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Research article

Predicting climate change impacts on marine fisheries, biodiversity and economy in the Canary/Iberia current upwelling system

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ABSTRACT

The vulnerability of fisheries to climate change (CC) is driven by exposure factors that can affect species and fisheries differently at regional level. Ecological and socioeconomic consequences of climate change were assessed by evaluating a set of species (N = 53), caught by Portuguese fleet, that are likely to be affected by changes in oceanographical conditions (climatic scenarios RCP4.5 and RCP8.5) by the middle of this century (2041–2060). A novel approach was used which consist in estimate species habitat vulnerability index to CC by combining species habitat suitability with species sensitivity (life history ecological-biological traits), that was considered the weighting score for habitat suitability estimations by niche ecological models. Exploited species denote little specialization and have a large marginalization range with results showing that shifts in environmental variables, expected in the future, did not alter general distribution patterns of study species. Specialization was associated with sea surface temperature while marginality to depth, indicating that species can find refuges at higher depths without losing distribution range. Predicted changes in habitat suitability values across all species varied between a decrease of 11 % and an increase of 7 %, with species mean shifts around ±4 %. Catch composition by species (similarity >95 % regardless scenario/area), functional groups (similarity >97 % regardless scenario/area), trophic level structure (similarity >98 % regardless scenario/area) and marine biodiversity (marine trophic index ~ 3.35 regardless scenario/area) projected for the middle of this century, showed similarities to the present scenario. Economic losses estimated for the middle of this century correspond to a maximum value of 3 % in catch and 2.3 % economically. Fisheries revenue could not be jeopardized due to CC until the middle of the century. Under results found maintaining sustainable fishing management strategies is the best way to mitigate CC effects.

1. Introduction

For over 100 years, several hypotheses have been stated to explain marine fisheries changes based on dynamics during the early life history of marine species [Peck et al., 2012]. Effects of environmental and climatic changes on both coastal resources and fisheries have been evaluated to unravel the role of these processes and how these are linked [Reynolds et al., 2001; Ware and Thomson 2005; Moore et al., 2021; Hughes et al., 2018]. Fishery communities and managers show most concerns on those impacts capable to affect directly fishing landings abundance and composition due to i) species distribution, as a consequence of the ability to adapt to new environmental conditions, commonly towards higher latitudes and deeper waters and ii) species productivity [Reynolds et al., 2001; Dulvy et al., 2008; Pecl et al., 2014; Cheung et al., 2009; Poloczanska et al., 2016; Pinsky et al., 2020].

Statistical models are commonly used to evaluate climate change (CC) projections on marine resources (review in Hollowed et al., 2013; e. g. "bioclimate envelopes", global-scale physical climate earth system models or regional ecosystem models that have been developed to understand how CC impact the structure and function of marine ecosystems). Other approaches include study environmental variability and fisheries time series (co)relationships that have been studied using a large range of approaches that differ in complexity, parametrization, forecast time horizon and type of resource modeled [Leitão et al., 2020]. Fisheries models used to explain environmental or CC shifts in marine resources require substantial data sources including size and

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age-structure to effectively integrate adjustments of size- and age-dependent processes. Population dynamic analyses have become the other choice to evaluate the consequences of environmental changes where environmental variables are integrated within a population dynamics model assessment of fish biomass, fishing mortality and recruitment changes (MacKenzie et al., 2012; Punt et al., 2021).

The vulnerability assessment framework (VAF) developed by the IPCC-Intergovernmental Panel for Climate Change [IPCC 2007] of the United Nations, has assumed a central place for evaluating CC impact in marine fishing resources. Current approaches consider exposure, sensitivity, and adaptive capacity of the species to CC relative to species life-history, and functional and ecological traits. Such characteristics can be considered proxies to evaluate the intrinsic ecological vulnerability of marine resources [Williams et al., 2008; Pecl et al., 2014], and consequently also socioeconomic factors to be evaluated by policy makers [Cinner et al., 2013]. For instance, egg and larval stages could potentially influence life history and adaptation of fish species to multiple environmental drivers, showing different levels of exposure and sensitivity to CC [Rijnsdorp et al., 2009].

Advances in fisheries oceanography and remote sensing have allowed researchers to increase the understanding of the marine variability, environmental dynamics at large scales and patterns of distribution for both diversity and abundance due to environmental constraints. For instance, Transition Zone Chlorophyll Front affects fish migration routes and foraging habitat, particularly for immature fish [Ramos et al., 1996; Polovina et al., 2001]. Warm water SST is in close proximity to the surface chlorophyll front, consequently shaping distribution patterns and variability in fish abundances. Despite dynamic ocean conditions vary across different spatial and temporal scales (years, decades, centuries, and beyond), geostatistical approaches have provided an unprecedent opportunity to establish correlations with species distribution patterns and therefore, enabling the prediction of future occurrences. Particularly, species distribution models (SDMs) have been widely used to evaluate the likely responses of species to CC [Hirzel et al., 2002, 2006; Hirzel and Le Lay 2008]. Ecological-based niche SDMs are founded on the assumption that species have specific environmental requirements for resilience (certain combinations of environmental conditions are necessary for individuals to survive, reproduce, obtain resources, etc), and therefore distribution should be shaped by descriptors of such environmental variability [Guisan and Zimmermann 2000; Elith and Leathwick 2009]. Ecological-based niche models have shown a remarkable ability to describe species distribution from explanatory factors that emerge from a set of environmental drivers, usually incorporated as ecogeographical variables or environmental data. These models rely on species presence and absence data to establish potential relationships with environmental data, that allow projections by simulating future changes in environmental variables. Simulations are based on atmosphere-ocean general circulation models, which predict future environmental scenarios based on different concentrations of greenhouse gases and mitigation strategies [Melo-Merino et al., 2020].

In the next decades, the marine environmental conditions at a global scale are expected to shift relatively to a recorded period 1986–2005 [Field et al., 2014], and marine resources increasingly affected by CC [Hollowed et al., 2013]. Ocean acidification and rising temperatures are problematic because of negative effects on marine ecosystems, resources and services upon which coastal communities largely depend [Turley and Boot 2011; Hughes et al., 2018]. Research indicates that CC may disproportionately affect the highest and lowest levels of marine food webs, leading to ripple effects throughout the entire ecosystem at global level [Ullah et al., 2018]. The latter authors found that in biomass at low trophic levels, such as prey species at the bottom of the food web, may be amplified as it travels up the food web, resulting in a greater average decrease in the biomass of larger, higher trophic levels (e.g. rising temperatures may result in decoupling between lower primary producers and consumers). Regional future projections of habit species shift in distribution have been used to estimate the economic impacts on marine fisheries [Jones et al., 2015; Moore et al., 2021]. Negative CC impacts include changes in the distribution and abundance of fish stocks, potentially increasing extraction costs for fishing industries with important annual losses by the year 2100 [Lam et al., 2016; Mills et al., 2023].

CC could affect local communities in coastal areas with high dependent on marine resources, particularly in the North Atlantic Ocean. Changes in sea surface temperatures and upwelling wind conditions may have an impact on the northern branch of the Canary Islands upwelling system, a highly productive ecosystem with commercially important fisheries [Vazquez et al., 2022]. Because climate change (CC) could significantly impact fisheries socioeconomically, we need to address key questions: (1) How well have we understood the relationship between climate and fisheries over the past decades? and (2) What approaches can help us better predict changes in marine resources and fisheries?

The main objective of this study was to understand how CC will affect fisheries along the mainland of the Iberian Portuguese coast. We started to analyze CC impacts on the main commercial species caught by the Portuguese fleet that comprises 92, 90 and 89 % of catches in three distinct oceanographic regions (north, center and south). A vulnerability index to CC was estimated based on species suitability information derived from Ecological-based niche models and ecological sensitivity which is based on species ecological/biological traits. To understand the likely ecological impact of climate change (CC) on the fishing sector, we assessed shifts in community composition, functional category, trophic level, and biodiversity between present conditions and future CC scenarios (IPCC scenarios RCP4.5 and RCP8.5), using species-level information. The vulnerability index allows us to measure species catch probability changes and consequently evaluate socioeconomic impact due to changes in fishing income. Therefore, we also evaluated how CC will affect overall fishing revenue by translating species catch probability shifts into economic consequences using species price values available from sales at auction.

2. Methods

2.1. Species occurrence data

Commercial species occurrence data were obtained from ocean Biodiversity information system (https://obis.org/), Global Biodiversity Information Facility (GBIF: https://www.gbif.org) and fishbase (www.fishbase.org). A total of 53 species, fish (N = 39) and invertebrates (N = 14), were selected (Supplements) due to their commercial interest following Bueno-Pardo et al. (2021). From 2000 to 2019, these species comprised 92 %, 90 %, 89 % of the landings in North, Center and South Portugal and represented economically 78, 78 and 74 % of the auction sales, respectively (DGPA- Direcção-Geral das Pescas e Aquacultura).

2.2. Climatic data

Data was compiled from POLCOMS-ERSEM climatic geo-biophysical model, available on the COPERNICUS platform. Monthly data included physical marine, biogeochemical and lower trophic levels effects on in the food chain (marine plankton). Data generated were produced using a marine ecosystem model (ERSEM - European Regional Seas Ecosystem Model), which is linked to ocean models of regional circulation (POLCOMS – the Proudman Oceanographic Laboratory Coastal Ocean Modeling System). The POLCOMS-ERSEM model45 forecasted a wide array of physical, chemical and biological variables for the Northeast Atlantic and adjacent seas at a resolution of 0.1° (approximately 11 km).

