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Original Article

Identifying assessment scales for food web criteria in the NE Atlantic: implications for the Marine Strategy Framework Directive

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The implementation of food web criteria in the Marine Strategy Framework Directive context faces several difficulties, namely the lack of data for relevant taxa, the absence of operational indicators, and spatially and temporally limited datasets. This work aims to identify ecologically relevant scales in the Celtic Seas (CS) and the Bay of Biscay and Iberian Coast (BBIC). Four food web criteria—mean trophic level (MTL), mean trophic level with cut-offs ($MTL_{\_3.25}$ and $MTL_{\_4}$), large fish indicator (LFI) and mean abundance across trophic guild (MATG)—were assessed using groundfish data and tested using generalized additive models, for six spatial scales and four temporal scales. In both subregions, MTL required yearly and locally defined assessment scales. As for $MTL_{\_3.25}$, it improved significantly when downsizing spatial scales but was temporally consistent. In the CS, locally defined scales and yearly data explained $MTL_{\_4}$ and LFI. While in BBIC, $MTL_{\_4}$ and LFI patterns were defined spatially by region and depth and temporally by year. MATG variability was unaffected by scales. Using the scales identified, food web criteriawere assessed for the Portuguese continental waters. Criteria failed to achieve Good Environmental Status in areas of the Southwest and South of Portugal. Although downsizing scales revealed that criteria were below the threshold at local/regional level, differences in classification are expected to be limited if spatial assessments are aggregated.

Keywords: demersal fish communities, ecosystem-based assessment, food web criteria, Marine Strategy Framework Directive, spatial scales, temporal scales

Introduction

Sustainable ecosystem-based management calls for a thorough understanding of the cause and effect relationship between human pressures and ecosystem states (Rombouts *et al.*, 2013; Large *et al.*, 2015) for a multitude of pressures affecting marine ecosystems (Tam *et al.*, 2017). In the European Union (EU), the Marine Strategy Framework Directive (MSFD) underpins an attempt to incorporate an ecosystem-based assessment (EBA) through the establishment of 11 descriptors that include environmental status and anthropogenic pressure indicators. The Directive obliges Member States (MSs) to achieve healthy and productive ecosystems or, in other words, "Good Environmental Status" (GES) of the marine environment for all descriptors (European Commission, 2008). The network of feeding interactions between co-existing species and populations (food webs) are an important aspect of all marine ecosystems and biodiversity. The functioning of food webs (the networks formed by the trophic interactions between species in ecological communities) reflects many aspects of ecosystem dynamics and biodiversity (Tam *et al.*, 2017). In the MSFD framework, descriptor 4—food webs (D4) establishes the environmental status assessment of the structure, functioning and dynamics of trophic guilds (TGs). It aims to ensure that “All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity”. The first implementation cycle ended in 2018 and has been an important milestone in marine environmental policies at the EU level, as it highlighted existing strengths and knowledge gaps (Palialexis *et al.*, 2014). Analysis of D4 implementation pointed out problematic metrics, a scarcity of fully operational indicators, dissimilar methodologies, and data scarcity/incongruences as factors that have been hindering its correct implementation (OSPAR Commission, 2012; Palialexis *et al.*, 2014). In fact, only few indicators have been fully operationalized, i.e. they are quantitatively defined, assessed in relation to a defined threshold, and respond clearly to anthropogenic activities (Rombouts *et al.*, 2013). Similarly, the Oslo and Paris Regional Sea Convention (OSPAR) assessment from 2017 pointed out issues like the lack of proper data and the difficulties in establishing clear reference points as the main knowledge gaps for a complete geographical analysis of D4 (OSPAR, 2017). The European Commission (EC) revised the decision on the methodological standards to determine GES (2017/848/EU), detailing methodological standards, re-defining the ecosystem elements, and identifying the scales of the assessment to support the implementation of the MSFD (European Commission, 2017a, b). The assessment of food web descriptor includes criteria classified as primary—D4C1 (trophic guild species diversity) and D4C2 (abundance across trophic), and secondary—D4C3 (trophic guild size distribution) and D4C4 (trophic guild productivity) (European Commission, 2017b). The revised Commission Decision (2017/848/EU) provided details of the elements for assessment: (i) should take into account a list of TGs to be assessed that should be established by MSs through regional or subregional cooperation, (ii) include a minimum of three TGs, (iii) two of the three guilds should be non-fish, (iv) at least one guild should be a primary producer, and (v) the TGs assessed should represent at least the top, middle, and bottom of the food chain. There has been an attempt to develop fully operational indicators that can integrate trophic structure and functions, together with their interactions. But the lack of comparable data within taxonomic groups has made such integration difficult (Rombouts *et al.*, 2013; Tam *et al.*, 2017; Ministério do Mar, 2020). When trying to understand if ecosystem status is directly linked to pressures, difficulties arise, since the environment is exposed to existing multiple pressures, such as natural and anthropogenic variability, which, coupled with to the temporal and spatial variation, make the diagnosis very difficult. Ideally, criteria should link pressure to ecosystem state at the appropriate spatial and temporal resolution (Henriques *et al.*, 2008; Shin *et al.*, 2010; Probst and Stelzenmüller, 2015; Preciado *et al.*, 2019). Tam *et al.* (2017) identified food web indicators that succeed in capturing the effects of anthropogenic pressures. Among these, integrated trophic indicators (mean trophic level (MTL), mean trophic index (MTI), etc.) and guild level biomass (guilds biomass) provide relevant indications for future surveillance and management actions of fish communities (Shannon *et al.*, 2014; ICES, 2015). Inclusively, MTL has been advocated for use in holistic EBA approaches, such as Ecological Network Analysis or Ecopath, providing meaningful and understandable information for decision-makers and trustworthy information for ecosystem management (Fath *et al.*, 2019). Length-based indicators were also considered appropriate metrics, especially when effects of fisheries on predators are targeted, providing relevant complementary information (Tam *et al.*, 2017). However, further optimization is required, especially targeting incongruencies such as the guilds accessed, the development of targets/thresholds and the use of appropriate scales, since a relevant assessment scale must be used to capture food web variability patterns and detect existing trends. In the NE Atlantic, the geographical scale defined by the EC for the asssesment of food webs is the subregion, with areas ranging from 1.857.164km^2 (for the Macaronesia) to 491.305 km^2 (for the North Sea), and subdivisions may be used if necessary (European Commission, 2017a). Other assessment areas can be informally defined by MSs, but these (and the subdivisions) should be nested within the region/subregions reported. The NE Atlantic subregions enclose a wide amplitude of environmental and oceanographic features that together with distinct anthropogenic pressures may require different assessment scales to detect existing patterns. The effects of using different spatial scales in assessments have been widely studied for coastal and benthic communities (e.g. Cole *et al.*, 2001; Östman *et al.*, 2017) that are easy to manipulate, although that is not true for highly motile species (e.g. fish communities), due to their motile properties and wide geographical distribution. For high mobility species, MSFD guidelines and OSPAR assessment have suggested that using wide assessment areas may fail to identify significant but localized impacts that could result in effects on ecosystems (OSPAR Commission, 2012; Walmsley *et al.*, 2017). Even though spatial scales that integrate wide migration ranges may be appropriate for large, long-lived taxa, these scales may span fundamentally different habitats and communities for lower trophic levels (TLs) (e.g. plankton or benthos), to the point that a synthesis at this scale becomes questionable (OSPAR Commission, 2012). The appropriate spatial scale at which food webs should be assessed can be set by the anthropogenic pressure under study, rather than by any ecological considerations, and by the availability and spatial extent of monitoring data for key taxa, which are also likely to influence the scale of the assessment (Rogers *et al.*, 2010; OSPAR Commission, 2012). In the Bay of Biscay, Preciado *et al.* (2019) detected a direct relation between fishing pressure and ecological indicators response at small spatial scales (i.e. local level). While in the North Sea, Adams *et al.* (2017) showed that size-based community indicators vary across space, species, and season, identifying International Council for Exploration of the Seas (ICES) rectangle units as an appropriate assessment scale. Furthermore, assessment scales should be agreed upon by MSs sharing subregions and should be nested into wider areas, to enable further spatial integration (Walmsley *et al.*, 2017) and enable a global GES assessment.

This work evaluated four food web criteria used to implement D4 in the Celtic Seas (CS) and in the Bay of Biscay and Iberian Coast (BBIC) over distinct spatial and temporal scales. We hypothesized that food web criteria estimates and the detection of pressures on food webs may be affected by scales used in the assessment (from wider to smaller assessment areas and longer to shorter temporal periods) and, therefore, can affect the development of management procedures and implementation measures. Mean TL (MTL), mean TL with thresholds ($MTL_{3.25}$ and MTL_{4}), large fish indicator (LFI), and mean abundance across TG (MATG) were assessed using six spatial and four temporal scales, using groundfish survey data (Moriarty *et al.*, 2019) and generalized additive models (GAMs), to identify the spatial and temporal scales that significantly describe indicator's variability. Using the assessment scales identified for the BBIC subregion, food web criteria were analysed and compared with the Portuguese continental region assessment, to understand if scales had any effect in the criteria status. The methodologies used were identical to the ones applied in the MSFD 2^{nd} cycle report, and since there are not any agreed threshold levels defined for food web criteria, a trend-based approach was carried out (OSPAR Commission, 2012; Ministério do Mar, 2020); the time series of each criterion were assessed through the non-parametric Mann-Kendall test. Outputs are expected to provide relevant information to increase reporting coherence and promote discussion concerning the most relevant scales to be used in D4 criteria assessment.

Material and methods

Study area and dataset

The study area comprehends two ecological subregions of the North-Eastern Atlantic Ocean: the continental shelf of the CS (off the west coast of United Kingdom, surrounding Ireland, the northwest coast of France) and the BBIC (the west coast of France, north of Spain, and west coast of Portugal) (Figure 1), with the exception of the Gulf of Cadiz.

The dataset used was extracted from the Groundfish Survey Monitoring and Assessment Data Products (Moriarty *et al.*, 2019). This dataset is based on the Database of Trawl Surveys (DATRAS), which is maintained by ICES and includes data from yearly trawl surveys that aim to assess demersal communities and to collect suitable data to perform stock assessment in the framework of the Common Fisheries Policy (CFP) (1380/2013/EU). DATRAS has an integrated quality check, although data available can vary with MS survey features, MS data uploading procedures, etc., and integration issues can arise. The features of each national survey are described in Supplementary Table S1. To solve discrepancies, Moriarty *et al.* (2017, 2019) made an extensive quality check across all MS datasets, compiling absent data and using existing parameters (e.g. swept area) to standardize the estimation of number of abundance and biomass per area (i.e. ind. km^{-2} and kg km^{-2}) for all MSs. The full processing methods are outlined in the supporting documentation (Moriarty *et al.*, 2017, 2019). Groundfish survey data have been used at national and international levels to assess food web status in the context of MSFD and RSC (MAMAOT, 2012; OSPAR, 2017; Tam *et al.*, 2017). The dataset included all surveys during the fourth quarter of the year (Q4—from September to December), from 2002 to 2014, and using otter trawl (OT) as sampling gear (Figure 1). The depth range analysed varied between 15 and 581 m.

