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Detecting adverse effect on seabed integrity. Part 1: Generic sensitivity indices to measure the effect of trawling on benthic mega-epifauna

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ABSTRACT

The benthic fauna of European continental shelves is a severely impacted community, mostly due to intense bottom trawling activity. Trawling effect may be dependent on the spatial and temporal distribution of abrasion, the habitat type including natural perturbation intensity and the fishing gear used. Nonetheless, there is an urgent need to identify or develop indices likely to measure the effect of trawling. For this purpose benthic fauna by-catch monitored in scientific trawl surveys carried out in all European waters in the frame of the Common Fishery Policy Data Collection Multiannual Program may be used. Benthic invertebrates data used in this study were collected during scientific bottom trawl surveys covering the English Channel, the North Sea and the North-West Mediterranean. Swept area ratios derived from VMS data were used to quantify the intensity of fishery induced abrasion on the seabed. Fifteen indices were investigated: taxonomic diversity metrics, functional diversity indices and functional indices, the two later based on sensitivity traits to physical abrasion. Their properties, such as their capacity to detect trawling effect, their statistical behavior or their ability to inform on community structure, were investigated. Among them, fours indices specific to fishery effect detection based on biological traits appeared to be the best performing benthic indices regarding these requirements: Trawling Disturbance Index (TDI), modified-Trawling Disturbance Index (mTDI), partial-Trawling Disturbance Index (pTDI), modified sensitivity index (mT). Maps of the distribution pattern of seabed sensitivity captured through each of these four indices were produced. This work has highlighted the need to use specific indices to monitor the effect of trawling on benthic communities but also that the use of different indices may be necessary to carry out this monitoring in all European waters.

1. Introduction

The European Union drew up the Marine Strategy Framework Directive (MSFD) in 2008 to achieve or to maintain good environmental status in the marine environment in 2020 at the latest. To control degradation factors and manage the consequences, the MSFD is divided in descriptors and criteria for which indicators and threshold values must be defined. Two of these descriptors, biodiversity (D1) and seabed integrity (D6) require that the human impact on benthic habitats is assessed regularly.

Bottom trawling and dredging are the most widespread source of anthropogenic disturbance occurring on over large surfaces of continental shelf benthic habitats (Hiddink et al., 2007; Halpern et al., 2008). Before the early 2000s, abrasion was derived from UE logbook that compiled information of fishing skippers, but records of fishing locations were not always reliable and were only confirmed for a small proportion of vessels by ship- or air-based surveillance (Lee et al., 2010). The development of satellite-based vessel monitoring systems (VMS) has revolutionized the knowledge of the spatial and temporal distribution of abrasion, providing large-scale high-resolution information of European fishing activity for largest fishing vessels (Lee et al., 2010; Eigaard et al., 2016). VMS data inform on the time spent to fish per area and time units (Lee et al., 2010). Knowing that differences in the gear and boat characteristics between activities (otter trawls, twin trawls, Danish seines, beam trawls or dredges) cause different benthic impacts, the utilization of total swept area ratio, per area and time unit better reflects fishing impact on seabed than the number of fishing hour (Eigaard et al., 2016, 2017). In Europe, the footprint of

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bottom impacting fishing on the continental shelf varies between 53 and 99% per habitat type of the seafloor down to 200 m (Eigaard et al., 2017), with patchy spatial and temporal distributions (Rijnsdorp et al., 1998, 2018; van Denderen et al., 2015).

Numerous studies have shown that bottoms trawls damage biogenic structure, disturb seabed sediments and affect the structure and the functioning of the benthic invertebrate community mainly by changing the species composition (Collie et al., 2000; Rumohr and Kujawski 2000; Thrush and Dayton 2002; Hiddink et al., 2006; Rijnsdorp et al., 2018). The differences in species composition between trawled and untrawled area indicate that each benthic species has different degree of sensitivity (Hiscock et al., 1999; Borja et al., 2003; Foveau et al., 2017) to trawling pressure. Most studies to evaluate the impact of fishing activities on benthic communities are conducted relatively nearshore with restricted spatial coverage (Brind'Amour et al., 2014) and focused mainly on the infauna, with a sampling realized with grabs, boxcorers or dredges (van Loon et al., 2018). Benthic data from scientific bottom trawl surveys carried out in all European waters in the frame of the Common Fishery Policy Data Collection Multiannual Program could be used to study the impact of trawling on the benthic mega-epifauna because 1) they represent the benthic fauna fraction the more directly affected by bottom-contacting fishing and 2) they integrate assemblages' composition over large areas (3–4 km) and are more representative of larger scale habitat structure (Foveau et al., 2017).

Many indices exist and detect differences or changes in the benthic fauna community in relation to anthropogenic pressure, but not all are effective for physical disturbance like trawling impact. Several univariate indices such as species richness, community biomass, Shannon index (Shannon and Weaver, 1963), Margalef diversity (Margalef, 1958), Pielou evenness (Pielou, 1969) and Simpson index (Simpson, 1949) have already been tested for assessing effects of trawls on benthic communities (Schratzberger et al., 2002; Svane et al., 2009; Atkinson et al., 2011; van Loon et al., 2018). Despite variable results in the literature, the use of diversity indices can highlight the disruptive effect of fishing on benthic communities (Blanchard et al., 2004). Other indices, specific to the trawling pressure and based on biological traits of benthic species like the Trawl Disturbance Indicator (TDI, de Juan and Demestre 2012) and the vulnerability index (Certain et al., 2015) appear as good candidates to evaluate trawling impact. Species' responses to trawling is believed to be mainly determined by their biological traits (Bremner et al., 2003; de Juan et al., 2009). The selected biological traits (mobility, fragility, position on substrata, average body size and feeding mode), were chosen because they determine individual sensitivity to trawling and they can be easily related to other concepts such as recovery capacity and vulnerability. In the present study, species vulnerability is understood as resulting from both species sensitivity and its exposure level to the disturbance. Finally, modelling approaches were developed to study the effect of trawling on benthic community like the Relative Benthic Status method (RBS; Pitcher et al., 2017), based on longevity or composition of benthic community (Eigaard et al., 2017; Rijnsdorp et al., 2018) or method based on biomass reconstruction (Lambert et al., 2011).

In view of the quantity of existing indices, previous studies have listed different requirements to inform on indicators quality and to classify potential indicators to be used for the assessment of the trawling impact on benthic communities (Queirós et al., 2016; ICES, 2017a). Thus indices must: reflect features of ecosystems that are relevant for structure and function (requirement 1: Theoretical basis), be sensitive to changes in trawling (requirement 2: Sensitivity), provides rapid and reliable feedback on the consequences of management (requirement 3: Responsiveness). The quality of sampling method (requirement 5) and the nature and quality of data (requirement 6: Quality of underlying data) must also be taken into account in the indices selection process. Finally, the existence of reference state (requirement 7), the cost of method (requirement 8: Cost effectiveness) and the cross regional applicability (requirement 9) were the three other requirements proposed to evaluate the quality of an indicator.

The aims of this study were to (a) list or define indices susceptible to measure the effect of trawling on benthic fauna that can be used in all European waters (b) test different properties of these indices and in particular their ability to relate to trawling intensity and to measure assemblages structures and (c) identify a suitable set of indices to be used for monitoring trawling impact on benthic communities in the frame of the MSFD requirements.

2. Methods

2.1. Study areas

The present study was performed in four different areas affected by contrasted and sometimes intense trawling pressure: the Gulf of Lion, the Eastern coast of Corsica, the English Channel and the southern North Sea.

The Gulf of Lion, situated in the NW Mediterranean, is a wave-dominated continental shelf incised by a number of submarine canyons and characterized by a micro-tidal regime (Tesi et al., 2007). Fine sediments (sand and mud) represent the majority of sedimentary types present in this area (Roussiez et al., 2005).

The Eastern coast of Corsica closes the north of the Tyrrenean Sea and is defined by a relatively small shelf, which width varies from 5 km in the north to over 25 km in the South. Depth increases rapidly with distance to the coast and reaches about 900 m in the central zone, between Corsica and Italy (http://www.emodnet.eu/bathymetry). Seabed is constituted of detritic sediments on the shelf and of mixed sandy to coarse sediment on the slope that are gradually replaced by deep-sea muddy sands and muds (http://www.emodnet.eu/seabed-habitats). This area is at present relatively sheltered from many anthropogenic threats such as intensive fishery.

The English Channel is a shallow epicontinental sea situated between France and England, subjected to megatidal currents (Larsonneur et al., 1982; Salomon 1990). Depth does not exceed 120 m, except in the Hurd Deep in the western basin, and seabed is constituted of fine sediments (fine sand and mud) in bays and estuaries and coarser sediments in offshore areas or area more exposed to tidal currents (Larsonneur et al., 1982).