Studies that considered analyses of environmental drivers on catch rates of commercial species at regional scale can improve our understanding of the environmental role on species. Environmental variables that were identified in local studies for demersal [Leitao, 2023], benthopelagics [Leitão et al., 2014a,b; Baptista et al., 2016], small-medium pelagics [Ullah et al., 2012; Leitão et al., 2014a,b; Leitão 2015a], cephalopods [Ullah et al., 2012; Sonderblohm et al., 2014] and bivalves [Baptista et al., 2014; Baptista and Leitão 2014] were selected to provide a set of ecogeographical variables (EGVs) to later incorporate into our Ecological-based niche models (ENMs). Additionally, the selection of EGVs was also based on studies performed at a global scale, allowing the assessment of environmental effects on commercial fish/invertebrate species and selection of variables that are likely to be well represented in the current class of global climate models [Sumaila et al., 2011; Cheung et al., 2009; Lam et al., 2016; Moore et al., 2021]. As a consequence of the selection process mentioned for the study area, ENMs incorporated the following EGVs: salinity, temperature (as sea surface temperature) and pH. Additionally, for the purpose of this study, the data on the zooplankton (mol m^{-3}) and phytoplankton (primary productivity; mol m^{-3}) biomass collected from COPERNICUS were added to obtain overall plankton biomass (plankton biomass productivity, hereafter PP), which was finally used in the ENMs assessment. The information for all EGV considered the first top sigma layer (30 layers) of the outputs of the model provided in each cover downloaded from COPERNICUS (Copernicus, 2021. DOI: https://doi.org/10.24381/cds.dcc9295c). Bathymetry data were acquired from the ETOPO (NOAA National Centers for Environmental Information. 2022: ETOPO, 2022 15 Arc-Second Global Relief Model. NOAA National Centers for Environmental Information. DOI: https://doi.org/10.25921/fd45-gt74 Accessed, 2022).

Average annual values from 2000 to 2019 data records were used to define present state of the Portuguese marine coast. Additionally, two hypothetical future scenarios were used as presented in the 5th Assessment Report of International Panel for Climate Change (IPCC 2013). Climatic scenarios were based on greenhouse gas emissions (GHG) which included two different Representative Concentration Pathway (RCP) scenarios: 1) RCP 4.5 (moderate impact - intermediate GHG emissions predicting an increase in water temperature of 1.4 °C until the middle of this century); and 2) RCP 8.5 (business usual - high GHG emissions predicting an increase of water temperature of 2 °C until the middle of this century). The middle of the century future period encompasses yearly average data between 2041 and 2060 as defined in the IPCC (2021).

2.3. Ecological-based niche models

Species distribution maps (SDMs) are commonly used to study distribution edges and to analyze species habitat suitability. Ecological-based niche models (ENMs) were selected from within the most used approaches. Factorial analysis of the niche or ENFA (Ecological Niche Factor Analysis) had two main advantages. First, presence-only based data were required, preventing unreliable information about species absences or pseudo-absences. Second, this analysis described species specific habitat requirements [Hirzel et al., 2002, 2006; Hirzel and Le Lay 2008], quantifying ecological niche through two uncorrelated factors: marginality and specialization (Supplementary material: Folder: ENFA for graphical explanation of ENFA axes, marginality and specialization, interpretation). Marginality described how far the species optimum was from the mean habitat across a study area. Higher marginality indicated that a species was found in habitats where conditions differed significantly from the mean of all habitats surveyed [Calenge, 2006; Santos et al., 2006]. Specialization measured habitat selection, indicating niche narrowness. Higher values indicated greater specialization to a particular habitat within the study area [Hirzel et al., 2002, 2006]. As a result, habitat suitability maps (HSMs) can be computed by combining both factors. From an ecological perspective species with a lower specialization and a higher marginalization show better capacity to adapt and sustain CC potential effects within a particular study area (Supplementary material: Folder: ENFA for graphical explanation of ENFA axes, marginality and specialization, interpretation). The set of oceanographical EGVs were used to compute ENMs for each species included in this study, following methodology described in Cánovas et al. [2015] where ENiRG package was used as incorporated in R Statistical Software (R CRAN Team, 2022).

Species are distributed across a variable environmental range on which abiotic factors determine its presence. An expert validation of observational data allocation was performed before computing niche analysis by using ENFA. Habitat suitability maps, representing species probability of occurrence in Atlantic Northwest European Shelf and Mediterranean Sea (Fig. 1). Specifically, model predictions were trimmed to species occurrence overall data, extending from Latitudes: 0° to 75°N; Longitudes: 43°E to 38°W. This geographical area was selected as representative to cover species' habitat geographical distributions.

The effect of environment variability (abiotic features) in niche preferences was assumed to be species-specific. Therefore, EGV data was weighted according to exposure scores for each species ENMs. Exposure represents the degree to which a species is exposed to future EGV variations with a potential to affect productivity or distribution in a specific region [Pecl et al., 2014]. Exposure values (ranging from 0 to 1) for each species by EGV [see: Bueno-Pardo et al., (2021); supplement 4) and the impact value (rank score weighted value) of each environmental variable (ph, PP, SO, SST) on species biological-ecological traits were obtained from Bueno-Pardo et al., (2021) [Table 2 column "weight factor2"]. The impact value of each environmental variable on species biological-ecological traits was min-max transform and multiplied by each species exposure value. This final score with species degree of exposure to an environmental variable ranged from 1 (low expected ecological effect) to 5 (high expected ecologic effect: low exposure <20 % (score 1); 20 % < moderate exposure <40 %; 40 % < exposure <60 %; 60 % < highly exposure <80 %; extremely exposure >80 % (score 5). Score values were then introduced to weight EGVs in ENMs for each individual species (Supplementary material: excel file: Details.xlsx, sheet: Weighting factor of ENFA EGV).

The strong connection between a species' preferred temperature and its depth changes suggests that warming could lead to shifts in species' depth distributions [Dulvy et al., 2008]. Therefore, depth (which is also a proxy to distance to coast) was also considered a limiting factor, and used as explanatory environmental variable, for species distribution. Species distribution along depth was used to trim distribution models, considering suitable areas for each species distribution the 95 % confidence interval of the mean depth as calculated from occurrences of each species using ETOPO 22.

Computed ENMs were used to predict marginality, specialization and derived HSMs for present, RCP4.5 and RCP8.5 future climate scenarios. Different oceanographic regions are identified along the Iberian Portuguese coast [Bettencourt et al., 2004]. The coast was therefore divided accordingly the ICES Northwest Atlantic IXa subdivisions areas for Portugal (Fig. 1): Northwest coast (IXaCN), Southwest Coast (IXaCS) and Algarve South Coast (IXaS-Algarve). Artisanal fleet in 2021 represented 95 % (5995 boats) of the fleet in mainland Portugal, with seine and trawling representing 3.1 % and 1.9 % of such a fleet [INE, 2021]. Artisanal and seine fleet fishing is mostly carried out near the coast while pelagic and crustacean trawls fishing is mandatory outside 12 nm. An additional spatial mask consisting of the 400 m depth limit was used. Therefore, habitat suitability analyses included fishing areas where most Portuguese mainland fleet operated [Gaspar et al., 2014] and covers the 200m depth, first slope break, coastal shelf areas with higher marine biological production. The mean habitat suitability value for each species was calculated from HSMs by averaging pixel values (raster maps) by region (hereafter, north, central and south regions were designated) for each climatic scenario. Future variations in mean habitat suitability of species occurrence (probability from 0 to 1) were then estimated by subtracting future from present mean values.

ENMs were evaluated by using a cross validation [Boyce et al., 2002; Hirzel et al., 2006]. The number of cells belonging to each habitat suitability class was split into 20 equals intervals ranging for

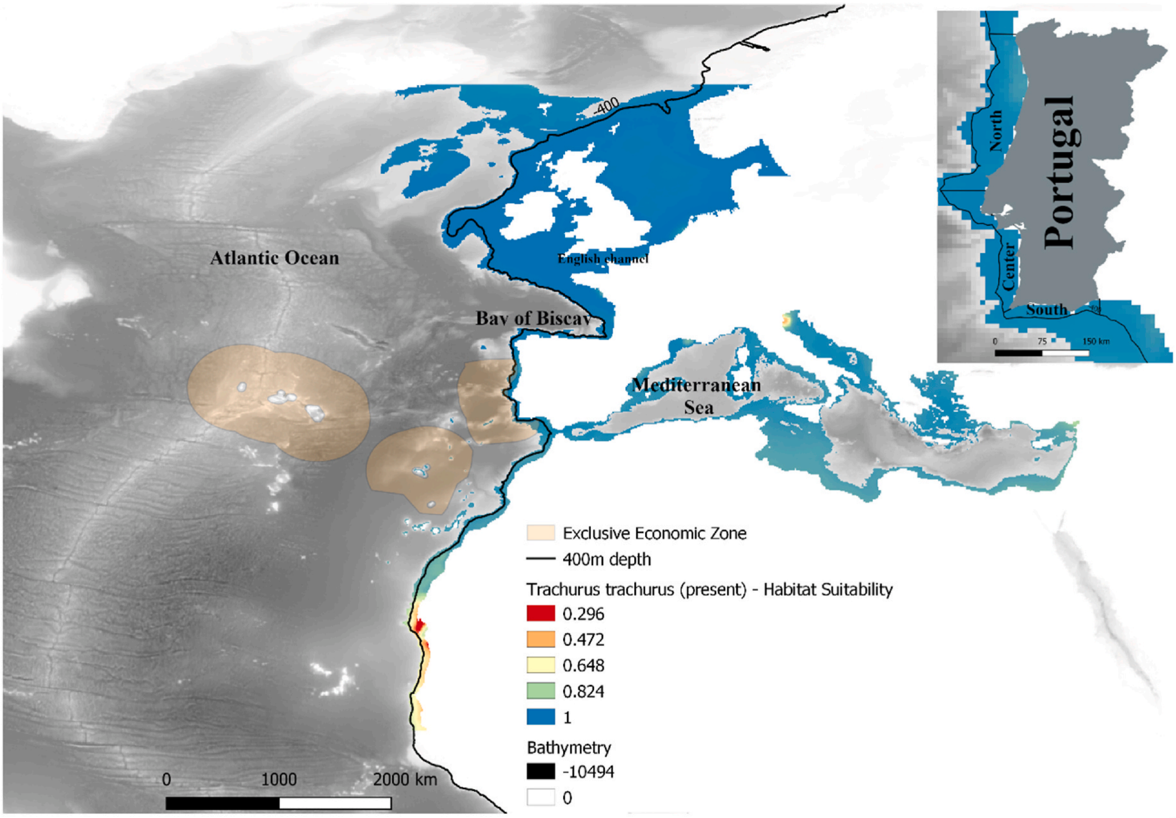

Fig. 1. Map showing geographical extension used in this study using as example *Trachurus trachurus* habitat suitability distribution (blue represent high probability while red low probability of occurrence) estimated by Ecological Niche Factor Analysis ecological-based niche model. Bathymetric information (grey range) is used as background. Exclusive economic zone for Portugal fisheries (orange) and coast areas division on Portugal mainland (north, center and south) are showed.

