The importance of regional differences in vulnerability to climate change for demersal fisheries

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Abstract

Regional differences in climate vulnerability are particularly important in many countries with socio-ecological gradients or geographical and environmental spatial segregation. Many studies are regularly performed at the national level, but regional assessments can provide more detailed information and important insights into intra-national vulnerabilities. They require detailed information of many socio-ecological components that are often neglected at the regional scale but are meaningful and operational at national and international levels. In this work, we developed a climate vulnerability assessment to investigate the vulnerability of demersal fisheries based on 19 indicators covering exposure, fisheries sensitivity, species sensitivity and adaptive capacity for nine coastal regions of Spain, contrasting Mediterranean to Atlantic areas. Exposure was consistently larger in the Mediterranean than Atlantic regions, while adaptive capacity showed the opposite trend. While fisheries and species sensitivity did not display a clear Atlantic-Mediterranean pattern, they were critical for capturing regional differences that have an impact on fisheries vulnerability. Fisheries-related indicators such as employment, species mean price, catch stability, landings of species with low commercial value or fleet power may be able to capture significant socio-economic differences at the regional level. Our results highlight the generally higher vulnerability of Mediterranean demersal fisheries, mainly due to the lower adaptive capacity and higher exposure of Mediterranean regions, while providing key regional elements for guiding national and international actions for adaptation. This study demonstrates that the spatial scale considered in the development of climate vulnerability assessments must recognise the spatial heterogeneity in the socio-ecological system within its unit of analysis in order to be a relevant tool for management and policy makers.

Introduction

The ocean plays a crucial role in the food security and livelihoods of millions of people worldwide. From 1961 human fish consumption has grown at a rate almost twice that of the world population, and higher than all other animal protein foods, fuelling a sector that currently creates almost 40 million direct employment positions worldwide (Barange et al., 2018; FAO, 2020). Nevertheless, numerous studies suggest that fisheries production is being compromised by climate change impacts on the marine environment (Hollowed et al., 2013; Moore et al., 2018; Barange et al., 2018). Among the most studied effects are the shifts in species distribution and marine productivity, with potential consequences for fisheries landings, the economy and food security. Evidence of alarming rates in these shifts has emerged over the last two decades, and they are expected to continue to increase in the future (e.g., Hollowed et al., 2013; IPCC, 2014a; Gattuso et al., 2015; Barange et al., 2018; Pinsky et al 2018; Free et al., 2019). However, these effects are not experienced homogeneously at a global scale, and the impacts of climate change depend on the environmental and socio-economic characteristics of each region (Alison et al., 2009; IPCC, 2014a; Payne et al. 2020).

Climate vulnerability assessment (CVA) is an analytical framework developed to understand, quantify and synthesize climate change impacts on socio-ecological systems (IPCC, 2001). In it, “vulnerability” is given as a function of the “sensitivity” of a system to climate change, the degree of “exposure” to climate hazards, and “adaptive capacity”, as the community's ability to prevent or compensate potential impacts of climate damage (IPCC, 2001). The CVA approach has recently been revised, and its focus has shifted from “vulnerability” to “risk”, partly intending to use terms that embrace uncertainties in simulations of future climate impacts (IPCC, 2014a). Despite these changes in nomenclature, the core of the CRA and CVA analysis framework remains essentially unchanged.

To date, several studies have used CVAs and CRAs to investigate the impacts of climate change on the fisheries sector to prioritise where to allocate adaptations funds and provide policy-makers with sufficient knowledge to undertake practical decisions. These studies consistently emphasise the importance of investing in adaptation mechanisms in light of climate change threats (e.g., Alison et al. 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al. 2019; Payne et al., 2020). This approach has recently been applied at a sub-national level, achieving more detailed information and leading to more accurate analyses of regional vulnerability (Pinnegar et al., 2019; Barnes et al., 2020; Payne et al., 2020). It follows that regional differences are particularly important in many countries with socio-ecological gradients or geographical (and environmental) spatial segregation, for which differences should be expected in the combined effects of: (i) the impacts of climate change (Exposure); (ii) the relevance of fisheries to their economies and diets (Sensitivity); and (iii) the limited capacity for social adaptation (Adaptive capacity) (Cinner et al., 2012; Pinnegar et al. 2019; Payne et al. 2020). However, quantifying these spatial differences poses the challenge of searching for a more diverse set of socio-ecological indicators that capture these important differences at the regional scale, while being meaningful and operational at the national level.

Spain is a paradigmatic example regarding all these characteristics, with two large contrasting areas associated to the Atlantic Ocean and the Mediterranean Sea, and clear gradients and spatial heterogeneity in the ecological, fisheries and socio-ecological contexts (e.g., Hidalgo et al., 2017; Punzón et al., 2020). Indeed, the characteristics of the biological communities and the fisheries that depend on them are also markedly different (FAO 2018, 2020). Among the common characteristics, demersal fishing plays an important role in both the Atlantic and Mediterranean areas with over 1/3 of the fleet and more than half the total Spanish fleet's power and gross tonnage (MAPA, 2019). To highlight the importance of regional differences in vulnerability to climate change, we use the demersal fishery to apply a vulnerability assessment framework and identify the Spanish coastal regions that are more threatened by climate change according to the following criteria: where the continental shelf is most exposed to the climate change impacts, where the fishing industry contributes the most to livelihoods and economic growth, and/or where social resources and infrastructure may limit adaptive capacity.

Material and methods

Spain is among the 25 largest seafood producers globally and hosts the largest fishing industry in the EU, representing 21% of the total of active companies and 25% of its turnover (STECF, 2019a). In 2017, Spain produced around 1 million tons of seafood, 18% of the total EU fleet landings, with an estimated revenue of 2,000 million euros (STECF, 2019b). The Spanish demersal fleet accounted in 2017 for more than 70% of the total revenue with an estimated value of 1,500 million euros (STECF, 2019b). With approximately 8,000 of coastline of km and 340 registered fishing ports (EUMOFA, 2020), Spanish coastal regions have distinct characteristics in terms of the relative contribution of different fleets, their dependence on fishing and their socio-economic realities. There are also marked differences between the Atlantic and Mediterranean regions, each having its own fisheries governance structures, with the International Council for the Exploration of the Sea (ICES) active in the Atlantic and the General Fisheries Commission for the Mediterranean (GFCM) in the Mediterranean, developing the fisheries assessment of fisheries resources (e.g., GFCM, 2019; ICES, 2019, for demersal species).