Food web criteria and scales analysed

Food web indicators selected for this study were MTL, $MTL_{\_3.25}$, $MTL_{\_4}$, LFI, and MATG. These are considered operational indicators for food web assessment (Tam *et al.*, 2017), and they are complementary and include at least three TGs (European Commission, 2017a). According to ICES and MSFD guidance, MTL, $MTL_{\_3.25}$, $MTL_{\_4}$, and MATG are adequate to report criteria D4C2 (abundance across trophic guilds), while LFI reports D4C3 (trophic guild size distribution) (ICES, 2015; Walmsley *et al.*, 2017). They have been used by MSs to report D4 in both MSFD and OSPAR contexts (OSPAR, 2017; Ministério do Mar, 2020). To calculate MTL, $MTL_{\_3.25}$, $MTL_{\_4}$, and MATG, the TL and the TG were assigned to each species. TL and TG were retrieved from online databases (e.g. Fishbase; Pauly and Watson, 2005; Beukhof *et al.*, 2019; Froese and Pauly, 2019). TL values are worldwide averaged TL estimations and are attributed in accordance with each species position in the food chain, determined by the number of energy-transfer steps to that level (Froese and Pauly, 2019). Due to the wide area under study, it was not possible to address regional particularities for each given region and therefore a fixed TL was used for each species. MTL was calculated as the mean trophic position of species in relation to their relative biomass for each survey and includes all TGs ($TL > 2$). MTL is calculated following the formula below:

$$\mathrm{MTL} = \frac{\sum_i (Y_{ik})*(\mathrm{TL}_i)}{\sum_i (Y_{ik})}, \tag{1}$$

where TL is the trophic level of species i and Y_{ik} refers to the biomass of the species i in year k (1). Two TL cut-offs were applied to MTL to decrease the influence of pelagic species: (i) MTL_3.25 with a cut-off of all species with a TL of <3.25, including all consumer species, and (ii) MTL_4.0 with a cut-off of all species with a TL of <4.0 (Pauly and Watson, 2005; Shannon *et al.*, 2014), addressing all predator species. MATG is the relative proportion of each guild's biomass in relation to the overall biomass (Auster and Link, 2009). The guilds considered were planktivorous, benthivores, piscivorous, and omnivorous (Beukhof *et al.*, 2019). To determine MATG values, the equation is as follows:

$$\mathrm{MATG} = \frac{\sum B_{\mathrm{TG}_{jk}}}{\sum B_{Total_k}}, \tag{2}$$

where B_{TG} is the biomass of the TG j, in year k. The LFI was developed for the North Sea (Greenstreet *et al.*, 2011) and uses the proportion of fish biomass density at length in relation to the overall biomass:

$$\mathrm{LFI} = \frac{\sum_i B_{L>\mathrm{LLF}}}{\sum_i B_{\mathrm{Total}}}, \tag{3}$$

The length value, large length fish (LLF) defining "large fish", has been determined for the North Sea (LLF = 40 cm). However, demersal communities reflect differences in their composition and structure across environments, habitat conditions, and latitudinal gradients (Fisher *et al.*, 2010). As a result, LLF values vary in the North Atlantic and have been derived for the CS (LLF = 50 cm) (Shephard *et al.*, 2011), the Bay of Biscay (LLF = 35 cm) (Modica *et al.*, 2014), and the Portuguese Iberian Coast (LLF = 30 cm) (MAMAOT, 2012), using the methodology proposed by Greenstreet *et al.* (2011). All criteria were calculated excluding data from pelagic, pelagic–neritic and pelagic–oceanic species, to reduce the influence of environmental variability and the corresponding effects on pelagic communities' recruitment (Preciado *et al.*, 2019). In addition, since groundfish surveys do not target pelagic communities, data concerning these species are likely to be incomplete and underrepresented.

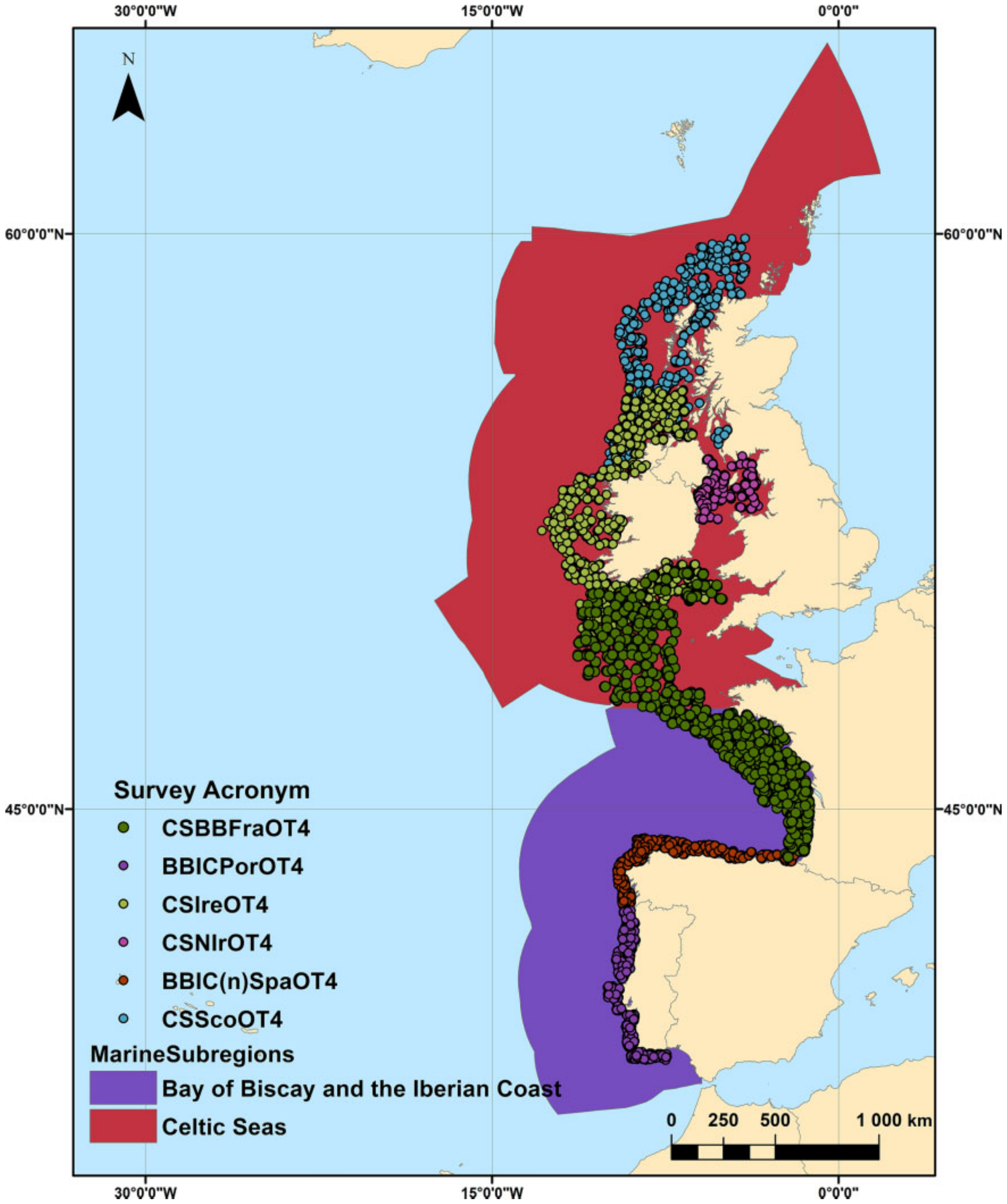

Figure 1. Study area showing the delimitation of the MSFD sub-regions - CS and BBIC -, and the EU MSs groundfish survey coverage, from 2002 to 2014 (Shapefiles and data source: Moriarty *et al.*, 2017; OSPAR, 2017). See Supplementary Table S1 for more details on the survey's acronyms and features.

Considering the MSFD legislation, food web (D4) assessment scales should be defined at the subregion level in the Northeast Atlantic (European Commission, 2017a) and as a result all criteria were assessed separately for the CS and BBIC. Each criterion was estimated for wider- to smaller-sized spatial and temporal scales. The scales selected are presented in Table 1, and their spatial coverage is shown in Supplementary Figures S1 to S4 in Supplementary Material. The spatial scales considered were Marine Subunit (MSU), Sector, Sector/Strata (Sec_Str), ICES rectangles, and equally distributed 1000 km^2 squares and 100 km^2 squares. MSU are spatial areas defined in the MSFD framework that consider MS subdivisions belonging to different subregions (e.g. France includes areas in the North Sea, the CS, and the BBIC subregions). Sectors are geographical subdivisions defined by all MSs to support demersal survey design areas. The combination sector and depth were also analysed, following the stratification used by the demersal groundfish survey (ICES, 2017). However, since MSs defined depth strata ranges differently, these were standardized according with the following depth ranges: (i) coastal (20–100 m), (ii) medium (100–200 m), (iii) deep (200–500 m),

Table 1. Spatial and temporal scales and units used to assess food web criteria in the CS and BBIC subregions (*n*: number of temporal and spatial units tested per scale).