0 (unsuitable areas) to 1 (optimal areas), indicating asserted presences in each class. Average predictions were estimated for 53 HSMs across all the species and 95 % confidence intervals were then estimated (Supplementary material; Folder: Boyce validation).

In order to assess modifications in species distributions, an index was formulated to evaluate the relative measure (RM) of habitat suitability (HS) shifts under future conditions compared to present conditions as followed: $\mathrm{RM} = \mathrm{HS}_{\mathrm{future}}/(\mathrm{HS}_{\mathrm{future}} + \mathrm{HS}_{\mathrm{present}})$, where $\mathrm{HS}_{\mathrm{future}}$ is the habitat suitability of the species in future predictions by the models and $\mathrm{H}_{\mathrm{present}}$ is the probability of the presence of the species as provided by the models under current climatic conditions. This provided degree of HS change for each species in the future compared to present varying between 0 (it indicates that future habitat suitability is low compared to the present, suggesting that the species might face challenges in the future environment, potentially leading to habitat loss or range shifts) and 1 (implies that future habitat suitability is high relative to the present, suggesting that the future environment is likely to be favorable or even more favorable for the species), where $\mathrm{RM} < 0.45$ indicated habitat contraction, and $\mathrm{RM} > 0.55$ indicated habitat expansion. RM-index values ranging between $0.45 < \mathrm{RM} < 0.55$ denoted no changes in distribution.

2.4. *Habitat vulnerability index*

Sensitivity was defined by the IPCC [2007] as the degree to which a species is affected, either adversely or beneficially by CC. Usually, life-history and ecological traits were the best proxies to evaluate such an intrinsic ecological sensitivity of marine resources to CC [Williams et al., 2008; Pecl et al., 2014; Cinner et al., 2013], representing an ability or inability of a species to respond to environmental variability. Scientific expert judgment associated with literature review is the most common way to estimate species climate sensitivity to biophysical conditions [Champion et al., 2023]. In this study, HSMs from ENMs [Wiens et al., 2009] were combined with ecological sensitivity to define species potential impacts to CC. Therefore, a species habitat vulnerability index (HVI) was developed to provide the probability of change considering both species habitat suitability changes due to CC (computed from average HSM) and a species sensitivity score (S_{i}) for each species:

$$\mathrm{HVI}_{\mathrm{i,a}} = HS_{\mathrm{i,a}} * S_{\mathrm{i,a}}$$

Where $S_{\mathrm{i}} = (1 + S_{\mathrm{i}})$ was the ecological sensitivity for each species *i* in a particular area *a* where S_{i} was the sensitivity score. S_{i} could be interpreted as a weighting factor for HSMs. HVI assumes that $S_{\mathrm{i,a}}$ is the potential driver (species intrinsic biological trait) that affect species probability distribution. S_{i} values were compiled from the sensitivity assessment framework conducted by Bueno-Pardo et al. (2021, supplements 4), with sensitivity scores across species ranging between 0 (low sensitivity) and 1 (high sensitivity). The vulnerability to CC impact on species potential distribution was then given by HVI values where positive HVI values denoted increase in habitat suitability while negative HVI values decrease in species habitat suitability.

HVI probability values were converted to percentage and statistical descriptors of HVI were estimated by region and scenario by species, Functional group and Trophic Level class (see section 2.6). To better understand the range of variation of HVI values (habitat suitability) the frequency distribution, by 2 % classes percentage, were plotted. The frequency occurrence of species which HVI was expected to increase (positive impact) or decrease (negative impact) more than 5 and 10 % habitat suitability was also calculated/plotted to summarize overall CC impact.

2.5. Ecological assignment and analysis

Ecological trait analyses can provide important information that complement those provided by species individual analyses. Functional trait approaches enhance ecological understanding by focusing on the mechanisms that govern interactions between organisms and their environments. Thus, measuring and understanding traits increases our understanding of ecological processes (Nock et al., 2016). Commercial species were assigned to Functional Groups (FG) using the SeaAroundUs classification criteria (SAUs: http://www.seaaroundus.org). This criteria incorporated taxonomy, habitat preferences, feeding habits and maximum size, as required for ecosystem modeling (http://www.seaaroundus.org/doc/saup_manual.htm#12). However, species data was organized regardless of species sizes in Benthopelagics, Shrimps, Pelagics, Demersals, Bathypelagics, Sharks, Pelagics, Lobsters, Bathydemersals, demersals, Crabs, benthic, Demersal Invertebrates, Cephalopods. Both landing and economic data for each scenario and region, were then grouped according to FG categories by cumulatively sum species (Supplementary material: Excel file “Details”, sheet: Species).

Trophic level (TL) indicated the position of a species in a food web relative to the primary producers. Two online databases with information on the biology of marine species were used to extract species biological data: FishBase (http://www.fishbase.org) and Sea Life Base (http://www.sealifebase.org). Species were assigned to each of five trophic groups considered [Froese et al., 2005; Graham et al., 2017]: TL 2.0–2.5 (detritivores, herbivorous fish; planktivorous bivalves), 2.5–3.0 (planktivorous/omnivores tending to be herbivorous), 3.0–3.5 (omnivores tending to be carnivorous/benthic invertebrates; planktivorous cephalopods), 3.5–4.0 (carnivores tending to be piscivorous) and higher than 4.0–4.5 (piscivorous). Catch and economic data, for each scenario and region, were grouped accordingly TL categories, by cumulatively sum species that belong to the same TL group (Supplementary material: Excel file “Details”, sheet: Species).

A set of statistical analyses were applied to test CC effects on fisheries. Multivariate clustering analyses were applied to evaluate changes between current and future CC scenarios in catch (landings and economic data) and functional-trophic ecological structure (FG and TL). Abundance and economic matrixes were estimated differently for catch (Bray-Curtis similarity index) and economic data (Euclidean distance similarity index). Multivariate similarity matrices were fitted with the UPGMA algorithm (unweighted pair group method with arithmetic mean) using a bootstrapping randomization technique (999 permutations). Therefore, such a procedure implied a agglomerative (bottom-up) hierarchical clustering method that produces a dendrogram that was represented by a tree in which the distances from the root to every branch tip is equal. Overall, clustering analyses allowed an assessment of i) regional differences, ii) scenario differences, and iii) differences among scenarios within each region.

2.6. Marine biodiversity and temperature preferences

Mean trophic index (MTI) from catches was adopted as a marine biodiversity indicator to measure the status of marine environment. MTI was able to detect shifts from high-trophic-level, predators, to low-trophic-level, that is invertebrates and plankton feeders [Pauly and Watson 2005]. Landings and TLs for each species were used to calculate MTI according to scenario and region. Species with TL below 3.25 were included, because they represent small and medium pelagic, which in upwelling associated systems comprised a large proportion of the landings [Leitão 2015b].

The mean temperature of the catch (MTC) was an indicator that has been proposed to assess the effect of global warming on exploited marine communities [Cheung et al., 2013]. The MTC represented the average inferred temperature preference of the exploited species, weighted by their annual catch, which was a proxy for the temperature preference of the naturally occurring fish community. The MTC was calculated for present and future scenarios based on each species marine preference temperatures, weighted by its catch. The preference temperatures for the species were acquired (Supplementary material: Excel file “Details”, sheet: Species) from the supplementary material works of Cheung et al. [2013] and Leitão et al. [2018].

2.7. Projections on landings and economic effects

Yearly data on fisheries catches were obtained from DGPA (Direcção-Geral das Pescas e Aquacultura) Portuguese fisheries office. Among other elements this database included landings (tonnes) and economic revenue (per kg) by species, sold by the fleet at auction (first auction price). The average mean price of each species in auction was extracted from DGRM records by species. Fishing data were grouped into annual periods and areas based on catch port data. Landing data from 2000 to 2019 were used to estimate “present” average landings composition. The current scenario was considered as the reference state. The yearly mean contribution of all species analyzed for the present scenario comprised 92, 90, and 89 % of total catch and 78, 78, and 74 % of total economic value for the north, center, and south regions, respectively. The inter-annual variability in catches landed in the period 2000–2019 was estimated by calculating species standard deviations ($SD_{present}$). The coefficient of variation ($SD_{present}/mean_{present}$ *100) was used to analyze present scenario intra-annual average landings variability.

Landings values by species, for each scenario (RCP4.5 and RCP8.5) and region, were estimated by multiplying average present landings values (period 2000–2019) by HVI (i.e. current catch value x future habitat suitability). Therefore, calculations provided an estimation of catch values (in tonnes) for each species in future CC scenarios. Assuming auction price will not change over time and that fleet exploitation pattern “census latus’ is conservative, the predicted economic value, revenue, was estimated for both RCP4.5 and RCP8.5 future scenarios. Thus, economic revenue was estimated for each species under different CC scenarios and regions by the coefficient obtained between future catch scenarios (tons) and average mean price (€/tons) between 2000 and 2019 period. By subtract future to present estimates (by species and for all cumulative catch), fisheries catch and economic shifts can be calculated, representing CC impact on marine exploited resources and economy.

3. Results

3.1. Ecological niche analyses: species analyses towards marginality and specialization

Fig. 2 showed a dispersion plot of marginality and specialization scores across species and FG. Marginality values highlighted that habitat preferences for those species differed from the mean conditions that described the habitat within our study area, e.g., *Sardinella maderensis* showed the highest marginality value, therefore indicating that this species presence is limited to a narrow area within our study area. Specialization values indicated species preferences for a particular habitat within our study area, e.g., *Lepidopus caudatus* showed the highest specialization value, therefore indicating that this species presence is limited to a particular habitat from all the available within our study area (Supplementary material; Folder ENFA for ENFA model interpretation and for individual results based on ordination analysis of marginality and specialization factors for each species included in this study; complete scientific names and commercial class of species are also in Supplementary material; Excel file “Details”, sheet: Species.