The North Sea is an extensive epicontinental sea surrounded by seven states (United Kingdom, France, Belgium, Netherlands, Germany, Denmark and Norway). The regime is macrotidal and depth increases northwards with a mean of 70 m (Huthnance, 1991). Seabed composition is dominated by sandy substrates, with locally some areas of muddy or mixed sediments (Diesing et al., 2013).

2.2. Biological data

Benthic fauna's samples, considered as bye-catch, were opportunistically collected and monitored (Callaway et al., 2002; Reiss et al., 2006; Brind'Amour et al., 2009, 2014) during four scientific bottom-trawling surveys. For each survey, species were sorted, identified, counted and weighed.

In the Mediterranean Sea, Mediterranean International Trawl Surveys (MEDITS, Jadaud et al., 1994) is conducted yearly in June since 1994 but benthic fauna is studied only since 2012. The sampling gear used is a bottom trawl made of four panels, well adapted for work in all depths (10 – 800 m), with a 20 mm stretched mesh size at the cod-end. The sampling scheme is stratified by depth evenly distributed over the whole study area. Hauls are 30 min long at 4 knots above 200 m and 60 min long at the same speed below 200 m (MEDITS, 2017). Due to the change in trawling duration beyond 200 m depth and the transition from photic to aphotic zone, only data sampled between 0 and 200 m were used in this study (448 stations in total, including approximately 54 stations in the Gulf of Lion and 10 in Corsica sampled each year from 2012 to 2018; Table 1).

Table 1
Number of observations used in this study.

Year	SURVEY (number of trawls) MEDITS (Gulf of Lion and Eastern coast of Corsica)	IBTS (English Channel and southern North Sea)	CGFS (English Channel)	CAMANOC (English Channel)
2008			98	
2009		50	98	
2010		75	92	
2011		87	99	
2012	65	84	89	
2013	63	85	93	
2014	64	82	94	40
2015	64	90	90	
2016	64	72	81	
2017	64	70	66	
2018	64	66	115	

In the English Channel and the North Sea, three scientific trawling cruise are carried out: International Bottom Trawl Surveys (IBTS) yearly in January/February since 1970 (Auber, 1992), Channel Ground Fish Surveys (CGFS) yearly in October since 1988 (Coppin and Travers-Trolet 1989) and CAMANOC in September 2014 (Verin and Travers-Trolet, 2014). For all three surveys, the sampling gear used is a Very High Vertical Opening bottom trawl with a 20 mm stretched mesh size at the cod-end. The sampling is randomly stratified evenly distributed over the whole study area and hauls are carried out during daytime for 30 min at 4 knots (ICES 2015, 2017b).

Data from CAMANOC and CGFS surveys were merged as the sampling occurred at the same period and in the same area: the English Channel. A total of 1055 stations sampled in September/October (CGFS and CAMANOC, 2008–2018) and 761 stations in January/February (IBTS, 2009–2018) were used in this study (Table 1).

2.3. Data preparation

Commercials 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 because they may be targeted by the fishery. As a result, abrasion distribution may not be independent from the presence of these species.

Biomass data were preferred to abundance data, as abundance could not be estimated for a number of colonial species such as hydroids or sponges. Data were standardized according to trawling swept area and expressed in g.km^{-2}.

To limit identification errors or biais due to the irregular presence of expert scientific staff, some taxons were aggregated at higher taxonomic levels. The following procedure was used: to be kept at its initial taxonomic level, a given species had to be observed in 90% of the sampled years (5 years for MEDITS, 8 years for IBTS and 9 years for CGFS), otherwise it was iteratively aggregated at higher taxonomic level (genus, family, order, class, phylum) until it fulfilled this criteria. For example, the ascidian *Molgula appendiculata,* observed only 2 years, was aggregated into the genus *Molgula*, which was observed every year. If, after applying this treatment, a given phylum was observed in less than 90% of the sampled years, it was removed from the analyses (Foveau et al., 2017).

2.4. Biological sensitivity traits

Following on previous studies, a set of five biological traits were selected to characterize potential responses of organisms to physical abrasion (de Juan and Demestre 2012; Bolam and Eggleton, 2014; Foveau et al., 2017). These traits are (i) position of organisms in the sediment; (ii) feeding mode; (iii) mobility capacity; (iv) adult size and (v) fragility of the structure of organisms. Each trait was subdivided into multiple "modalities" to encompass the range of possible attribute of all taxa. To allow quantitative analysis, a score was assigned to each modality, varying from low sensitivity (0) to high sensitivity (3) (Table 2; Foveau et al., 2019). When a taxon was aggregated at higher taxonomic level, scores were assigned to the group using the highest value observed in this group for each trait after that the homogeneity of each modality's score was investigated. The standard deviation of any given index score had to be below 1.5 and that of the sum of scores had to be below 2.5 (Foveau et al., 2017). In the opposite case, the taxonomic group was removed from the analysis. When the deleted taxon represented more than 25% of the total station's biomass, the station was removed from the dataset. A species-traits matrix was produced for each survey in order to compute functional indices

In most cases, deleted taxon due to taxonomic or functional trait uncertainties accounted for less than 10% of the total biomass sampled. However, in some station, deletions represent more than 25% of biomass. They cause differences in the number of stations used for the calculation of the different type of indices (Table 3).

2.5. Fishing impact data

To compute the abrasion induced by fishery over the seabed, expressed as swept surface area ratio per year, fishing trajectories and gear type were used and aggregated yearly following Eigaard et al. (2016) methodology. In the English Channel and southern North Sea, the spatial and temporal distribution of bottom fishing was estimated from Vessel Monitoring System (VMS) data for ground-towed gears (beam trawlers, dredgers and otter trawlers) over the 2009–2017 period over a 3′x3′ resolution (ICES, 2019). The data was readily available and downloaded in March 2019 through OSPAR website (https://www.ospar.org), in which they are referenced as "OSPAR Bottom Fishing Intensity – Surface".

For the French part of Mediterranean Sea, a similar approach was taken using available VMS data aggregated monthly (between 2009 and 2017) on a 1′x1′ grid (fishing duration in hour by country, month, vessel length class and gear type) (Jac and Vaz, 2018).

Intra-annual (only in the Mediterranean Sea where monthly abrasion data were available) and inter-annual variabilities of abrasion distribution over the available period were explored through pair-wise correlations and found to be statistically negligible. It was then decided to use the highest (90th percentile) abrasion value over the entire available time series at each location to avoid overlooking past impacts and reflect the probably long recovery time needed for sensitive species. This 90th percentile was chosen to filter out the most extreme values

Table 2
Biological sensitivity traits to physical abrasion and associated scores.

Scores	Position in the sediment	Feeding mode	Mobility	Adult size	Fragility
0	Deep burrowing	Scavengers	Highly mobile (swimming)	Small (< 5 cm)	Hard shell, burrow, vermiform, regeneration
1	Surface burrowing (first cm)	Deposit feeders/predators	Mobile (crawling)		Flexible
2	Surface		Sedentary	Medium (5–10 cm)	No protection
3	Emergent	Filter feeders	Sessile (attached)	Large (> 10 cm)	Fragile shell/structure

Table 3
Number of stations used for indices calculations in each studied area.

Type of indices	MEDITS - GoL	MEDITS - Corsica	IBTS	CGFS + CAMANOC
Taxonomic diversity indices	378	70	761	1055
AMBI	373	68	711	1031
Functional indices	372	68	721	1006

Calculation of univariates indices were performed with all available data (all sampling stations). GoL = Gulf of Lion

