Table 4: Correlation between indices and abrasion, and the type of model selected for each habitats in English Channel in September/October. * indicates that P< 0.05 ; ** indicates that P< 0.01 ; *** indicates that P<0.001 ; - indicates that there is no negative significant correlation. Values in red represent the trawl intensity above which impact of fishing is not detectable. The lack of value next to an asterisk means that the correlation is significant and negative on the entire abrasion range but no breakpoint could be found. Grey shading indicates the index choose for this habitat.

Habitats	TDI	mTDI	pTDI	mT	Selected model	AdjR²
A5.14	*	*	**	-	Neglinear	0.03
A5.15	12.34**	12.34***	***	***	Segment2	0.27
A5.25/26	**	***	***	***	Neglinear	0.21
A5.27	-	*	*	-	Neglinear	0.20

In winter, based on IBTS observations, only two habitats were sufficiently covered to be studied and trawling impact was detected over each of them (Table 5). In habitat A5.15, two of the four indices are no longer able to detect the effect of trawling above an abrasion intensity of about 71.10 for the mT and 18.13 for the pTDI (Figure B.14; Table B.14). No lower bond threshold values were found even though one un-impacted observation (null abrasion) was available. For habitat A5.14, this impact appeared detectable over the whole range of abrasion sampled and no threshold value could be found in spite of the very high observed abrasion values (Figure B.13; Table B.13).

Table 5: Correlation between indices and abrasion, and the type of model selected for each habitats in English Channel in January/February. * indicates that P< 0.05 ; ** indicates that P< 0.01 ; *** indicates that P<0.001. Values in red represent the trawl intensity above which impact of fishing is not detectable. The lack of value next to an asterisk means that the correlation is significant and negative on the entire abrasion range but no breakpoint could be found. Grey shading indicates the index choose for this habitat.

Habitats	TDI	mTDI	pTDI	mT	Selected model	AdjR²
A5.14	**	**	***	***	Neglinear	0.22
A5.15	***	***	18.13*	71.10*	Segment2	0.32

3.5. Evaluation of habitat disturbance and loss

The study of the relationship between each index and the abrasion allowed determining the ecological state of each habitat in the three studied areas (Table 6, 8 & 10). Thus, in the Gulf of Lion, only very small areas were considered in GES (maximum 10 % of the habitat for A5.39). On more than three quarters of the surface of habitats A5.38 and A5.39, which cover together about 50% of the studied area, original benthic communities were considered to be replaced by communities perfectly adapted to the impact of fishing (Figure 4, Table 7). Conversely, in Corsica, no habitat was classified as lost and about 40% of the studied habitat surface was in GES. In the two Mediterranean areas studied, undetermined ecological status on the investigated habitats resulted from lack of observations on the entire range of existing abrasion, but concerned less than 10% of each habitat (except for habitat A5.38). Although habitats A5.46 and A5.47 were jointly assessed in Corsica and in the Gulf of Lion to increase both the number of observations and the abrasion range, they were reported separately to better illustrate the assessment of the ecological status of habitats in Corsica (Table 6).

Table 6: Ranges of abrasion values (in SAR.y^{-1}) corresponding to the different ecological status in the Mediterranean habitats

Habitats	Area	GES	Undetermined	Adverse effects	Adverse effects or habitat loss	Probably habitat loss
A5.38	GoL	0	]0 - 2.70[			≥ 2.70
A5.39		0	]0 - 2.06[			≥ 2.06
A5.46		0		]0 - 20.77]	]20.77 - 28.49]	
A5.47			[8×10^{-4} - 0.08[	[0.08 - 11.07]	]11.07 - 20.22]	
A5.46	Corsica	0		]0 - 5.74		
A5.47		0	]0 - 0.08[	[0.08 - 3.46]		

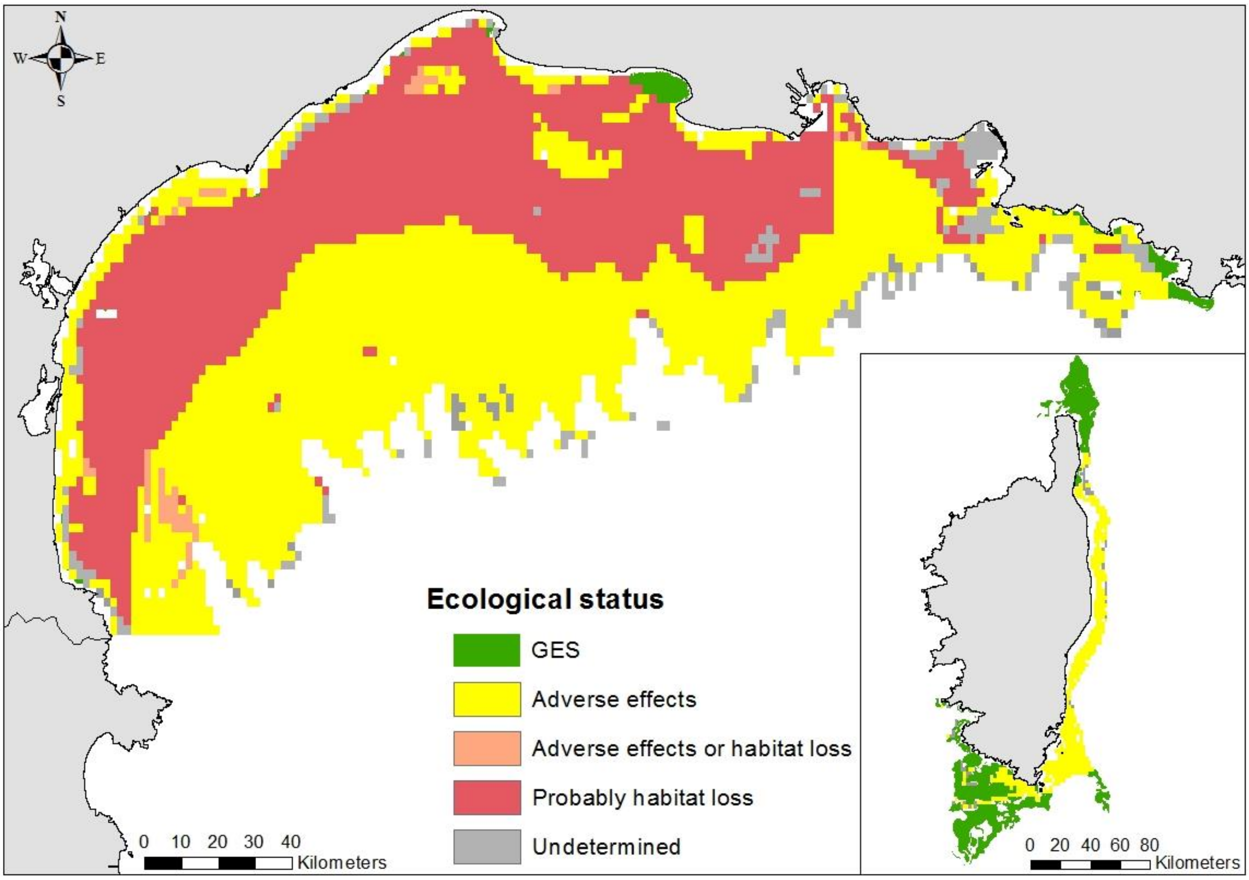

Figure 4 : Ecological status of benthic habitats in the Western Mediterranean Sea

Table 7: Proportion of the Golf of Lion (GoL) and Corsica habitats in each of the ecological status category

Ecological status	A5.38 (GoL)	A5.39 (GoL)	A5.46 (GoL)	A5.47 (GoL)	A5.46 (Corsica)	A5.47 (Corsica)
GES	3 %	10 %	5 %	-	46 %	32 %
Adverse effects	-	-	89.4 %	96.4 %	54 %	62.5 %
Adverse effects or habitat loss	-	-	5.6 %	1.8 %	-	-
Probably habitat loss	77 %	83.7 %	-	-	-	-
Undetermined	20 %	6.3 %	-	1.8 %	-	5.5 %

Table 8: Ranges of abrasion values (in $SAR.y^{-1}$) corresponding to the different ecological status in the North Sea habitats

Habitats	GES	Undetermined	Adverse effects	Adverse effects or habitat loss	Habitat loss
A5.15	0		]0 - 5.90]		> 5.90
A5.25/26	0	]0 - 0.11[	[0.11 - 11.14]	]11.14 - 51.27]	
A5.27	0		]0 - 16.15]	]16.15 - 62.76]	
A5.37		[0.004 - 0.60[	[0.60 - 13.41]	]13.41 - 26.47]	

In the South of the North Sea, a majority of habitats was considered as impacted (adverse effects) but not lost (Table 8, Figure 5) and only very few small and scattered areas were considered as lost (less than 5% of each habitat). Since an important part of the North Sea is apparently untrawled, many areas were considered in GES, especially in the western part. As a result, about 51.5% of the habitat A5.15 was considered in GES in respect to fishing physical impact to the seabed (Table 9). Undetermined ecological status represented from 4% in habitat A5.25/26 to almost 13% of habitat A5.37.

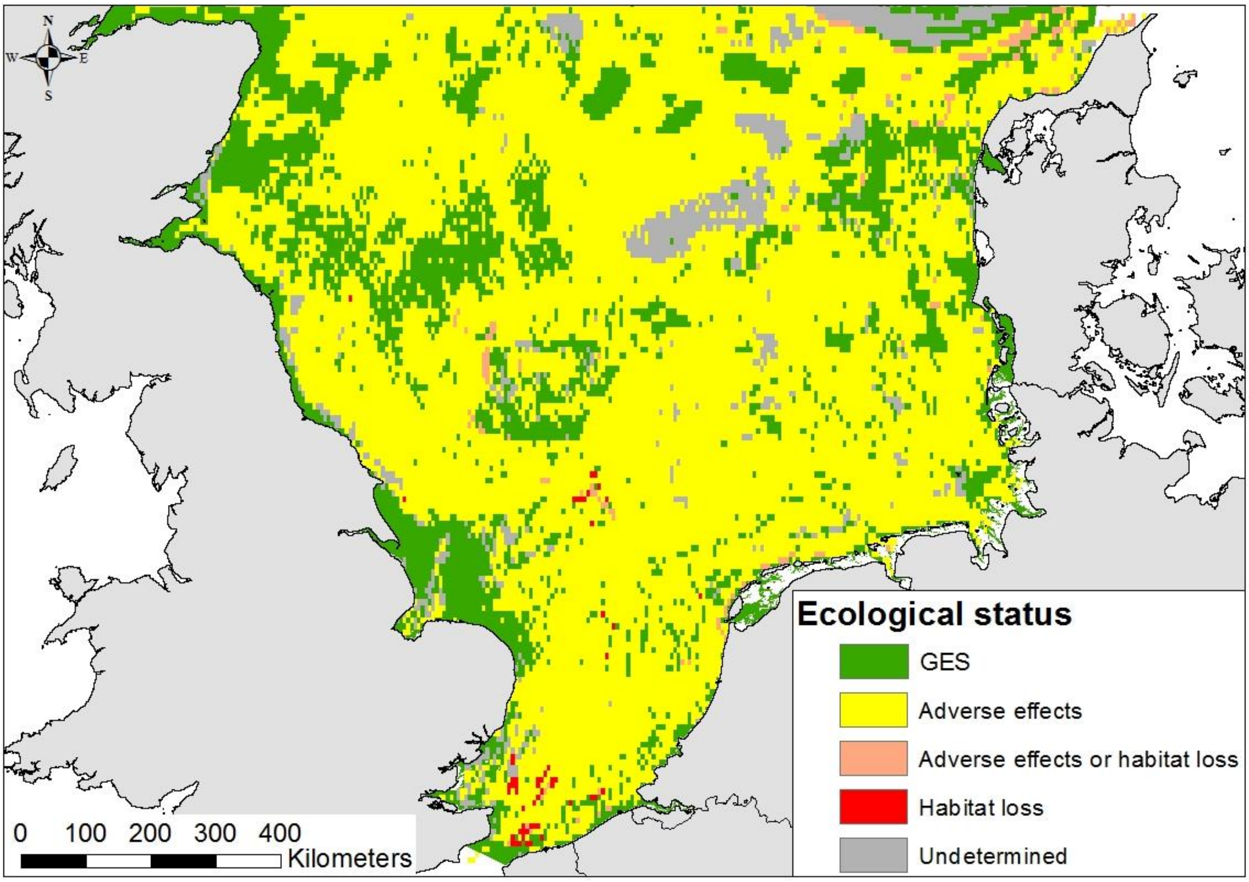

Figure 5 : Ecological status of benthic habitats in the southern North Sea

Table 9: Proportion of southern North Sea habitats in each of the ecological status category

Ecological status	A5.15	A5.25/26	A5.27	A5.37
GES	51.5 %	0.5 %	6 %	-
Adverse effects	45 %	93.6 %	93.4 %	86.5 %
Adverse effects or habitat loss	-	2 %	0.6 %	0.7 %
Habitat loss	3.5 %	-	-	-
Undetermined	-	3.9 %	-	12.8 %

Table 10: Ranges of abrasion values (in SAR.y-1) corresponding to the different ecological status in the English Channel in autumn and winter according to abrasion

Habitats	Season	GES	Undetermined	Adverse effects	Adverse effects or habitat loss	Habitat loss
A5.14	Autumn	0		]0 - 29.58]	]29.58 - 36.72]	
A5.15		0	]0 - 0.03[	[0.03 - 12.34]		> 12.34
A5.25/26		0	]0 - 0.03[	[0.03 - 21.42]	]21.42 – 33.40]	
A5.27			[0.05 - 1.29[	[1.29 - 26.14]	]26.14 - 35.67]	
A5.14	Winter	0		]0 - 29.58]	]29.58 - 36.72]	
A5.15		0	]0 - 0.03[	[0.03 - 18.13]		> 18.13

For the two habitats sampled in the English Channel in autumn and in winter, only few differences were observed in the habitat A5.15, with a threshold after an abrasion of 12.34 in autumn and 18.13 in winter (Table10).