Grouping species in FG and TL could be also used to explain general patterns across species for marginality and specialization scores. A total of 4 FG, pelagics, bathypelagic, demersal, demersal invertebrates, together with 3 TL classes (TL:2.0–2.5; TL:3.0–3.5; TL:3.5–4.0) were allocated at higher marginalities. The other FG and TL showed marginalities lower than 1.2. All FG showed a specialization value lower

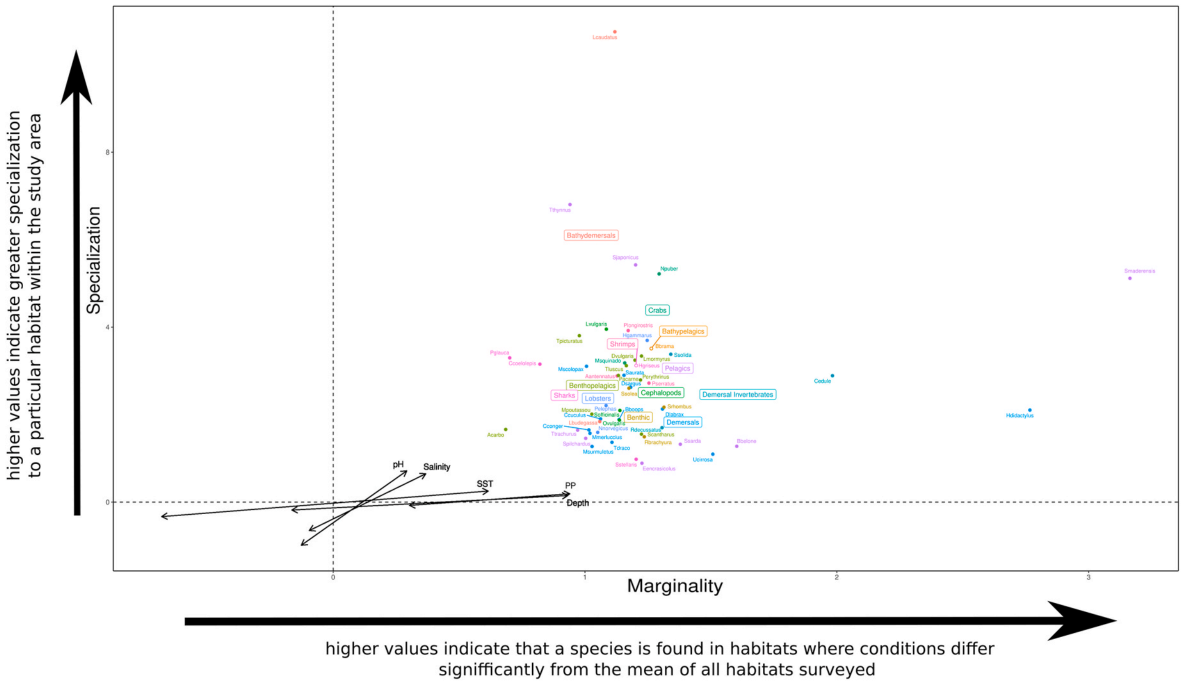

Fig. 2. Scatter plot of overall marginalities and specializations by species and functional groups (represented as centroids), grouped by using the same color. Environmental Geographical Variables – (EGV: Salinity, pH, PP - Primary Production, SST - Sea Surface Temperature, Depth) ranges are also presented as double arrows, showing variations across both marginality and specialization axes. The length of these arrows are proportional to the contribution of each EGV towards ENFA factors overall species represented in this study. See Supplement1 for ENFA model interpretation and for individual results based on ordination analysis of marginality and specialization factors for each species included in this study. Complete scientific names, Functional groups and trophic classes details in species are also in Supplementary material; Excel file “Details”, sheet: Species.

than 4, except for crabs and bathydemersals. From an ecological perspective, all the functional groups showed similar marginality values with a low specialization, indicating a better capacity to adapt and sustain CC potential effects within a particular study area. In contrast, there were only 2 functional groups that showed significantly higher specialization values: crabs and bathydemersals, therefore indicating less ability than the other groups to sustain CC potential effects.

3.2. Ecological niche analyses: EGV contribution to marginality and specialization

Depth showed the highest contribution towards marginality overall species across this study area (Supplementary material; Folder: ENFA < ENFA Factor EGV: MarginalitySpecialization ENFA factors Scatter plots. pdf). Primary production also showed a high contribution towards marginality factor, although ranged from negative to positive contributions, highly depending on the species considered. FG grouping showed that primary production EGV contributed the most for bathypelagics, demersal invertebrates, benthic and crabs, together with pelagics and sharks, making this variable the second most important variable to describe habitat allocation for those species. Salinity contributed less towards marginality factor, also showing a high dependency on the species considered. Benthopelagics, bathydemersals, shrimps and cephalopods, together with sharks, were allocated in areas where salinity contributed the most towards the description of particular habitats for those species. These three variables alone can be used to summarize marginality conditions overall species with accuracy (Fig. 2). pH and sea surface temperature, showed the lowest marginality contributions to the analyzed overall species. Both sea surface temperature and pH showed a positive contribution towards marginality for pelagics, bathydemersals and sharks.

Sea surface temperature (SST) showed the highest contribution values towards specialization in our analyses, therefore making this variable the best explanatory variable to describe species habitat selection (Supplementary material; Folder: ENFA < ENFA Factor EGV: MarginalitySpecialization ENFA EGV factors Scatter plots.pdf). Specialization related to SST varies accordingly specific group of species. Species with positive specialization showed a better fit in warmer waters (positive contribution towards specialization axis) while species with negative specialization better fit cold water future changes. The rest of the EGVs showed a similar contribution towards specialization.

3.3. Ecological niche analyses: ENFA cross-validation

Boyce index data fitting analyses (53 ENFA models fitted) showed that presence data were fairly predicted (Supplementary material; Folder: Boyce) by our models across the study area (Fig. 1). An important remark that can be also extracted from this cross-validation is that most of the predicted presences were already allocated within the study area, therefore showing that ENFA model is predicting presence of species over large areas within the study area, Atlantic Northwest European Shelf and Mediterranean Sea. (Supplementary material; Folder: Boyce). These results showed that masking and clipping ENFA results according to biological and ecological traits for the studied species could be a suitable option to obtain accurate species suitability distribution maps.

3.4. Species-fisheries shifts

HVI values showed a variation for the same species across areas and RCP future scenarios (Fig. 3). HVI ranged between a decrease in 11.5 % for crab *Necura puber* (velvet swimming crab) in North region for scenario RCP8.5 (maximum decrease value for a single species by region and scenario) to an increase of around 7 % for *Thunnus thynnus* (Atlantic bluefin tuna) in Centre region for scenario RCP4.5 (maximum increase estimated value for a single species by region and scenario). Based on HVI values for both scenarios, only 1 species is expected to decrease more than 10 % in catch for RCP8.5 (Fig. 3; Supplementary material;

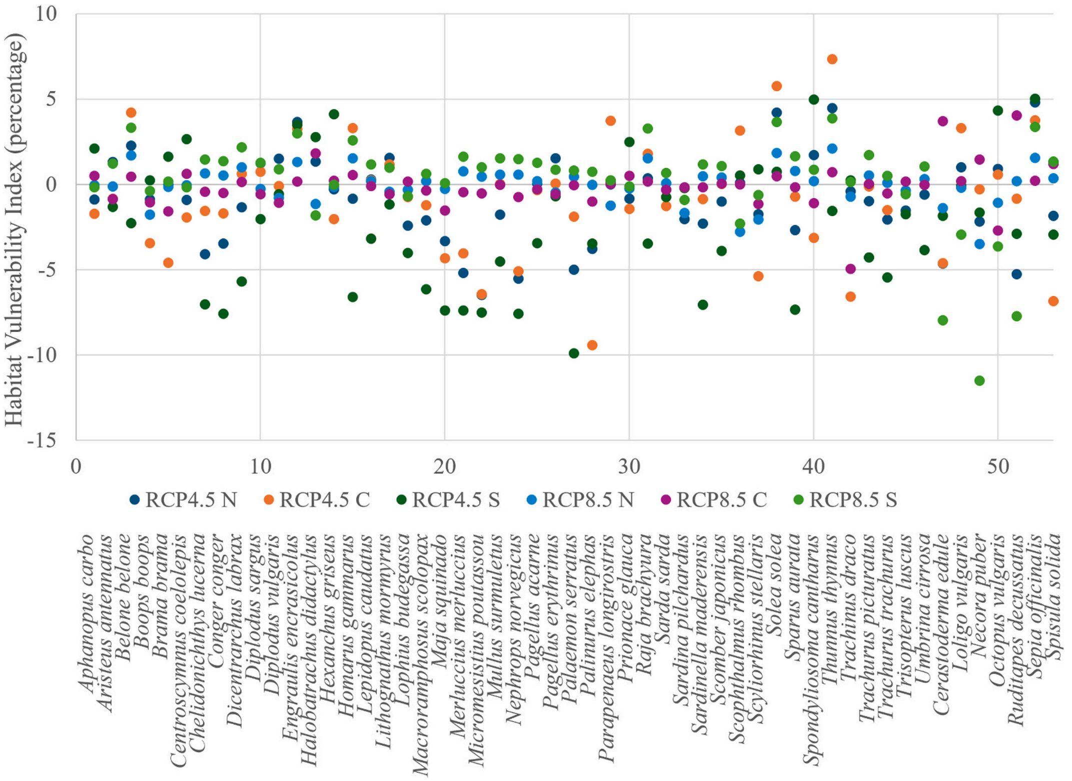

Fig. 3. Expected changes in species habitat suitability distribution based on Habitat vulnerability Index values (HVI), predicted for the middle of the century (2040–2061) by species, region (N-north, C-center and S-south) and scenario (RCP4.5 and RCP8.5). Percentage values refer to increase (positive values) or decrease (negative values) in species habitat suitability.