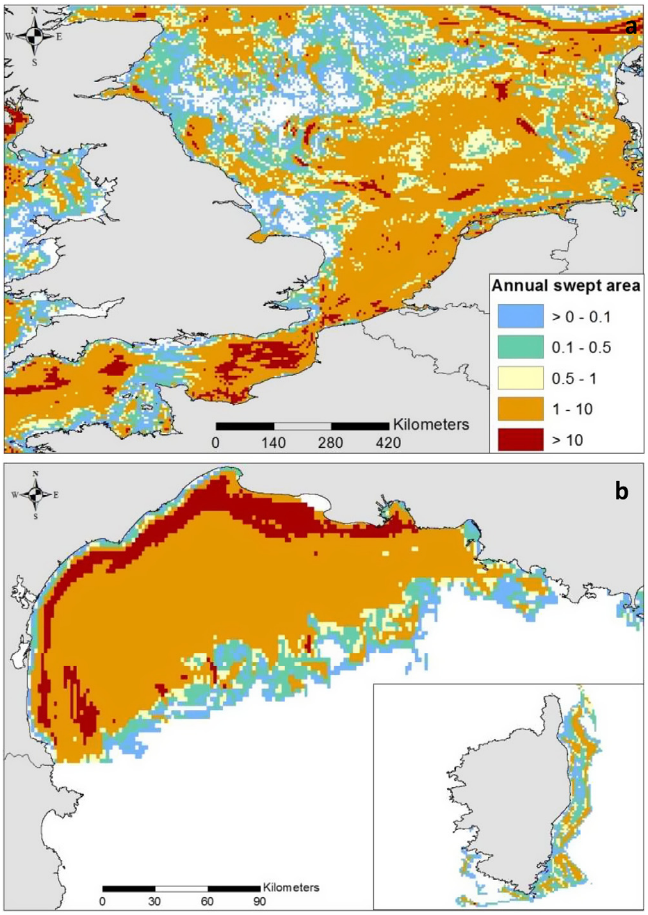

Fig. 1. 90th inter-annual percentile of the abrasion in the English Channel and southern North Sea during the period 2009–2017 (a) and in the Gulf of Lion during the period 2009–2017 (b).

that may be related to measurement or computation errors. As a result, a map of 90th inter-annual percentile of the abrasion in each study area was computed over the respective available period of time for each area, at 3′x3′ resolution in the English Channel and southern North Sea and at 1′x1′ resolution in Mediterranean Sea (Fig. 1).

2.6. Biotic indices

Three types of sensitivity indices were investigated: 1) taxonomic diversity metrics; 2) functional diversity indices and 3) functional sensitivity indices specifically constructed to detect impacts on benthic communities. The effect of trawling on the biomass of the community was also studied.

Five common taxonomic diversity indices were calculated: species richness (S, the total number of taxon), Margalef index (Margalef, 1958), Shannon diversity (H', Shannon and Weaver, 1963), Pielou evenness (J', Pielou, 1969) and Simpson index (λ, Simpson, 1949). The first two focus on species or individuals richness while the others are weighted by abundance or biomass to assess equitability between species (J') or give more or less influence to rare species (H' and λ). These indices were calculated in R, using the vegan 2.5–2 package (Oksanen et al., 2019) and by using individual biomass.

Functional Richness (FRic, Cornwell et al., 2006; Villéger et al., 2008), Functional Specialization (Fspe; Bellwood et al., 2006, Villéger et al., 2010), Functional Evenness (FEve; Mason et al., 2005) and Functional Divergence (FDiv; Mason et al., 2005) were investigated using the species-traits matrix described earlier. These indices were used because they highlight variation in specific function among benthic communities (Mouillot et al., 2013). Before calculating functional diversity indices, Multiple Correspondence Analysis (MCA) was performed with package PCAmixdata 3.1 (Chavent et al., 2017) on the species-traits matrix because the traits are categorical and functional indices were designed for continuous traits (Villéger et al., 2008). Scores from MCA were used with species biomass matrix to calculate functional indices (Mouillot et al., 2013). Functional richness (FRic) allows quantifying the amount of function available in assemblages (there is a positive correlation between the value of the index and the number of functions). Functional Specialization (FSpe) quantify the specialization degree of species based on the assumption that generalist are at the center of the functional space while specialist are on the periphery. This metric quantify the radial distribution of species on the functional space, the higher the index is, the more specialized species are (Mouillot et al., 2013). Functional evenness (FEve) may be defined as the homogeneity of the distribution of biomass in the functional space. FEve varies between 0 (main species in term of biomass have same functions) and 1 (main species in term of biomass are functionally different) (Villéger et al., 2010). Functional divergence (FDiv) quantifies if the main species in term of biomass are near to the limits of the multidimensional volume of the functional traits space. This metric varies between 0 (main species in term of biomass are close to center of gravity of functional space) and 1 (main species in term of biomass species are very far from the center of gravity (Villéger et al., 2008).

Functional sensitivity indices are designed to detect particular impacts on communities. In contrast to functional diversity indices for which each trait level is given equal weight, semi-quantitative trait scoring indicates the potential sensitivity of each species to a given pressure. Functional sensitivity indices therefore integrate this scoring in their calculation. The tested indices were: AZTI Marine Biotic Index (AMBI; Borja et al., 2000), Trawling Disturbance Index (TDI; de Juan and Demestre 2012), modified TDI (mTDI, Foveau et al., 2017), partial TDI (pTDI) and the modified vulnerability Index (mT; modified from Certain et al., 2015). TDI-derived indices were developed specifically to detect trawling impact, while mT is issued from a general framework allowing to address any pressure as long as specific sensitivity traits were available to detect it.

AMBI was developed to characterize the response of benthic communities of soft substrates to natural or anthropogenic disturbances, particularly the eutrophication, in coastal environments (Borja et al., 2000). Although this index is not appropriate to study the effect of physical pressures, as it was built to deal mainly with the effect organic enrichment on benthic communities, it was tested in this study because of its large use in studies of benthic fauna, particularly in the framework of the Water Framework Directive (van Hoey et al., 2015). It uses the percentages of abundance of each ecological group (G1 to G5; from sensitive to highly opportunistic species) which are known to differ according to the level of disturbance (Eq. (1)).

$$AMBI = \frac{(0 \times \%G1) + (1.5 \times \%G2) + (3 \times \%G3) + (4.5 \times \%G4) + (6 \times \%G5)}{100} \tag{1}$$

For calculating TDI, mTDI and pTDI, scores of the five categories of sensitivity traits (Table 2) were summed for each species and this value is considered as the species sensitivity index (SI) to trawling disturbance. Thus, highly vulnerable species could have a maximum score of 15.

For the TDI (Eq. (2)), species are distributed into five groups according to SI: group 1, SI ranged from 0 to 4; group 2, SI = 5–7; group 3, SI = 8–10, group 4, SI = 11–13 and group 5, SI = 14–15. The biomass of each group was calculated as the sum of biomass of all taxa within each group.

$$TDI_x = \frac{Log1 \times Log(G1_x + 1) + Log(G2_x + 1) + Log\, 4 \times Log(G3_x + 1) + Log8 \times Log(G4_x + 1) + Log\, 16 \times Log(G5_x + 1)}{Log(N_x + 1)} \tag{2}$$

where $G1_x$-$G5_x$ were the total biomasses of each group in the x[th] observation and N_x the total biomass of the x[th] observation

Another indice based on the species sensitivity was proposed by Foveau et al. (2017), the mTDI (Eq.3).

$$mTDI_x = \sum_{1}^{N_x} \frac{Bi_x}{Bn_x} \times SI_i \tag{3}$$

with N_x, the number of taxons in the x[th] observation; Bi_x, biomass of the i[th] taxon in the x[th] observation; Bn_x, summed biomass of the x[th] observation and SI_i, the sensitivity index (SI) of the i[th] taxon

To focused only on sensitive species (SI > 7) and thus try to better detect the effect of trawling, a further modification of mTDI was proposed (pTDI ; Eq. (4)).

$$pTDI_x = \sum_{1}^{N_x} \frac{Bij_x}{Bn_x} \times SI_{ij} \tag{4}$$

with Bij_x, biomass of the i[th] taxon of the list j of sensitive taxon (SI > 7) in the x[th] observation; and SI_{ij}, SI of the i[th] taxon of the list j of vulnerable taxon, ; Bn_x, summed biomass of the x[th] observation (including all observed taxa)

Values of these three indices are high when the biomass is dominated by sensitive species and decrease as they are replaced by less sensitive species in the assemblage.

For the calculation of the modified vulnerability Index (mT), the scores of all modalities were rescaled between 0.25 (low sensitivity) and 1 (high sensitivity) (Certain et al., 2015). A sixth trait was used for the calculation of mT: the protection status of each species. A score of 1 was attributed for species indexed on the Vulnerable Marine Ecosystems in Mediterranean Sea list (OCEANA, 2016) and presents on the OSPAR list of threatened and/or declining species and habitats (OSPAR, 2008). A score of 0.5 was attributed for all other species. The six traits were separated between direct and indirect factors. Although named vulnerability and sensibility factors respectively by Certain et al. (2015), they were renamed in this study to avoid confusion with the earlier definitions of these terms. Direct factors are relative measures of elements controlling the probability of being impacted by a given pressure type, trawling in our case. Indirect factors are relative measures of elements describing the conservation status of species and their indirect sensitivity to disturbance (e.g. filter feeders can be disturbed by the resuspension of sediments due to trawling).Then, for both type of factors, a hierarchy was established between primary factors that directly control the sensitivity and aggravation factors that may not be important on their own, but may worsen pre-existing sensitivity. The factor classification used in our study is detailed in Table 4.