In autumn in the English Channel, only small coastal areas were found in GES and 9% of habitat A5.15 was classified as "habitat loss" (Table 10 & 11, Figure 6). In this particular case study, the proportion of inadequately sampled habitats seemed quite substantial and resulted in a large amount of grey areas. In addition, the ecological status of nearly 3.6% of the studied habitats could not be determined with, in particular, 14.5% of habitat A5.27 and 8.4% of habitat A5.25/26 labelled as undetermined.

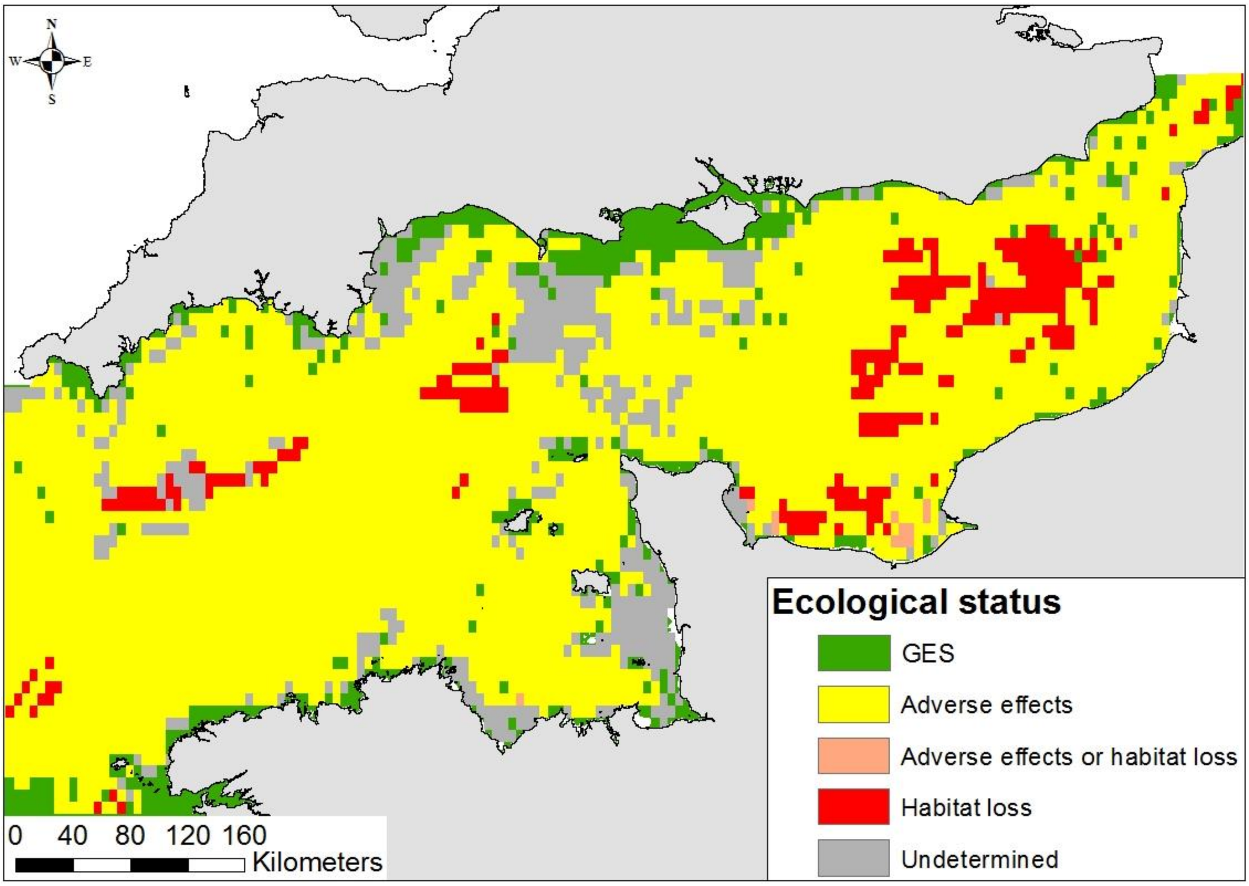

Figure 6 : Ecological status of benthic habitats in the English Channel

Table 11: Proportion of English Channel habitats in each of the ecological status in autumn

Ecological status	A5.14	A5.15	A5.25/26	A5.27
GES	15.5 %	0.5 %	8 %	-
Adverse effects	84.3 %	88.0 %	77.4 %	83.5 %
Adverse effects or habitat loss	0.2 %	-	6.2 %	2.0 %
Habitat loss	-	9.0 %	-	-
Undetermined	-	2.5 %	8.4 %	14.5 %

3.6. Uncertainty maps

Modeled uncertainties were different between habitats and areas but were relatively low in most areas particularly in the English Channel and in Corsica (Figure 7). In the southern North Sea, models uncertainties were higher in the West while in the Gulf of Lion, the uncertainties were higher (0.2 < RMAE ≤ 0.5) for the most offshore habitats. Note that the areas where abrasion was zero are classified in the category "Very low uncertainties".

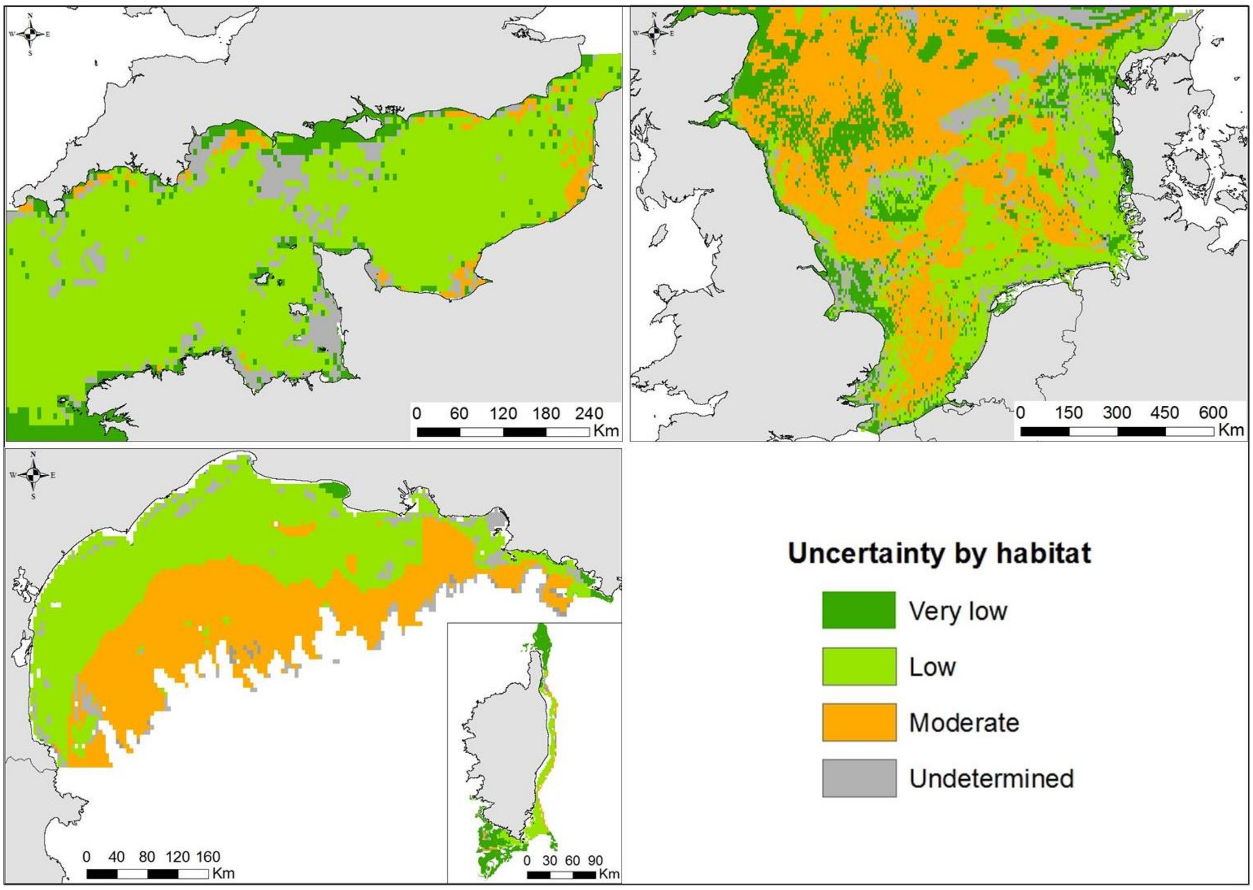

Figure 7: Models uncertainties by habitat in the three studied areas.
Very low correspond to 0≤RMAE≤0.1; Low correspond to 0.1<RMAE≤0.2; Moderate correspond to 0.2<RMAE≤0.5

4. Discussion

4.1. Method uncertainties

4.1.1. Data variance

In the majority of the habitats sampled in this study, the variance explained by models seemed low as is often the case with noisy data. This variability mostly resulted from inter-annual variations due to the pooling of several years of surveys together. Inter-annual variations could be due to several factors: the natural variability of each population (quality of recruitment and different growth between years), the separation time between the last fisher trawling operation and the scientific haul or even location inaccuracy of the haul station across years. Working at habitat level increased the effect of temporal over spatial variability of the benthic communities in the three studied areas. Although this should increase model uncertainty, it appeared relatively moderate in most instances due to relatively low mean absolute error between modeled predictions and observations. However, other sources of uncertainties such as errors in the calculation of abrasion values or in modeled habitat classification should also be taken into account in the present approach.

4.1.2. VMS data

The use of VMS data for the calculation of abrasion induces a certain number of uncertainties. Firstly, VMS positioning is required only for vessels of 12 m or longer (EC 2009) since 2012, and 15 m or longer before that. The trawling operations carried out by smaller vessels are therefore not taken into account in the abrasion data and it is conceivable that the coastal areas considered in GES are actually trawled or dredged by the small vessels in particular in estuaries or bays. As a consequence, some areas, in particular coastal areas, may be wrongly considered as untrawled and therefore in GES. Moreover, the signal frequency is limited to once every two hours (Shepperson et al. 2018), which further reduces the accuracy and spatial resolution of the abrasion values (ICES 2018). The use of aggregated VMS data (3’x3’ in the English Channel/southern North Sea and 1’x1’ in the Mediterranean Sea) does not allow us to have the precise location of the trawl hauls and induces potential errors on the allocation of abrasion values to the different sampled stations. However, if the distribution of fishing activities is random within each grid cells, the compilation of several years of abrasion strongly reduces this bias by making the distribution of the abrasion homogenous within the cell (Ellis et al. 2014; Eigaard et al. 2017). Despite all these potential sources of biais, no uncertainty assessment method for the abrasion calculation has been proposed. Nevertheless, the generalization of the use of VMS to all professional fishing vessels and the increase of the signal frequency to less than 30 minutes would make it possible to overcome these methodological biases in the near future which seems preferable to systematically excluding near shore areas from the assessment. Finally, the English Channel, the southern North Sea and the Mediterranean Sea have been subjected to industrial trawling for decades (Englehard 2008; Hidalgo et al. 2009; Thurstan et al. 2010) and in the present study, the data on abrasion only concern the 2009 – 2017 period. As a result, there is no certainty that areas considered untrawled are pristine areas or fully recovered from past trawling disturbances.

4.1.3. EUNIS classification

The use of EUNIS habitat classification and predictive maps also leads to uncertainties. Indeed, boundaries between habitats classes can be uncertain or habitats can be wrongly described due to erroneous description and classification of the continuous physical variables such as substrate types or energy classes. To evaluate uncertainties specific to each area, a confidence assessment method was already developed by Populus et al. (2017) to obtain a classification in three levels (low, moderate, high) of the habitat type confidence (https://www.emodnet-seabedhabitats.eu).

The assessment of the total uncertainty of the method proposed in the present study would require combining the error arising from three sources of uncertainties: model error, abrasion calculation error and EUNIS classification confindence levels. Currently, only the uncertainty maps of the models developed in this study, and maps of EUNIS habitats uncertainties exist and provide a partial overview of the overall uncertainty.

4.2. Variation in threshold values

Habitat response to fishing pressure was shown to vary with geographic basins and even seasons. Indeed, the habitat A5.15 was sampled in the North Sea and the English Channel but was considered lost after an abrasion threshold of 5.90 in the North Sea and 12.34 in the English Channel. Several reasons may explain these differences.