Excel file "Details", sheet: Species).

Overall, average HVI estimation revealed a general decrease in probability of occurrence for scenario RCP4.5 regardless of the area, expecting a decrease of about 1–2 %. For RCP8.5 future scenario, overall average HVI variations range between a decreasing or increasing for less than 1 % among areas (Table 1). Frequency distribution of HVI scores revealed that most species were not expected to experience a change above the 10 % threshold in absolute value. Most predicted shift values for the species studied were grouped between classes that range between minus 4 % to plus 4 %, regardless of the fishing area and scenario (Fig. 4).

Three species increased their HVI for scenario RCP4.5 more than 5 %, both *Solea solea* and *T. thynnus* in center region and *Sepia officinalis* (cuttlefish) in South region. For scenario RCP4.5 4 species in center (9 %), 5 species (11 %) in north and 11 species in South (25 %) are expected to decrease more than 5 % (Figs. 3 and 4, Table 1).

The similarity analyses reveal that catch composition by species differs 38 % between south and both Center and North regardless of CC scenario (Fig. 5). Cluster analyses (R-correlation value = 0.86) revealed that catches composition similarity among CC scenarios, within a region, is very high, more than 95 % similarity between all pair-wise combinations. From an economic perspective, catch composition patterns also revealed high similarity within a region for different CC scenarios with distance among scenarios less than 2–3 %. However, catches compositions at economic level differ around 30 % between south and both North and center regions.

3.5. Fisheries ecological shifts

Pelagic contributed the most to total catch, comprising presently around 78.6, 72.3 and 66.3 % of catch composition in north, center and south regardless of scenario (Fig. 6). However, at economic level, other FG are also relevant (Supplementary material; Excel file "Details", sheet: TL_FG) such as, by decreasing order, cephalopods, demersals, benthopelagics and crustaceans specifically in the south region (around 19 %).

Shifts in habitat suitability due to CC affect differently FG depending on the region and scenario (Table 1). Estimated values ranged between a decrease around 7.5 % for lobster in south for RCP4.5 to an increase of 4.3 % for cephalopods in south for RCP4.5. For the same FG, the expected change was positive or negative depending on the region, e.g. benthic species for RCP4.5. For RCP8.5, FG shifts due to CC ranged within small values, from a decrease of ~2.8 (south, Cephalopods FG) to an increase of 3.3 % (South, Benthic FG). A decrease of less than 5 % in habitat suitability was just observed in RCP4.5 scenario for lobster in center (~5.2 %) and south (~8 %), crabs in south (~7.2 %), and demersal invertebrates in center region (~7 %). The above changes also affected economically catch composition. The decrease of economic revenue was observed for those FG mentioned above and demersal fish in the South (see: Supplementary material; Excel file "Details", sheet: TL_FG).

Catch (R-correlation value: R = 0.97) and economic (R-correlation value: R = 0.99) FG data grouped by areas, regardless of the CC scenario (Fig. 5). FG catch composition differed around 15 % between south and both North and center samples. Similarity values for FG analyses of catches across scenarios within regions exceeded 97 %, indicating very low dissimilarity among CC scenarios within each region. This trend was also observed at the economic level, where the distance between scenarios within regions was minimal, while the distance between regions, particularly between the south and the central/northern areas, was significantly higher (Fig. 5)

Catch composition is presently composed mostly of TL:3–3.5, that is omnivores fish tending to be carnivorous, contributing with around 63, 73 and to 64 % of the catches in weight and around 39, 45 and 29 economically (Fig. 6; Supplementary material; Excel file "Details", sheet: TL_FG). The present contribution of carnivorous (TL:3–3.5) and piscivorous (TL:4–5) species to total catch is also relevant, around 20, 14

Table 1

Summarized color ramp map with Habitat Vulnerability Index (HVI) indicating habitat shifts predictions due to climate change scenarios (RCP4.5 and RCP8.5) across North, Centre and South. Information was compiled for the catch and economic changes (53 commercial species), Functional group (FG) and Trophic Level (TL) categories. In the table it is highlighted the percentage of number of species, FGs and TL categories which catch/economic changes in the future can decrease (minus sign) or increase (plus sign) more than 5 and 10 %.

			RCP4.5			RCP8.5			
			North	Centre	South	North	Centre	South	Legend
Species Habitat changes	Catch /economic changes	Minimum	-6.47	-9.41	-9.91	-3.48	-4.94	-11.51	-12
		Maximum	4.81	7.33	5.02	2.10	4.03	3.88	-11
		Mean	-0.88	-0.77	-2.12	-0.01	-0.11	0.24	-10
		SD (±)	2.55	3.27	3.77	1.10	1.28	2.78	-9
									-8
		Higher than 5%	0.0	3.8	1.9	0.0	0.0	0.0	-7
		Less than - 5%	9.4	11.3	24.5	0.0	0.0	5.7	-6
		Higher than 10%	0.0	0.0	0.0	0.0	0.0	0.0	-5
		Less than -10%	0.0	0.0	0.0	0.0	0.0	1.9	-4
									-3
Functional groups categorieses	Catch changes	Benthopelagics	-2.33	-2.23	-4.09	0.04	0.16	1.25	-2
		Shrimps	-3.12	-0.86	-0.03	0.26	-0.05	0.33	-1
		Pelagics	-1.64	-0.27	-2.46	-0.90	-0.10	0.17	0
		Demersals	-4.03	-2.70	-5.71	0.63	-0.47	1.21	1
		Bathypelagics	-0.03	-4.60	1.62	-0.14	-1.59	0.17	2
		Sharks	-1.16	-2.12	1.15	-0.89	0.38	-0.57	3
		Lobsters	-3.90	-5.19	-7.55	0.87	-0.72	1.49	4
		Bathydemersals	-1.78	-0.59	-4.00	-0.20	0.12	-0.64	5
		Crabs	-2.75	-3.95	-7.16	-1.90	-1.26	-0.39	6
		Benthic	1.50	3.57	-2.60	1.42	0.31	3.27	7
		Demersal Invertebrates	-3.81	-6.55	-2.93	-0.86	1.36	1.17	24
		Cephalopods	1.25	1.33	4.37	-0.81	-2.00	-2.76	
	Economic changes	Benthopelagics	-1.52	-1.70	-2.42	-0.12	0.30	1.08	
		Shrimps	-2.73	-0.67	-0.10	0.22	-0.04	0.38	
		Pelagics	-1.44	-0.42	-2.11	-0.77	-0.20	-0.09	
		Demersals	-3.44	-1.85	-6.37	0.70	-0.30	1.58	
		Bathypelagics	-0.03	-4.60	1.62	-0.14	-1.59	0.17	
		Sharks	-0.99	-1.92	1.11	-0.55	0.46	-0.57	
		Lobsters	-4.63	-5.24	-7.54	0.73	-0.73	1.49	
		Bathydemersals	-1.80	-0.64	-4.01	-0.20	0.14	-0.67	
		Crabs	-2.44	-3.44	-6.89	-2.76	-0.88	-0.94	
		Benthic	2.49	4.90	-1.10	1.17	0.41	3.28	
		Demersal Invertebrates	-3.15	-5.57	-2.94	-0.38	1.81	1.04	
		Cephalopods	1.20	1.34	4.30	-0.80	-1.99	-2.79	
Trophic level categories	Catch changes	TL: 2.0-2.5	-3.81	-6.55	-2.93	-0.86	1.36	1.17	
		TL: 2.5-3.0	3.50	2.26	-1.19	1.26	0.04	0.85	
		TL: 3.0-3.5	-1.76	-0.09	-2.17	-1.21	-0.05	0.24	
		TL: 3.5-4.0	-1.72	-0.70	-3.59	0.11	-0.37	1.05	
		TL: 4.0-5.0	-1.90	-2.26	0.71	-0.27	-1.23	-2.01	
	Economic changes	TL: 2.0-2.5	-3.15	-5.57	-2.94	-0.38	1.81	1.04	
		TL: 2.5-3.0	2.96	-0.18	-2.28	1.14	-0.16	0.70	
		TL: 3.0-3.5	-1.43	0.44	-1.65	-1.12	-0.09	0.32	
		TL: 3.5-4.0	-1.34	0.50	-2.00	0.20	-0.17	1.54	
		TL: 4.0-5.0	-0.87	-0.83	2.29	-0.45	-1.76	-2.74	

and 11 % and 10, 12 and 18 % for north, center and south, respectively. However, at economical level piscivorous (TL:4–5) contribution is higher than carnivorous (TL:3–3.5) regardless of the area. Cluster analysis by TL grouped catch (R-correlation value: R = 0.99) and economic (R-correlation value: R = 0.99) data by areas, regardless of the CC scenario.

Climate change-induced shifts in species habitat suitability affect TL groups differently, depending on the region and scenario (Table 1). The range of change in TL catch composition across all groups was lower for RCP8.5 (−6.55 to +3.5 %) than for RCP4.5 (−2.50 to +1.4 %). For RCP4.5 the TL:2–2.5 showed a decrease in catch between 3 and 6.5 % while for RCP8.5, changes were low (−1 to +1 %). Economically, higher losses were observed for TL:2–2.5 in RCP4.5 CC scenario, 3.2, 5.6 and 2.9 %. A decrease in catch and economic value exceeding 5 % was recorded only for trophic level (TL) 2–2.5 in the central region under RCP4.5.