Table 4
Direct and indirect factors and their hierarchical classification.

	Short description	Factor type	Factor hierarchy
F_1	Position in the sediment	Direct	Primary
F_2	Mobility	Direct	Primary
F_3	Adult size	Direct	Primary
F_4	Fragility	Direct	Aggravation
F_5	Feeding mode	Indirect	Primary
F_6	Protection status	Indirect	Primary

The direct component of the index, t_i, of each individual taxon i, is obtained by applying equation (5) with $a_i = F_{i1} \times F_{i2} \times F_{i3}$, $g_i = F_{i4}$ and $\gamma = 0.5$. The indirect component of the index, s_i, of the i[th] taxon is obtained by applying equation (5) with $a_i = (F_{i5} + F_{i6})/2$ and $g_i = 0$.

$$t_i = a_i^{1-g_i/(g_i+\gamma)} \tag{5}$$

The modified vulnerability Index (mT_x) in then calculated as in equation (6).

$$mT_x = -\sum_{i=1}^{N_x} \frac{Bri_x}{t_i \times s_i} \tag{6}$$

with Bri_x, relative biomass of the i[th] taxon of the station × and Nx the total number of taxon of the station x. This index tends to increase as the assemblage sensitivity increases.

All index calculations were performed using R version 3.4.2 (R Core Team 2017).

2.7. Indices evaluation and selection

In order to find which indices were most appropriate to monitor the impact of trawling on benthic communities, five different tests were carried out while distinguishing different surveys and geographic basins. The two first tests ensured that the index reflects the abrasion pressure. Thus, spearman correlation tests (Hollander and Wolfe, 1973) were conducted to determine the correlation level between indices and abrasion in each area studied. Similarity, their spatial distribution was also tested with the calculation of an index of difference in spatial pattern (Lee et al., 2010). This indicator varies between 0 (same spatial pattern) and 1 (many differences in the spatial patterns). Three complementary tests were carried out to discriminate the indices having good correlations with abrasion. Thus, the percentage of variance of the community structure explained by each index was determined by performing a redundancy analysis (RDA; van den Wollenberg, 1977) on the community biomass matrix and using each index in turn as sole constraining factor. The statistical behavior, and more particularly the nature of the distribution, of each index was also studied with the calculation of their skewness and kurtosis (Groeneveld and Meeden, 1984) because a normal distribution of the index will facilitate the use of this index for further statistical regression approaches.

In order to simplify the assessment of all indices properties, a qualitative scoring scheme was used. For each study area and property studied, a score was attributed to each index by dividing its test value by the maximum test value obtained for this property in this area. For example, if the maximum value of spearman correlation in the Gulf of Lion was 0.5 for the TDI, the biomass that has a correlation value of 0.25, has a score of 0.25/0.5 = 0.5. In the particular case of the Lee index which decreases when spatial similarity increases, the minimum test value was divided by higher tests values. For skewness and kurtosis tests, when their values were between −1 and 1, a score of 1 was assigned for that index in the study area, conversely, a score of 0 was assigned if theirs values were outside these bounds. Scores were then summed over areas for each index and as the study considers four areas, the maximal score by index was 4. A total score was computed summing each index scores over each of the five properties investigated. A ponderation of 2 was applied for the two major properties, spearman correlation test and Lee spatial correlation index, as they were the main focus of the present study. So, the maximal total score per index was 28. Once a total score per index was computed, indices could be ranked according to their performance and those with the highest score were selected.

Spearman correlation between each selected indices was also studied to better understand the differences between them. Selected indices relations to abrasion by zones were illustrated using boxplot over abrasion classes. After log- or arcsin transformation of indices that do not have a normal distribution, each index were locally averaged over time and subjected to a variographic analysis and interpolated using ordinary krigging in R using package geoR 1.7–5.2.1 (Ribeiro Jr and Diggle, 2018). Kriged estimates were mapped to illustrate the distribution pattern of seabed sensitivity captured through each of the four indices.

3. Results

Results of the evaluation of the indices relationships to abrasion both in term of ranked values or spatial pattern are presented in the Table 5 for each studied areas. Over all studied areas, the four indices which present the highest spearman correlation values (higher total score) are the TDI, the mTDI, the pTDI and the mT. For other indices, the Spearman correlation was often not significant, in particular in the North Sea (IBTS data) or even counter-intuitively reversed in Corsica. For the Lee index, all indices showed fairly similar results excepted Species richness, Margalef index and mT for which values were slightly better. The spatial correlation between indices and abrasion is lower in Corsica and in the North Sea (IBTS data) than in other areas.

The measure of percentage of variance of the community structure explained by each index and skewness and kurtosis tests are presented in Table 6. Almost all indices had a close to normal distribution in at least 3 of the 4 studied areas; only community biomass, FRic and FSpe did not. The percentage of community structure variance explained by each index is very variable from one area to the next. Apart from FRic and FEve, all indices based on biological traits better explained the community structure (higher score).

The total scores were computed by summing all scores for each type of test (Tables 5 and 6). According to this result, the four better performing indices were TDI, mTDI, pTDI, and mT.

All TDI derived indices were very correlated by construction as were Species richness to Margalef indices or Shannon, Pielou and Simpson indices (Table S1). Moreover, since the strength of the relationship to abrasion is given precedence over the other investigated properties, it is only natural that the best performing indices end up mechanically correlated with each other (and with abrasion).

For all indices and studied areas, overall values of indices appeared to decrease with abrasion (Figs. 2–5) which was already revealed by significantly negative (although weak) correlation between the indices and abrasion (Table 5). For the majority of indices, variations of index

Table 5
Results of spearman correlation tests and spatial correlation index for each index in the four studied areas.

Indices	Spearman correlation test					Spatial correlation (Lee index)				
	GoL	Corsica	IBTS	CGFS + CAM	Score	GoL	Corsica	IBTS	CGFS + CAM	Score
Community biomass	-0.15**	-0.05	0.001	0.26***	1.28	0.71	0.58	0.76	0.66	2.37
Species richness	0.13*	0.31**	0.10**	0.09**	1.77	0.31	0.44	0.49	0.42	3.82
Margalef index	0.13*	0.32**	0.10**	0.11**	1.86	0.31	0.44	0.49	0.42	3.82
Shannon index	0.24**	0.13	0.01	-0.02	1.10	0.32	0.47	0.52	0.43	3.65
Pielou Index	0.21**	0.07	-0.10**	-0.11**	1.40	0.32	0.48	0.53	0.43	3.62
Simpson index	0.19**	0.15	-0.01	-0.03	1.01	0.32	0.46	0.52	0.42	3.61
FRic	0.19**	0.36**	0.09*	0.15**	2.44	0.38	0.58	0.58	0.56	3.02
FDiv	0.08	-0.01	-0.14*	-0.21**	1.00	0.30	0.54	0.56	0.41	3.55
FEve	0.21**	-0.07	0.01	-0.11**	1.11	0.30	0.56	0.57	0.42	3.50
FSpe	0.14**	0.28*	0.03	0.05	1.41	0.30	0.53	0.54	0.41	3.60
AMBI	-0.26**	0.36**	0.003	-0.08**	1.99	0.42	0.57	0.58	0.52	3.02
TDI	-0.33**	0.07	-0.35***	-0.34***	3.08	0.32	0.56	0.57	0.47	3.34
mTDI	-0.31**	-0.08	-0.28**	-0.32***	2.80	0.31	0.52	0.53	0.42	3.59
pTDI	-0.26**	-0.09	-0.35***	-0.37***	3.01	0.30	0.72	0.72	0.61	2.87
mT	-0.34**	-0.01	-0.22**	-0.30***	2.47	0.29	0.50	0.50	0.37	3.86

GoL = Gulf of Lion. CGFS + CAM = CGFS and CAMANOC surveys * indicates that $P < 0.05$; ** indicates that $P < 0.01$; *** indicates that $P < 0.001$; ns indicates no significant difference. Grey shading indicates best scores

Table 6
Results of RDA and normality tests for each index in the four studied areas.