Firstly, although this habitat was classified in the same way in EUNIS, it is possible that benthic communities slightly differ between the two basins. Indeed, in this habitat, for instance, two main facies are defined in the EUNIS classification: A5.151 (facies with *Glycera lapidium*, *Thyasira spp.* and *Amythasides macroglossus*) and A5.152 (facies with *Hesionura elongata* and *Protodorvillea keferteini*). Only the consideration of the level 5 of EUNIS could confirm this hypothesis and may explain these differences. Additionally, the apparently higher trawling resistance of the benthic communities of habitat A5.15 in the English Channel compared to the North Sea could also be due to differences in hydrodynamics between the two basins. Many studies have shown that natural disturbance due to waves and tides increases the resilience of benthic communities to fishing disturbance (Diesing et al. 2013; van Denderen et al. 2015) in at least two ways. Firstly, the resilience can be increased by selecting for fast-growing opportunistic species which quickly recolonize disturbed areas and can reach sexual maturity before the next disturbance event (Pianka 1970). Second, species that display traits that pre-adapt them to withstand the disturbance may have an advantage in naturally disturbed habitats (Diesing et al. 2013). The intense hydrodynamism in the English Channel relative to the North Sea can therefore result in more resistance of the English Channel's benthic communities to trawling and therefore the value of fishing intensity causing habitat to be "lost" is higher. To verify this, the Kostylev approach (Kostylev and Hannah 2007; Foveau et al. 2017) could be used to combine a pool of environmental layers explicitly linked to relevant ecological processes known to affect the seabed. These, such as salinity, temperature, oxygen saturation, sediment grain size or friction velocity at seabed may in turn be used to predict and map habitat sensitivity. The combination of both EUNIS and process-driven sensitivity would certainly enable a better distinction of these habitats.

Circalittoral coarse sediment (A5.15) was sampled in autumn and in winter in the eastern English Channel and sensitivity difference was highlighted between the two seasons. This habitat seemed less sensitive to trawling in winter than autumn (habitat considered lost from a value of 12.34 abrasion in autumn to 18.13 in winter). It is very likely that this resulted from differences in the number of observations available for each season. The study of the seasonal effect on the sensitivity of benthic habitat to trawling requires to use similar sampling station set for each season and may also require monthly VMS data and was clearly out of the scope of this study. The most "robust" season, i.e. with the largest sample size on each habitat, was chosen to build the assessment of habitat disturbance and loss. As all habitats of the English Channel were largely sampled in autumn, this season was chosen for the assessment of the ecological status of the benthic habitats of this area.

More importantly, this study has highlighted how different indices performance may vary amongst habitats and/or abrasion range. Although the four indices used were closely related by construction, they displayed different abilities to describe benthic communities' sensitivity to trawling as a result of the inequal weighting given to different biological traits present in these communities. These indices sensitivity appeared somehow dependent of each community overall traits' composition. The approach proposed here, based on precautionary principle, may easily be extended to another set of complementary indices that may be more suited for different habitats, abrasion range, biotic data type or to investigate another type of pressure altogether.

4.3. On the difficulty to find and sample low abrasion reference areas: a methodological bolt

In the French part of the Mediterranean Sea, there was no clear relationship between abrasion and any of the four selected indices in muddy habitats (A5.38 and A5.39). For these, there was no observation located in low abrasion areas and sampling was carried out in areas with abrasion levels higher than 2. These values being high (the surface being totally swept twice a year), we assume that the original communities of these habitats have already been completely replaced by communities adapted to trawling, which would justify the lack of relationship between indices and abrasion levels. These particularly severe results may be explained by the particular environmental conditions prevailing of this geographical area.Firstly, as the hydrodynamics is relatively low in the continental shelf of the Gulf of Lion (absence of tide or high current), benthic communities are not naturally adapted to disturbances and would therefore be very sensitive to any additional physical disturbance such as trawling. Similarly, the oligotrophic nature of the Mediterranean Sea (Estrada 1996) could also lead to higher fragility of benthic habitats to trawling than would be in more productive environments such as the English Channel or the North Sea. In fact, oligotrophy results in low species abundance and smaller individuals biomasses (Smith et al. 2000), which reduces community resilience. Finally, the accuracy of the habitat maps may also be questioned as differences in assemblage of benthic communities are known to exist between the East and West of the Gulf of Lion (Labrune et al. 2007, 2008). These differences being related to the sediment granulometry, the use of a more accurate habitat map or the use of the Kostylev habitat approach (Kostylev and Hannah 2007) may possibly correct this bias in the future.

The absence of pressure free, ideally pristine, areas for most habitats in the different basins investigated prevents the use of a method based on an observed reference state to contrast and monitor the trawling disturbance. Indeed, only few stations (a maximum of 11 stations by habitats and 33 stations in total) were sampled in un-impacted areas in the four surveys available and this may be explained in two ways.

Firstly, as in many other geographical areas (Nilsson and Ziegler 2007; Baird et al. 2015), the totality of the trawlable habitats of the European shelves is trawled (eg. habitat A5.27 in the Channel and A5.37 in the North Sea) and, therefore, no reference area exists for these habitats. In this case, the creation of protected areas where trawling is banned may possibly allow, after a certain delay (probably very long), the restoration of the original community that may then be used as reference.

Secondly, the small number of stations sampled in untrawled areas is due to gaps in the sampling design of the chosen surveys. Indeed, scientific trawl surveys are not dedicated to the study of the effect of trawling but to the evaluation of fish stocks, so sampling is not carried out according to an abrasion gradient but following a random stratified sampling scheme deemed relevant for each area and the targeted stocks (MEDITS 2017). The addition of complementary observations to existing scientific trawl surveys in untrawled or lesser trawled habitats such as A5.15 in the English Channel or A5.38 in the Gulf of Lion would enable to investigate their original communities and set reference states. The increase in the number of observations could also reduce the surface of indeterminate status areas that represented more than 10% of the total area of some habitats (eg. A5.37 in the North Sea and A5.27 in the English Channel).

4.4. Non-linear impact of trawling on benthic fauna

The response of benthic fauna community structure to environmental impacts is often non-linear with increasing change above a threshold value of the impact factor (Josefson et al. 2008). Trawling seems to non-linearly impact benthic fauna according to the fishing intensity (Hiddink et al. 2008, 2011) and/or the season (Kaiser et al. 1998). In this work, it was considered that relationship between indices (ie. sensitivity of benthic community) and abrasion is segmented and composed of two threshold values between which trawling impacts negatively and significantly the benthic fauna. It has been hypothesized that below a certain annual value of abrasion (probably extremely low) the sensitivity of the community (and therefore the value of the index) does not vary significantly. Between this value and the absence of abrasion, benthic community is considered in a good ecological status. Beyond this threshold value of abrasion, the pressure is strong enough to progressively alter the benthic community (decrease of index values), in particular by inducing a decrease in trawl-sensitive species by minimizing their ability to recover. This process could be considered as a physical disturbance (change to the seabed from which it can recover if the activity causing the disturbance pressure ceases ; ICES 2018) and define “adverse effects” in the ecological classification of the seabed in this study. In addition to affect benthic communities, especially epifauna, trawling results in a change in physical habitat. In fact, trawling induces changes (i) in grain size, with an increase in coarse sediment and a decrease in mud (Palanques et al. 2014; Mengual et al. 2016), (ii) an increase in the organic carbon content in the first centimeters of sediments (Palanques et al. 2014) and (iii) a flattening of the bottom topography by eliminating natural irregular feature such as ripples, bioturbation mounds, biogenic reefs or seagrass mats (Fonteyne 2000). Such physical modifications of the bottom may also modify original benthic communities, which may be, in very heavily trawled areas, completely replaced by others, perfectly adapted to these disturbances. Consequently, beyond a certain abrasion value, the index cannot respond negatively to the increase in abrasion and the original habitat (biotic and abiotic) may be considered as lost because it is a permanent modification of the seabed that can last a very long time, even after stopping trawling (ICES 2018).

4.5. Towards the restauration of benthic habitats?

Restoration of benthic habitat is a long process as reported by Sheehan et al. (2013) which observed a partial recolonization of the epifauna, three years after trawling ban in the western English Channel, Tuck et al. (1998) which showed that 18 months were necessary to the recovering of infaunal communities in Scottish Sea lochs and Desprez (2000) and Sardá et al. (2000) which underlined recovery delays between one to three years for macrobenthic invertebrates like molluscs, crustaceans and echinoderms (in the eastern English Channel and Catalan western Mediterranean respectively). However, the complete recovery of original communities, including slow growing species such as sponges or cold water corals may take several years or decades. Determining recovery time is very important for the management of the marine ecosystem and complementary studies are required on benthic recolonization of areas where trawling is permanently banned.

The assessment of the ecological status of benthic habitats not only provides information on the integrity of the seabed to date, but can also provide some clues about its evolution. Indeed, areas where the habitat is considered as lost will not have the same capacity to return at the GES than impacted areas (adverse effects category) when fishing pressure is reduced or removed. The habitat type (Collie et al. 2000), the ecological connectivity of the areas (Eno et al. 2013) and the diversity of responses between different species to disturbance (Muntadas et al. 2016) also play an important role in the resilience of benthic communities. The presence of a large number of small areas considered in good ecological state in the English Channel and in the North Sea would appear beneficial for all the benthic habitats of these two zones. The existence of untrawled areas and the important productivity of these two marine basins will allow some species to withstand the impacts of trawling through recruitment or regeneration processes (Osman and Whitlatch 1998; Pranovi et al. 1998; Frid et al. 2000). Although the interruption of trawling would certainly lead to environmental status improvement, all habitats will not necessary return to GES at the same speed. In the worst case scenarios, areas where the original community is fully replaced by a fishery adapted community (habitat loss), if too isolated from a potential source original population, could potentially never regain their original state even with complete trawling exclusion.

4.6. Extension of the approach to coastal areas and other pressures

In the present study, only the specific effect of fishing disturbance on the seabed was taken into account. A large part of the European continental shelf surface is exclusively submitted to the fishery induced abrasion pressure and the present work offers an operational and cost-efficient method to evaluate its impact on seabed integrity in the frame of the MFSD. The assessment of the ecological status of benthic habitats should also account for other anthropogenic physical pressures such as aggregate extraction, placement of physical structures (oil and gas extraction, renewable energy, harbours and coastal defense, tourism/recreation, road and rail transportation, pipelines and cables, wrecks, artificial reefs…), or dredge disposal (ICES 2019b) to provide a full picture of the ecological status of the benthic habitats in studied areas. In coastal areas, the impact of other pressures, also including pollution and eutrophication may largely exceed that of fishing and prevent habitat restoration even if fishery pressure is lessened. The threshold detection approach, developed in this work, could be applied to other pressures types (with indicators specific to these pressures) and could thus respond to this need. However, a pressure and habitat-by-habitat approach, using the most appropriate observed biological data, seems more relevant and defensible than a global approach. Using ecological status classification of benthic habitats for each pressure and aggregating them would allow a general assessment (combining all pressures) of the ecological states of the seabed. The development of methodologies to aggregate environmental status resulting from different types of pressure and to account for potential cumulative effect of these impacts are necessary to monitor the sea-floor integrity as a whole.

Finally, this work meets different criteria of the MSFD because pressure thresholds values for the adverse effects of physical disturbance were defined (D6C3) and an assessment of the extent of benthic community “loss” or “alteration” was realized (D6C4 and D6C5). In all investigated areas, the percentage of habitat impacted by trawling pressure seems to exceeds the recommended 30% of the total surface while only a few habitats exceed the value of 5% of lost habitat (Unknow 2016). Decrease of impacted surfaces is recommended, but this should not be done at the cost of increasing habitat loss surfaces as a result of fishing effort displacement. It necessary should be assorted of an overall bottom trawl effort reduction.

5. Conclusions

The establishment of the MSFD by the European Union in 2008 requires the development methodological standards for determining the good environmental status. Trawling appearing as one of the strongest pressure on the seabed, the definition of thresholds for each habitat type that may be trawled is required. However, the absence of sampling on certain habitat or poor sampling distribution along the abrasion gradient, for some habitat, showed the necessity to increase the sampling effort especially in low and high abrasion areas. The evaluation of the impact of trawling on benthic communities highlighted that the vast majority of the investigated sub-regions were adversely impacted or lost as a result of seabed impacting trawling.

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Appendix A. Supplementary material – Details on habitat sampled

Table A.1 : Number of MEDITS' observations in each habitat and corresponding abrasion ranges.
The three abrasion values represent the minimum value, the median and the maximum value in the Gulf of Lion (GoL) and eastern Corsica. Grey shading indicates habitats sufficiently covered by the available observation (more than 40 observations). A5.46 and A5.47 in GoL and Corsica had to be merged.