Scope of the analyses	Spatial scales	Spatial units	
		CS	**BBIC**
Wider scale	MSU	CS_Fra, CS_Ire, CS_Sco ($n = 3$)	BBIC_Por, BBIC_Spa, BBIC_Fra ($n = 3$)
	Sector (country-level demarcations)	East Irish Sea, Irish Coast, . . ., VIIb, windsock_lam ($n = 22$)	Cn, Cc, Cs, . . ., SAG, POR, VSA ($n = 20$)
	Sector/Strata [1 - coastal (20–100 m); 2 - medium (100–200 m); 3 - deep (200–500 m); 4 - slope (>500 m)]	VIa1, VIa2, VIa3, VIIb1, . . ., Cc2, Cn2, Cc4, Cs4 ($n = 35$)	Gs1, Gs2, Gs3, Gs4, Gn1, Gn2, Gn3, Gn4, . . ., VSA1, VSA2, VSA3 ($n = 56$)
	ICES rectangles[1]	48E5, 48E4, 47E5, 47E4, . . ., 26D9, 25E3, 25E2, 25E1, 25E0 ($n = 110$)[1]	24E6, 24E5, 24E4, . . ., 04E0, 03E1, 03E0, 02E2, 02E1 ($n = 65$) [1]
	1 000-km^2 squares	298, 299, 301, 302, . . ., 3 440, 3 441, 3 442 ($n = 551$)	3 443, 3 446, 3 485, . . ., 5 824, 5 826, 5 827 ($n = 298$)
Smaller scale	100 km^2 squares	57 182, 56 899, 56 898, . . ., 25 193, 25 192, 25 058 ($n = 1\ 068$)	25 499, 25 357, 25 073, . . ., 1 044, 1 043, 918 ($n = 772$)
	Temporal scales	**Temporal units**	
Wider scale	5 years	2002–2008, 2009–2014 ($n = 2$)	2002–2008, 2009–2014 ($n = 2$)
	3 years	2005–2007, 2008–2010, 2011–2014 ($n = 3$)	2005–2007, 2008–2010, 2011–2014 ($n = 3$)
	2 years	2002–2005, 2006–2007, 2008–2009, 2010–2011, 2013–2014 ($n = 5$)	2002–2005, 2006–2007, 2008–2009, 2010–2011, 2013–2014 ($n = 5$)
Smaller scale	Year	2002, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2013, 2014 ($n = 10$)	2002, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2013, 2014 ($n = 10$)

[1] See further explanation on ICES rectangles nomenclature here: https://www.ices.dk/data/maps/Pages/ICES-statistical-rectangles.aspx, last accessed 20 of June 2020.

and (iv) slope (>500 m). ICES rectangles were used since they serve as a basis for sampling stratification in some areas of the NE Atlantic Area (ranging between ≈7000 and 12 000 km^2). An artificial grid of 1000 and 100 km^2 rectangles was applied to the survey area and used as spatial assessment units. The temporal scales considered yearly datasets, and the aggregation of yearly data into 5-year datasets, 3-year datasets, and 2-year datasets. The temporal span was limited to the MSs with the shortest time series, between 2002 and 2014. For each spatial and temporal unit, the estimated biomass index was only considered when a minimum of two tows were conducted. The analysis of temporal and spatial scales was made independently for each criterion and scale analysis.

Model selection

GAMs were employed to explore how each spatial and temporal scale contributed to explain ecological criteria and its corresponding residuals. GAMs are powerful tools for exploring linear or non-linear response of variables to predictors without being constrained to an underlying parametric model of a specific form, which is particularly useful when ecological thresholds of non-linear responses are of interest (Wood, 2006). Each scale was used as a model predictor and criteria estimates were the response variables. As a result, a model was built per spatial and per temporal scale for each ecosystem criterion. Environmental variables, such as depth and temperature, were added identically to each model as explanatory variables. These variables are known to contribute widely to the existing variability of demersal communities, therefore including them in the model allowed to identify their contribution to the overall variability and to distinguish it from the variability obtained due to the scales tested (Pranovi *et al.*, 2016; Preciado *et al.*, 2019). Depth was available for each trawl surveyed, and the average temperature for Q4 was obtained using EU Copernicus Marine Service Information with a spatial resolution of 0.04 × 0.04 degrees. Spatial and temporal scales were parametric, and all environmental variables were continuous and were included as a smoothed variable in the model. The Gamma distribution was used for all analyses since all response variables were continuous, had positive values, and were slightly skewed, and the log identity link has been assumed (Zuur *et al.*, 2009). The full GAMs for all the food web indexes were the following:

$$\begin{aligned}&\mathrm{MTL},\ \mathrm{MTL}_{\_3.25},\ \mathrm{MTL}_{\_4}\ \mathrm{LFI\ or\ MATG}\\ &\sim\ \beta_0 +\ f(\mathrm{scale}) + s(\mathrm{temp}) + s(\mathrm{dep}) + \varepsilon,\end{aligned}$$

where MTL, MTL$_{\_3.25}$, MTL$_{\_4}$, LFI, and MATG are the food web criteria; β_0 is the intercept; f indicates the variables that were included as factors in the formula (i.e. each spatial and temporal scale); s is the spline smoother; and ε is the error term; scale represents the different spatial and temporal scales under test, temp is the temperature, and dep is the depth. To compare the performance of each spatial and temporal scale in predicting food web criteria, models with increasing complexity of scales were compared through the relative deviance explained by each model, and its corresponding Akaike's information criteria (AIC). ANOVA F-ratio test was also used to verify if smaller-sized scales contributed significantly to explain deviance. The dataset used in each GAM was independent for all criteria. Afterwards, the most adequate spatial and temporal scales for each criterion were combined into a final GAM, to understand how each predictor influences ecosystem criteria. In addition, p-values based on an ANOVA F-ratio test were used to evaluate the significance of each predictor assessed. Prior to any analysis, the correlation between explanatory variables was tested for collinearity among all variables through pairwise correlation coefficient (r) and Variance Inflation Factor (VIF). A mild negative collinearity was found between smaller-sized spatial scales and temperature for a few models (e.g. $r \approx -0.5$ and VIF < 4). However, since models were not used to make predictions, which is the step where collinearity can have stronger effects (e.g. loss of predictive accuracy) and GAMs can perform relatively well in medium collinearity (Dormann *et al*., 2013), both predictors were considered in the models, to avoid losing relevant information. Data normality and homogeneity of variances were verified through Shapiro–Wilk's test and Bartlett test, respectively. When data were not normal, criteria were transformed. All statistical analyses were performed using R software (R Core Team, 2019), using the package "mgcv" to construct GAMs (Wood, 2011).

Effects of scales on the GES assessment—a case study for the Portuguese continental shelf

Using the scales identified in the previous section for the BBIC subregion, food web criteria were assessed and compared against MSFD results for the Portuguese continental shelf, to understand if spatial and temporal scales have the effect on D4 assessment status. Portuguese authorities assessed food web criteria in the first and second MSFD cycles, but the metrics and methods used differed. In the first report, only MTL and LFI were implemented, while in the second, MTL, $MTL\_{3.25}$, MTL_{4}, and LFI were reported. The comparisons made in this work were limited to MTL, $MTL\_{3.25}$, MTL_{4}, and LFI, since these were reported in the most recent assessment. In both reports, food web criteria were assessed considering the continental platform subdivisions that correspond to three spatial units: (i) from Caminha to Peniche, (ii) from Peniche to Lagos, and (iii) from Lagos to Vila Real de St° António; and yearly datasets, from 1989 to 2017 (MAMAOT, 2012; Ministério do Mar, 2020). To establish GES, a statistical trend analysis was applied to the time series of each assessment unit of MTL, $MTL\_{3.25}$, MTL_{4}, and LFI. If the temporal trend was non-significant or if it was significantly increasing, the criteria were considered in GES. If the temporal trend exhibited a significant decrease, it was considered below GES. The statistical trend was investigated through the non-parametric Mann-Kendall test that was applied to each criterion and spatial unit of assessment. This test does not require datasets to be normally distributed and is frequently used to assess environmental and biological data to distinguish consistent trends from environmental variability. In the second report, all food web criteria assessed were in GES (see Supplementary Table S2) (Ministério do Mar, 2020).

Results

Identifying scales for food web criteria assessment in the North Atlantic subregions

CS

MTL

GAM comparison revealed that the best model to explain MTL included 100 km^2 spatial units as predictor, explaining 77.0% of the variance. The temporal model that best suited MTL included year as temporal scale and explained 33.2% of the variance (Table 2a). Although the GAMs showed that 100 km^2 spatial units per year were the most adequate scales, when downsizing the analysis in the final model, the number of spatial units that included two trawls per spatial and temporal unit was extremely low. As a result, the final GAM included 1000 km^2 units and year as scales, together with temperature and depth. The final model explained 61.6% of the variance and all predictor variables had a significant effect (Table 3). MTL increased widely from shallow areas to 100 m of depth; it varied irregularly between 100 and 500 m of depth and decreased abruptly in deeper waters. MTL spatial distribution patterns varied irregularly. Year analysis showed that MTL peaked in 2002 and decreased abruptly after that until 2006. Afterwards, MTL increased and two additional peaks were found, one in 2008 and a second in 2013 (Figure 2a).

$MTL\_{3.25}$

AIC analysis revealed that the most suitable model to assess $MTL\_{3.25}$, included Sector/Strata spatial scale, and explained 7.0% of the variance. Concerning temporal scales, AIC analysis showed that the best temporal model included 3-year spatial units and explained 5.3% of existing variance (Table 2a). The final model included Sector/Strata, 3 years, temperature, and depth as variables and explained 7.7% of existing deviance (Table 3). All variables were significant, except for temperature: $MTL\_{3.25}$ was low in shallow depths and increased with depth until 80 m. After 100 m, $MTL\_{3.25}$ decreased rapidly until 150 m, increasing irregularly until 500 m of depth. $MTL\_{3.25}$ for spatial scales was very irregular. $MTL\_{3.25}$ peaked in 2002, decreasing afterwards (Figure 2b).

MTL_{4}

The spatial model presenting lowest AIC values included ICES rectangles as a spatial scale and explained 20.6% of the variance. AIC analysis of temporal models revealed that the best-performing model used year as temporal scale and explained 9.1% of the variance (Table 2a). In the CS region, the final GAM for MTL_{4} included ICES units, year, temperature, and depth as predictor variables and explained 22.5% of deviance (Table 3). All variables had a significant effect. MTL_{4} decreased significantly with temperature. In relation to depth, MTL_{4}, increased steadily until 300 m of depth and stabilized. ICES units at higher latitude had lower MTL_{4} patterns. MTL_{4} was highest in 2002, decreasing throughout the time series until 2008 and gradually increasing until the end of the time series (Figure 2c).

LFI

The spatial scale model showing the lowest AIC results included 1000 km^2 as assessment scale and explained 47.4% of the variance. The model using year as temporal scale presented the lowest AIC and explained 5.7% of the variance (Table 2a). The final model used 1000 km^2 and year as spatial and temporal scales, in addition to the overall predictors, and explained as much 45.5% of the variance (Table 3). All variables had a significant effect except temperature. LFI increased significantly with depth. The 1000 km^2 analysis revealed that squares exhibited lower LFI values. Year analysis revealed that LFI was higher in 2006 and 2011 and lower in 2002 and 2010 (Figure 2d).

MATG

For MATG, spatial scale models explained low values of deviance. AIC comparison showed that including spatial scales in the model did not improve the model adequacy. However, ANOVA test showed that including MSU spatial scale significantly explained deviance. Temporal scales did not contribute to decrease AIC and did not explain existing deviance (Table 2a). As a result, the final

Table 2. Model selection parameters for food web criteria (MTL, MTL_3.25, MTL_4, LFI, MATG) using the spatial and temporal scales identified in the assessment (see Table 1) for the (a) CS and (b) BBIC subregions.