Indices	Percentage of variance of the community structure explained					Skewness					Kurtosis					Total score
	GoL	Corsica	IBTS	CGFS + CAM	Score	GoL	Corsica	IBTS	CGFS + CAM	Score	GoL	Corsica	IBTS	CGFS + CAM	Score	
Community biomass	4.8	19.8	0.4	0.9	1.17	5	1.8	17.07	11.45	0	31.24	2.60	365.71	166.16	0	8.47
Species richness	1.3	14.5	2.9	0.9	1.13	0.48	0.91	0.89	0.73	4	-0.19	-0.02	0.64	-0.45	4	20.31
Margalef index	1.4	14.5	2.9	0.9	1.13	0.48	0.91	0.89	0.72	4	-0.19	-0.02	0.64	0.66	4	20.49
Shannon index	12.0	15.7	2.0	1.5	1.94	-0.75	0.03	-0.19	-0.09	4	-0.27	-0.72	-0.64	-0.45	4	19.44
Pielou Index	13.0	17.5	1.0	1.2	1.88	-0.95	-0.41	-0.25	-0.37	4	0.046	-0.73	-0.4	-0.33	4	20.28
Simpson index	11.0	16.2	1.4	1.4	1.79	-1.47	-0.54	-0.74	-0.78	3	1.39	-0.60	-0.36	-0.21	3	17.03
FRic	1.8	5.8	1.4	0.6	0.63	1.33	2.06	1.26	4.34	0	2.43	3.57	-0.41	32.40	1	12.55
FDiv	7.3	20.8	0.7	5.6	2.17	-0.43	-0.61	1.26	-0.27	3	-0.50	-0.16	-0.41	-0.65	4	18.27
FEve	2.4	0.7	0.4	0.6	0.35	0.14	-0.076	2.10	0.25	3	0.08	-0.40	2.43	0.23	3	15.57
FSpe	8.1	32.7	3.4	6.3	3.12	0.11	-0.61	2.28	1.53	2	-0.39	-0.75	8.73	1.85	2	17.14
AMBI	6.1	17.2	6.2	5.5	2.82	0.44	0.65	0.76	0.95	4	-0.46	-0.48	0.20	1.39	3	19.84
TDI	8.1	16.1	6.4	4.4	2.79	-0.14	-0.34	1.19	0.73	3	0.10	-0.77	0.35	-0.25	4	22.63
mTDI	11.9	13.5	6.1	4.2	2.93	-0.10	-0.32	1.56	0.96	3	-0.75	-0.40	1.75	0.68	3	21.68
pTDI	7.8	12.5	2.5	6.5	2.37	-0.05	-0.44	1.10	0.67	3	-0.55	0.36	0.04	-0.75	4	21.13
mT	13.0	8.5	5.4	2.7	2.53	0.32	-0.35	-0.40	1.45	3	-0.32	0.19	0.11	5.63	3	21.19

GoL = Gulf of Lion; CGFS + CAM = CGFS and CAMANOC surveys. Grey shading indicates best scores.

values in abrasion class were very high as for example for the pTDI (in CGFS and CAMANOC surveys; Fig. 5) where the index varies between 0.07 and 15 for an abrasion below 1 and between 0.006 and 14 for an abrasion higher than 10.

The distribution patterns of the trawling sensitivity of the benthic communities, in the Gulf of Lion, were almost the same for the four indices (Fig. 6). Thus, the degree of sensitivity of the communities was positively correlated with the distance to the coast, with communities that were not very sensitive to trawling in the coastal zone (lower values of the indices) and communities that were much more sensitive

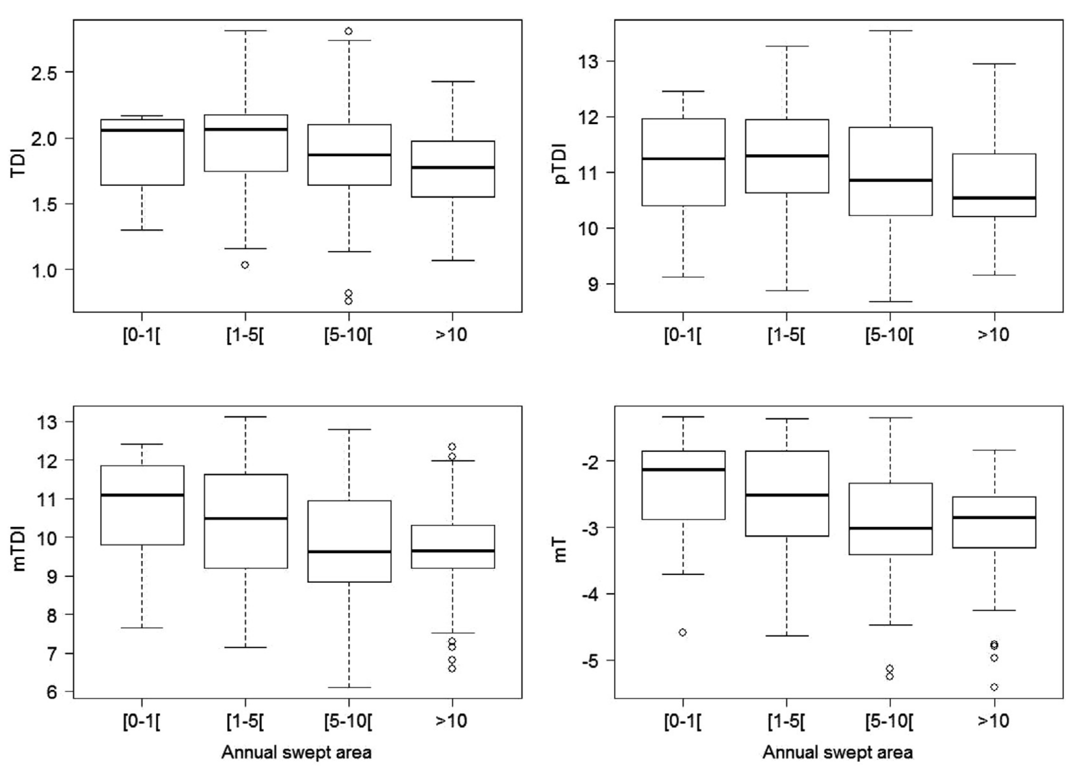

Fig. 2. Values of the four selected indices by class of abrasion in the Gulf of Lion.

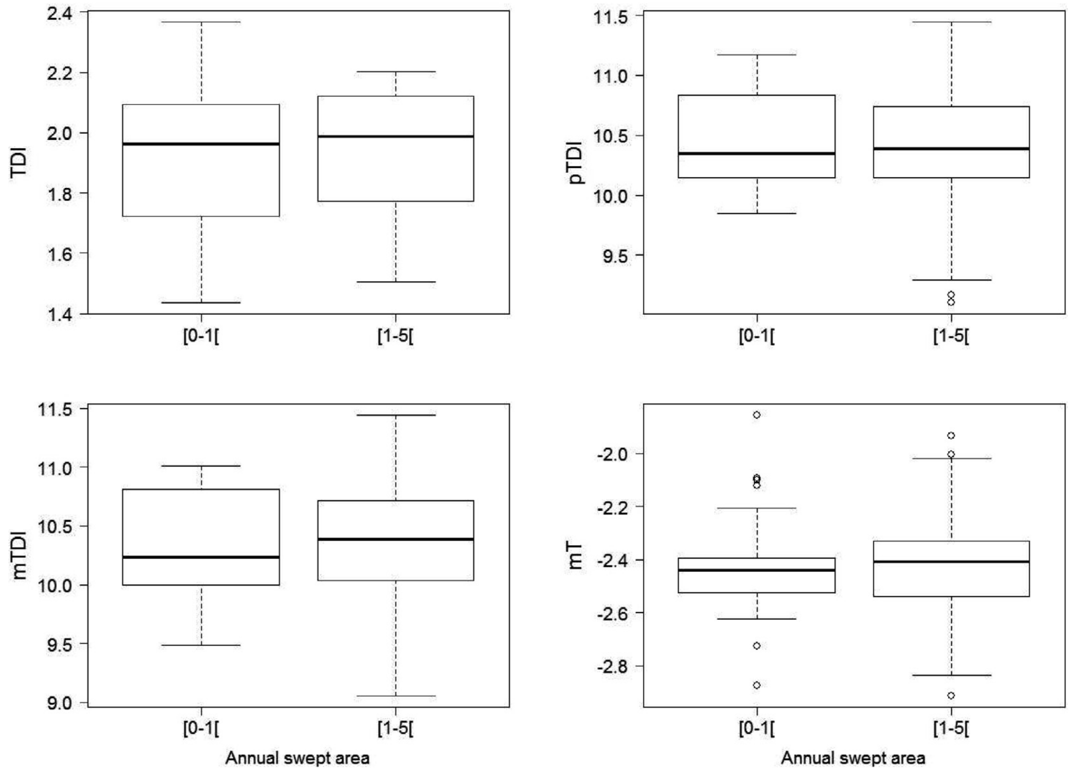

Fig. 3. Values of the four selected indices by class of abrasion in Corsica.

offshore (higher values of the indices).