Habitats	Areas	Number of observations	Number of un-trawled stations	Abrasion range ($SAR.y^{-1}$)	Sampled abrasion range ($SAR.y^{-1}$)
A5.38	GoL	49	0	0 – 10.79 – 38.18	2.70 – 17.22 – 29.15
A5.39	GoL	129	0	0 – 5.59 – 29.66	2.06 – 5.25 – 13.79
A5.46	GoL	24	0	0 – 4.02 – 28.49	0.20 – 3.81 – 20.77
A5.47	GoL	170	0	8×10^{-4} – 3.49 – 20.22	0.08 – 3.64 – 11.07
A5.46	Corsica	56	9	0 – 0.34 – 5.74	0 – 0.11 – 2.03
A5.47	Corsica	12	0	0 – 0.15 – 3.46	0.08 – 0.75 – 2.03

Table A.2 : Number of IBTS' observations in each North Sea habitat and corresponding abrasion ranges.
The three abrasion values represent the minimum value, the median and the maximum value. Grey shading indicates habitats sufficiently covered by the available observation (more than 40 observations)

Habitats	Number of observations	Number of un-trawled stations	Abrasion range ($SAR.y^{-1}$)	Sampled abrasion range ($SAR.y^{-1}$)
A5.13	7	0	0 – 1.91 – 8.42	1.59 – 1.98 – 2.14
A5.14	15	0	0 – 0.62 – 31.53	0.0001 – 1.06 – 7.64
A5.15	108	11	0 – 1.15 – 32.70	0 – 3.43 – 16.51
A5.25/26	121	0	0 – 1.61 – 51.27	0.11 – 2.02 – 11.14
A5.27	226	10	0 – 0.98 – 62.76	0 – 1.17 – 16.15
A5.37	84	0	0.004 – 1.30 – 26.47	0.60 – 1.74 – 13.41
A5.44	1	0	0 – 0.15 – 5.45	0.007
A5.45	3	0	0.002 – 0.95 – 18.24	6.94 – 7.08 – 7.08

Table A.3 : Number of observations in each English Channel habitat and corresponding abrasion ranges for the two sampling season.
The three abrasion values represent minimum, median and maximum value. Grey shading indicates habitats with a good representativeness in the sampling (more than 40 observations)

Habitats	Season	Number of observations	Number of un-trawled stations	Abrasion range ($SAR.y^{-1}$)	Sampled abrasion range ($SAR.y^{-1}$)
A4.1	Autumn	9	0	0 – 0.14 – 5.16	0.98 – 1.06 – 1.06
A4.2		2	0	0 – 0.17 – 6.20	0.30 – 0.75 – 1.20
A5.13		2	0	0 – 1.09 – 25.21	5.47 – 6.22 – 6.97
A5.14		264	3	0 – 0.86 – 36.72	0 – 4.60 – 29.58
A5.15		495	0	0 – 3.40 – 78.71	0.03 – 14.00 – 74.15
A5.23/24		29	0	0.04 – 2.69 – 22.58	0.65 – 6.21 – 14.10
A5.25/26		140	0	0 – 1.51 – 33.40	0.03 – 3.75 – 21.42
A5.27		42	0	0.05 – 2.98 – 35.67	1.29 – 11.98 – 26.14
A5.33		3	0	0.008 – 1.81 – 16.40	9.29
A5.35		4	0	$6{\times}10^{-4}$ – 0.21 – 18.16	1.16 – 6.46 – 9.29
A5.37		11	0	0.76 – 1.71 – 16.88	2.61 – 2.61 – 5.91
A5.45		5	0	0 – 3.55 – 18.46	2.50 – 2.90 – 8.85
A4.2	Winter	1	0	0 – 0.17 – 6.20	1.20
A5.13		1	0	0 – 1.09 – 25.21	6.97
A5.14		60	1	0 – 0.86 – 36.72	0 – 5.29 – 29.58
A5.15		71	0	0 – 3.40 – 78.71	1.55 – 10.41 – 72.34
A5.25/26		10	0	0 – 1.51 – 32.09	0.46 – 1.16 – 8.52
A5.27		5	0	0.05 – 2.98 – 35.67	9.41 – 18.83 – 26.14
A5.37		3	0	0.76 – 1.71 – 16.88	2.61

Appendix B - Details on selected models in each studied areas

1. Mediterranean Sea

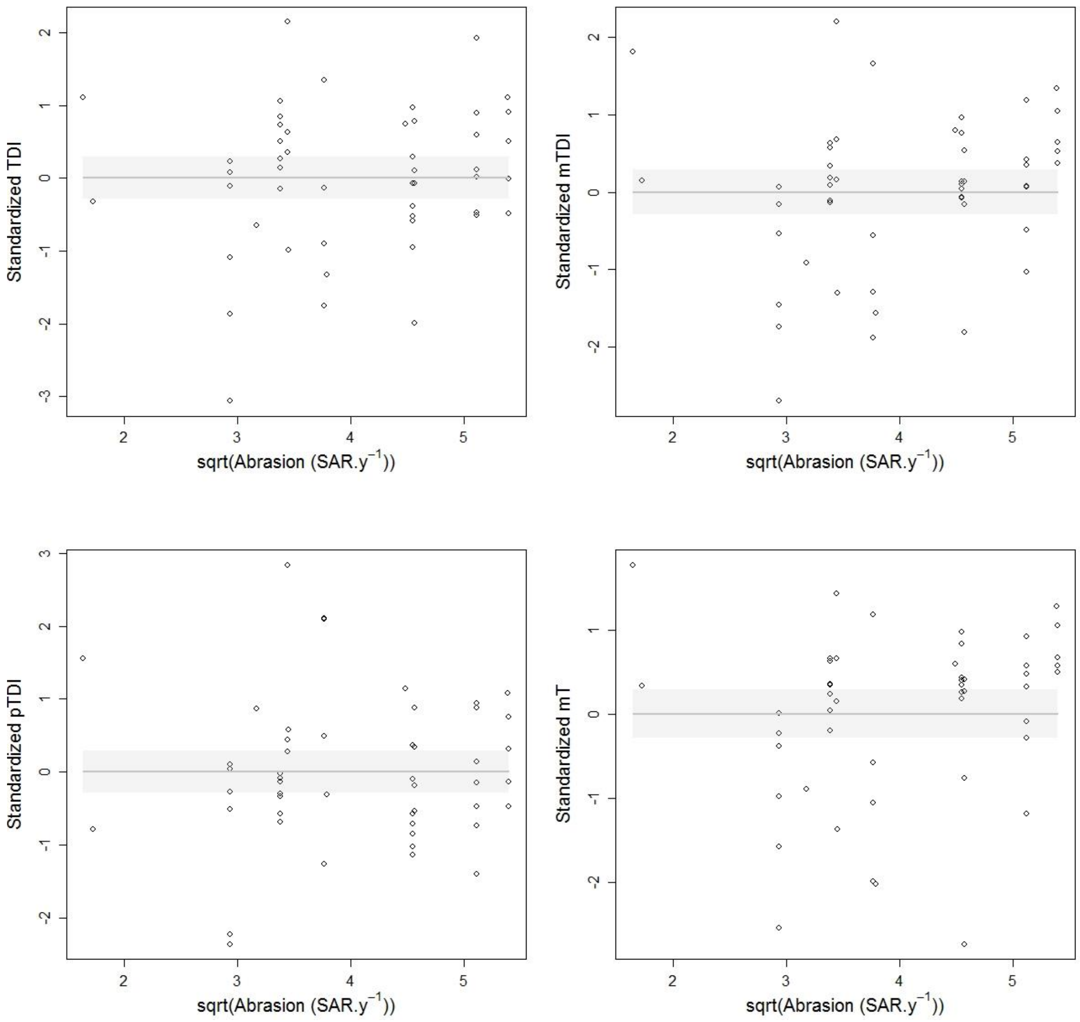

Figure B.1: **Indices modelled relationships to fishery abrasion in habitat A5.38: Mediterranean communities of muddy detritic bottoms.** Null models (grey lines and 95% confidence interval in grey shading) were the only fitting models for all indices. No negative significant relationship and no thresholds could be detected.

Table B.1: Summary of the modelling results in the habitat A5.38

Grey shading indicates the index and the model selected for this habitat

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	0.14
	Neglinear	0.13	-	-
mTDI	Null	-	0	0.15
	Neglinear	0.18	0.01	-
pTDI	Null	-	0	0.14
	Neglinear	0.02	-	-
mT	Null	-	0	0.17
	Neglinear	0.18	0.01	-

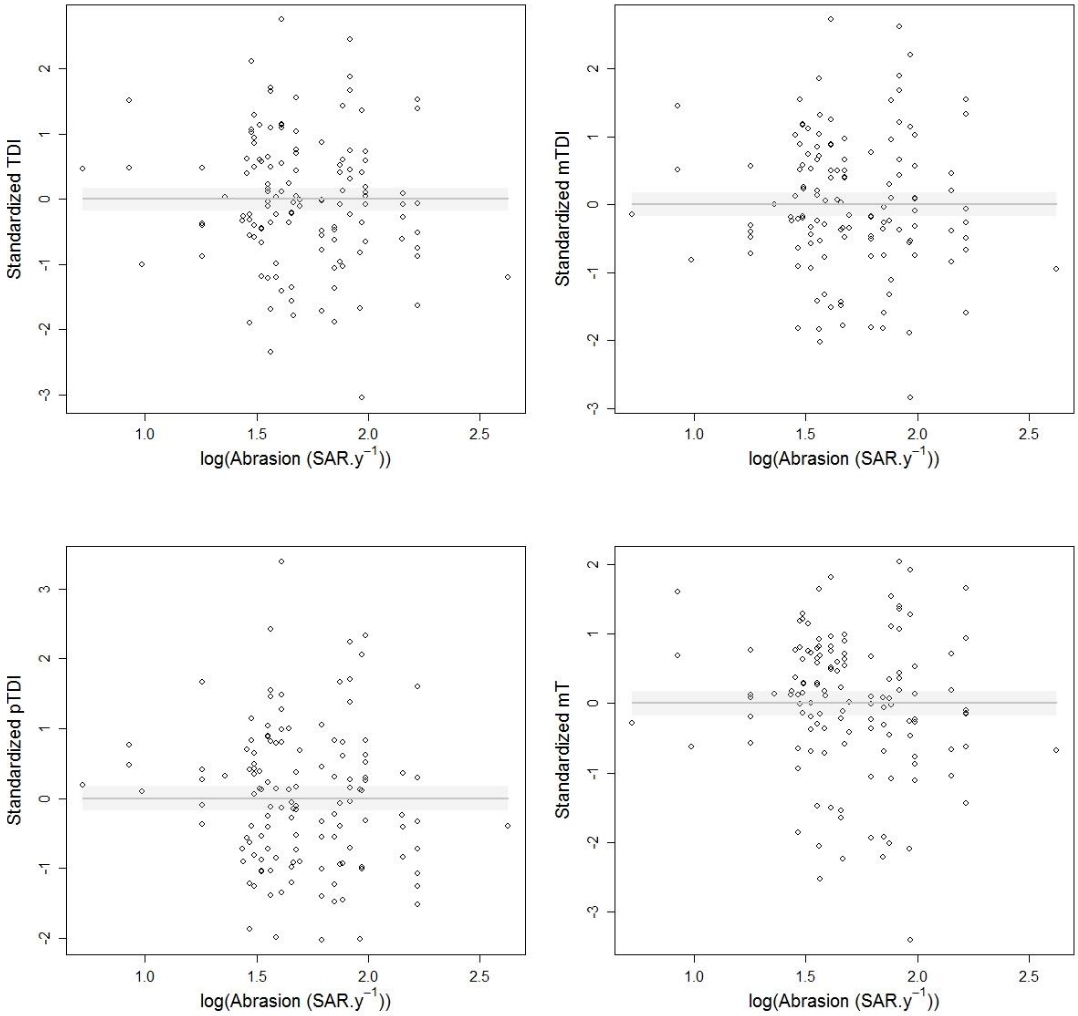

Figure B.2**: Indices modelled relationships to fishery abrasion in habitat A5.39: Mediterranean communities of coastal terrigenous muds.** Null models (grey lines and 95% confidence interval in grey shading) were the only fitting models for all indices. No negative significant relationship and no thresholds could be detected.