In this context, taking into account: (i) the importance of demersal fishing in Spain; (ii) the heterogeneity of its coastal regions; (iii) and the importance of the fishing sector for livelihood and food security, we investigated the regional vulnerability of demersal fisheries based on 19 indicators covering exposure (E), fisheries sensitivity (FS), species sensitivity (SS) and adaptive capacity (AC) for nine coastal regions of Spain: Galicia, Asturias, Cantabria, Basque Country, Catalonia, Valencia, Balearic Islands, Murcia and Andalusia. This spatial coverage allowed us to assess differences among these administrative areas and, more generally, between the Atlantic and Mediterranean domains to measure the impact of climate change on fisheries, contrasting these two large areas. Note that Andalusia was considered a Mediterranean region, although part of its coast (the Gulf of Cádiz) is within the Atlantic domain. We made this assumption in order to maintain this region in our analyses, as most indicators could not be partitioned for the Atlantic and Mediterranean regions. The Macaronesian region (i.e., Canary Islands) has not been included in the study due to the minor role played by demersal fishing on its insular shelf and also, in order to maintain the comparability between the Atlantic and Mediterranean areas.

Exposure (E) is defined as the nature and degree to which a system is subjected to significant climatic variations such as temperature anomalies, extreme weather events, or other climate change effects (Füssel & Klein, 2006; IPCC, 2007). The analysis of physical variables is widely considered in vulnerability analysis studies to determine the degree of exposure of the fisheries sector, affecting its operational capacity, economic benefits and food security (Alison et al., 2009; Pinnegar et al., 2019). In this study, we focused on the sea surface temperature trends and the continental shelf area of each region, which was included as a proxy of the probability of exposure to other climate impacts (IPCC, 2014b; Barange et al., 2018; Maxwell et al., 2019) (Table 1). The continental shelf contains an important part of the fishing resources and the effects of climate change on the species that inhabit this area directly threaten the fishing activity and economic productivity. With this in mind, we assume that the regions with the largest shelf areas will tend to have a greater number of impacts associated with climate change, as well as the occasional and/or extreme impact of some of them. Fisheries sensitivity (FS) is defined as the component of total sensitivity that refers to the socio-economic sub-system: employment, food security, among others (Colburn et al., 2016; Pinnegar et al., 2019; Tables 1). We used four indicators to assess the fisheries sensitivity in each of the nine coastal regions: Fleet power, Fleet age, Fish consumption, Employment (Table 1). Among the characteristics of the fleet, fleet power is highly correlated with tonnage and indicates larger vessels which are less flexible regarding fishing areas and fishing gear.

Adaptative capacity (AC) is the degree of adjustment that ecological, social or economic systems can achieve to balance the actual or projected climate and its impacts, including actions that moderate, prevent damage or exploit beneficial opportunities (Noble et al., 2014; UNFCCC, 2018). It includes elements such as the level of social capital, human capital, and the adequacy and effectiveness of governance structures, and it presupposes an indissoluble relationship between climate change actions and the central imperatives of reducing poverty, increasing food security and ending hunger (Haddad, 2005; Yohe et al., 2006; Tol & Yohe 2007; Vincent, 2007). In this study, in addition to these elements that are widely used in climate vulnerability analysis studies we considered factors of adaptive capacity related to: the mean number of landing ports per fishing vessel, or the potential of small scale and recreational fishing (Tables 1). The possibility of landing outside the base port offers the fishing fleet options for avoiding extreme weather events and seeking a higher economic return on sea voyages. Artisanal and recreational fishing emerge in this scenario as an option for migrating boats and fishing crews to these small-scale fisheries and the tourist market, an opportunity for adaptation since climate change affects fishing yields and viability. Note than some of these factors could serve as either sensitivity or adaptive capacity indicators. To assess the species sensitivity (SS) to climate change, we collected information on relevant biological traits of the most landed species in both the Atlantic and Mediterranean areas between 2016 and 2018. These traits included temperature preferences (mean and range), spawning duration (months), and depth range, in addition to landing stability and market data (Alison et al., 2009; Hare et al., 2016). These indicators were calculated at the species level and subsequently weighted by the mean CPUE of each species in each region during the period 2016-2018, to represent the sensitivity of the biological communities (Tables 1).

Construction of the vulnerability index

A consistent application of weighting criteria has been suggested as an important step to avoid an arbitrary classification of the indicators (Johnson et al., 2016). Because each indicator has its own units, we rescaled the indicators between 0 and 1 to make them unitless and comparable. However, by doing so, we artificially equalled the range of variability of all the indicators. To compensate for this, we use the Coefficient of Variation of each indicator (CV) as a weighting factor, and thus we ended up with a set of unitless and comparable indicators ranked according to their original variability. Following this approach, we computed the exposure (E), fisheries sensitivity (FS), species sensitivity (SS) and adaptive capacity (AC) indices which varied between 0 and 1. The final vulnerability was calculated by adding exposure (E), fisheries sensitivity (FS), species sensitivity (SS), and subtracting adaptive capacity (-AC).

$$V = E + FS + SS - AC$$

The final vulnerability scores were higher for the most vulnerable regions (i.e., high exposure, high sensitivity and low adaptive capacity), and lower for the least vulnerable ones. These final index scores were normalised between 0 to 1, with 0 being the lowest vulnerability and 1 the highest vulnerability.

Table 1. Summary of variables and data sources used to calculate exposure, fisheries and species sensitivity and adaptive capacity of the coastal regions to vulnerabilities associated with climate change impacts on marine demersal fisheries.

Component	Indicator	Variable	Interpretation	Data sources
Exposure	Sea surface temperature	Mean projected sea surface temperature increase (°C at 0.5 m depth) by 2050	Projected trends in the regionalisation of the IPCC climate scenarios indicate future exposure of the region to water temperature changes.	COPERNICUS, 2020
	Continental shelf area	Surface of the continental shelf (km²) between 0 and 200 m	A larger extension of continental shelves (0-200 m) makes fishing regions more exposed to the impacts of climate change as extreme weather events.	EMODNET, 2019
Fisheries sensitivity	Employment	Persons working in marine fisheries as % of the total economically active population	Employment in the sector is a direct indicator of its size. In this case, the number of registrations in the sea regime quantifies the fisheries sector capture component. The larger the size, the greater the sensitivity to change.	INE, 2018
	Fleet power	Mean average power of demersal fleet (kW) (2016-2018)	Average vessel power is a measure of fleet capacity; the more powerful fleets are considered the most sensitive and possibly the least adaptive.	STECF, 2019
	Fleet age	Average vessel age (2016-2018)	Older and therefore less efficient fleets are considered to be more sensitive to the effects of climate change.	STECF, 2018
	Fish consumption	Per capita consumption of fishery products (kg/year).	High consumption of seafood is directly related to dependence on this source of protein and, consequently, to sensitivity to climate change.	MAPA, 2019
Species sensitivity	Price	Price of the main commercial species	The species with the highest market value typically are subject to the greatest fishing pressure, which is why it is estimated that they are more sensitive to climate change.	STECF, 2017