In the North Sea, despite small differences, distribution patterns of the trawling sensitivity of benthic communities were substantially the same for the four indices (Fig. 7). Benthic ecosystems of the South and the East part of the North Sea appeared particularly impacted by the trawling and so not very sensitive (lower values of the indices). Values of indices were high only in a small area in the West of the North Sea making it particularly vulnerable to trawling, with the presence of species considered to be sensitive to trawling.

Concerning the English Channel, three of the four indices (TDI, mTDI, mT) had low values in the Eastern Channel and the northern part of the Western Channel (Fig. 8), reflecting areas already heavily

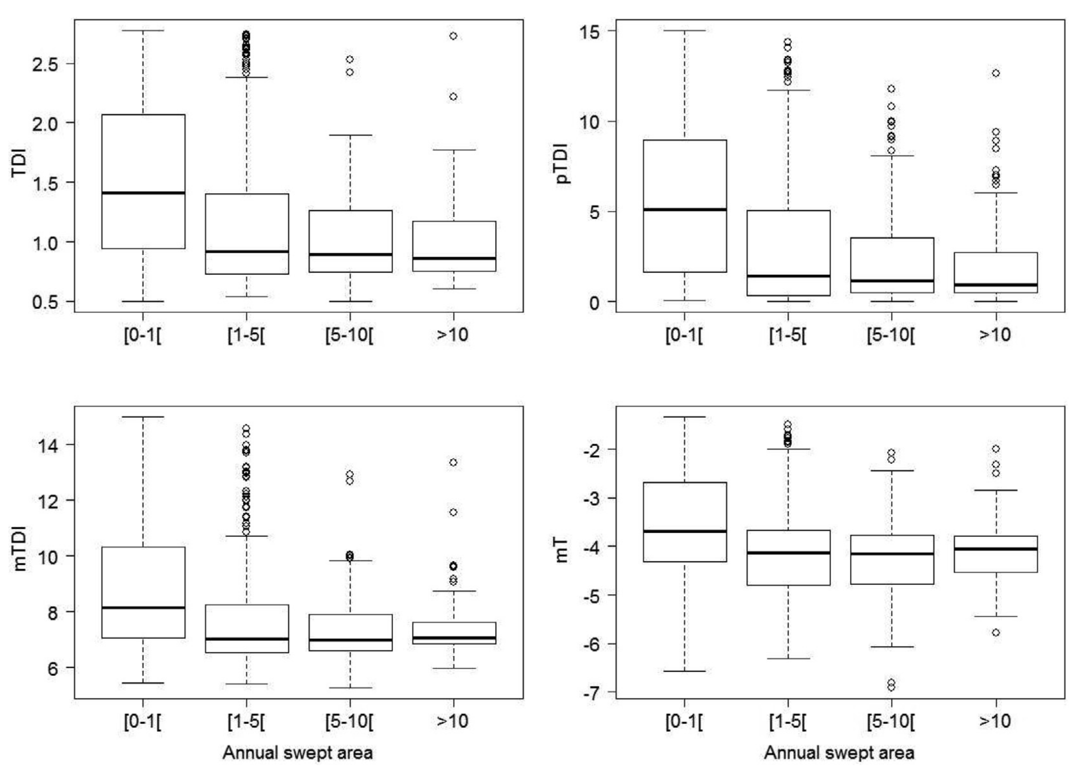

Fig. 4. Values of the four selected indices by class of abrasion for the IBTS data (eastern English Channel and southern North Sea).

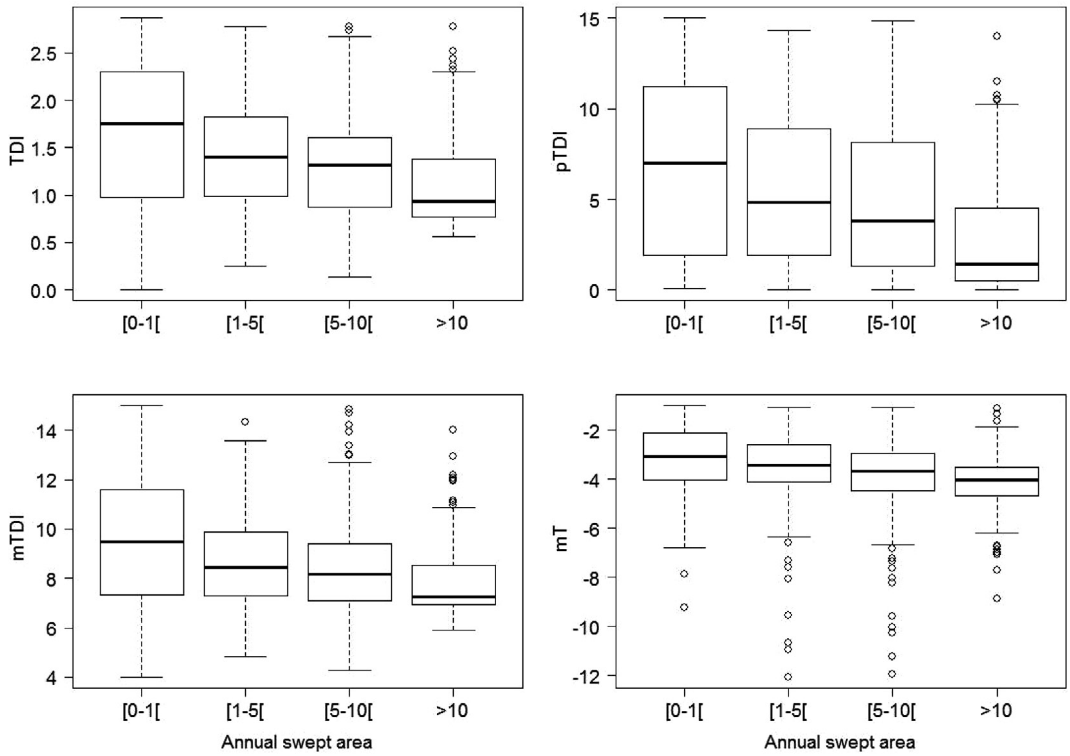

Fig. 5. Values of the four selected indices by class of abrasion for the CGFS and CAMANOC data (English Channel).

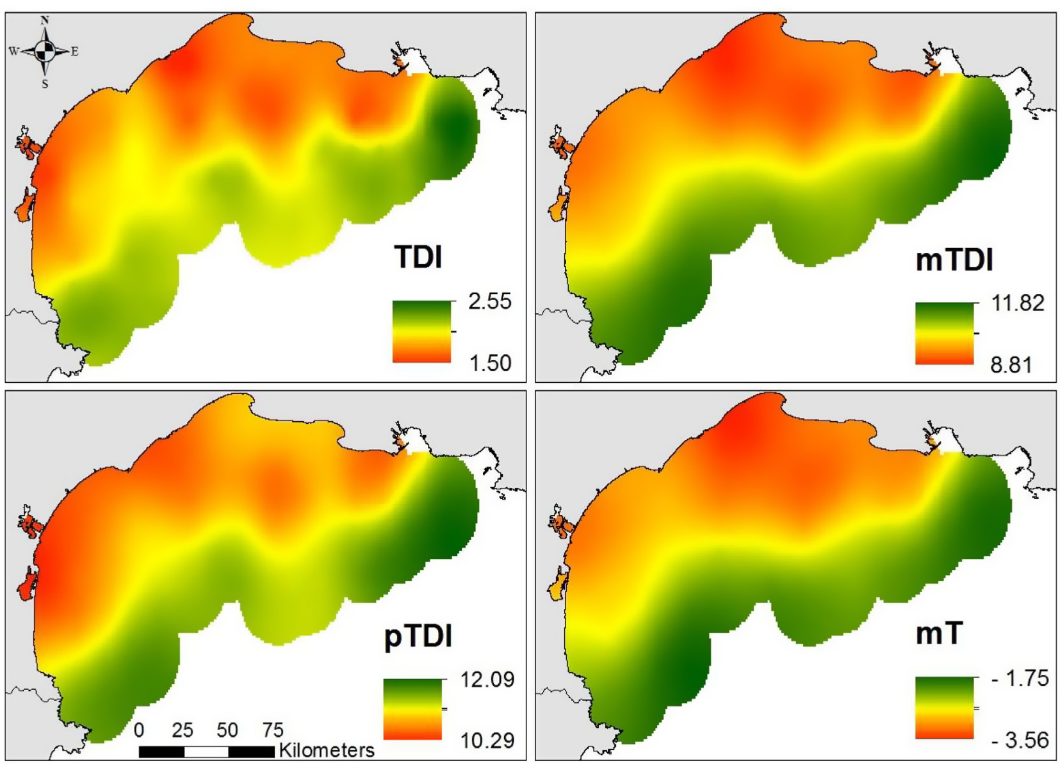

Fig. 6. Distribution pattern of benthic sensitivity to trawling in the Gulf of Lion (MEDITS data).

impacted by trawling. Except around Plymouth, the Western English Channel looks particularly sensitive to trawling, as highlighted by the pTDI results.