Table B.2: Summary of the modelling results in the habitat A5.39

Grey shading indicates the index and the model selected for this habitat

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	0.13
	Neglinear	-0.35	2.10^{-3}	-
mTDI	Null	-	0	0.14
	Neglinear	-0.18	-	-
pTDI	Null	-	0	0.15
	Neglinear	-0.30	-	-
mT	Null	-	0	0.14
	Neglinear	-0.42	0.01	-

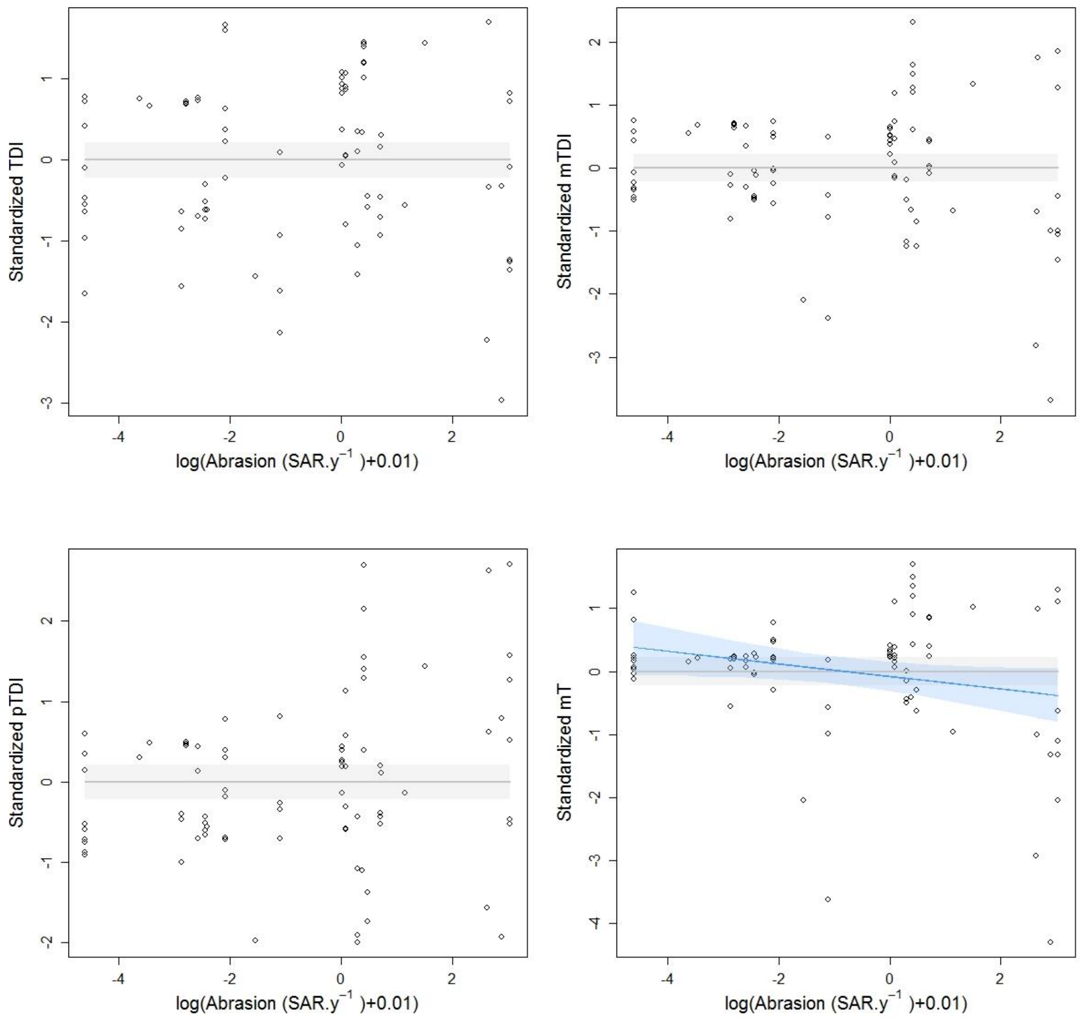

Figure B.3**: Indices modelled relationships to fishery abrasion in habitat A5.46: Mediterranean communities of coastal detritic bottoms.** Null models (grey lines and 95% confidence interval in grey shading) were the only fitting models for TDI, mTDI and pTDI but neglinear model (blue line and 95% confidence interval in blue shading) was more suited for mT index. No significant thresholds could be detected.

Table B.3: Summary of the modelling results in the habitat A5.46

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.02	-	-
mTDI	Null	-	0	-
	Neglinear	-0.05	-	-
pTDI	Null	-	0	-
	Neglinear	0.10*	0.04	-
mT	Null	-	0	-
	Neglinear	- 0.10*	0.04	0.11

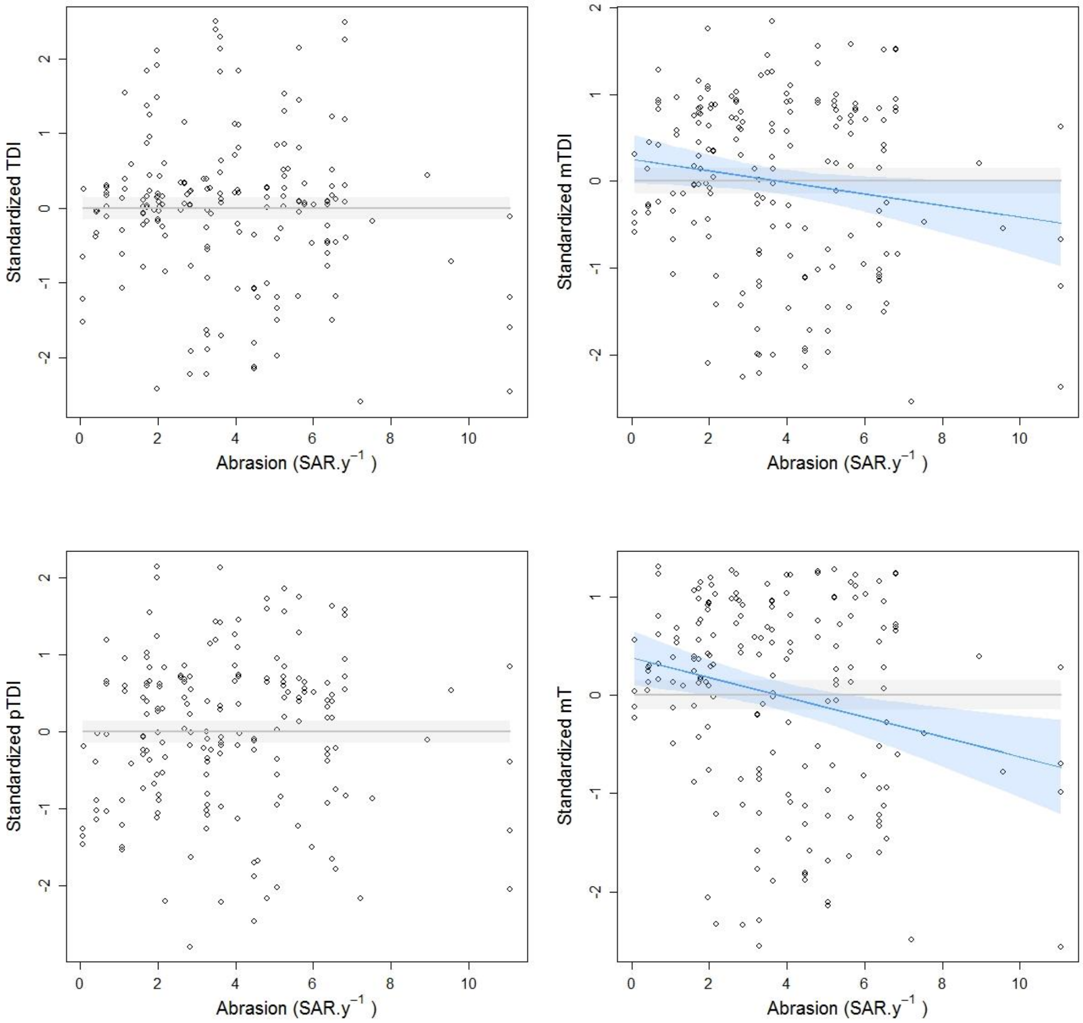

Figure B.4: **Indices modelled relationships to fishery abrasion in habitat A5.47: Mediterranean communities of coastal detritic bottoms**. Null models (grey lines and 95% confidence interval in grey shading) were the only fitting models for TDI and pTDI but neglinear models (blue lines and 95% confidence interval in blue shading) were more suited for mTDI and mT index. No significant thresholds could be detected.

Table B.4: Summary of the modelling results in the habitat A5.47

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.05	7.10^{-3}	-
mTDI	Null	-	0	-
	Neglinear	-0.09**	0.04	0.19
pTDI	Null	-	0	-
	Neglinear	0.01	-	-
mT	Null	-	0	-
	Neglinear	- 0.10**	0.05	0.21

2. North Sea

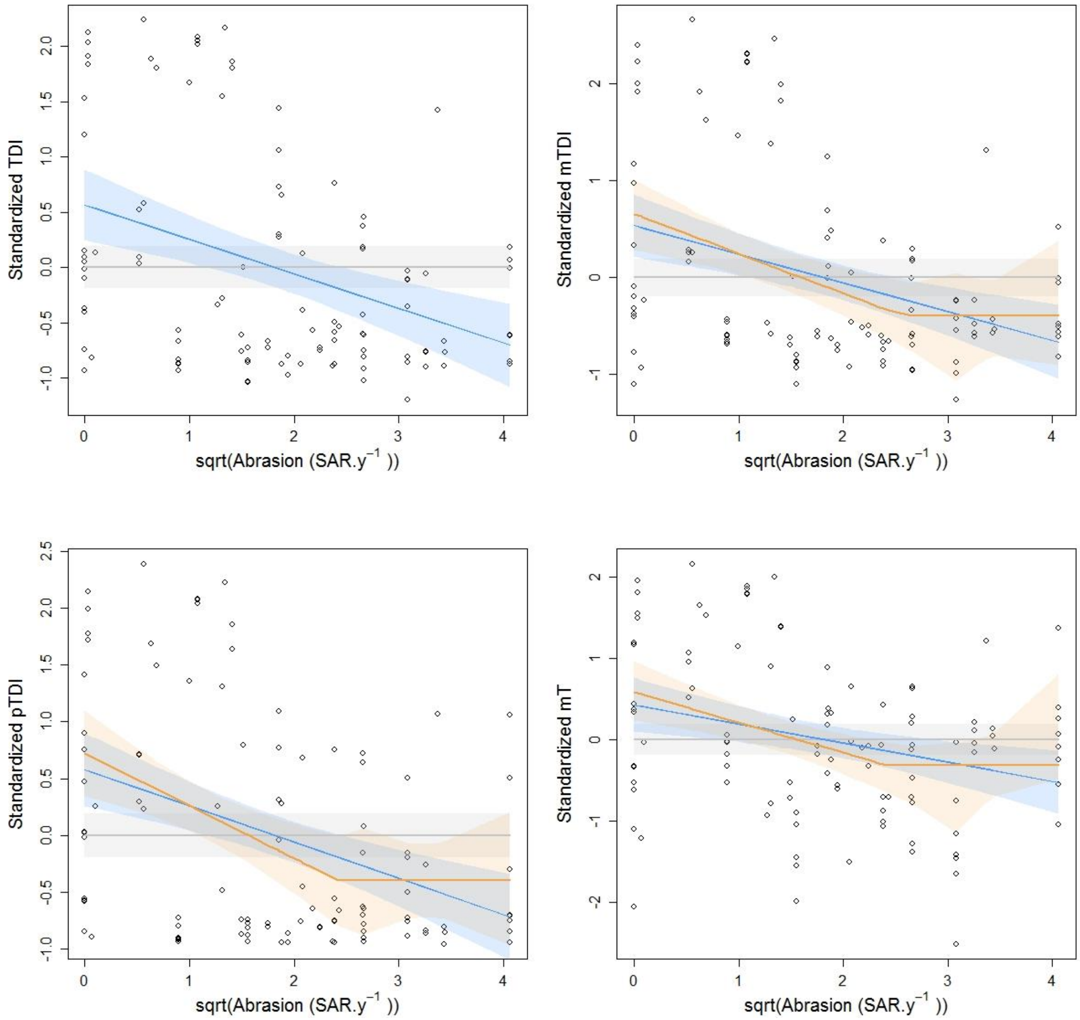

Figure B.5: **Indices modelled relationships to fishery abrasion in habitat A5.15: Deep circalittoral coarse sediment.** Null models (grey lines and 95% confidence interval in grey shading) and neglinear models (blue lines and 95% confidence interval in blue shading) fitted for all indices but segmented2 (orange lines and 95% confidence interval in orange shading) model was more suited for mTDI, pTDI and mT.