	CPUE stability	Coefficient of variation of the CPUE for the main commercial species by region (2015-2018)	Species with the most variable CPUE are generally those most dependent on environmental conditions and are therefore considered the most sensitive to climate change.	IEO, unpublished data.
	Temperature sensitivity	Preferred temperature range of a species (i.e., range between the 10th and 90th percentile, T10 and T90) divided by its preferred mean temperature.	The species most sensitive to temperature changes will have to withstand narrower temperature ranges and have an affinity for lower temperatures.	AQUAMAPS, 2020
	Depth range	Bathymetric range (quantile-10 (D10) of the depth distribution and the quantile-90 (D90)	Inhabiting narrower depth ranges increases species' sensitivity to climate change by limiting their ability to migrate at higher depths.	IEO, unpublished data
	Spawning period	Spawning season of each species (months/year)	Species with shorter spawning periods will be more sensitive to the seasonal temperature changes expected due to climate change.	FishBase; SeaLife, 2020
Adaptive capacity	Low value species landings	(CPUE of species with low commercial value/total CPUE) * 100 (2016-2018)	The percentage of landings of species with low commercial interest indicates less dependence on resources of high commercial value and is considered an indicator of greater adaptability.	IEO, unpublished data
	Landings outside the base port	Mean number of ports where each vessel landed (2016-2018)	Landings outside the main port can be considered as indicators of the fleet's ability to adapt, for example to adverse weather conditions or market opportunities.	IEO, unpublished data.
	Per capita GDP	Per capita gross domestic product	Higher GDP per capita allows for less economic dependence on any single activity, including fisheries, and therefore indicates greater ability to adapt to change.	INE, 2019
	Education	% of the population that complete non-university studies	The percentage of education is an indicator of the population's empowerment, allowing greater adaptation to changing conditions.	MEFP, 2019

Small scale fisheries	Number of boats using small-scale fishing gear	A larger small-scale fleet represents more opportunities for workers to move within the fishing sector from large-scale to artisanal fishing in order to guarantee their profits and livelihoods.	MAPA, 2019
Recreational fisheries	Number of recreational fishers	Recreational fishing emerges as an option for migrating boats and fishing crews to the tourist market, an opportunity for adaptation since climate change affects fishing yields and viability.	Gordoa et al., 2019
Associations	Number of Local Fisheries Action Groups (GALPs) added to the number of Associative Entities of Autonomous Scope (AAS) of the fishing sector	The associative capacity of the sector is related to a greater capacity to adapt to climate change.	REGP, 2019
Gear diversity	Shannon diversity index of main fishing gear (2016-2018)	A greater diversity of fishing gear within the fleet is related to a greater diversity of target species. Diversification increases the capacity to adapt.	STECF, 2019

COPERNICUS - European Union Earth Observation Programme; EMODNET – European Marine Observation and Data Network; INE - National Statistical Institute of Spain; STECF - Scientific, Technical and Economic Committee for Fisheries; MAPA - Ministry of Agriculture, Fisheries and Food of Spain; IEO - Spanish Institute of Oceanography; MEFP - Spanish Ministry of Education and Vocational Training; REGP - Spanish Network of Fisheries Groups.

Results

Exposure (E)

The increase sea surface temperature marked the difference in exposure between the Atlantic and Mediterranean (Wilcoxon $\rho = 0.019$, $p < 0.05$). The Mediterranean regions presented higher warming trends (between 0.023^{o}C/year and 0.028^{o}C/year) than the Atlantic regions (between 0.014^{o}C/year to 0.04^{o}C/year). Note that the highest sea surface temperature increases in the Mediterranean are twice the highest increases in the Atlantic (Fig. 1a). The continental shelf indicator was characterised by high inter-regional variability (Fig. 1b). However, no significant difference was found between the Atlantic and Mediterranean areas (Wilcoxon $\rho = 0.540$, $p > 0.05$).

Fisheries Sensitivity (FS)

In terms of fisheries sensitivity, the indicator with the greatest inter-regional variability was the fisheries employment. The result in the Atlantic region of Galicia (2.1%) was by far the largest, while this indicator ranged between 0.2 and 0.5% in the other regions. The difference between Atlantic and Mediterranean areas was significant (Wilcoxon $\rho = 0.049$, $p < 0.05$). The per capita consumption of fishery products was between 21 and 30 kg/year throughout Spain, with higher consumption in the Atlantic than in the Mediterranean area (Wilcoxon $\rho = 0.019$, $p < 0.05$). The demersal fleet was generally older in Mediterranean regions (Mean $\approx$ 38 years) than the Atlantic ones (Mean $\approx$ 27 years), while this difference was not significant (Wilcoxon $\rho = 0.109$, $p > 0.05$; Figure 1e). Fleet power, used as a proxy for the demersal fleet catch capacity, showed high inter-regional variability, but no distinct pattern between Atlantic and Mediterranean areas was identified (Wilcoxon $\rho = 0.902$, $p > 0.05$; Figure 1f).

Adaptive capacity (AC)

Our results showed that three out of the five largest artisanal fleets belong to Mediterranean regions and two to Atlantic ones (Figure 1g). Although there was no clear pattern between these two major areas (Wilcoxon ρ = 0.903, p > 0.05), the inter-regional scale differences were high. Gear diversity was generally higher in the Mediterranean regions, although no significant different was revealed between the two areas (Wilcoxon ρ = 0.208, p > 0.05; Figure 1h). Regarding the mean number of ports for landing, there were more for the Atlantic than for the Mediterranean, showing a clear difference (Wilcoxon ρ = 0.048, p < 0.05; Figure 1i). The inter-regional variability was also pronounced for this indicator. In terms of low commercial value species landings, we also found significant differences between the Atlantic and Mediterranean areas (Wilcoxon ρ = 0.019, p < 0.05), with the Mediterranean regions showing a lower percentage of catches of low commercial value than the Atlantic (Figure 1j).

The Gross domestic product (GDP) ranged between 19.000 and 33.000 € throughout Spain, with the highest GDP belonging to the Atlantic Basque Country region, while Andalusia and Murcia, both located in the Mediterranean were the regions with the lowest GDP (Figure 1k). No significant difference was found between the Atlantic and Mediterranean areas (Wilcoxon ρ = 0.389, p > 0.05). The rate of non-university education was higher for the Atlantic than for the Mediterranean (Wilcoxon ρ = 0.023, p < 0.05; Figure 1l). In terms of civil participation in fisheries management organisations, the Atlantic region of Galicia was noteworthy for having the largest number of associations, including Local Support Groups (GALP`s) and Associative Entities of Autonomous Scope for the fishing sector (Figure 1m). Apart from this region, no pattern emerged between the Mediterranean and Atlantic areas (Wilcoxon ρ = 0.368, p > 0.05). Regarding the number of recreational fishers, the largest numbers belonged to Mediterranean regions but still, inter-regional variability was high and no generalised pattern between Atlantic and Mediterranean areas could be recognised (Wilcoxon ρ = 0.902, p > 0.05; Figure 1n).