4. Discussion

Most of the studies focusing on benthic communities use grab or box-corer for sampling (Engel and Kvitek, 1998; Kenchington et al., 2001; Atkinson et al., 2011; Rijnsdorp et al., 2018; van Loon et al., 2018). These methods only sample a small area at a time (generally

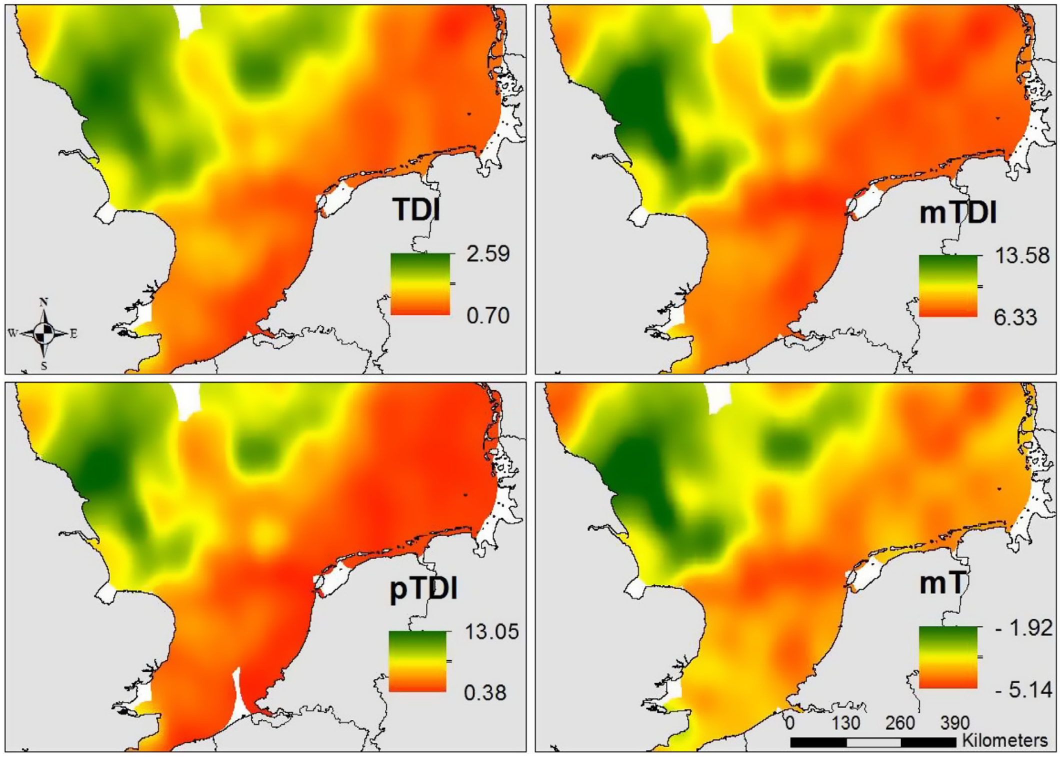

Fig. 7. Distribution pattern of benthic sensitivity to trawling in the southern North Sea (IBTS data).

about between 0.1 and 0.5 m^2) whereas trawling methods sample large-scale benthic communities. Grab and core methods mainly collected infauna species (Rumohr, 1999) and do not effectively sample the larger epifauna and megafauna component of the seabed (Bergman and Van Santbrink, 2000). Therefore, biomass and abundance of species such as sponges, hydrozoans, sea stars or crabs are underestimated despite their strong sensitivity to trawling (de Juan and Demestre, 2012). Although it is often considered a non-quantitative method (Eleftheriou, 2013), bottom trawls may be appropriate to investigate the effect of trawling. This method allows capturing the benthic fauna fraction which is the more directly affected by bottom fishing: the epifauna (Rumohr, 1999; Reiss et al., 2006; Foveau et al., 2017). The

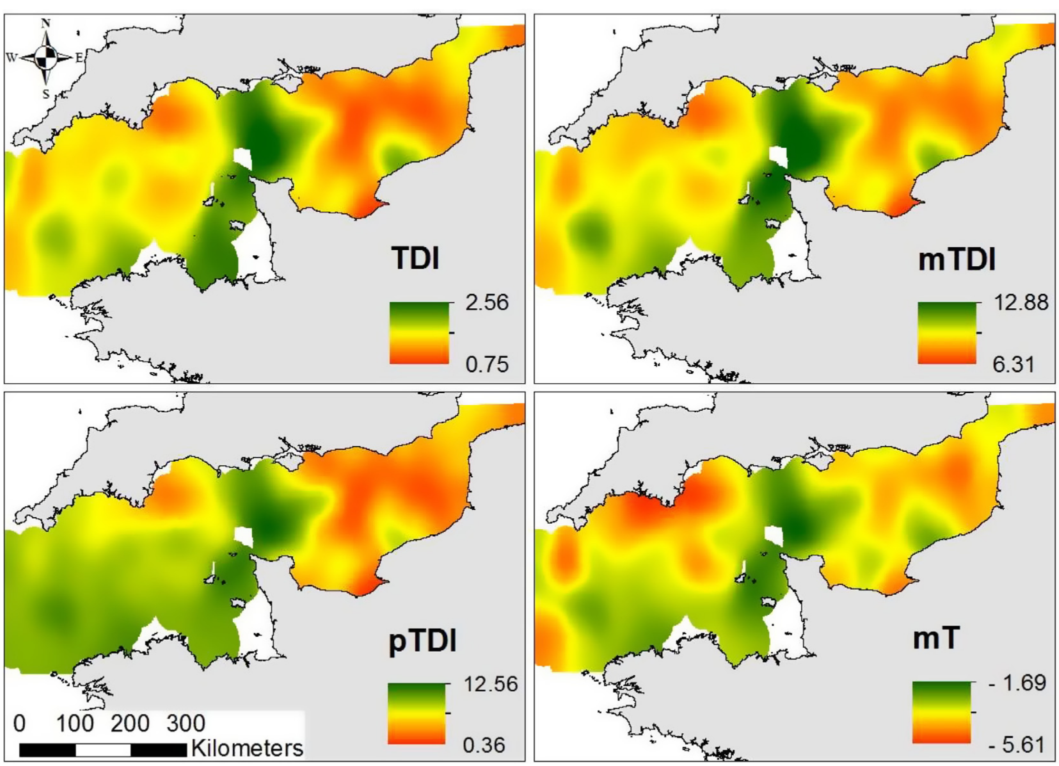

Fig. 8. Distribution pattern of benthic sensitivity to trawling in the English Channel (CGFS and CAMANOC data).

use of this sampling technique also allows the observation of benthic assemblages over large areas, in agreement with the large-scale distribution of abrasion. Benthic invertebrates forming a significant proportion of by-catch in the trawl fisheries (Reiss et al., 2006; Foveau et al., 2017), scientific bottom trawling surveys carried out yearly in different countries for the purpose of the Common Fishery Policy may be a useful and cost-effective way to obtain a large amount of good quality data over a wide spatial extent and potentially long temporal range.

As numerous studies on trawling impact showed that organisms' responses to disturbance depend on their biological traits (Thrush et al., 1998; Blanchard et al., 2004; de Juan et al., 2007; Kenchington et al., 2007; Strain et al., 2012), the selection of traits used in the calculation of functional indices is an important step in the process. The utilization, in our study, of a set of biological traits known to respond positively or negatively to trawling disturbances (Thrush et al., 1998; de Juan et al., 2007; Gray and Elliott 2009), allows to better monitor the effect of trawling on benthic ecosystem. For example, the feeding mode of the species induces different responses to trawling, since burrowing scavengers may benefit from trawling disturbance or discards, whereas filter feeders can be highly affected by increased sediment resuspension (de Juan et al., 2007). Other traits could reflect the resilience of species and might be used as indicators of trawling disturbance such as the species longevity (Rijnsdorp et al., 2018), the reproduction mode or the dispersion mechanisms (Bremner et al., 2006). However, the lack of information about these biological traits for a large number of species did not allow us to include them in indices calculations. Moreover, some of these traits, such as longevity, are probably environment specific and may need to be locally adapted which further complicate their use for generic index calculation.