Table B.5: Summary of the modelling results in the habitat A5.15

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	Threshold 1	Threshold 2	AdjR²	RMAE
TDI	Null	-	-	-	0	-
	Neglinear	-0.31***	-	-	0.14	-
mTDI	Null	-	-	-	0	-
	Neglinear	-0.29***	-	-	0.12	-
	Segment2	-0.41**	-	6.52**	0.13	-
pTDI	Null	-	-	-	0	-
	Neglinear	-0.32***	-	-	0.14	-
	Segment2	-0.46**	-	5.91**	0.15	-
mT	Null	-	-	-	0	-
	Neglinear	-0.23*	-	-	0.07	-
	Segment2	-0.37*	-	5.90*	0.09	0.16

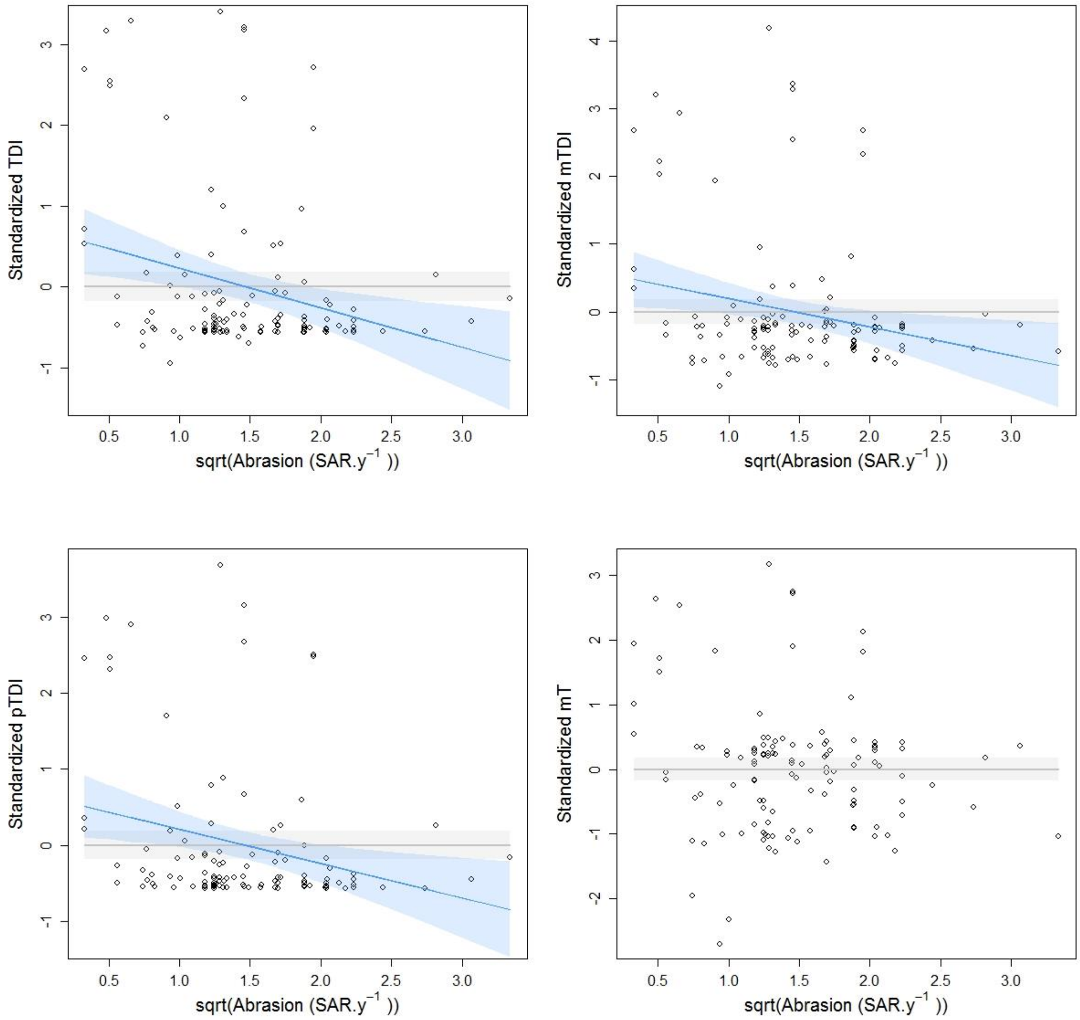

Figure B.6: **Indices modelled relationships to fishery abrasion in habitat A5.25/26: Circalittoral fine sand/muddy sand.** Null model (grey lines and 95% confidence interval in grey shading) was the only fitting model for mT but neglinear models (blue lines and 95% confidence interval in blue shading) were more suited for TDI, mTDI and pTDI. No significant thresholds could be detected.

Table B.6: Summary of the modelling results in the habitat A5.25/26

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.49**	0.07	0.15
mTDI	Null	-	0	-
	Neglinear	-0.42*	0.05	-
pTDI	Null	-	0	-
	Neglinear	-0.45**	0.06	0.15
mT	Null	-	0	-
	Neglinear	- 0.24	0.01	-

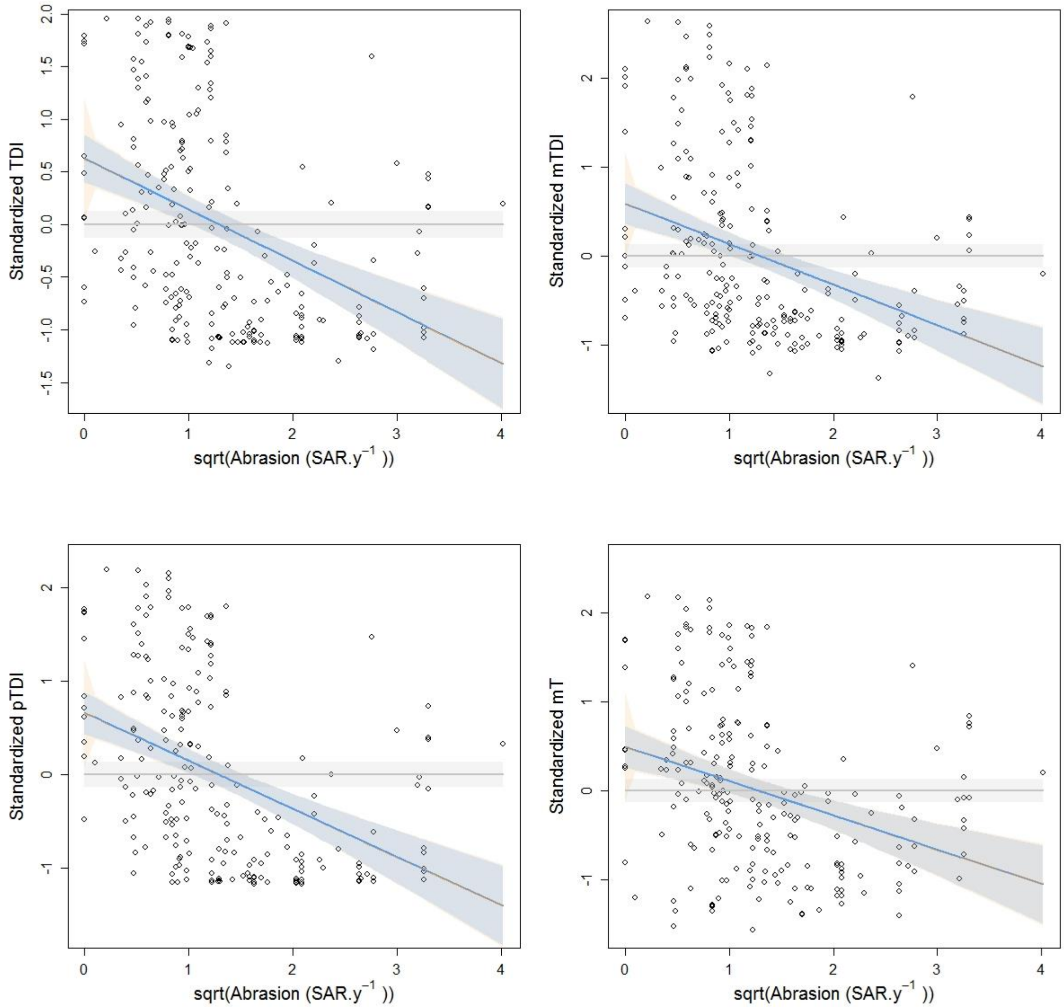

Figure B.7: **Indices modelled relationships to fishery abrasion in habitat A5.27: Deep circalittoral mud.**
Null models (grey lines and 95% confidence interval in grey shading), neglinear (blue lines and 95% confidence interval in blue shading) and segment1 (orange) models fitted all indices. In all cases neglinear and segment1 models were so similar that their graphic representation fully overlapped but neglinear models were more suited (higher adjusted R-squared) for all of these. Significant threshold could be detected in all cases but were not retained here.

Table B.7: Summary of the modelling results in the habitat A5.27

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	Threshold 1	Threshold 2	AdjR²	RMAE
TDI	Null	-	-	-	0	-
	Neglinear	-0.49***	-	-	0.15	-
	Segment1	-0.48***	3.10^{-3}***	-	0.15	-
mTDI	Null	-	-	-	0	-
	Neglinear	-0.46***	-	-	0.13	-
	Segment1	-0.44***	$1.6.10^{-5}$***	-	0.13	-
pTDI	Null	-	-	-	0	-
	Neglinear	-0.51***	-	-	0.18	0.23
	Segment1	-0.49***	1.10^{-6}***	-	0.17	-
mT	Null	-	-	-	0	-
	Neglinear	-0.39***	-	-	0.09	-
	Segment1	-0.37***	3.10^{-4}***	-	0.09	-

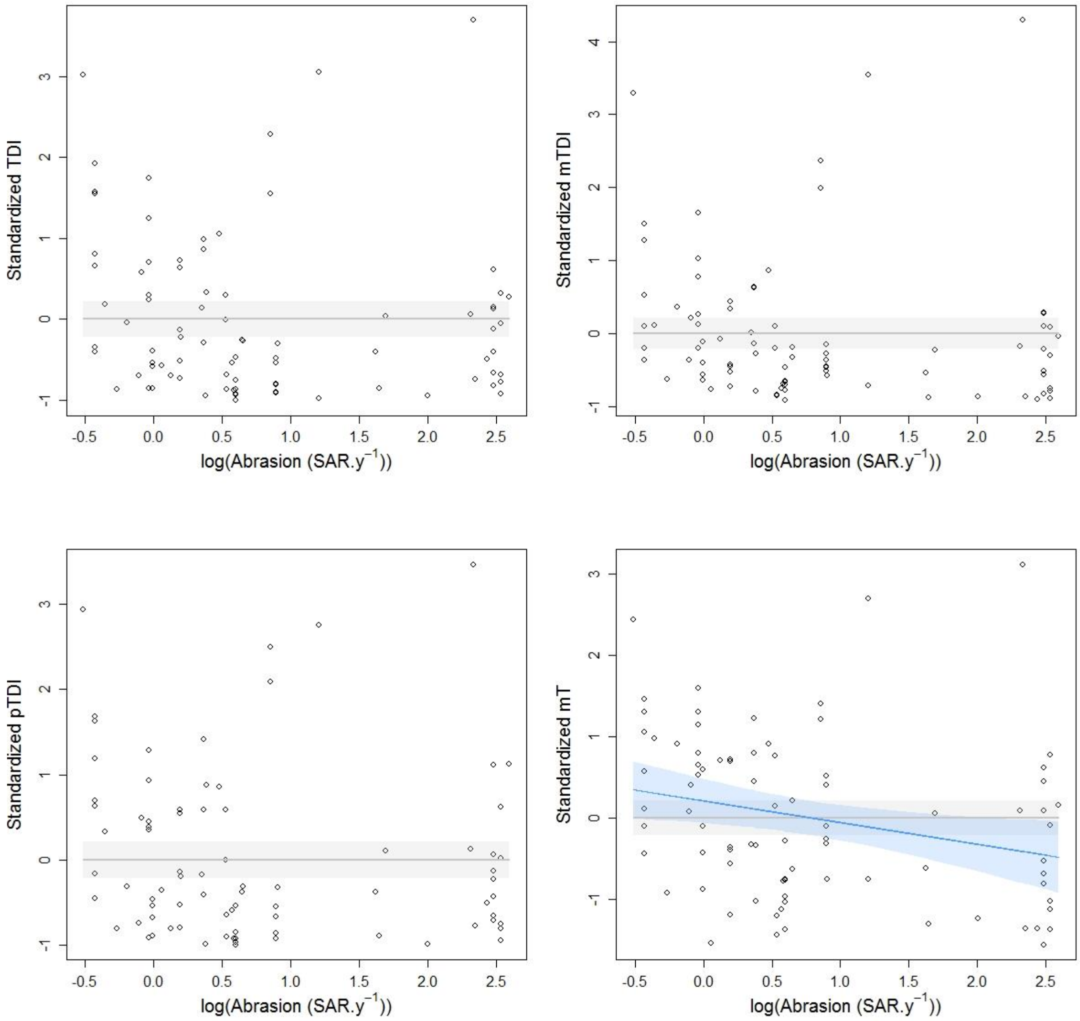

Figure B.8: **Indices modelled relationships to fishery abrasion in habitat A5.37: Deep circalittoral mud.**
Null model (grey lines and 95% confidence interval in grey shading) fitted all indices but neglinear models (blue lines and 95% confidence interval in blue shading) were more suited for mT. No significant thresholds could be detected.