	MTL			MIT_3.25			MTL_4			LFI			MATG		
Food web criterion	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)
(a) CS															
Spatial scale model															
Criterion ∼ s(temp) + s(depth)	−1 946.90	0.29	29.6	913.25	0.07	4.8	3 459.85	0.11	7.0	−1 508.30	0.04	3.9	**2 096.94**	**0.00**	**0.2**
Criterion ∼ MSU + s(temp) + s(depth)	−1 962.71	0.29	30.3	914.97	0.07	4.8	3 461.45	0.11	7.1	−1 522.98	0.05	4.3	**2 099.34**	**0.00**	**0.2**
Criterion ∼ Sector + s(temp) + s(depth)	−2 008.54	0.34	36.3	907.56	0.09	6.3	3 296.29	0.19	13.8	−1 803.87	0.13	12.4	2 125.09	0.00	0.3
Criterion ∼ Sec_Str + s(temp) + s(depth)	−2 029.08	0.37	39.7	**899.94**	**0.10**	**7.0**	3 297.73	0.20	14.6	−1 718.33	0.17	16.2	2 145.16	0.00	0.3
Criterion ∼ ICES + s(temp) + s(depth)	−2 080.64	0.44	49.9	918.25	0.14	15.1	**3 252.98**	**0.24**	**20.6**	−2 025.43	0.30	27.3	2 282.87	−0.01	0.4
Criterion∼ 1 000 km^2 + s(temp) + s(depth)	−2 099.11	0.49	59.1	1 170.67	0.22	25.5	3 414.40	0.33	35.2	**−2 158.16**	**0.44**	**47.4**	2 935.49	−0.04	0.8
Criterion ∼ 100 km^2 + s(temp) + s(depth)	**−2 113.72**	**0.57**	**77.0**	1 322.65	0.25	33.2	3 452.31	0.37	44.4	−2 054.05	0.45	53.5	3 350.51	−0.06	1.0
Temporal scale model															
Criterion∼ s(temp) + s(depth)	−1 946.90	0.29	29.6	3 916.83	0.07	4.8	3 459.85	0.11	7.0	−1 508.30	0.04	3.9	**2 096.94**	**0.00**	**0.2**
Criterion ∼ 5_year + s(temp) + s(depth)	−1 947.98	0.30	30.6	3 918.28	0.07	4.9	3 461.84	0.11	7.0	−1 515.20	0.05	4.2	2 098.93	0.00	0.2
Criterion ∼ 3_year + s(temp) + s(depth)	−1 960.74	0.31	31.7	**3 870.67**	**0.08**	**5.3**	**3 417.98**	**0.13**	**8.9**	−1 543.27	0.06	5.3	2 102.42	0.00	0.2
Criterion ∼ 2_year + s(temp) + s(depth)	−1 977.70	0.32	32.4	3 887.99	0.08	5.3	3 436.59	0.12	8.1	−1 531.16	0.06	4.9	2 104.69	0.00	0.2
Criterion ∼ year + s(temp) + s(depth)	**−1 982.58**	**0.33**	**33.2**	3 876.17	0.08	5.4	**3 423.70**	**0.13**	**9.1**	**−1 545.85**	**0.06**	**5.7**	2 113.25	0.00	0.2
(b) BBIC															
Spatial scale model															
Criterion ∼ s(temp) + s(depth)	−2 392.29	0.10	10.2	−282.80	0.05	3.3	612.55	0.12	8.4	−593.44	0.17	12.8	2 154.52	0.00	0.2
Criterion ∼ MSU + s(temp) + s(depth)	−3 171.02	0.35	35.5	−282.00	0.05	3.5	531.17	0.15	10.8	−596.14	0.17	13.1	**2 145.93**	**0.01**	**0.4**
Criterion ∼ Sector + s(temp) + s(depth)	−3 589.64	0.46	46.6	−356.70	0.12	8.4	409.93	0.22	16.5	−872.56	0.27	22.7	2 163.07	0.01	0.5
Criterion ∼ Sec_Str+ s(temp) + s(depth)	−3 954.33	0.51	52.7	−370.85	0.19	14.8	**160.40**	**0.31**	**26.0**	**−1 001.41**	**0.33**	**28.4**	2 214.81	0.00	0.7
Criterion ∼ ICES + s(temp) + s(depth)	−3 718.86	0.46	48.5	−412.32	0.22	17.0	215.22	0.30	26.6	−925.59	0.31	26.8	2 235.60	0.00	0.7
	−4 020.90	0.55	59.0	−461.65	0.34	31.7	168.19	0.38	38.0	−876.85	0.37	36.1	2 594.31	−0.01	1.0

Continued

Table 2. continued

Food web criterion	MTL			MIT_3.25			MTL_4			LFI			MATG		
	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)	AIC	R2	Explained deviance (%)
Criterion ~ 1 000 km^2 + s(temp) + s(depth)															
Criterion ~100 km^2 + s(temp) + (depth)	−4 073.02	0.62	72.6	−528.34	0.38	39.2	230.56	0.45	48.5	−830.81	0.42	47.6	3 092.53	−0.04	1.6
Temporal scale model															
Criterion ~ s(temp) + s(depth)	−2 392.29	0.10	10.2	−282.80	0.05	3.3	4 085.84	0.12	8.4	−593.44	0.17	12.8	2 154.52	0.00	0.2
Criterion ~ 5_year + s(temp) + s(depth)	−2 406.00	0.10	10.8	−282.87	0.05	3.4	4 079.97	0.12	8.7	−591.58	0.17	12.8	2 156.47	0.00	0.2
Criterion ~ 3_year + s(temp) + s(depth)	−2 426.24	0.11	11.6	−278.02	0.05	3.4	4 081.30	0.12	8.8	−619.68	0.18	13.9	2 159.29	0.00	0.3
Criterion ~ 2_year + s(temp) + s(depth)	−2 421.44	0.11	11.6	−277.05	0.05	3.4	4 086.68	0.12	8.7	−629.37	0.19	14.3	2 161.78	0.00	0.2
Criterion ~ year + s(temp) + s(depth)	−2 463.92	0.12	13.4	−269.22	0.05	3.5	4 069.96	0.13	9.6	−693.27	0.31	25.8	2 170.36	0.00	0.3

Deviance explained and AIC are given. The models with large values for deviance explained and small values for AIC are underlined, showing the best models. s is the function to set up the model using spline-based smooths.

model for MATG included MSU, temperature, and depth. The model explained 0.2% of the variance, but only depth had a significant effect on MATG (Table 3). MATG decreased significantly with depth (Figure 2e).

BBIC

MTL

AIC analysis revealed that the best model to explain MTL included 100 km^2 as spatial scale and explained 72.6% of deviance. The most adequate temporal model included year temporal units and explained 13.4% of deviance (Table 2b). Although GAMs showed that 100 km^2 spatial units were the most adequate, when downsizing the analysis in the final model, the number of trawls per spatial and temporal unit was lower than two for most 100 km^2 units. As a result, the final GAM for MTL in BBIC included 1000 km^2, year, depth, and temperature as variables and explained 60.8% of the variance. All variables had significant effects (Table 3). MTL increased irregularly with temperature. As for depth, MTL presented low values at shallow depths, increasing steeply until 100 m of depth, where it stabilized. Spatial scale had a strong effect and spatial unit at the North of Spain and South of Portugal presented higher estimates. MTL lowest value was registered in 2006, increasing afterwards until 2009–2010, and decreasing until the end of the time series (Figure 3a).

MTL$_{\_3.25}$

AIC analysis revealed that the most suitable model used 100 km^2 as spatial units, explaining 39.2% of the variance. The most suitable temporal model included a 5-year dataset as predictor, explaining 3.4% of the variance (Table 2b). The final model for MTL$_{\_3.25}$ included 1000 km^2, 5 years, depth, and temperature as predictors and explained 29.8% of deviance. Significant effects were found for 1000 km^2 spatial units, temperature, and depth (Table 3). MTL$_{\_3.25}$ increased with temperature until 15°C and then stabilized. At temperatures >18°C, MTL$_{\_3.25}$ decreased. MTL$_{\_3.25}$ increased non-linearly with depth: increasing until 100 m, stabilizing between 100 and 300 m, and increasing again between 300 and 600 m. The 1000 km^2 unit's variability was higher in Northern units and in the South of the Portuguese peninsula (Figure 3b).

MTL$_{\_4}$

The model presenting lowest AIC values included Sector/Strata as a spatial scale and explained 26.0% of the variance. As for temporal scales, the best-performing model included year as scale and explained 9.6% of the variance (Table 2b). As a result, the final MTL$_{\_4}$ model included Sector/Strata, year, temperature, and depth as independent variables, explaining 23.9% of the variance—all variables had a significant effect (Table 3). MTL$_{\_4}$ increased with temperature until 17°C, decreasing steeply until the maximum temperature registered. As for depth, MTL$_{\_4}$ increased until 200 m, stabilizing between 200 and 400 m of depth. Spatial units revealed highly variable patterns. MTL$_{\_4}$ was particularly variable in coastal units (20–100 m), while in medium and deeper unit's variability was lower. Year analysis revealed that MTL$_{\_4}$ decreased markedly in 2006, increased in 2009, and increased again until 2013 (Figure 3c).

LFI

The spatial scale model showing lower AIC results included Sector/Strata units as assessment scale, explaining 28.4% of the variance. The most appropriate temporal model used yearly data and explained 25.8% of the variance (Table 2b). The final LFI

Table 3. Results of the final GAMs performed for food web criteria (MTL, MTL_$_{3.25}$, MTL_$_4$, LFI, MATG) using the scales identified in the assessment for the CS and BBIC subregions.