One of the aims of this study was to select a generic index capable of detecting the effect of trawling on benthic communities in all European waters. The combination of five selection properties allowed us to select four indices (TDI, pTDI, mTDI and mT index) responding to the fishing pressure. These four indices are highly correlated at large scale since they are based on the same set of biological traits and were chosen for their significant correlation to abrasion. However, the lower correlations between mT and the TDI derived indices indicate that their mathematical formulation still matters. As a result, their usefulness may be zone-dependent since the correlation between mT and abrasion seems stronger than that of TDI derivatives in the Gulf of Lion and vice versa in the English Channel/southern North Sea. Therefore, although closely related, it seems difficult to select only one of these for impact assessment and their behavior at habitat scale needs to be investigated. Despite their apparently significant relationship to abrasion in most studied areas (except in Corsica), large observation variability resulted in weak correlation values. This very large variability probably resulted from the fact that benthic habitats were not differentiated in this study, and that trawling does not have the same impact on all seabed habitats, particularly because bottom-trawl catchability depends on the nature of the bottom (Reiss et al., 2006). Thus, tracking trawl effects on benthic communities, for example, should be done at a finer resolution (e.g. EUNIS Level 4) choosing which ever index is the most sensitive in the studied area (in application to the precautionary approach).

As for the other indices tested, despite their potential relevance to other aspects, they do not appear to be relevant for monitoring the effect of trawling on benthic communities. For example, for the species richness and Margalef index, contrasting results were observed between zones, mainly with high values only in Corsica for "Spearman correlation" and "Percentage of variance of the community structure explained" criteria. These differences disqualified these indices as they could hardly be used in other zones than Corsica. In the case of Pielou index, its rejection was based on the fact that its correlation with abrasion was negative in the Channel/southern North Sea and positive in the Mediterranean. Therefore, due to this lack of coherence, this index cannot be generalized to all European waters. Moreover, the high scores obtained by the majority of diversity indices are partly due to their relatively superior statistical behavior (normal distribution) which, also a useful property, is not sufficient to qualify these indices that should also be informative. Community biomass were also weakly relevant to monitor the effect of trawling. Indeed, in the present study, the absence of significant negative correlation between the community biomass and the abrasion seemed consistent across most of the studied areas. In contrast, many anterior studies found a negative effect of trawling on the biomass of benthic community (Collie et al., 2000; Jennings et al., 2001; Queirós et al., 2006). The biomass of the community is known to be influenced by the nature of sediments and particularly silt and clay contents (Queirós et al., 2006; Hinz et al., 2009). It is therefore possible that, due to the lack of differentiation between habitats, the variance of biomass is too high at basin scale to detect anything about the effect of trawling. Such responsiveness sensitivity may hinder the operational use of this measure.

Concerning diversity indices, the great disparity of indices' responses to the effect of fishing between studied areas is also consistent with existing literature. Previous studies have shown a negative influence of fishing on Shannon, Pielou and Simpson index (Smith et al., 2000; Shirmohammadi et al., 2012). On the opposite, others could not detect any significant effect (Svane et al., 2009; Atkinson et al., 2011), or even evidenced a positive effect of abrasion on the Simpson index (Shirmohammadi et al., 2012) and on the Pielou index for a few months of the year in the Mediterranean Sea (Smith et al., 2000). Heterogeneity in these results highlights that the effect of trawling on species number or biomass is unclear, but rather appears to modify functional components of benthic communities, with for example a decrease of epifaunal sedentary suspension feeders in trawled areas (de Juan et al., 2007). Except for the FRic, the functional indices calculated in this study did not appear to respond to trawling activities in all studied areas. The positive correlation between FEve and FSpe and abrasion in the Mediterranean suggests that trawling leads to an increase and dominance (in terms of biomass) of specialized species. In the opposite, the negative correlation between FDiv and FEve and the abrasion in the southern North Sea suggests that increased trawling induced a dominance of functionally close generalist species (close to center of gravity of functional space). Functional indices are, in essence, sensitive to the trait composition of the benthic community which may result in change in the index response to trawling depending on the trait composition of each area. Such information is valuable, from an ecological point of view, to anticipate trawl-induced change in a given community, but does not satisfy the requirements of a general index of sensibility, as its interpretation remains strongly context-dependent. Concerning the functional richness (FRic), the positive correlation with the abrasion in all studied areas suggests that trawling led to an increase of the functional diversity of the benthic community by attracting for example different scavengers (Collie et al., 2000; Thrush and Dayton, 2002). However, regarding its poor scores obtained for other properties, this index is also a poor candidate to evaluate the effect of trawling on benthic communities.

Based on biological traits known to be influenced by trawling, the four retained indices (TDI, mTDI, pTDI and mT index) were specific to the trawling effect. This suggests that it seems illusory to find a generic indicator able to respond to all the pressures experienced by benthic habitats and, therefore, that the study of the ecological status of seabed must rely on several indicators specific to each type of impact. In addition, the different effectiveness of indices between study areas suggests the systematic use of a set of indices, the combination of which should provide information on the ecological status of the area in terms of fishing pressure.

Unlike the results obtained in the other three zones, very low correlations are observed between tested indices and trawling effort in Corsica. The lack of significant relationship between the majority of the indices and the abrasion may be explained by the limited number of data available in this area. Furthermore, abrasion being relatively low over the whole of Corsica (Jac and Vaz, 2018), the benthic communities were sampled on a low abrasion gradient (less than 5 vs. 0.08 to 29.15 in the Gulf of Lion). It seemed unlikely that there would be a change in indices values over such a reduced abrasion gradient, especially since the small number of samples would tend to exacerbate the natural variability at the same abrasion intensity. Absence of relation between selected indices and low abrasion range might indicate that the effect of trawling on the benthic community is undetectable at these levels. Thus, relation between indices and trawling effort appeared not to be linear over the entire abrasion range and the likely presence of thresholds seems to be emerging.

Sensitivity indices proposed here to satisfactorily assess the effect of trawling meet many of the requirements suggested in previous studies (Queirós et al., 2016; ICES, 2017a):

1) They are based on biological traits known to be affected by trawling. This agrees with the first requirement (Theoretical basis), which directly reflects the changes that trawling induces on the community, through the change in the proportion of each trait in the community.
2) This makes these indices particularly sensitive to the trawling pressure (requirement 2: sensitivity).
3) The four selected indices present consistent and significant changes as a result of a pressure change (third requirement: responsiveness), since the resilience of the species after reducing or removing abrasion depend on their biological characteristics. Lambert et al (2014) showed that in high current areas, species with low mobility would have a faster recovery time than other species. Considered as a very important requirement for the species' sensitivity to trawling, the increase of low-mobility species biomass, due to a reduction of abrasion, leads to an increase in the value of indices.
4) The use of yearly scientific trawl surveys' data allows to respond positively to several criteria such as data quality (requirement 6) and the repeatability of the method (requirement 5).
5) The acquisition of data is done with limited costs (requirement 8) since the surveys already exist and the identification and the measurements (weighing and counting) are mostly carried out on board.
6) Although it is often very difficult to distinguish the effect of a physical pressure, such as trawling, from the effect of the environment on benthic communities, these indicators can be considered as specific (requirement 4: specificity) as they use known biological traits providing specific information on the species' sensitivity to trawling.
7) The use of four contrasted study areas in this work allows us to conclude positively on the cross regional applicability (requirement 9).
8) Finally, even if this is not mentioned in the requirements, the fact that the four indices are negatively correlated to abrasion makes them easily interpretable.

5. Conclusions

The establishment of the MSFD by the European Union in 2008 requires the development of indicators to assess and to monitor the effect of human pressures on the marine environment. Trawling appearing as one of the strongest pressure on the seabed, the development of indices to study its impact was necessary. Evaluation of the efficiency of fourteen different indices showed the necessity to use indices specific to trawling to detect its effect on benthic habitat in very contrasted regions. Indeed, based on this study, four specific indices (TDI, the mTDI, the pTDI and the mT index) were put forward and evaluated as suitable to detect the impact of trawling. However, their detection power varied geographically and although closely related, it seems difficult to select and recommend only one of them. In conclusion, to monitor the effect of trawling on benthic communities in all European waters, these indices would need to be systematically screened and the locally most suitable one chosen for impact assessment.

CRediT authorship contribution statement

J.A.C. Cyrielle: Methodology, Validation, Formal analysis, Data curation, Writing - original draft, Visualization. **Nicolas Desroy:** Conceptualization, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Gregoire Certain:** Methodology, Resources, Writing - review & editing. **Aurélie Foveau:** Resources, Writing - review & editing. **Céline Labrune:** Writing - review & editing. **Sandrine Vaz:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106631.

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