Table B.8: Summary of the modelling results in the habitat A5.37

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.15	0.01	-
mTDI	Null	-	0	-
	Neglinear	-0.16	0.01	-
pTDI	Null	-	0	-
	Neglinear	-0.10	-	-
mT	Null	-	0	-
	Neglinear	- 0.27*	0.06	0.17

3. English Channel

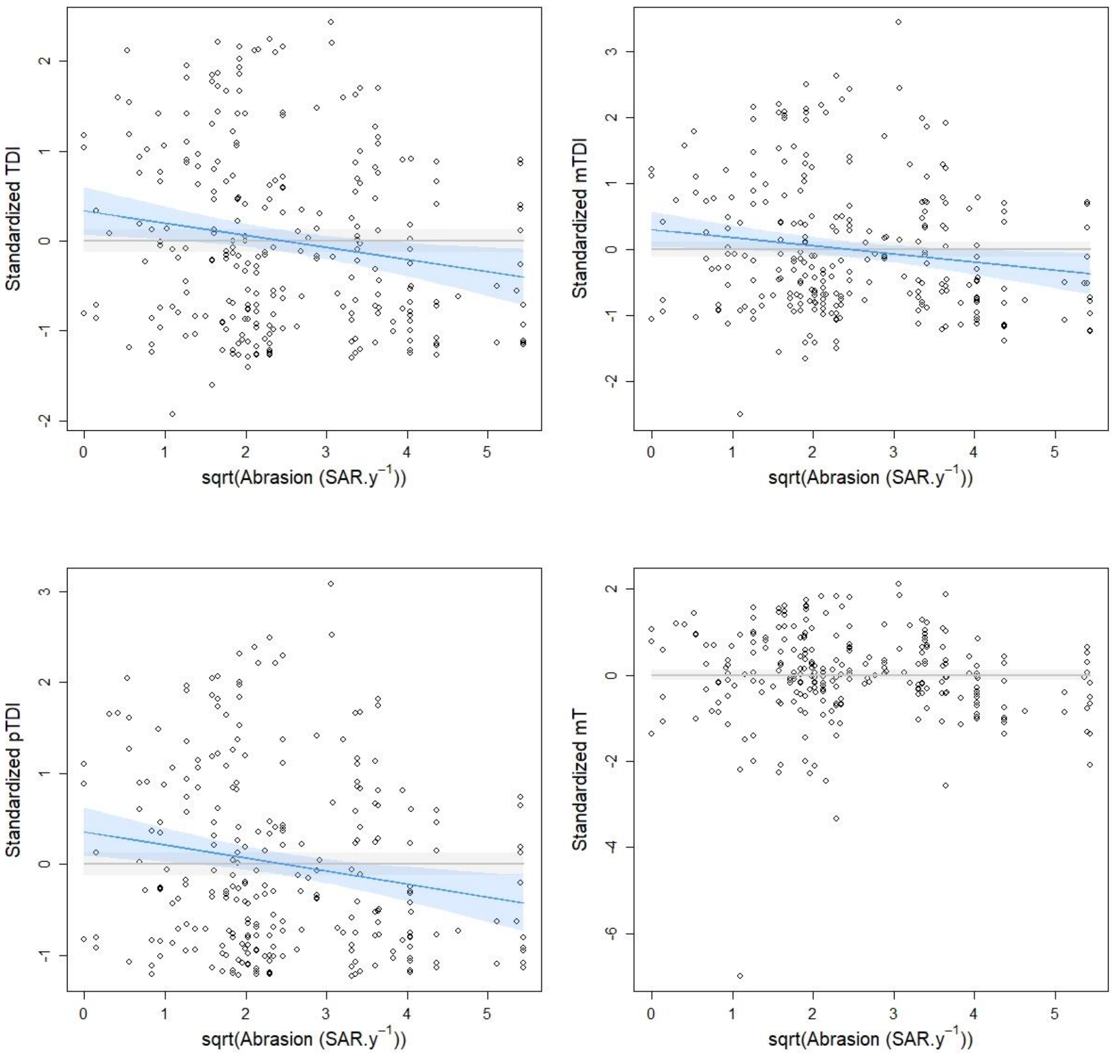

Figure B.9: **Indices modelled relationships to fishery abrasion in habitat A5.14 (in autumn): Circalittoral coarse sediment.** Null model (grey lines and 95% confidence interval in grey shading) was the only fitting model for mT index and neglinear models (blue lines and 95% confidence interval in blue shading) were more suited for TDI, mTDI and pTDI. No significant thresholds could be detected.

Table B.9: Summary of the modelling results in the habitat A5.14 in autumn

Grey shading indicates the index and the model selected for this habitat. * indicates that P<0.05 ; ** indicates that P<0.01

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.13**	0.02	0.19
mTDI	Null	-	0	-
	Neglinear	-0.12*	0.02	-
pTDI	Null	-	0	-
	Neglinear	-0.14**	0.03	0.19
mT	Null	-	0	-
	Neglinear	- 0.08	6.10^{-3}	-

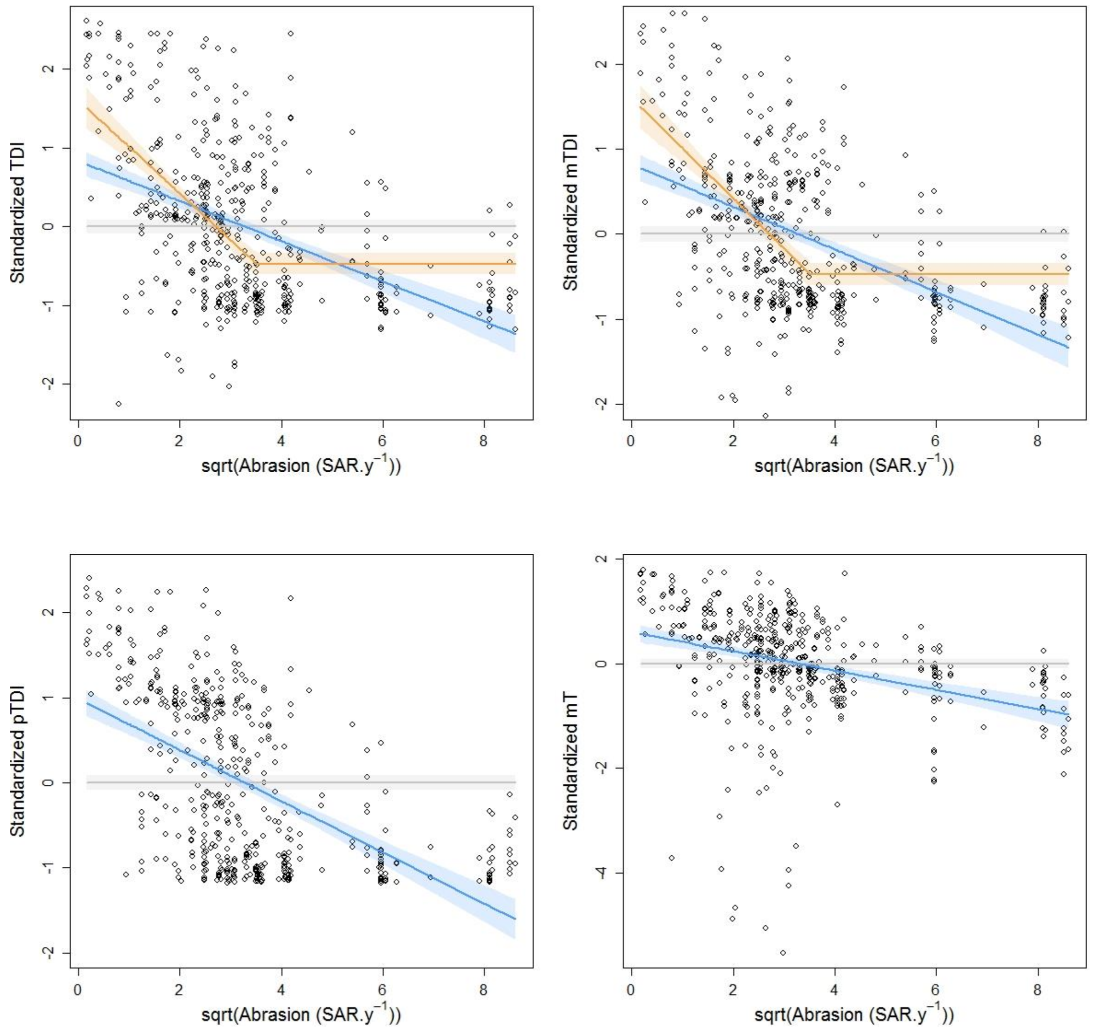

Figure B.10: **Indices modelled relationships to fishery abrasion in habitat A5.15 (in Autumn): Deep circalittoral coarse sediment.** Null models (grey lines and 95% confidence interval in grey shading) and neglinear models (blue lines and 95% confidence interval in blue shading) fitted for all indices but segment2 models (orange lines and 95% confidence interval in orange shading) were more suited for TDI and mTDI indices.

Table B.10: Summary of the modelling results in the habitat A5.15 in autumn

Grey shading indicates the index and the model selected for this habitat. ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	Threshold 1	Threshold 2	AdjR²	RMAE
TDI	Null	-	-	-	0	-
	Neglinear	-0.26***	-	-	0.21	-
	Segment2	-0.59***	-	12.34**	0.28	-
mTDI	Null	-	-	-	0	-
	Neglinear	-0.25***	-	-	0.20	-
	Segment2	-0.58***	-	12.34***	0.27	0.15
pTDI	Null	-	-	-	0	-
	Neglinear	-0.30***	-	-	0.29	-
mT	Null	-	-	-	0	-
	Neglinear	-0.18***	-	-	0.10	-

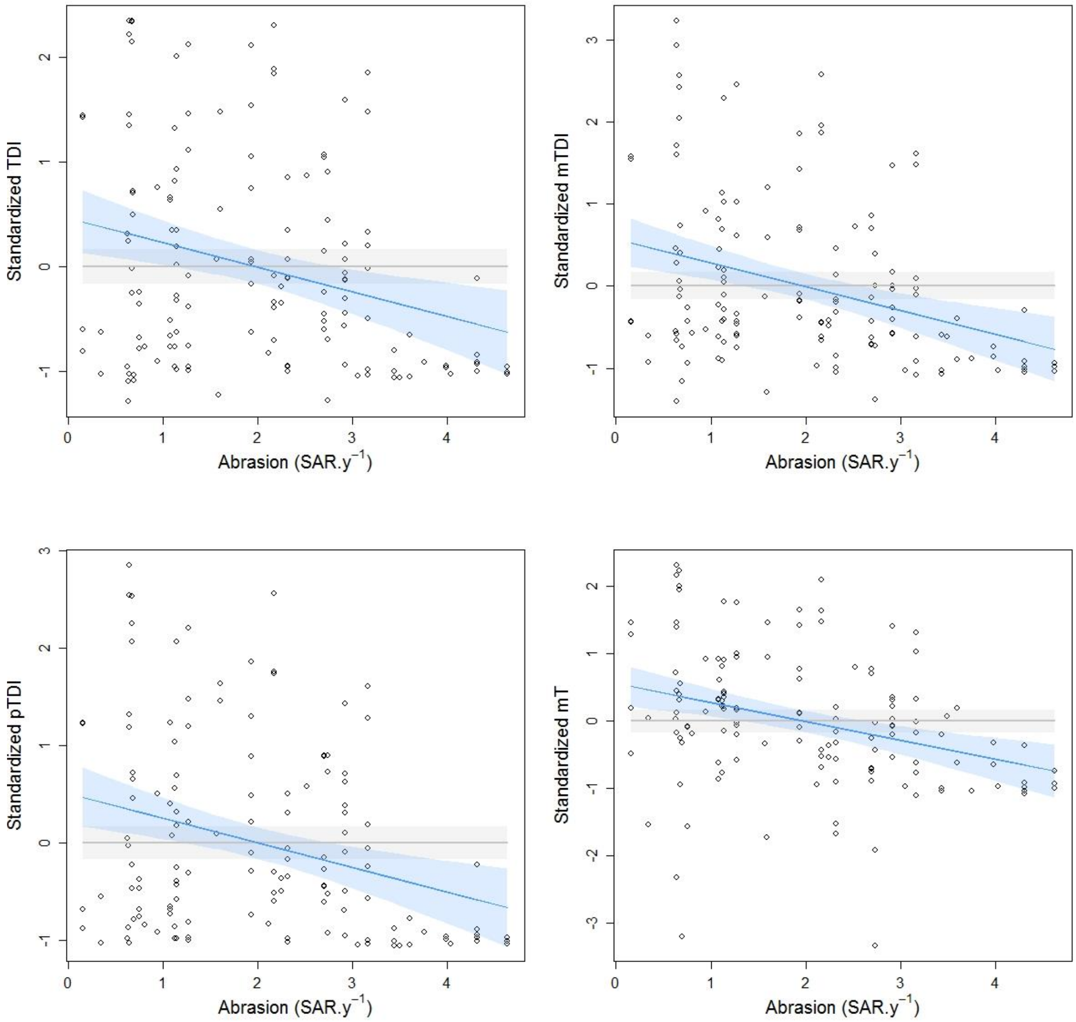

Figure B.11: **Indices modelled relationships to fishery abrasion in habitat A5.25/26: Circalittoral fine sand/muddy sand.** Null models (grey lines and 95% confidence interval in grey shading) and neglinear models (blue lines and 95% confidence interval in blue shading) fitted all indices but neglinear models were more suited in all case.. No significant thresholds could be detected.