CS	*df*/edf	*F*	*p*-Value	BBIC	*df*/edf	*F*	*p*-Value
MTL (deviance explained: 61.6%)				MTL (deviance explained: 60.8%)			
1 000 km^2	153	3.159	<0.001	1 000 km^2	129	14.29	<0.001
Year	9	4.782	<0.001	Year	9	7.89	<0.001
s(temp)	1.000	0.426	0.514	*s*(temp)	7.249	2.987	0.002
s(depth)	8.438	8.990	<0.001	*s*(depth)	7.937	29.647	<0.001
MTL_$_{3.25}$ (deviance explained: 7.65%)				MTL_$_{3.25}$ (deviance explained: 29.8%)			
Sec_Str	34	4.815	<0.001	1 000 km^2	246	5.573	<0.001
3_year	3	4.926	0.002	5_year	1	3.674	0.055
s(temp)	1.002	2.760	0.601	*s*(temp)	6.336	2.323	0.018
s(depth)	6.804	2.995	2.494	*s*(depth)	3.785	7.240	<0.001
MTL_$_4$ (deviance explained: 22.5%)				MTL_$_4$ (deviance explained: 23.9%)			
ICES	110	8.074	<0.001	Sec_Str	52	14.356	<0.001
Year	9	12.198	<0.001	Year	9	5.722	<0.001
s(temp)	1.001	19.81	<0.001	*s*(temp)	3.849	13.85	<0.001
s(depth)	4.488	19.98	<0.001	*s*(depth)	5.167	24.02	<0.001
LFI (deviance explained: 45.5%)				LFI (deviance explained: 30.9%)			
1 000 km^2	145	3.541	<0.001	Sec_Str	52	12.16	<0.001
Year	9	2.366	0.013	Year	9	17.19	<0.001
s(temp)	1.370	0.485	0.678	*s*(temp)	3.114	1.735	0.141
s(depth)	1.000	11.383	0.001	*s*(depth)	6.244	28.525	<0.001
MATG (deviance explained: 0.17% %)				MATG (deviance explained: 0.37%)			
MSU	2	1.288	0.276	MSU	2	7.96	<0.001
s(temp)	1.590	0.411	0.636	*s*(temp)	1.047	12.681	<0.001
s(depth)	1.701	8.152	<0.001	*s*(depth)	3.633	4.562	0.001

Degrees of freedom (df), deviance explained (%), and statistical significance of the explanatory variables of each GAM are shown. *s* is the function to set up the model using spline-based smooths.

model included Sector/Strata and year as scales and explained 30.9% of the variance. Spatial and temporal scales and depth significantly influenced LFI estimates (Table 3). LFI increased abruptly with depth until 100 m. It decreased steeply between 100 and 300 m and increased again abruptly until 500 m of depth. Sector/Strata units revealed high variability but no clear pattern. Year analysis showed that LFI peaked in 2002 and 2006 and that its lowest value was registered in 2008 (Figure 3d).

MATG

For MATG, spatial scale models explained low values of deviance. AIC comparison showed that using MSU as assessment units improved model adequacy, explaining 0.4% of the variance. Temporal scales did not contribute to decrease models AIC (Table 2b). The final GAM for MATG included MSU, temperature, and depth as independent variables and explained 0.4% of the variance. All variables were significant (Table 3). MATG decreased linearly with temperature and decreased with depth; however, it showed an irregular pattern: increasing until 100 m, stabilizing until 400 m, and in deeper waters, from 400 m onwards, MATG exhibited an increasing trend. MATG was lowest in the French subunit and highest in the Portuguese subunit (Figure 3e).

Effects of scales on the MSFD implementation—Portuguese continental waters case study

MTL, MTL_$_{3.25}$, MTL_$_4$, and LFI were estimated using the scales identified in the previous section, for the BBIC subregion. Since the most appropriate temporal scale for MTL_$_{3.25}$ was wider (i.e. 5 years instead of an annual time series), the Mann-Kendall test was not applicable. As an alternative, a *t*-test comparison was made between MTL_$_{3.25}$ estimates for the first 5 years of the time series—considered as the reference period—and the last 5 years of the time series—considered as the assessment period. If the *t*-test was significant and the criterion average decreased, it was considered below GES. If results were non-significant or significantly increasing, the criterion was considered in GES.

Assessment for D4 criteria showed that food webs were not in a good status in all areas of the Portuguese continental waters. MTL estimates, using 1000 km^2 and year scales, demonstrated that for most units the time series were stable or had a significantly increasing trend. However, in the South region of Algarve—at intermediate and deep waters off Vila Real de S^{to} Antonio—the time series for the spatial unit 5285 were significantly decreasing (Figure 4a, Supplementary Table S3). MTL_$_{3.25}$ was calculated using 1000 km^2 and 5-year scales, and although most spatial units presented non-significant or significantly increasing values, the *t*-test revealed a significant decrease in MTL_$_{3.25}$ in the 5685 spatial unit. The unit is located in the Southwest coast of Portugal, offshore V. N. Milfontes (Figure 4b, Supplementary Table S4). MTL_$_4$ was estimated using Sector/Strata and year scales, and the Mann-Kendell analysis revealed that all Sector/Strata time series were stable or increasing, except for the ARR2 area, where the time series exhibited a significant decrease. ARR2 is located at intermediary depths off Arrifana, on the SW of Portugal (Figure 5a, Supplementary Table S5). LFI was estimated for Sector/Strata and year scales. Results for the Mann-Kendell test showed that, in the South region, the time series for POR1 and VIG3 were significantly decreasing. These units locate in the coastal waters of Portimão, between 20 and 100 m, and offshore Vila Real de S^{to} Antonio, between 200 and 500 m of depth (Figure 5b, Supplementary Table S6).

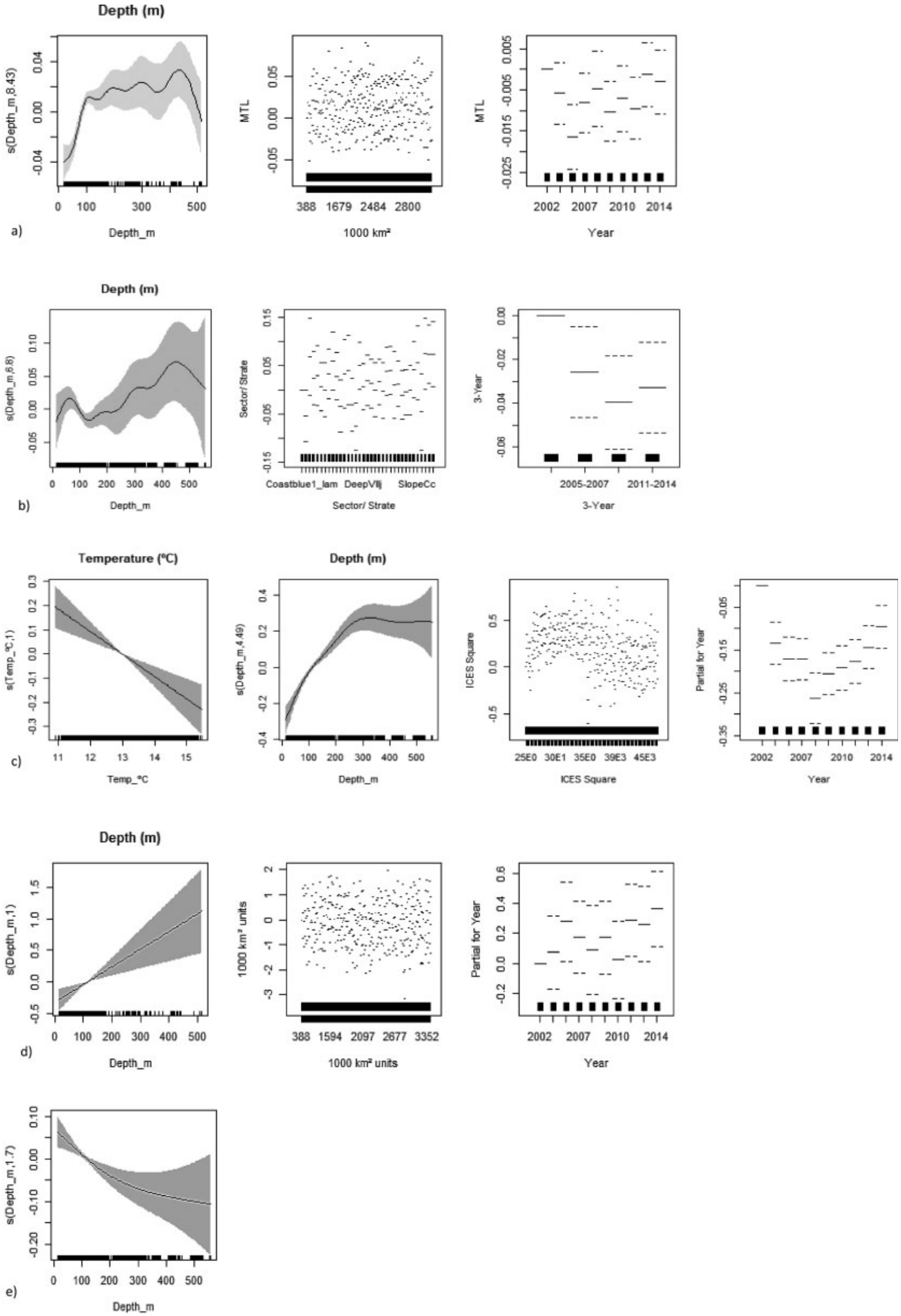

Figure 2. GAM outputs using spatial scale, temporal scale, and smoothed temperature and depth as explanatory variables of changes observed for food web criteria in the CS subregion: (a) partial effects of depth, spatial scale (1000 km^2) and temporal scale (year) as explanatory variables of MTL; (b) partial effects of depth, spatial scale (Sector/Strata) and temporal scale (3 years) as explanatory variables of MTL_3.25; (c) partial effects of temperature, depth, spatial scale (ICES rectangles), and temporal scale (year) as explanatory variables of MTL_4; (d) partial effects of depth, spatial scale (1000 km^2) and temporal scale (year) as explanatory variables of LFI; and (e) partial effects of depth as explanatory variable of MATG. Only significant variables are shown. The dashed lines give the standard errors around the parametric variables and the grey bands show 95% confidence intervals.

