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Eco-socio-economic vulnerability assessment of Portuguese fisheries to climate change

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ABSTRACT

Understanding ecological, and socio-economical vulnerabilities is fundamental towards developing and implementing regional adaptation strategies to climate change. The Portuguese coast is situated in a transition zone between temperate ecosystems to the north, and subtropical with Mediterranean characteristics, to the south, with distinct oceanographic regions (north, centre, and south), fish assemblages and socioeconomic realities of fish communities across these regions. We develop a framework to assess fisheries climate vulnerability in each port. A total of 32 ecological and socio-economic indicators were used to measure exposure, sensitivity, and adaptive capacity of the fishing sector to climate change by combining i) environmental projections ii) information from fishing communities (surveys at ports) and iii) landings and socio-economic data from official statistics offices. The vulnerability to climate change across regions, and its expected impact on fishing fleets and local communities, was low-moderate. Such information will enable fishing communities and decision makers to respond to expected climate change effects and direct/indirect associated activities. This framework comprises background information for developing mandatory EU climate adaptation plans that aim to improve the resilience of fisheries socio-economic systems.

1. Introduction

Historically, oceans have provided human societies with a vast array of services, goods, and commodities, ranging from transportation to climate regulation, and from cultural nourishment to food resources (Palumbi et al., 2009; Stocker, 2015; Payne et al., 2021). Worldwide, nearly 250 million people are employed in the fisheries and aquaculture sector, including processing and marketing, and an estimated 59 million are engaged directly, full-time, or part-time, in capture fisheries (FAO, 2020). In 2017, nearly 3.3 billion people relied on fish for over 20% of their average protein intake, up from about 2.6 billion in 2007 (FAO, 2007; FAO, 2020), showcasing an increased trend in fish protein consumption worldwide. Numerous studies have attempted to raise awareness on how climate change (CC) is affecting oceans, and with it, the fisheries industry (Cochrane et al., 2009; Jones et al., 2015; Lam et al., 2016). Warming of the oceans has been linked to changes in the structure of ecosystems (Melo-Merino et al., 2020; Moura et al., 2020), from community compositions and marine productivity, to the distribution of marine species (Lima et al., 2022) and their capacity for growth and survival (Murciano et al., 2021). Thus, CC is expected to impact countries and fisheries in different ways, leading to regional impacts tightly connected to local socio-economic and environmental factors (Allison et al., 2009; IPCC, 2012; IPCC, 2014; Payne et al., 2021; Aragão et al., 2022).

Fisheries provide sustenance to many communities worldwide, often being the sole activity generating revenue, especially when considering local or small-scale fisheries (SSF) dependent communities, where fishers work from small boats in inland or coastal waters employing many different types of fishing gear (Allison and Ellis, 2001). Globally, most fishers are inserted into SSF but, despite being very numerous, they are often placed far from regional, national, or global decision-makers (FAO, 2020), with their opinion often unheard. In the foreseeable future, owing to several causes, such as pollution, habitat degradation, unsustainable fisheries, CC, and decadal variability, more fishers will be placed in precarious situations, as global marine fisheries appear to be on an economic downturn (Hare et al., 2016; Murciano et al., 2021).

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Indeed, in >50% of the world's countries, fishers wages fall below medium-living-wages (Giron-Nava et al., 2021). Assessing impacts from the above-mentioned sources, it is ever more important to help the transition into sustainable fisheries. To address this issue, climate vulnerability assessments (CVA) have been widely applied.