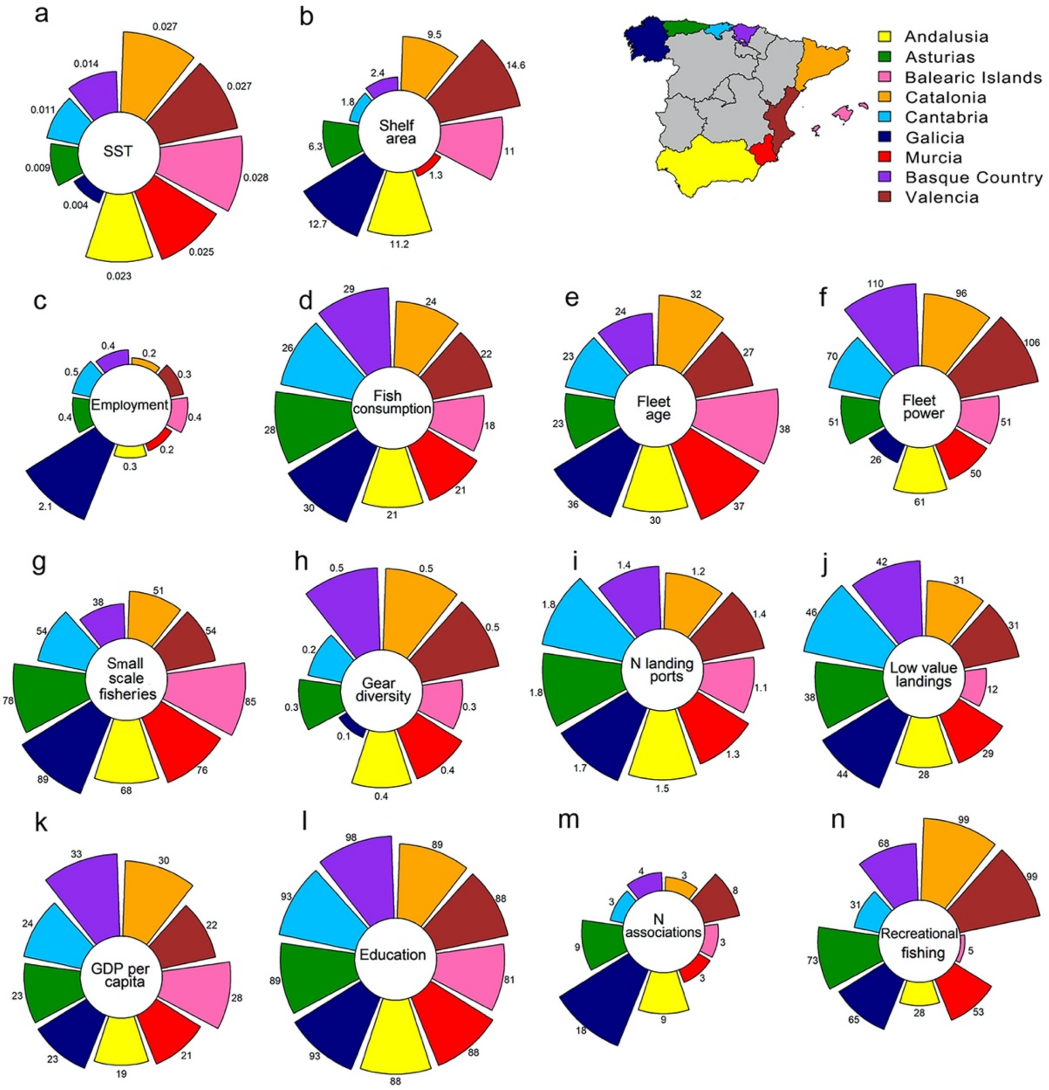

Figure 1. The figure shows the indicators of *Exposure*: (a) Continental shelf area, (b) Sea surface temperature trend; *Fisheries Sensitivity*: (c) Fisheries employment, (d) Fish consumption per capita, (e) Fleet age, (f) Demersal fleet power; and *Adaptive capacity* (g) Small scale fisheries, (h) Gear diversity, (l) Landings outside the base port, (j) Low-value species landings, (k) Per Capita GDP, (l) Non-university education, (m) Autonomous Community Associations, (n) Recreational fisheries**.** The map shows the colours designated for each coastal region that follow the same pattern in the presentation of the indicator results.

Species Sensitivity (SS)

In terms of the economic value of commercial species, our results showed major price variations with the Mediterranean showing a higher price for most of the species investigated (5.48 ± 5.71 € in the Atlantic and 6.49 ± 6.71 € in the Mediterranean; Figure 2a, 2b). Despite major price variations not significant differences between the Atlantic and Mediterranean areas was found

(Wilcoxon ρ = 0.389, $p > 0.05$). In terms of life history traits, the spawning period showed similar patterns between the Atlantic and Mediterranean biological communities (Wilcoxon ρ = 0.474, $p > 0.05$; Figure 2c, 2d). Regarding the species depth ranges, we found differences between the species when contrasting Atlantic and Mediterranean populations, such as for Conger conger, Scyliorhinus canicula and Lophius spp., with generally wider ranges in the Mediterranean populations (181.78 ± 90.08 m. in the Atlantic and 235.59 ± 145.38 m. in the Mediterranean; Figure 2e, 2f). No significant difference was found between the two major areas (Wilcoxon ρ = 0.777, $p > 0.05$). In terms of temperature, the Mediterranean and Atlantic areas showed a similar temperature range (11.71 ± 4.27 °C in the Atlantic and 10.67 ± 3.65 °C in the Mediterranean; Figure 2g, 2h). Species that require low mean temperatures displayed intermediate temperature ranges (except for *Parapenaeus longirostris*), and species requiring higher mean temperatures displayed both high and low temperature ranges. This interaction translated into temperature sensitivity showed a similar pattern between Atlantic and Mediterranean areas (Wilcoxon ρ = 0.74, $p > 0.05$), being slightly higher in the Mediterranean community (1.7 ± 1.23 in the Atlantic and 1.81 ± 1.16 in the Mediterranean).