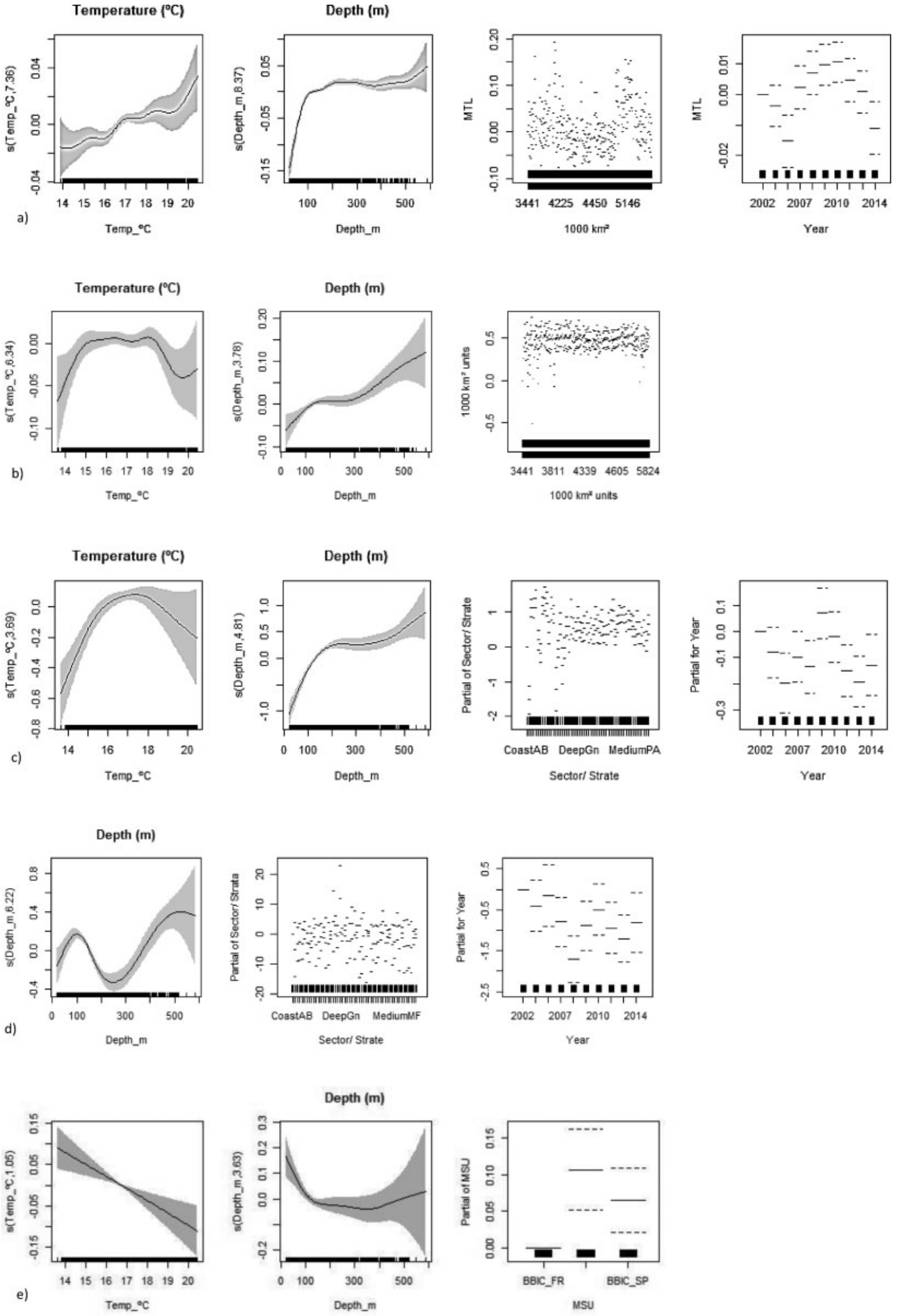

Figure 3. GAM outputs using spatial scale, temporal scale, and smoothed temperature and depth as explanatory variables of changes observed for food web criteria in the BBIC subregion: (a) partial effects of temperature, depth spatial scale (1000 km^2) and temporal scale (year) as explanatory variables of MTL; (b) partial effects of temperature, depth, and spatial scale (1000 km^2) as explanatory variables of MTL$_{\_3.25}$; (c) partial effects of temperature, depth, spatial scale (Sector/Strata) and temporal scale (year) as explanatory variables of MTL$_{\_4}$; (d) partial effects of depth spatial scale (Sector/Strata) and temporal scale (year) as explanatory variables of LFI; and (e) partial effects of temperature, depth, and spatial scale (MSU) as explanatory variables of MATG. Only significant variables are shown. The dashed lines give the standard errors around the parametric variables and the grey bands show 95% confidence intervals.

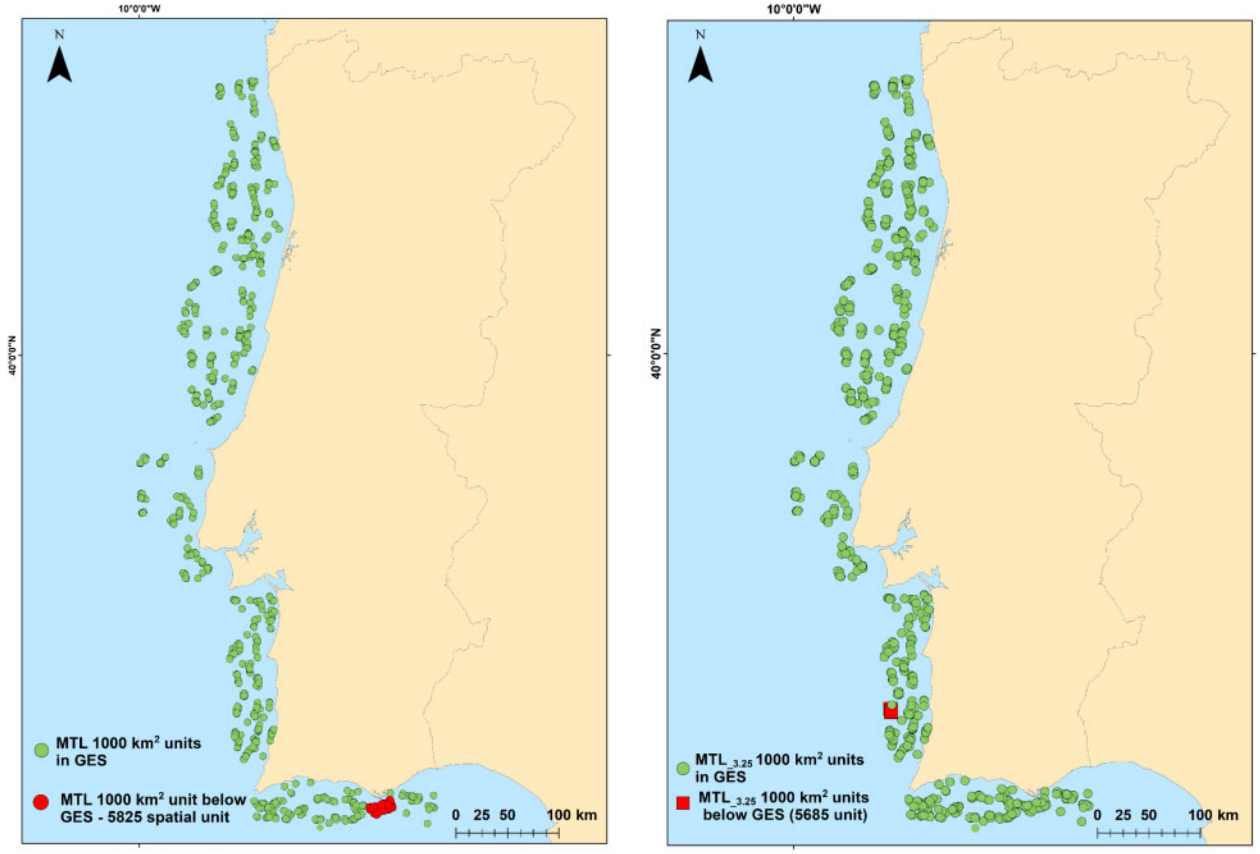

Figure 4. GES assessment status for food web criteria in the Portuguese continental waters: (a) MTL assessment using 1000 km^2 spatial units and year as temporal units and (b) MTL$_{\_3.25}$ assessment using 1000 km^2 spatial units and 5 years as temporal units. Information is shown per haul. Green—spatial units in GES; red—spatial unit below GES.

Discussion

Indicators are determinant to evaluate environmental status, to define management objectives and to establish measures that maintain healthy marine ecosystems (European Commission, 2008). Few studies have addressed scale effects on marine communities indexes and are mostly focused on coastal ecosystems, specific taxa, and a scarce number of dimensions (e.g. one or two scales), in an attempt to model the relation of spatial scales with human pressures, environmental variables, and their impact on indicators (Pranovi *et al.*, 2016). By addressing a widespread number of scales across two geographical areas of the NE Atlantic, the present study isolated the effects of each scale and identified the scales that most adequately explained significant patterns of food web criteria in the CS and in the BBIC.

This study revealed that spatial scales had wider effects than temporal scales in explaining all food web criteria, for the two subregions. In fact, downsizing spatial scales of models allowed to identify significant community patterns for all criteria studied. In stable marine environments, studies contrasting spatial variability and temporal variability showed that spatial variability, arising from habitat heterogeneity, is greater than temporal variability, resulting from temporal fluctuations due to temperature, nutrients, and pollution, well buffered in the marine environment (Barnard and Strong, 2014). In the Baltic Sea, interannual variation has been considered residual when compared to spatial variation, explained by habitat heterogeneity and natural local/regional environmental patterns, such as temperature, depth (Bergström *et al.*, 2016). Similar results were found for the North Sea, where ICES spatial rectangles presented a range of temperature of ~4°C, while yearly temporal scales presented a range of ~0.8°C (Thompson *et al.*, 2020). Such results suggest that depicting spatial areas of inference may improve results further than increasing resampling the same locations (Bergström *et al.*, 2016; Östman *et al.*, 2017). However, the differences found in the present work can also be a consequence of a higher number of spatial scales being tested when compared to temporal ones.

The most appropriate scales identified for each criterion differed between CS and BBIC, except for MTL, which required similar-sized spatial scales in both subregions, 100 km^2 units, and 1 year. Although downsizing the assessment to 100 km^2 spatial units could significantly improve the variance explained, it had implications on the quality of the assessment, since the spatial units that have the minimum number of samples required for the analysis were low. As a result, the immediately upper spatial scale was used—1000 km^2 square units. Similarly, previous studies of MTL in the Bay of Biscay revealed that small-scale resolution was crucial to investigating heterogeneous pressures, such as fisheries impacts on benthic and demersal communities (Arroyo *et al.*, 2019; Preciado *et al.*, 2019). This criterion includes all TL that can contribute to its extensive variability and likely explains that