Table B.11: Summary of the modelling results in the habitat A5.25/26

Grey shading indicates the index and the model selected for this habitat. ** indicates that P<0.01 ; *** indicates that P<0.001

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.24**	0.07	0.21
mTDI	Null	-	0	-
	Neglinear	-0.29***	0.10	0.15
pTDI	Null	-	0	-
	Neglinear	-0.25***	0.08	0.20
mT	Null	-	0	-
	Neglinear	- 0.28***	0.10	0.12

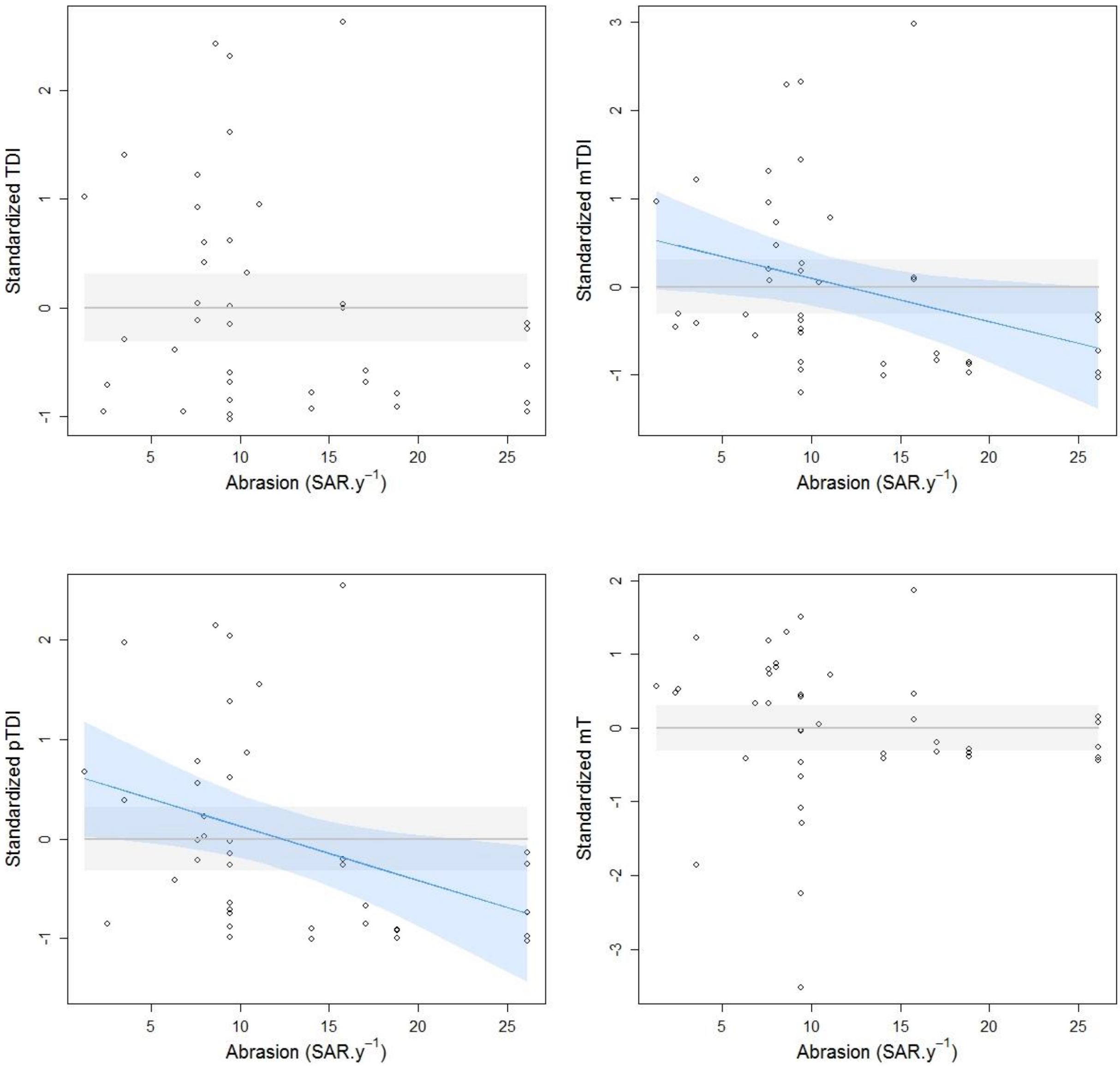

Figure B.12: **Indices modelled relationships to fishery abrasion in habitat A5.27: Deep circalittoral sand.**
Null models (grey lines and 95% confidence interval in grey shading) were the only fitting models for TDI and mT indices but neglinear model (blue lines and 95% confidence interval in blue shading) was more suited for mTDI and pTDI indices. No significant thresholds could be detected.

Table B.12: Summary of the modelling results in the habitat A5.27
Grey shading indicates the index and the model selected for this habitat. *indicates that P<0.05

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.04	0.04	-
mTDI	Null	-	0	-
	Neglinear	-0.04*	0.08	0.17
pTDI	Null	-	0	-
	Neglinear	-0.05*	0.11	0.20
mT	Null	-	0	-
	Neglinear	- 0.02	-0.01	-

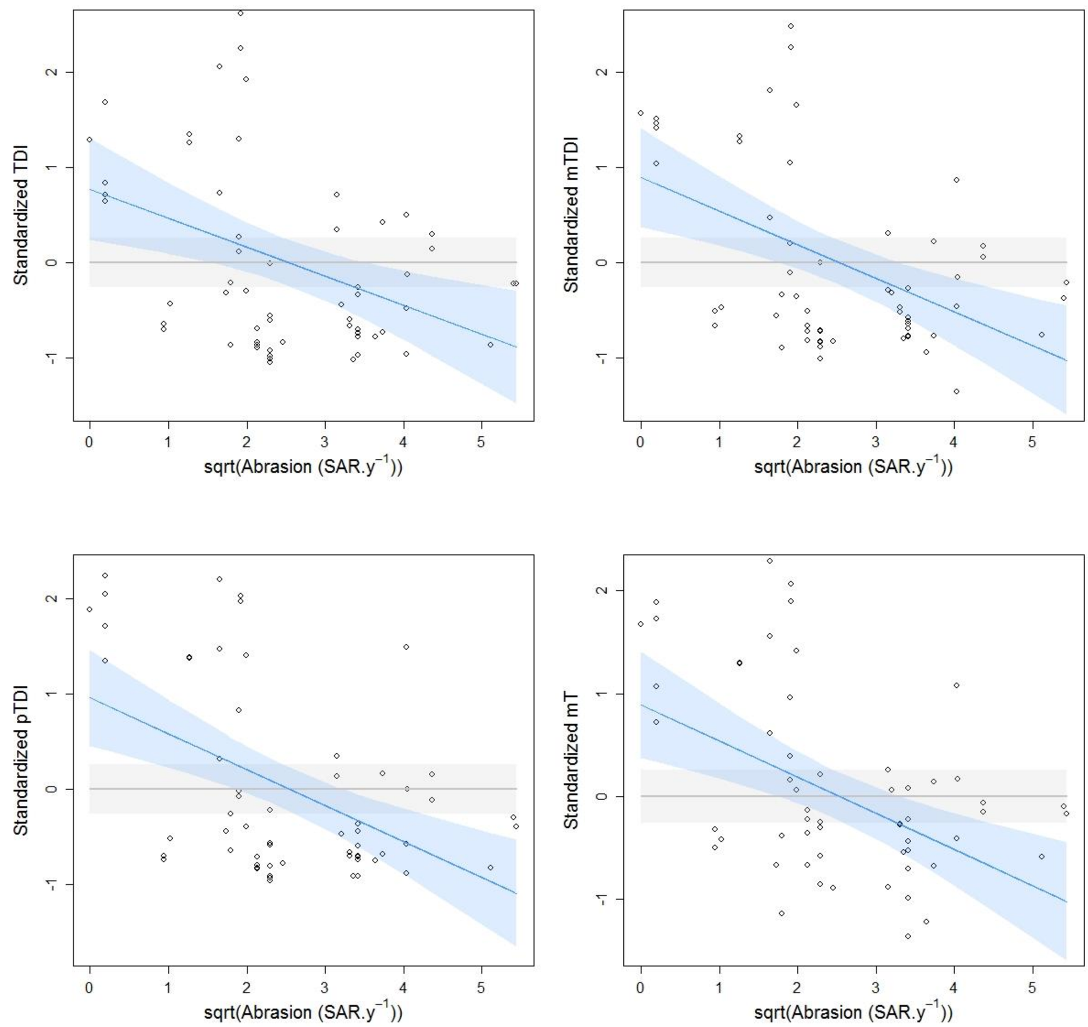

Figure B.13: **Indices modelled relationships to fishery abrasion in habitat A5.14 (in Winter): Circalittoral coarse sediment.** Null models (grey lines and 95% confidence interval in grey shading) and neglinear models (blue lines and 95% confidence interval in blue shading) fitted all indices but neglinear models were more suited in all case. No significant thresholds could be detected.

Table B.13: Summary of the modelling results in the habitat A5.14 in winter

**indicates that P<0.01 ; ***indicates that P<0.001

Indices	Models	Slope	AdjR²	RMAE
TDI	Null	-	0	-
	Neglinear	-0.31**	0.14	-
mTDI	Null	-	0	-
	Neglinear	-0.23**	0.08	-
pTDI	Null	-	0	-
	Neglinear	-0.38***	0.22	-
mT	Null	-	0	-
	Neglinear	- 0.35***	0.19	-

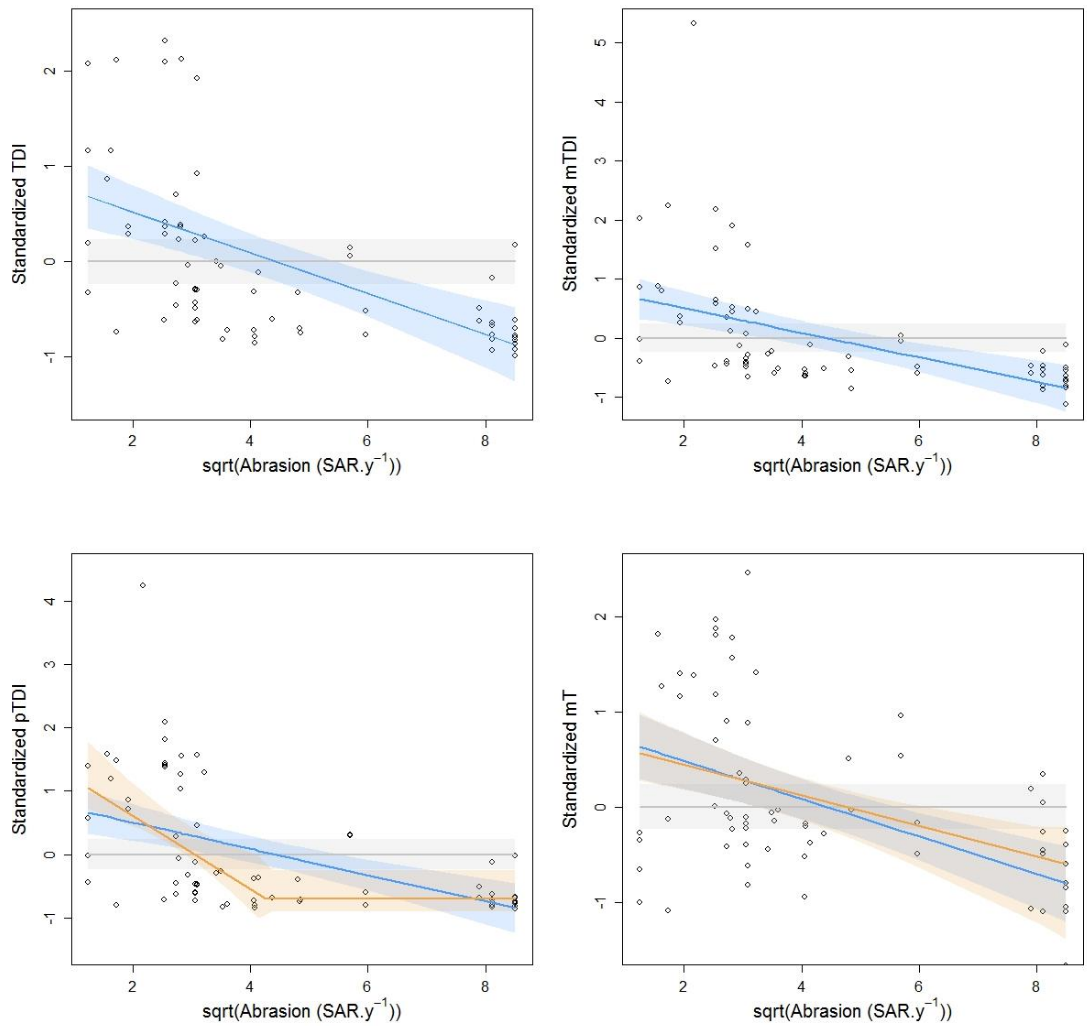

Figure B.14: **Indices modelled relationships to fishery abrasion in habitat A5.15 (in Winter): Deep circalittoral coarse sediment.** Null models (grey lines and 95% confidence interval in grey shading) and neglinear models (blue lines and 95% confidence interval in blue shading) fitted for all indices but segment2 models (orange lines and 95% confidence interval in orange shading) were more suited for pTDI and mT indices.

Table B.14: Summary of the modelling results in the habitat A5.15 in winter

*indicates that P<0.05 ; **indicates that P<0.01 ; ***indicates that P<0.001

Indices	Models	Slope	Threshold 1	Threshold 2	AdjR²	RMAE
TDI	Null	-	-	-	0	-
	Neglinear	-0.21***	-	-	0.28	-
mTDI	Null	-	-	-	0	-
	Neglinear	-0.20***	-	-	0.24	-
pTDI	Null	-	-	-	0	-
	Neglinear	-0.21***	-	-	0.26	-
	Segment2	-0.60**	-	18.13*	0.32	-
mT	Null	-	-	-	0	-
	Neglinear	-0.20***	-		0.23	-
	Segment2	-0.16**	-	71.1*	0.22	-