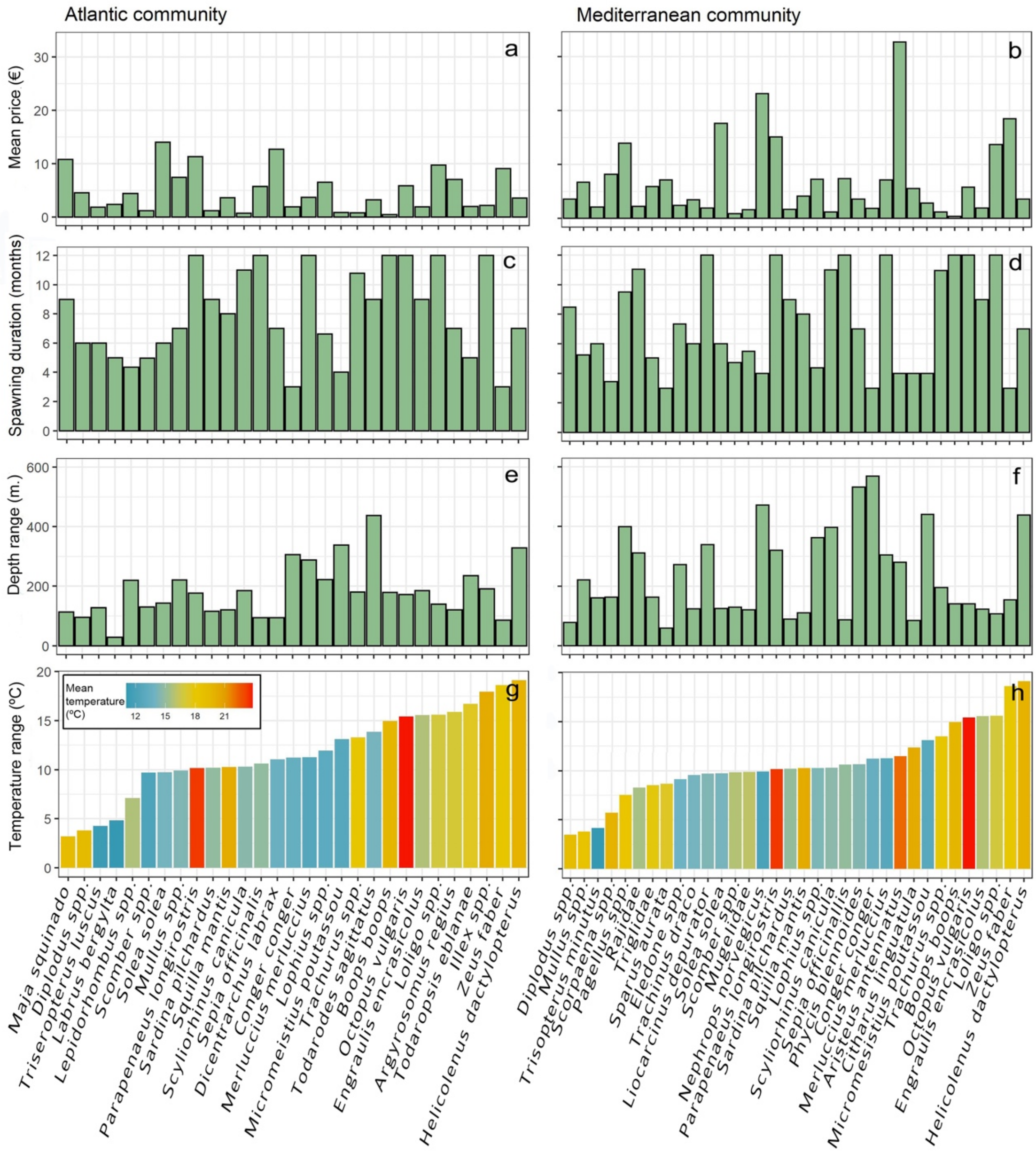

Figure 2. Species sensitivity indicators for the Atlantic and Mediterranean main commercial species targeted by demersal fisheries. Mean price of the main commercial species (a, b); spawning period (c, d); depth range (e, f) and temperature range (g, h).

The stability of landings showed high inter-regional variability. In general terms, stability was lower in the Atlantic area than in the Mediterranean (Wilcoxon $\rho = 0.037$, $p < 0.05$; 0.051 ± 0.047 and 0.078 ± 0.064 respectively; Figure 3). The mean species sensitivity was similar in the Atlantic and Mediterranean areas (Wilcoxon $\rho = 0.493$, $p < 0.05$; 0.46 ± 0.24 and 0.44 ± 0.22 respectively; Figure 4). Some species were particularly sensitive in the Atlantic (e.g., *Zeus faber* and *Maja squinado*) and in the Mediterranean (e.g., *Aristeus antennatus* and *Sparus aurata*), but generally, the species present in both areas had similar sensitivity values; e.g., *Diplodus spp*. And *Solea solea* were among the most sensitive while *Boops boops* and *Scyliorhinus canicula* were among the least sensitive.

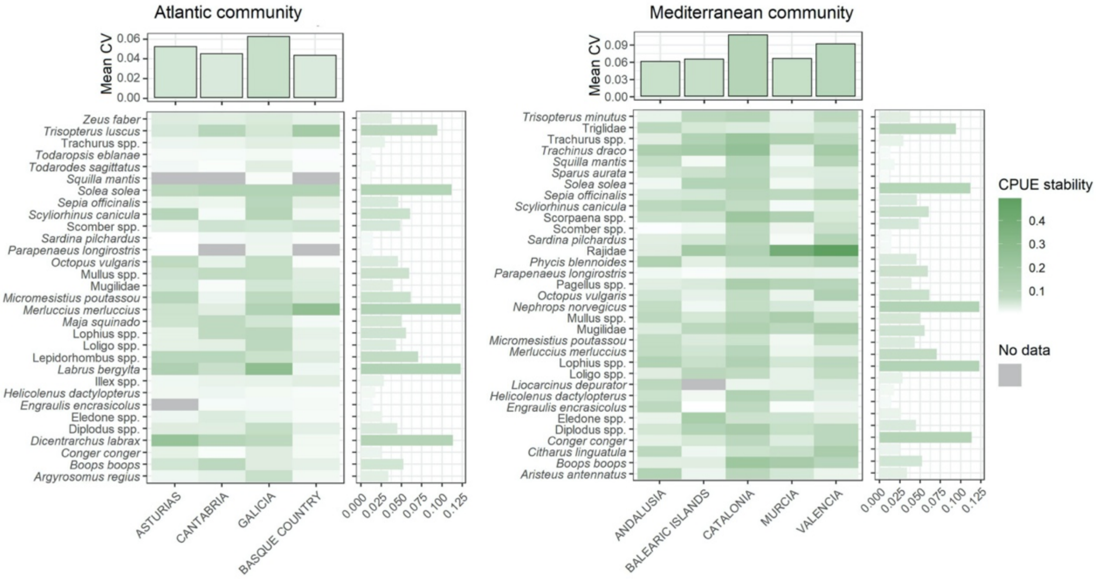

Figure 3. Indicator of stability of landings for Atlantic (left) and Mediterranean (right) species based on the mean CPUE stability (1/CV). Differences between species and regions are shown for both large areas.