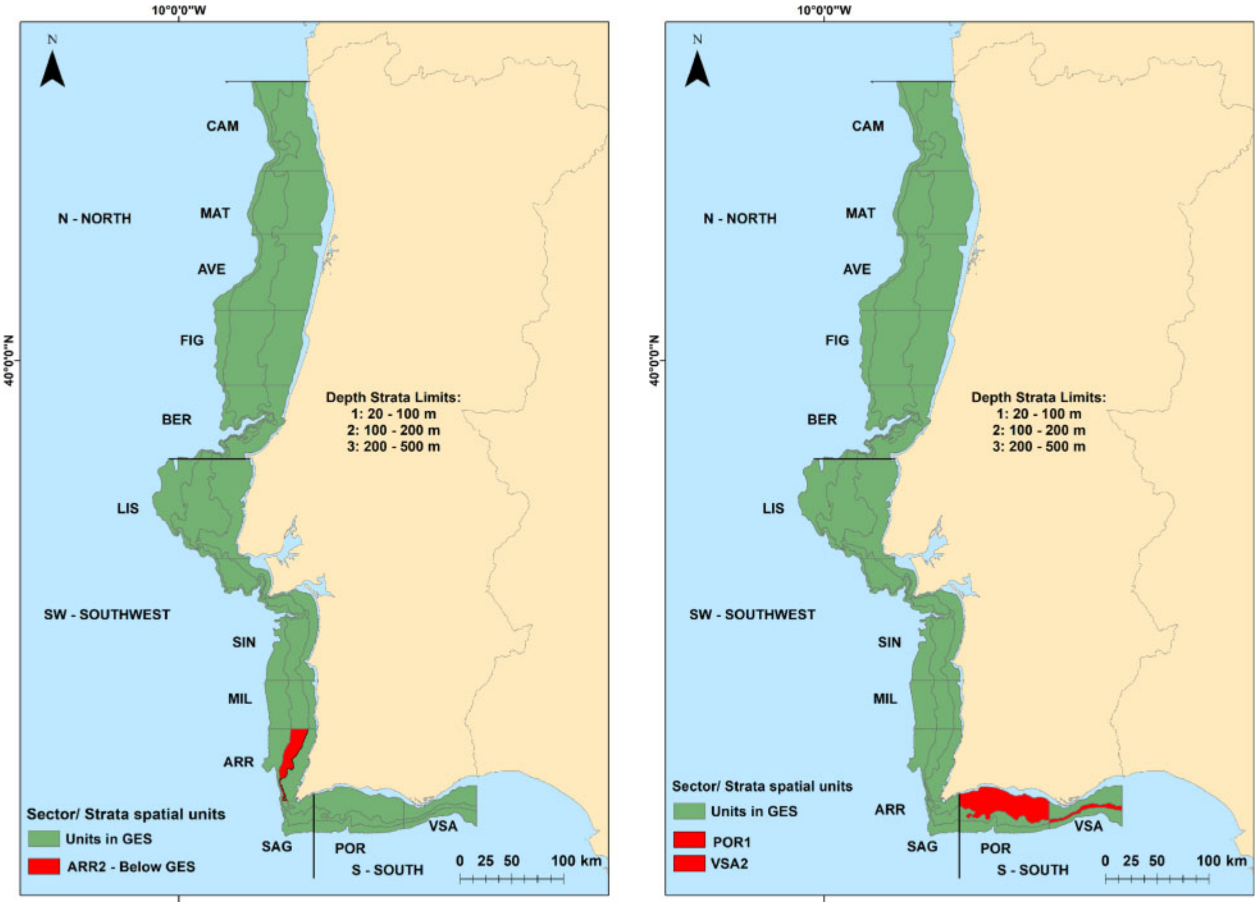

Figure 5. GES assessment status for food web criteria in the Portuguese continental waters: (a) MTL_$_{4}$ assessment using Sector/Strata and year as spatial and temporal scales and (b) LFI assessment using Sector/Strata and year as spatial and temporal scales. Green—spatial units in GES; red—spatial unit below GES.

small-sized scales were required to explain existing deviance. Furthermore, although TL values are available in online databases (e.g. www.fishbase.org), these are worldwide averages based on data from different ecosystems and may not reflect the characteristics of a given region. Mean TL values, averaged over time and area, may conceal high TL variability associated with food web dynamics (Greenstreet, 1997), environmental variation or human pressures (Pinnegar *et al.*, 2002; Chassot *et al.*, 2008; Vinagre *et al.*, 2012), and ontogenetic changes (Shannon *et al.*, 2014; Thompson *et al.*, 2020). Nevertheless, when calculated with MTL_$_{3.25}$ and MTL_$_{4}$, MTL can provide a ratio between TL limits for consumers (MTL), secondary consumers (MTL_$_{3.25}$), and predators (MTL_$_{4}$) (Shannon *et al.*, 2014), allowing to identify temporal trends across three TGs. This indicator is associated with the detection of fishing pressure on secondary consumers and top predators, which are targeted by fisheries, creating an effect known as "fishing down the food web" (Pauly and Watson, 2005). Although this indicator was initially designed for application to landing data sources, survey data sources are more encompassing than catch-based data: (i) species sampled depend on survey design and not on market forces, (ii) include non-commercially targeted species, and (iii) often include young stages and pre-recruits. However, they also present limitations, since time series are often short and datasets are restricted to the demersal communities. Furthermore, MTL calculated using survey data is more prone to fluctuations due to lower TL species and to the inclusion of more species than catch-based data (Shannon *et al.*, 2014).

The most appropriate scales to assess MTL_$_{3.25}$ were Sector/Strata and 3 years, in the CS and 1000 km^2 and 5 years in BBIC. In the CS, downsizing scales revealed a significant spatial pattern based on region and depth strata together with a 3-year temporal scale, showing temporal stability. In the BBIC subregion, the most suitable assessment scale for MTL_$_{3.25}$ was 1000 km^2 and 5 years showing that spatial variability was wider, when compared with the CS, while temporal variability was more stable, i.e. yearly time series could be combined into 5-year datasets.

MTL_$_{4}$ assessment required ICES rectangular units and year in the CS, while in BBIC, the most suitable spatial scales were Sector/Strata and year. The most adequate scale in the CS, ICES rectangles, is used for gridding survey data to make simplified analysis and visualization, and amalgamate latitudinal and longitudinal divided areas in rectangles; but the area of rectangles varies across latitude. In the CS subregion, their dimension varies between 12 000 km^2, in the Northernmost units, and 7000 km^2, in the Southernmost units. Still, in this subregion, these units tend to be smaller than the Sector/Strata units, which cover wide areas of the Celtic waters. ICES statistical rectangles have been identified as an appropriate scale of assessment in the North Sea, to assess length-based community indicators. In this region, significant differences were found between LFI results for ICES rectangles (Engelhard *et al.*, 2015; Adams *et al.*, 2017). MTL_4 was higher at lower latitude rectangles [from the Northwest of France (25E0 unit) to the Southeast and Southwest of Ireland (35E0)] in opposition to the Northern units, what may result from local community trends (e.g. environmental factors, lower recruitment) or from higher fishing effort in the Northern areas. In the BBIC subregion, Sector/Strata and year explained higher variability, showing that spatial variability occurs at regionally and bathymetrically defined areas, while temporal scales vary annually. There was lower variability for MTL_4 criterion in this subregion, revealing that spatial scales used in the assessment can be wider when compared with MTL and $MTL_{3.25}$. The decrease in mean TL, in heavily fished ecosystems, was registered by Guénette and Gascuel (2012), using the total landings in the CS and BBIC, from 1950 to 2008. These authors showed that TL declined from 3.75 to 3.52, at a rate of 0.03 TL per decade, and at a steeper rate of 0.08 TL/decade between 1950 and 1970, concluding that a pervasive overexploitation has been occurring over the last 30 years.

To assess LFI criterion, the most adequate scales were 1000 km^2 units and year in the CS, while in BBIC, scales were identical to MTL_4: Sector/Strata and year. In the CS subregion, LFI was explained by finer assessment scales to capture spatial heterogeneity. Small-scale spatial heterogeneity in the CS LFI was observed previously, as LFI values showed positive spatial autocorrelation up to about 40 km, indicating regions of similar fish community size structure that remained stable. In the North Sea, LFI assessment at ICES rectangles level also showed markedly differing trends, probably driven by regional differences in habitat and benthic community (Adams *et al.*, 2017), but these are averaged out at a larger scale. For the BBIC subregion, outputs provided an important implication for management since, assessing communities for higher guilds—predators (i.e. MTL_4 and LFI), revealed consistency regarding the scales identified: sector/strata and year.

MATG was unexplained by scales in both subregions, showing that, for both regions, the most adequate spatial scale was MSU and that temporal scales had no significant effects. The rates of deviance explained were low (between 0.1 and 0.3%), and both spatial and temporal scales had a minor role in explaining deviance. Therefore, when evaluating anthropogenic impacts, MATG assessment should consider other sources of variability that can have a greater role in explaining MATG heterogeneity and analysis should consider each guild separately. In the North Sea, Thompson *et al.* (2020) found seven distinct feeding guilds, related with predator size and habitats. These authors showed that guilds were consistent through time; however, they may aggregate at regional level. Nevertheless, the present work was based on previously established guilds (Beukhof *et al.*, 2019) and did not consider specimens size what can introduce bias. Further limitations can also arise: groundfish surveys are designed with the purpose of sampling commercially exploited fish and shellfish and do not cover all guilds considered relevant in food web assessment. Therefore, some TGs may be underrepresented (i.e. herbivorous, benthivorous, planktivorous). As a result, further research and development should be made considering MATG and monitoring programmes should identify regionally relevant guilds and focus on all considered guilds (ICES, 2015; Walmsley *et al.*, 2017; Thompson *et al.*, 2020).

These results strongly support the idea that spatial scales have to be defined differently for each subregion and through the cooperation of MSs (ICES, 2015; Walmsley *et al.*, 2017). Furthermore, they also highlight the need to consider the population (or a sub-set of the population) targeted by the indicator used, since scales also vary in accordance. Overall, spatial variability patterns were disclosed when spatial assessment scales were downsized. Scales related with regional and depth physical features—Sector/Strata—or with latitudinal and/or equally defined spatial scales, such as ICES rectangles or 1000 km^2 spatial units, significantly improved criteria estimation and detected significant differences at community level. As for temporal scales, even though its effects were significant in most final models, when compared to spatial scales, they had lower influence. Such outputs can be related with the size of the time series available (i.e. 14 years) (Blanchard *et al.*, 2010) or with the lack of seasonal variability in the analysis, which is known to enclose higher ecological variability (Adams *et al.*, 2017). $MTL_{3.25}$ assessment showed that temporal scales could be merged; however, food web assessments are recommended to consider annual averages (i.e. yearly time series) that enclose growth, mortality, and feeding fluxes between food web components and integrate seasonal variability at the lowest TLs. In addition, the use of annual averages allows to address temporal trends to establish the status of communities over time (Blanchard *et al.*, 2010; OSPAR Commission, 2012).

Depth had a relevant role in explaining criteria variability, while temperature was less significant. Food web patterns varied non-linearly with depth that showed high influence in most criteria. Food web criteria were lower at shallow depths (from 20 m to 100–300 m of depth, depending on model), stabilized at intermediate depths, i.e. 200–300 m, and/or increased irregularly in deeper areas. The only exception was for LFI, in the CS, that exhibited a steep decreasing trend. In the North Sea, community trends showed the strongest decline in shallow waters, where high fishing effort occurs, while in the deep area this relationship was not observed (Piet and Jennings, 2005). Similar patterns were found in the Bay of Biscay for trophic indicators, pointing out a different relation with depth in the upper continental slope of this region. However, an increasing trend of fishing effort in deeper waters may lead to a more acute decrease of food web indicators in deeper areas (Preciado *et al.*, 2019). For MTL and MTL, Heymans *et al.* (2014) found that ecosystem traits (i.e. latitude, ocean basins, depth) influence TL of the catch, thus suggesting the need to account for these confounding traits when evaluating fishing indicators and using them as ecosystem indicators. These drivers interact with fishing, making the impacts of various pressures difficult to disentangle and the setting of targets and thresholds even more problematic (Arroyo *et al.*, 2019).