The TL catch and economic data ordination showed that similarity among scenarios within the same region was high (Fig. 5). Pair-wise TL cluster analyses showed similarity above 88 % between north and south samples when compared with central catch samples. Within each region,

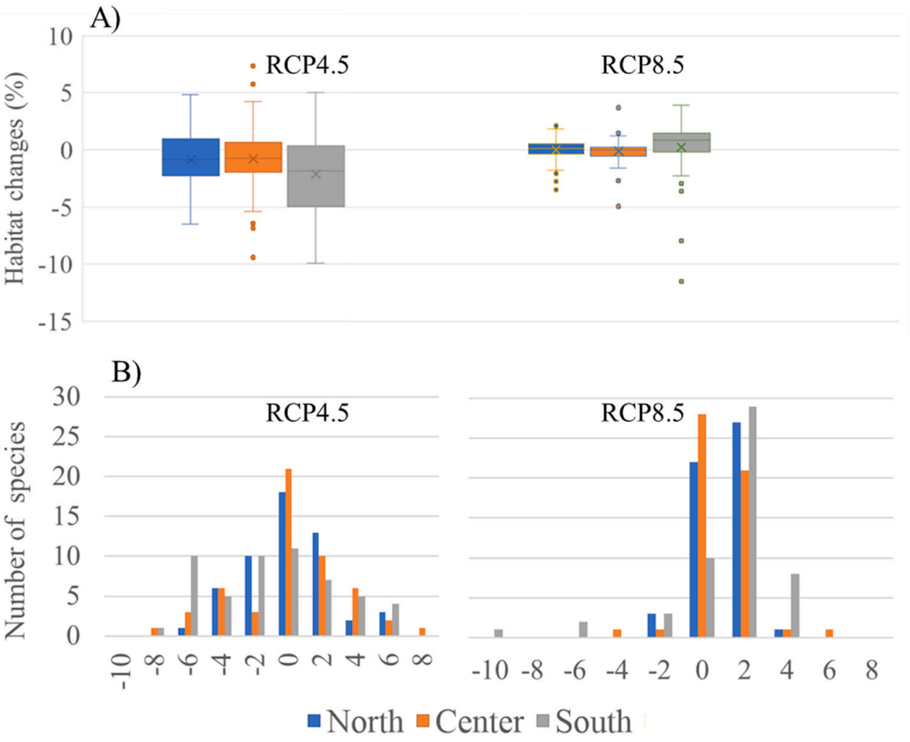

Fig. 4. A) Box plots with percentage of changes of habitat suitability measured by the habitat vulnerability index (HVI) for 53 commercial species. The information with species changes is detailed in Fig. 4. B) frequency distribution of the number of species expected to decrease or increase by 2 % habitat suitability classes.

similarity among scenarios was consistently equal to or greater than 98 %.

3.6. Biodiversity and temperature preference shifts

Marine biodiversity values (MTI) ranged between 3.3 and 3.42 regardless of the region/scenario with higher values in the central region (Fig. 7A). The mean temperature of the catch (MTC) did not show meaningful variations among scenarios for a given region although shows an increase from the North to South region (Fig. 7B).

3.7. Overall catch and economic shifts

For RCP4.5 an average loss per year of 1020(±440), 831(±192) and 160tonnes/year (±84) in landings and 115(±89), 365(±223) and 239k€/year (±181) economical was estimated for North, center and South. For RCP8.5 an average lost per year of 464 (±207), 49(±16) and 9.5 tonnes/year (±10 tonnes/year) in landings and 357 (±64), 155 (±54) and 185K€/year (±10) economical was estimated for North, center and South. The above values means that average total lost due to CC will range from 0.05 % (South, RCP8.5) to 1.6 % (North, RCP4.5) at catch level (Fig. 7C) while economically from 0.4 (South, RCP8.5) to 1.6 % (North, RCP4.5).

For the present scenario the estimated mean (±SD) intra-annual catch variation is 61895 (±35350), 76437(±36756) and 27813 tonnes/year (±15892) and 37305 (±16994), 20624 (±12003) and 42731 k€/year (±17111) per year in north, center and south coast, in weight and economic value, respectively. The intra-annual catch coefficient variation for the present scenario ranges around approximately 57 % regardless of the areas. The amount of catch change due to CC represents only a minor fraction when e compared with each region intra-annual landings and economic variation, between 0.1 (RCP8.5 South) and 3 % (RCP4.5 South) in catch and 0.7 (RCP4.5 Center) to 2.3 % (RCP4.5 North) economically (Fig. 7D).

4. Discussion

Many questions remain regarding the impact of climate change (CC) on fish resources at regional and local levels. The integrated analysis herein used, considering species, ecological/ecosystem, and economic factors, allows predict CC impact on fisheries. Additionally, expert assessment of species ecological traits, that is information on species sensitivity to CC, was first time used to model future habitat suitability, accordingly future predicted scenarios (RCP4.5 and RCP8.5), and estimated species vulnerability to CC. Expected suitability habitat changes relative to present climate was estimated for a total of 53 commercial species, later used to evaluate community composition, functional and trophic structure, biodiversity and economical changes due to CC.

Niche models are capable to provide a measure of the strength of association of studied species with their habitats, allowing to categorized fish species as specialists, those found only on specific habitats, or generalists, those associated with a broader habitat range. Specialization and marginality factors showed, regardless of CC scenario, that shifts in environmental variables expected in the future will not change general distribution patterns of selected commercial species in the different areas of the Portuguese mainland coast. Overall, the species, low specialized and large marginal ranges, were described without cluster for geographical area or climatic scenario. These results are contrasting with high specialized relationships that have been observed in tropical and polar communities, including in less complex habitats such as seagrass beds, gorgonian fields, sponge beds, and macroalgal stands for fish [Bouchard et al., 2022; Cusa et al., 2019] and invertebrates [Stella et al., 2011; Glynn and Enochs, 2011]. In these systems such a degree of specialization makes species very dependent on habitat requirements (habitat specialists), ecological/biological features and feeding habits.

Downscaling CC impacts on species habitat suitability required understanding the regional effect of such changes on ecosystems and species within a specific region. The results of regional niche modeling exercises can be interpreted much better when the ecological and mathematical assumptions of the modeling process are made explicit.

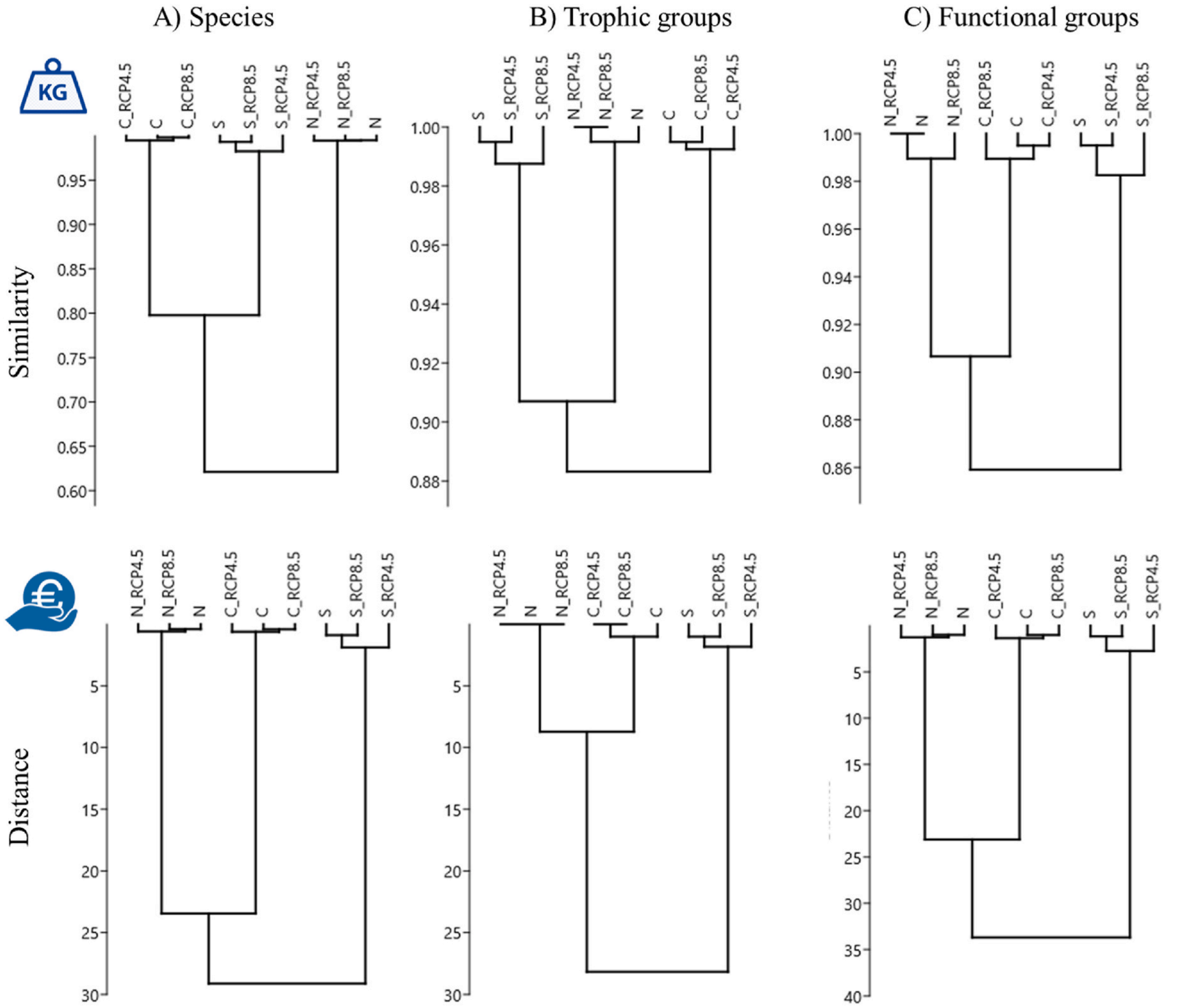

Fig. 5. Cluster analyses of catch composition (upper panel) and economic composition (lower panel) by area (N – North, C-Center, S-South) and scenario (RCP4.5 and RCP8.5) for A) species, B) Trophic groups and C) Functional groups.

Apparently successful models of distributions often ignore biotic factors [Soberónand and Nakamura 2019], i.e. species ecological/biological life traits. These are obtained from peer-reviewed information and expert knowledge (Bueno-Pardo et al., 2021) which can quantify the sensitivity of species to biophysical conditions (Champion et al., 2023). The approach in this study, including HVI estimation, allows niche models not to ignore species biotic factors. Additionally, ENFA analysis includes a selection of EGV widely used elsewhere, although excluding ice cover [e.g. Cheung et al., 2009], which made results to be comparable with other studies with caution.