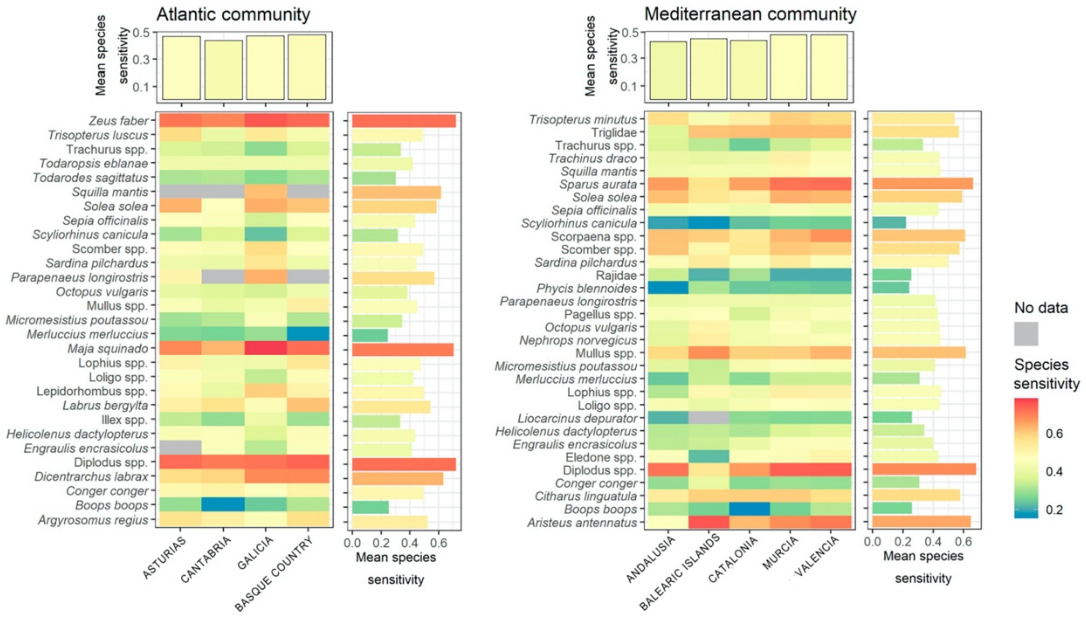

Figure 4. General species sensitivity for Atlantic (left) and Mediterranean (right) based on the combination of the species sensitivity indicators. Differences between species and coastal regions are shown for both large regions.

Integrative indicators and overall vulnerability index

The integrative exposure index showed that the regions with the highest degree of exposure were: Valencia, Catalonia, Balearic Islands and Andalusia (Figure 5a), marking a clear distinction between the Atlantic and Mediterranean areas (Wilcoxon $\rho = 0.025$, $p < 0.05$). The regions with the greatest fisheries sensitivity were Galicia and the Basque Country (Figure 5b). The result in Galicia was driven mainly by the large number of jobs in the fishing sector, which was the indicator ranking highest regarding inter-regional variability and thus had the largest contribution to the fisheries sensitivity index (Figure 5b). The Basque Country had the largest demersal fleet power among all the regions studied, which justifies its position as the second most sensitive region in terms of its fishing fleet. As these two regions are located in the Atlantic, the mean fisheries sensitivity of the Atlantic area was generally higher than that of the Mediterranean area (Figure 5b). However, no significant difference was found between Atlantic and Mediterranean areas (Wilcoxon $\rho = 0.867$, $p < 0.05$).

In terms of species sensitivity Murcia, Valencia and Andalusia were the most sensitive regions, pointing to a more sensitive pattern for the Mediterranean area (Wilcoxon $\rho = 0.493$, $p < 0.05$; Figure 5c) mostly due to the differences in the mean price of the main commercial species. Our analyses have shown that the regions with the least adaptive capacities were the Balearic Islands and Murcia (Figure 5d). The results showed a distinct pattern between the Atlantic and Mediterranean regions (Wilcoxon $\rho = 0.025$, $p < 0.05$), with a lower adaptive capacity in the Mediterranean region mainly due to the lower number of landing ports, and the lower landings of species of low commercial value (Figure 5d), both indicators being relatively higher than in the Atlantic regions.

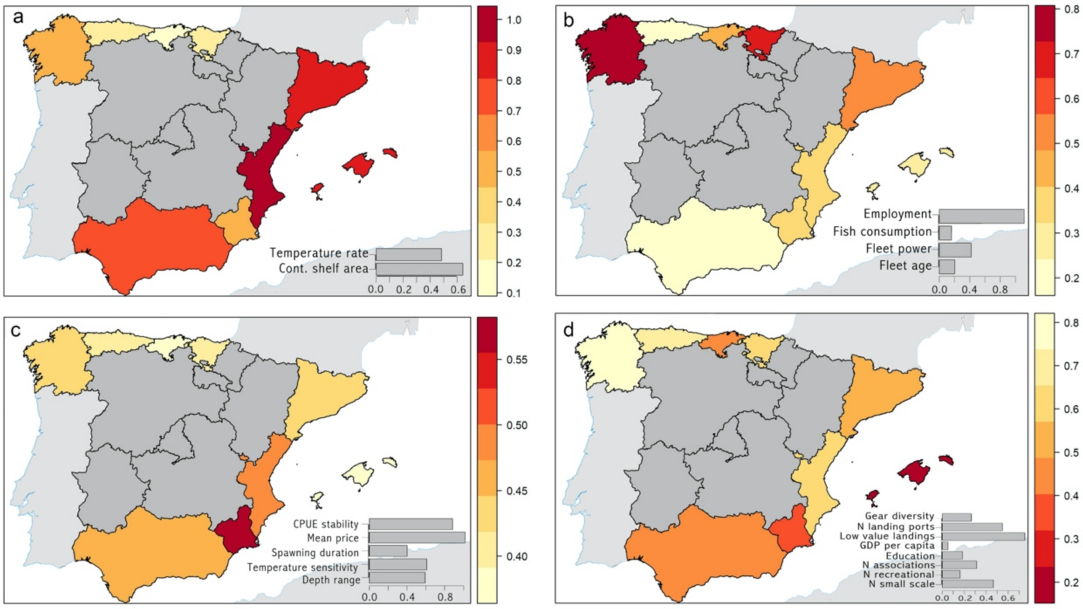

Figure 5. Thematic maps illustrating Exposure (a), Fisheries Sensitivity (b), Species Sensitivity (c) and reverse Adaptive Capacity (d) of the Spanish coastal regions (see scale bar; darker colours indicate higher scores associated with higher sensitivity, higher exposure, and lower Adaptive capacity). The grey bars indicate the weight of each indicator in constructing the indexes considering their respective Coefficients of Variation.

In the Mediterranean area Valencia, Balearic Islands, Catalonia and Andalusia emerged as the most vulnerable regions, while the less vulnerable regions were in the Atlantic, i.e., Cantabria, Asturias and Basque Country (Figure 6). These results highlight the generally higher vulnerability of Mediterranean demersal fisheries (Wilcoxon $\rho = 0.026$, $p < 0.05$), partly due to the lower adaptive capacity of Mediterranean regions and their higher exposure. Galicia was an exception in the Atlantic, with intermediate vulnerability values associated with relative higher exposure (a broad continental shelf) and high fisheries sensitivity (Figure 6).