Temperature, on the other hand, exhibited irregular patterns per criterion and subregion. MTL_4 decreased with temperature in the CS. All other criteria were not affected. In BBIC, MTL increased with temperature. $MTL_{3.25}$ and MTL_4 increased with temperature until 18°C and decreased abruptly until 20°C. In the present study, the environmental stability of the Northeast Atlantic, especially in the CS subregion, appeared to be wide and therefore temperature reflected such aspects on the spatial areas surveyed (Barnard and Strong, 2014). Studies in the CS revealed that fishing had a stronger effect than temperature in size-based metrics patterns such as maximum length and time series trends (Blanchard *et al.*, 2005). However, the time series used in the present study may be short to detect differences due to temperature, as historical time series are required to identify such changes. Collinearity between temperature and scales might have decreased the effects of temperature in the analysis, but since no correlation was found between these factors and scales (i.e. the main predictors under study), both variables were kept to ensure that environmentally driven variability was explained. Temperature influence has been registered for the Portuguese coast and Mediterranean, where it had effects on fisheries landings for thermal affinity fish groups along the Portuguese coast (Teixeira *et al.*, 2014) and at FAO spatial level in the Mediterranean (Pranovi *et al.*, 2016). Therefore, it is important to recognize that long-term environmental changes could be impacting overall indicator values because temperature can affect body size (e.g. Fisher *et al.*, 2010) and climate change can alter the depth distribution of species (Dulvy *et al.*, 2008), altering community patterns. Model results obtained in this study support that such effects are more likely to occur in the BBIC subregion, what was confirmed by the level of change in space: the spatial difference in mean annual temperature was ∼3.4°C in the CS, while in BBIC was 5.6°C.

The main findings of the present work suggest that, although long-term monitoring in reference areas is crucial for obtaining a historical baseline (e.g. Pinnegar and Engelhard, 2008), the assessment scales of highly motile marine species would generally gain in adequacy by downsizing the size of spatial assessment units instead of increasing its frequency in time. Such outputs also emphasize the importance of assigning area-specific levels for assessments that can after be aggregated, rather than relying on averaged values for wide areas that can mask local results and have several implications for management (Walmsley *et al.*, 2017). The need for further investigation concerning adequate criteria, metrics, and methods together with assessment scales has been widely acknowledged (MAMAOT, 2012; ICES, 2015; Walmsley *et al.*, 2017). This work used GAMs to ascertain relevant scales for food web criteria estimation, while addressing the role of additional environmental variables. Criteria varied mostly with depth and scales, thus implying that these effects need to be accounted, to disentangle confounding variables, when building models to understand effects of anthropogenic pressures, e.g. fishing pressure (Shin *et al.*, 2010; Heymans *et al.*, 2014). These outputs provide important insights on factors influencing food web assessment, contributing to decrease scales' mismatch in the detection of community patterns and/or anthropogenic effects (e.g. fishing impacts), when using groundfish datasets. The spatial scale at which these specific community indicators reflect changes was previously unknown, and this is an indispensable feature to identify relevant units of assessment and management actions and to organize the spatial network of monitoring programs that can address the environmental status over larger spatial scales (Östman *et al.*, 2017). Spatial management of anthropogenic threats to populations of marine guilds can only be effective where model predictions correctly identify key habitats, distribution patterns, and threat hotspots (Maxwell *et al.*, 2015).

Ideally, future studies should include additional factors, such as taxa/species contribution, or season, to enhance criteria knowledge in the regions of study (Adams *et al.*, 2017). It is worth mentioning that assessments were limited by the data available. The datasets used were retrieved in the framework of the CFP, under the data collection framework surveys, designed to provide scientific information for the stock assessment of species with relevant commercial interest (International Bottom Trawl Surveys), and are not designed for the specific assessment of food web criteria. These surveys are not fully comprehensive, not representing lower TL species (e.g. zooplankton, herbivorous, planktivorous) or even high predators such as seabirds and marine mammals. It is also important to recall that pelagic species were excluded from this study due to underrepresentation. Consequently, the survey-based dataset used here represents a limited information source, given that it is based on a subset of the species present, capturing mostly bento-demersal species. Whenever possible, combining data from different surveys (e.g. pelagic and demersal surveys) in the same ecosystem should be explored (Shannon *et al.*, 2014). Assessments may also be limited by aspects such as differences between vessels and sampling gears used by each MS (Shannon *et al.*, 2014; Moriarty *et al.*, 2019), and by the availability and spatial extent of data for key taxa. Outputs of the present study have also shown that as spatial scales become smaller (e.g. 100 km^2) data quality decreases, as the number of fishing hauls is lower, what can further bias the assessment.

Effects of scale on MSFD assessment for the Portuguese continental waters

The scales identified in the present work revealed distinct food web patterns at a local, regional and depth strata levels, for the Portuguese continental waters. To some extent, these outputs are in agreement with studies made on the Portuguese coast that showed assemblages were associated with depth patterns and with latitude (Moura *et al.*, 2020, and references therein). However, results suggested that further disaggregation of scales may be required, especially for criterion enclosing a wider range of TLs (i.e. MTL and MTL$_{\_3.25}$). Estimating food web criteria, considering the assessment scales identified in this work, revealed that GES was not achieved in specific units for MTL, MTL$_{\_3.25}$, MTL$_{\_4}$, and LFI criteria. MTL and MTL$_{\_3.25}$ analysis revealed that specific spatial assessment units of 1000 km^2 squares were below GES, in the South and Southwest of the Portuguese economic exclusive zone; MTL was below GES at intermediate depths off Vila Real de S^{to} Antonio and MTL$_{\_3.25}$ off V.N. Milfontes; while MTL$_{\_4}$ and LFI exhibited units below threshold, considering Sector/Strata units, in the Southwest and South coast: more precisely, MTL$_{\_4}$ was not in GES at intermediate depths off Arrifana (ARR2), and LFI registered significant decrease in the coast of Portimão (POR1) and offshore V. R. de S^{to} Antonio (VIG3). Decreasing trends identified in the present work may result from specific communities' sensitivity and environmental variability and from anthropogenic pressures such as fishing and nutrient and organic enrichment, which are considered the main pressures exerted in food webs in the BBIC subregion (ICES, 2019). By selectively extracting species, fishing can alter the structure of food webs, species richness, and the predator–prey relation (Piet and Jennings, 2005; ICES, 2019; Preciado *et al.*, 2019). When studying MTL landings for Portugal mainland waters, Baeta *et al.* (2009) showed a decrease at a rate of about 0.005 per year, from 1970 to 2006, highlighting fishing pressure effects on the average TL of the catch. Eigaard *et al.* (2017) showed that, between 2010 and 2012, in the Portuguese Iberian region, the footprint of bottom trawling per unit landings was one of the largest in European waters. In fact, the South area is heavily targeted by the Portuguese demersal fish and the crustacean fishing fleet, which can have an impact at the community level (Ministério do Mar, 2020; Moura *et al.*, 2020). Analysis of the crustacean trawl fishing fleet, using VMS data, revealed that the main trawling pressure is exerted in the South and Southwest Portuguese margins, on muddy and muddy-sand bottoms, between 100 and 700 m water depths. In the North and Central-West coasts, the effort is minor, occurring at shallower waters and across a wider range of habitats. A decrease in landings per unit of effort has also been registered for demersal fish in the SW and S areas (Bueno-Pardo *et al.*, 2017). Despite such effort, it is important to recognize that the Portuguese coast is characterized by variable environmental drivers and is particularly affected by upwelling regimes, which can strongly affect community composition (Moura *et al.*, 2020). Nevertheless, in an attempt to control such effects, pelagic species were removed from the analysis, enabling the detection of fishing effects at higher TLs and on larger and long-lived species (Shannon *et al.*, 2014).

Downsizing the current spatial scale of assessment for the Portuguese continental waters enabled the detection of decreasing trends for food web criteria, providing relevant information for management. The current MSFD assessment report established that food webs in the Portuguese continental waters were in GES, calculating the weighted average for three zones of the Portuguese continental waters: North, Southwest, and South, using a time series between 1989 and 2017 (Ministério do Mar, 2020). However, the results of the present study, using Sector/Strata as assessment scales and survey data from 2002 to 2014, revealed that significant food web patterns existing on the Southwest and South areas may be overlooked if smaller assessment units are not used. Recent studies, in the Portuguese continental waters, have shown that downsizing assessment scales for the fish group within descriptor 1 (biodiversity) revealed a significant biomass index decrease in the S area for ecologically sensitive species (i.e. *Michrochirus variegatus*) (Machado *et al.*, 2020). These results confirm that criteria estimations that result from averaging wide spatial units may fail to reflect regional or locally defined food web patterns related with community specificities or anthropogenic pressures (OSPAR Commission, 2012; Walmsley *et al.*, 2017), which should be taken into consideration when designing monitoring/surveillance programmes to inform management plans and conservation measures. After the assessment, several integration methodologies can be used to aggregate small-sized spatial scales and TGs into a final assessment classification for food webs at the subregion level (Barnard and Strong, 2014; Walmsley *et al.*, 2017).

Final remarks

Spatial scales revealed wider effects for all criteria and subregions, when compared with temporal scales. The outputs highlight that spatial scales may need to be downsized if bento-demersal community patterns are to be identified for each subregion. Each subregion had different scale requirements, reflecting local and/or regional patterns. MTL models showed that using 1000 km^2 scales detected significantly different community patterns in both subregions. As for MTL$_{\_4}$ and LFI, these were significantly explained by ICES rectangles and 1000 km^2 squares in the CS and by Sector/Strata in BBIC subregion, where scales were related with region and depth strata patterns. MATG was marginally explained by spatial and temporal scales. Considering environmental variables, depth had a significant role in explaining criteria variability, while temperature had a low influence. Overall, food web assessment would benefit from downsizing the assessment scale, especially for criteria including higher variability, e.g. MTL, but there is also the need to improve the current scientific knowledge for lower TGs, which are not considered as priority since they have no commercial interest, especially at spatially relevant scales. The assessment of food web criteria for the Portuguese continental waters, using the spatial and temporal scales considered in the present study, showed that food webs present a decreasing trend in locally defined areas in the S and SW, for MTL and MTL$_{\_3.25}$, and in regionally defined areas of the SW and S, for MTL$_{\_4}$ and LFI. Community patterns found here may result from natural variability, or from anthropogenic pressures, which are especially high in the SW and S of the Portuguese waters, but they pinpoint the need to detail food web assessment in these regions for surveillance purposes. More information on potential impacts is also needed and these should be addressed at similar scales in future assessments, to match pressure-status effects.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability

The datasets analysed in this study are publicly available and can be found here: https://data.marine.gov.scot/dataset.

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