Most of the species commercially exploited in Portugal showed low shifts range in response to CC measured. The probability of occurrence weighted by their sensibility to each particular EGV reveals low habitat suitability changes. This observation could be due to the fact that none of the species studied has south and north limits delimited on the Portuguese coast. Therefore, even if a species predictably moves progressively north, as response to abiotic changes due to CC scenarios tested, a considerable time delay is expected until habitat suitability conditions in south regions shift to a point niche no longer fits species requirements. For our study area, HVI reveals small differences in the probability of occurrence for our set of species, showing R-score values near the central point denoting no retraction or habitat expansion for the species. Mean HVI values for all studied species ranged mostly between −2 and +4 % revealing the worse scenario (negative impact) for the fisheries (all community/species mean) of a maximum mean decrease of 2 % in overall catch. Large global scale fisheries studies have reported to shift in species distributions by tens to hundreds of kilometers per decade towards higher latitude regions [Cheung et al., 2009; Poloczanska et al., 2016] and into deeper waters [Dulvy et al., 2008; Pinsky et al., 2020] under ocean warning scenario. CC impacts that have been identified on a global scale are generally negative for both the tropics and small islands development fishery systems [Champion et al., 2023; Bell et al., 2021; Kleisner et al., 2017]. In contrast, CC impacts could provide potential gains to fisheries in northern latitudes [FAO 2016]. Our results for the study area match previous global studies [FAO 2016; Payne et al., 2021], in which the impact of CC predicted in fisheries for the Iberian region in the next decades should be low. These match also other regional studies results for this area. For instance, in Northeast Atlantic a visible north-westward shift/expansion is expected for marine-estuarine opportunist species but not in our study area (Janc et al., 2024). In Mediterranean and North European seas studies on maximum catch potential shifts denoted also moderate shifts along Portuguese coast (Lamine et al., 2023).

Species found in close regions are likely to share the same similar niche. Therefore, we could expect such species to display a similar response. Generally, there are consistent patterns in HVI estimations across areas and scenarios. HVI estimations among areas/scenarios showed similar values with same trends (negative or positive impact). However, HVI values also showed that species at close regional scales can also display different responses to CC depending on the area or

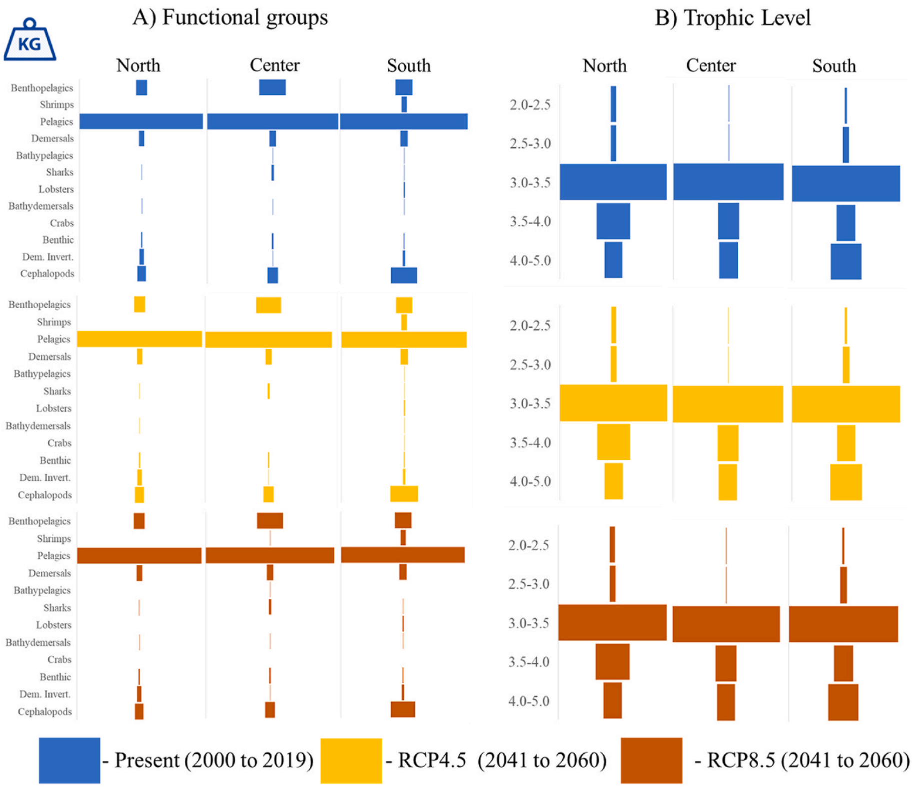

Fig. 6. Catch composition percentage by scenario (RCP4.5 and RCP8.5) and region (North, Center, South) for Functional Groups (A) and Trophic level classes (B). Detailed information on catches composition and economic value, in percentage, for different scenarios and regions in Supplementary material; Excel file "Details", sheet: TL_FG.

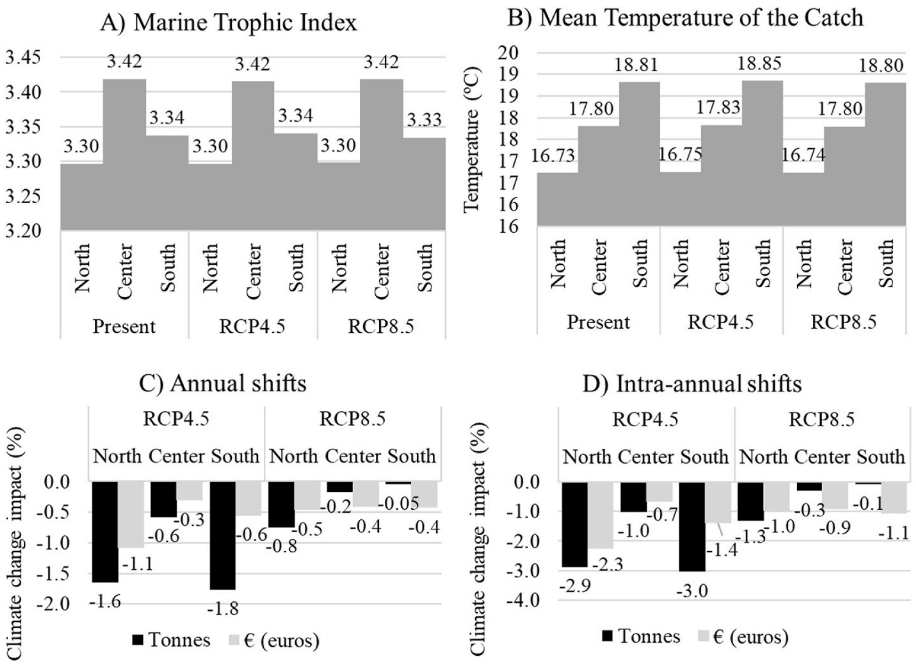

Fig. 7. A) Marine trophic index values (MTI) as indicator for marine biodiversity; B) Mean temperature of the catch index; C) future (2041–2060) predicted annual shifts (in percentage) in catch/economic due to climate change impact and D) climate change impact (in percentage) relatively to present intra-annual catch/economic variation for RCP4.5 and RCP8.5 future scenarios.

scenario without a clear positive or negative trend (similar results also in: Lezama-Ochoa et al., 2024; Pinsky et al. 2013). In the Iberian coast, temperate species are exposed to different annual environmental changes. In consequence, each species could have adapted to local environmental cycles such as inter-annual season habitat shifts across regions. This observation should affect HVI estimations across areas. In fact, shifts due to CC impacts were small compared to intra-annual shifts induced by natural variability. Therefore, habitat suitability variability values estimated across regions-scenarios for the different species represent the expected variability range in habitat suitability of a species in Iberian Portuguese system in the future. The HVI by species across regions/scenarios indicates the “natural” variability induced by future local EGVs conditions to CC impacts. This also allows delivery accurate information on species/fisheries response range to CC for policy makers when impacts are assessed, and adaptations measures discussed.

One way marine species adapt to CC is shifting vertically to deeper areas [FAO 2016]. Such observation agrees with our results in which depth showed the highest contribution towards marginality overall species in our models. Depth has been reported to be a feature that allows adaptation as a response to CC, under for instance SST increase, with species searching for refugia to higher depths [Dulvy et al., 2008; Pinsky et al., 2020]. The large marginality to EGV depth indicates that most commercial species of the Portuguese coast can find refuge in habitat at higher depth without any lost in their habitat suitability.

Sea surface temperature (SST) showed the highest contribution values towards specialization in our analyses, therefore making this variable the best explanatory variable to describe species habitat selection. Species with positive specialization to SST are searching for specific SST while species with negative specialization better fit cold water future changes. The studied species are distributed in other coastal areas where temperature is several degrees higher on average (for example, the Mediterranean Sea, where the SST is higher compared to the south Portuguese Iberian region), or lower (Bay of Biscay or English Channel), comparatively to Portuguese Iberian coast. Geographical boundaries for ENFA model analyses were wide enough to cope with this range in species habitat preferences and SST, with ENFA models revealing a good fit as denoted by the Boyce index. SST can be considered one of the main drivers that affects the distribution of species although overall species specific HVI values indicate small shifts on habitat suitability. Along the Portuguese Iberian coast, the SST is not expected to change equally across regions [Bueno-Pardo et al., 2021; Baptista et al., 2017]. García-Reyes et al. (2015) showed that coastal upwelling-favorable winds in poleward portions of eastern boundary (EBU) of the upwelling Canary major system have intensified and will continue to do so in the future. Portuguese coast locates in on EBU Canary system north branch. Thus, the rate of SST increase near the coast is expected to be buffered in coastal nearshore due to intensification of UPW [Leitão et al., 2019a,b; Piedracoba et al., 2024] compared to open ocean [Varela et al., 2018; Kessler et al., 2022]. Despite the slight increase in MTC between 1989 and 2009 in Portugal due to warm affinity species [Leitão et al., 2018], namely in the South, future projections reveal little changes in MTC for the middle of the century compared to present conditions. Thus, the increase of warmer species in the catches, subtropical species, due to temperature-induced shift in species distribution might not change catch composition proportionality until middle of the century as species, FG and TL analyses support similar structure in catch composition in the future.