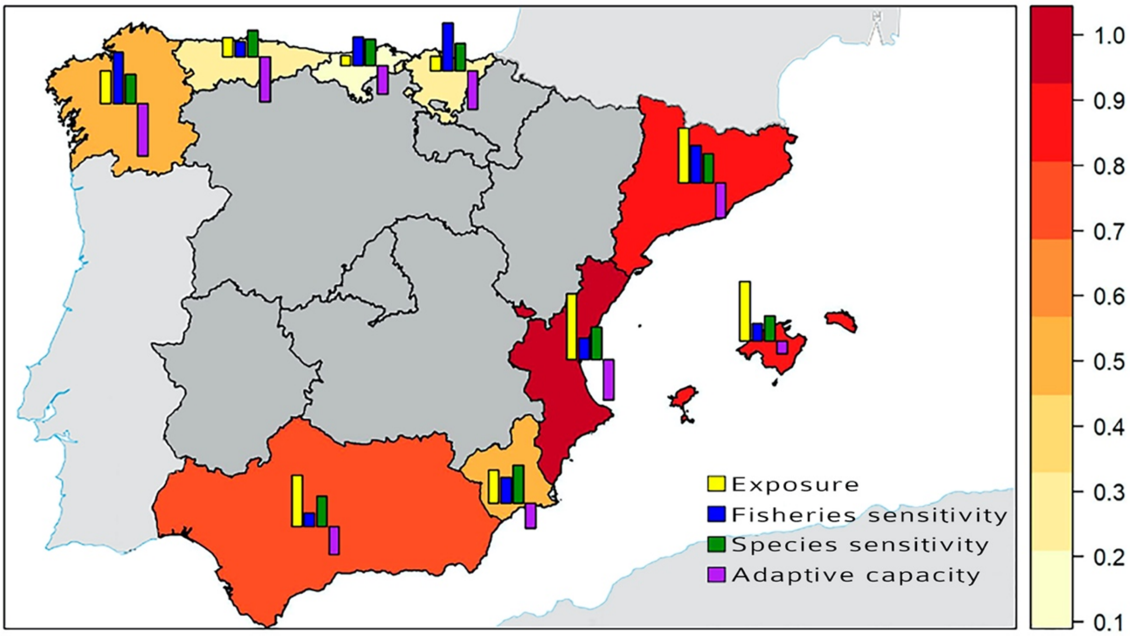

Figure 6. Map illustrating climate vulnerability for each Spanish coastal region based on combined scores for all four attributes (E, FS, SS, AC). The vulnerability index is rated between 0 and 1 (see scale bar; darker colours indicate higher scores associated with higher vulnerability).

Discussion

Our study conducted a CVA at the regional level based on 19 indicators of exposure, adaptive capacity, and demersal fisheries and species sensitivity. The work sought to balance the vulnerability of species' biological traits and each region's specific socio-economic characteristics, highlighting each coastal region's capacity to be resilient against the observed and expected diversity of climate change impacts. Despite the increasing number of CVAs (and CRAs), there is a general lack of assessments specifically considering socio-economic and ecological uniqueness at regional scales, particularly in the European regions. This research gap could be related to the results of previous CVAs performed at the national level, which indicated a generally low vulnerability of the European continent to the risks of climate change, mostly due to its greater adaptive capacity, when compared to less economically developed regions (Allison et al., 2009; Ding et al., 2017). However, recent examples show the need to downscale CVAs (e.g., Pinnegar et al, 2019), mainly when designing effective management approaches

(Holsman et al., 2019, 2020). In this regard, the European regions present unique challenges in terms of climate risks on a regional scale (Payne et al., 2020), requiring further detailed analyses at a finer resolution. Within Europe, Spain emerges as one of the countries with the most vulnerable fishing sector, despite recent studies at a sub-national level that point to intermediate vulnerability values for the Spanish coastal regions (Payne et al., 2020). Beyond clear Atlantic-Mediterranean differences, our study also revealed and characterised previously unknown spatial differences in demersal fisheries vulnerability, of concern to national and international bodies in charge of the development of climate change adaptation plans.

Our results point to a generally higher exposure of the Mediterranean coastal regions to climate change risk, than is the case for the Atlantic regions. Indeed, sea surface warming has been more rapid in the Mediterranean Sea than in the Atlantic in the last decades (e.g., Belkin, 2009) and these contrasting warming rates are predicted to persist (Adloff et al., 2015; Aznar et al., 2016). Temperature predictions are also the most widely accepted output of climate forcing models and have good short to medium-term predictive power (e.g., Aznar et al., 2016). However, other climate change related factors such as acidification, changes in rainfall and, frequency and intensity of extreme meteorological events such as hurricanes or cyclones are not so ubiquitous in the CVA literature, even though they can have clear effects on fisheries vulnerability (Colburn et al., 2006; Metcalf et al., 2015; Wabnitz et al., 2018; Pinnegar et al., 2019). This is a limitation for most CVA, which fail to incorporate additional climate factors as these often lack regionalised projections under climate change scenarios. Thus, in addition to the predicted temperature trends, we considered the continental shelf area of each coastal region to account for other climate change-related factors. Indeed, the relatively broader shelf areas in most Mediterranean regions leave their demersal biological communities and fisheries more exposed and thus more vulnerable to the diversity of impacts expected to increase in the Mediterranean, such as the increase of extreme events and heatwaves, changes in vertical mixing and productivity regimes, or changes in the regional circulation and population connectivity (Hidalgo et al., 2018; Darmaraki et al., 2019; Ser-Giacomi et al., 2020, MedECC 2020). In contrast, CVAs published on European fisheries do not capture this difference, since the exposure indicators considered were different and mainly focused on the diversity of the portfolio of species captured as an indicator of fishery resilience (Payne et al., 2020). This metric is highly relevant over large geographic scales (i.e., broad Europe) as it captures the differences between regions with low diversity of fish in the catches, such as the northern European countries, and the high diversity in southern Europe. However, within the national scale, the number of species captured in different regions would generally be more similar, as is the case in Spain (Punzón et al., 2020).