Fisheries productivity is a function that relies on abundance, species’ geographic range, life history traits, and ecology. Our models predict the effects of CC on fisheries productivity by incorporating changes in plankton production (PP). Shifts in biogeography and changes in net primary production are projected to affect total catch potential that would decrease by 3.1 million tonnes per degree Celsius of atmospheric warming until the end of the century at a global level [Cheung et al., 2016]. However, PP is expected to increase in coastal areas for the middle of the century along Portuguese coastal areas [Bueno-Pardo et al., 2021; Leitão et al., 2023]. PP was not one the biggest contributors towards the niche factors. Most temperate species in our analyses during larvae stages found suitable survivor conditions near inshore coastal areas where food (plankton) availability is expected to prevail. These species, that have high distribution range and inhabit coastal areas from the Mediterranean Sea/North Africa to the English Channel, showed high marginality scores for PP. This shows these species larvae have adapted regional food conditions in early life stages over large spatial or temperature scale/range. Considering the small expected catch change due to CC when intra-annual catch variability is considered, it is likely that catch shifts become effected by close regional oceanographic conditions, such as: i) the ingress into nursery estuaries [Teodósio et al., 2016], ii) food availability (“Optimal environmental window” theory [Cury and Roy, 1989]), iii) wind/currents upwelling (“Ocean triads’’ theory [Agostini and Bakun, 2002]:) or iv) match-mismatch plankton production [Cushing 1990] that interact and/or overlay with CC impacts in early larvae life cycle phase. In short lived species (e.g. horse mackerel), with long spawning season (batch spawners), favorable environmental conditions in a period out of the spawning peak can contribute to compensate for the loss of larvae during the peak of spawning season due to adverse environmental conditions [Leitão 2015a]. Thus, spatial distribution is likely depending on the timing, intensity and frequency of local environmental events, possibly leading to poor inferences about the productivity/distribution estimations.

An increase in catch as a consequence of CC could be considered a positive outcome at the socioeconomic level, particularly when a species has a high economic value. However, such impacts need to be properly contextualized at an ecological/ecosystem level, such as evaluating functional or trophic level shifts. Because environmental forcing influences distribution and recruitment success, species sharing common ecological traits may display coherent spatial and temporal patterns in distribution/production determined by the overall environmental fluctuations [Myers 2001]. Although trophic cascades are difficult to demonstrate in marine systems, they can have significant impacts on the abundance and biomass of different trophic groups, causing inverse patterns of abundance and biomass among these groups. At global level studies showed that ocean primary production changes by CC can affect upper trophic level production [Cheung et al., 2016]. Magurran et al. (2015) propose that biotic homogenization mirrors the spatial pattern of unevenly rising ocean temperatures in North Atlantic, suggesting that CC is primarily responsible for spatial homogenization patterns. FG and TL analyses show high similarity between present and both RCP scenarios. Such observation could be explained by a smooth transition in oceanographic characteristics along the Portuguese coast and by the intrinsic species resilience that denoted overall little specialization and large marginalization scores from the species niche analyses.

Species niche-based factors like adaptation to CC are likely to affect biodiversity. Results reveal that the level of biodiversity shifts expected for the middle of the century under the study scenarios (RCP4.5 and RCP8.5) are not likely to change compared to the present. Despite fisheries habitat/refuges could extend into higher depths, which are also habitat/refuges to species under CC (species denoted higher marginality to depth), we can postulate if such natural refuges will longer operate as adaptation/refuge areas to mitigate CC, namely when fishery is expanding offshore/depth waters [Leitão 2015b]. Empirical data already show that coral reefs fish assemblages trophic pyramid shape varies depending on given human-mediated gradients along two orders of magnitude in reef fish biomass [Graham et al., 2017]. Climate fluctuations may impede the efficacy of fishery management strategies. Meanwhile fishery exploitation could also compromise the resilience or adaptability of resource populations to climate fluctuations. If in next decades, the three segments of the Portuguese fleet (artisanal, seine, trawl) keep their relative proportions (artisanal sector comprises 95.6 % of the fleet) and denotes little technological and catchability changes, minimal trophic structure and biodiversity changes can be recorded for the middle of the century.

Some species such as lobster and other crustaceans have denoted higher vulnerability values compared to most studied species. Prawn *Palaemon serratus* and lobster *Palinurus elephas* in South and center region for RCP4.5 and *Necura puber* crab in south for RCP8.5 will lose around 10 % until the middle of this century. These are highly prized species, but no target fishery occurs to lobster while the prawn is collected in crustacean trawl métier. Trawls as a métier are considered to have little sensitivity to CC due to the diversity of high prized species caught [Albo-Puigserver et al., 2022]. Artisanal fleet also does not target specific species that are likely to present high sensitivity to CC [Albo-Puigserver et al., 2022]. Our findings do not suggest a decrease in other groups like cephalopods in opposition to Schickele et al. (2021) for Iberian coast and Bay of Biscay. Increasing catch of sensitive species to CC probably means an increase in the vulnerability risk due to additive fisheries and CC impacts, and vice versa with economic consequences.

CC impacts the economics of fishing through changes in revenues (fish price and landings), costs (fixed plus variable costs), fisheries subsidies, other food supply sectors such as aquaculture [Sumaila et al., 2016] or fishing discards [Leitão and Baptista 2016]. Projections on ecological impacts can be used to mirror economic impacts [Moore et al., 2021; Lam et al., 2016] assuming the inflation, average prices and fleet composition/activity and the ratio between mains species catches (trophic issues) are kept conservative relatively to present scenario. Mainland Portuguese consumption is assured by seafood imports (2/3 of the total consumed is imported, that is 1/3 is fishery production), occupying rank 3 in fish worldwide per capita consumption [Leitão et al., 2023]. Our estimations about mean annual losses for both RCP4.5 and RCP8.5 scenarios of CC vary between 9.5 (RCP8.5 South) to 1020 tons per year (RCP4.5 North), representing economically a potential maximum decrease in revenue between 115 (RCP4.5 center) to 831 thousand euros/year (RCP4.5 North). Moreover, economic impact of CC Iberian Portuguese coast is expected to be low with overall economic losses representing 1–3 % compared to intra-annual economic shifts in the catch. Global economic studies on CC reported losses from 15 to 30 % maximum fisheries catch revenue for Iberian Portuguese coast (Lam et al., 2016), values far from present results. Predicted temperature changes (i.e. one single variable as predictor) for 16 major species in USA (encompassing East Coast, Gulf of Mexico, US West Coast and Alaska) predict annual losses reach $278–901 million by 2100, for instance due to Pacific cod and snow crab declines Alaska fisheries, with losses twice as high under a very high scenario (RCP8.5) than an intermediate scenario (RCP4.5). These values are also far from those estimated in the middle of the century in this study that encompasses 56 species. In opposite, the impact of global warming on fish stocks has been predicted to be positive on Iceland and Greenland fisheries economy due to cod and Atlantic-Scandian herring increase [Arnason, 2007]. However, fishing communities which present both low ecological vulnerability to CC (e.g. low shifts in species, catches structure etc) and low economic losses, may still be highly vulnerable to CC, particularly when those allocations are highly exposed to specific CC drivers such as sea level rise, wind and/or storms frequency changes that could widely affect the fishing sector socioeconomically [Pinto et al., 2023].

5. Conclusions

The geographically framing of your projections allowed predictions on species vulnerability to changes in habitat conditions across different fishing areas (different oceanographic regimes) within continental platform (photic zone), that match with fishing areas where worldwide fishing fleets operate. Marginality and specialization scores together with habitat vulnerability index predictions, that considered weighting species according to their sensitivity to CC, reveal that most species will display certain stability in their predicted distribution until the middle of this century. Such observation could indicate that species will remain in a dynamic equilibrium coupling the current-future climate (2041–2060). The large marginality score obtained for depth indicates that study species are able to find refugees inhabiting deeper areas without losing their habitat suitability. Present results, limited to a regional scope due to CC heterogeneous responses at different spatial-temporal scales, indicate that fisheries exhibit low vulnerability to CC along the south (a transitional area between temperate and subtropical regions) and central/northern (temperate region) Iberian coast, a rich biome influenced by the northern branch of the Canary Eastern Boundary Upwelling System. Predicted changes in habitat suitability values across all species varied between a decrease of 11 % and an increase of 7 %, with species shifts frequently recorded around ±4 % regardless of the species, regions or scenario. Only 5 species, including 4 invertebrates' species, had their future distribution changing between 6 and 11 %. Predicted diversity and economic losses were minimal, namely when considering present intra-annual present catch variability. Economic revenue can slightly decrease to a maximum of 2.3 %. Catch diversity, availability, composition and trophic structure will be little affected until the middle of this century, and fisheries revenue could not be jeopardized due to CC. The integrated approach used in this study, which evaluates the impact of CC from the species to the economic level and incorporates sensitivity (ecological traits) to weight habitat suitability, is a significant asset for assessing CC impact on fisheries. Decision makers should prioritize adaptation plans considering CC impacts at an ecosphere level. For environmental management proposed present findings can be used to compare marine with terrestrial CC impacts. These results can be also used by managers to develop mandatory EU climate adaptation plans (No. 130/2019 of 2 August). Under results found maintaining a sustainable fishing management has the best strategy for mitigating CC effects.

CRediT authorship contribution statement

F. Leitão: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **F. Cánovas:** Software, Investigation, Formal analysis, Data curation, Conceptualization.

Authors contribution

FL develop study rational; FL and FC conceived and designed/performed the analysis, analyzed and interpreted the results. FL wrote the first draft. Both authors read, commented, and approved the final version of manuscript.

Data availability statement

All requested information can be available on reasonable request.

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.jenvman.2025.125537.

Data availability

Data will be made available on request.

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