Fisheries sensitivity proved to be mostly related to the number of jobs in the extractive sector, with Galicia being the most sensitive region in this regard at the national level (STECF, 2019a). The important fishing tradition in Galicia has led to the development of maritime industry that includes activities such as processing and manufacture of canned fish, crustaceans and molluscs. The relevance and socio-economic impact of these activities, have made the fishing sector one of Galicia's main economic drivers. Indeed, employment dependency, either directly as the number of jobs or indirectly as the percentage of the active population within the fisheries sector, is the most widely used attribute for exploring fisheries sensitivity (Allison et al., 2009; Morzaria-Luna et al., 2014; Ding et al., 2017; Wabnitz et al., 2018; Pinnegar et al., 2019). However, it is also important to notice the high spatial heterogeneity in other factors beyond employment that contribute to fisheries sensitivity. As an alternative to the number of fishing boats or licenses (as in Colburn et al., 2006; Morzaria- Luna et al., 2014), which might correlate with the employment dependency, we considered two attributes related to fleet capacity, i.e., the mean age of the fishing vessels and their mean power. Fleet age can be considered a proxy for efficiency in fishing and fuel consumption. The demersal fishing fleet in Spain is generally above 20 years mean age, with several Mediterranean regions approaching 40 years mean age, double the life expectancy for this kind of fishing vessel (Knittweis et al., 2016). An old fishing fleet will suffer from physical deterioration and normal obsolescence, decreasing its capacity to cope with change because it is technologically outdated. While the fishing fleet in Europe has been generally aging and reducing its size in the last decades, fishing power is still increasing in most countries (Rousseau et al., 2019). Fishing power is highly correlated with tonnage and depicts how much a vessel can fish. While the variability in fleet age is moderate, there is high variability in fishing power, with few coastal regions having a larger share of more powerful industrial vessels, both in the Atlantic and Mediterranean (i.e., Basque Country, Catalonia and Valencia). On the other end, Galicia shows the lowest fishing power, as a large percentage of its fishing fleet is composed of small-scale fishing vessels (MAPA, 2019). Another important factor considered in our study was the consumption of fish protein as a measure of nutritional dependence. The Atlantic regions presented higher results than Mediterranean ones.

Regarding species sensitivity, the Atlantic-Mediterranean pattern was not as evident. Species sensitivity was the least variable index, pointing to the crucial role of socio-economic differences in explaining fisheries vulnerability patterns among regions. While about 15% of species in both Atlantic and Mediterranean regions showed high sensitivity (>0.6), their contribution to the overall community sensitivity was low, as they were not among the most abundant species captured by demersal fisheries. Species sensitivity is closely associated with biological and ecological species traits pertaining to their distribution and life-history (Musick, 1999), which was relatively similar between species captured in the Atlantic and Mediterranean. Indeed, the species captured in higher abundances ranked as having low or moderate sensitivities, which reduced species sensitivity index variability among regions. In contrast, to the most used temperature statistics (i.e., maximum preferred temperature ranges [TP90]) (as in Sunday et al., 2015; Hare et al., 2016; Pinnegar et al., 2019), we combined mean and temperature range attributes in an easily computed and broadly applicable indicator of temperature sensitivity. This allowed us to identify species-specific sensitivities within the Atlantic and Mediterranean regions, though not differences between regions. It is important to highlight the difference in species-specific responses to climate change impacts on the marine environment. This reinforces the need for regional studies linking species and climate change all over different ontogenetic stages in order to produce better and more efficient management plans (Catalán et al., 2019; Holsman et al. 2019, Twiname et al., 2020). In addition to the most widely used distribution and phenology parameters such as the depth range and spawning time, which are important as resilience indicators (Sunday et al., 2015; Hare et al., 2016), we also estimated the stability of the stocks through the CV of their landings. Together with landing stability, the price analysis emerged as a tool to highlight the pressure suffered by each fish stock, considering that the species with the highest commercial value are therefore subject to higher exploitation rates and will be more vulnerable to climate change risks (Pinnegar et al., 2019; Hiddink et al., 2019). The Mediterranean area has shown itself to be slightly more sensitive, and this could be related to the market characteristics of some of its regions (i.e., the Balearic Islands), which operate in a market that is more local and therefore more restricted compared to the Atlantic region, influencing its ability to compete in terms of prices and product varieties.

Another important factor that marked the difference in the vulnerability index between Atlantic and Mediterranean areas was adaptive capacity, driven partially by lower levels of landings of species of low commercial value in the Mediterranean regions. This could be explained due to the combination of a lower availability of these species and the fact that they are mostly consumed as a proximity fisheries product, as opposed to what occurs in the Atlantic, where there is a higher availability of these species, a higher contribution of catches from other European fishing areas and a higher contribution and supply to the national market (STECF, 2019a). A larger catch of low commercial value species can be related to a greater capacity to adapt, since the fishery is less dependent on a small group of high commercial value species that are under greater fishing pressure. The capture of species of lower commercial value emerges as an alternative when the species of higher value may suffer from the impacts of climate change such as change in distribution and changes in biological patterns. Other indicator that provides flexibility is the possibility of landing part of the catch in different ports, which allows the fleet to adapt in the face of difficulties and impacts associated with climate change, such as adverse weather (e.g., extreme events), but also providing the possibility of taking advantage of better market opportunities. The combination of these two indicators also explains the lower adaptive capacity in Mediterranean area and particularly the Balearic Islands region, indicating a great dependency of a local and more constrained market (UE, 2011). The transition of fishing crews from large-scale fishing to artisanal fishing and the recreational fishing sector has also been considered an important indicator of adaptation capacity. In this context, the Atlantic region of Galicia shows an adaptative advantage over the other regions with a much larger artisanal fishing fleet that provides more opportunities for the workers to move around within the fishing sector in order to guarantee their profits and livelihood (Gordoa et al., 2019). Note than some indicators could benefit from scaling up by making their values relative to size of other indicators improving the perception of the size to the opportunity (e.g. ratio between recreational and small-scale fishery). However, with the methodological approach taken, this would increase correlation with other indicators affecting the interpretation of our results.

The overall vulnerability index showed a clear pattern between the Atlantic and Mediterranean areas and regions within these two areas. The results for each region are unique in the combination of their dependence on the fishing sector, socio-economic development, and exposure to climate risks regionally. Nevertheless, some regions demand more specific studies due to their biogeographic complexity. For example, Andalusia presents a more pronounced geographical heterogeneity than other regions with part of its territory on the Mediterranean and part on the Atlantic, calling for more specific vulnerability studies for this region which consider its uniqueness. Using demersal fishing on the Spanish coast as an example, the present study highlights the importance of regional scale analyses to achieve more refined diagnoses in climate vulnerability assessments. These studies may be instrumental in supporting decision-making at both national and international levels, as the design of efficient adaptation management strategies requires cross-scale risks (including exposure, sensitivities and differences in adaptive capacities) (Holsman et al., 2020). Future analyses should be conducted to explore the complexity of natural and socio-economic systems, their interactions and their trade-offs. This shows that customised fisheries adaptation planning is urgently needed at the regional level, given that the expected large-scale policies may limit flexibility and compromise their effectiveness (Holsman et al., 2019, 2020). Management results can be more effective when they adopt dynamic measures that locally consider social and environmental variability (Levin et al., 2013). Besides the possibility of not achieving the expected results, the adoption of large-scale adaptation planning can lead to a lack of confidence in fisheries management even within well-managed systems (Levin et al., 2013; Mumby et al., 2017). While the spatial scale for CVA should minimise the complexity and variability (spatial heterogeneity) in the socio-ecological system within its analysis unit, it must be relevant and operational for management purposes. With this in mind, our study calls for a more detailed consideration of the intra-national vulnerabilities in other countries to reveal additional and important socio-ecological sources of fisheries vulnerability to climate change.

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