CVAs are an analytical framework specialized in understanding, quantifying, and synthesizing CC impacts on socio-ecological systems (IPCC, 2001). In this type of framework, "vulnerability" is generally calculated as a function of three components: "exposure" to climate hazards and "sensitivity" to CC, which are summed, and the "adaptive capacity" (AC), which considers the ability that a given community has to adjust or take advantage of potential effects related to CC, which is subtracted (IPCC, 2019). Generally, CVAs are applied to a system at different levels of organization (global, nation, local, etc.), aiming to identify the most vulnerable components of the systems and how best to deal with them (Hare et al., 2016). In this way, CVAs provide decision makers with key information to undertake practical measures directed at lowering the vulnerability of social-ecological systems (Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2021; Aragão et al., 2022). To quantify exposure, sensitivity, and AC, CVAs use indicators. The choice of indicators is perhaps one of the most important stages when implementing CVAs. According to (Monnereau et al., 2017), choices in the implementation of vulnerability assessments can influence the perception of which groups/regions are most vulnerable. Indeed, most critics of existing vulnerability assessments point to conceptual weaknesses ranging from lack of focus, arbitrariness, or a weak conceptual framework, to methodological flaws and limited data availability (Eriksen and Kelly, 2007; Füssel, 2009; Park et al., 2012; Monnereau et al., 2017). To minimize and avoid these problems, proper planning must go into the stage of selecting and creating each indicator. It is fundamental that, via one or more indicators, the elementary aspects of the fisheries sector of a given region are covered, while also tapping into its unique ecological and socio-economic characteristics and intrinsic needs and complexities. For instance, when addressing the ecological component, we must consider that different species will present different levels of vulnerability to CC (Bueno-Pardo et al., 2021; Albo-Puigserver et al., 2022). Considering the socio-economic component, we need to ponder on different communities having different needs and resource availabilities, which translates into different capacities to cope with CC (Murciano et al., 2021). These differences often arise due to a combination of variables which can be physical (i.e., spatial segregation or geographical gradients), social (i.e., human capital, local demographics, or social connections), or information related (i.e., management of resources or community knowledge) (Murciano et al., 2021; Aragão et al., 2022).

Portuguese fisheries exhibit a high diversity of commercially relevant species found at low abundances, albeit some small pelagics, such as sardine (*Sardina pilchardus*), mackerel (*Scomber colias*), and horse mackerel (*Trachurus trachurus*), are the dominant captures (PSOEMN-2019 Volume III-C/PCE, n.d.). The Portuguese fisheries sector operates mostly near-shore, landing a very diverse species portfolio (Sousa et al., 2005), thus taking advantage of the diversity of the ecosystems (PSOEMN-2019 Volume III-C/PCE, n.d.). These characteristics include many SSF, coastal and estuarine (Leitão and Baptista, 2017), who also exhibit a strong cultural link, where several fishing communities still see fishing as a family tradition (Pita and Gaspar, 2020). This occurs most often with boat-owners, who incentivize their children to get into fisheries, passing boat ownership to them as a family "legacy". These cultural views increase the importance and relevance of fisheries as a socio-economic activity (Leitão and Baptista, 2017). Effectively, these coastal communities are very dependent on fisheries in cultural and socio-economic manners. Furthermore, the high per capita consumption of fisheries products in Portugal is among the world's highest, above 50 kg per capita (FAO, 2020), revealing the need for fisheries to continuously provide national markets with fish (Leitão and Baptista, 2017). Despite being a relatively small country, regional differences are also present in the Portuguese fisheries sector, and these are most evident in the trawl and artisanal fisheries. Portuguese trawlers in the north and centre areas mostly focus on fish, while in the south, many trawlers target crustaceans. Considering artisanal fisheries, the most noticeable difference is related to vessel size, with larger vessels in the north than in the south of the country.

Previous fisheries vulnerability assessments have highlighted the need to account for local differences between fishing communities (Payne et al., 2021; Aragão et al., 2022). However, in Portugal, specific assessments at local level have not yet been conducted. Therefore, the objective of this study was to perform an assessment of the eco-socio-economic vulnerability to CC of the continental Portuguese fishing sector at the local level. Specifically, we developed 32 indicators to evaluate the dimensions of vulnerability (exposure, sensitivity, and AC) of the Portuguese fisheries, and identify the aspects that contribute most to the vulnerability and the differences between regions. We combined qualitative and quantitative data obtained from official fisheries databases and from interviews to fishers. Considering oceanographic/environmental variability (Cunha, 2001; Bettencourt et al., 2004), fish assemblages (Sousa et al., 2005), and socio-economic spatial variability described along different regions of the Portuguese coast (Pita and Gaspar, 2020), we hypothesise that different degrees of vulnerability exist along the Portuguese coast. Additionally, the present framework allowed the identification of factors explaining the vulnerability of the systems, thus allowing the identification and prioritization of required actions to improve the resiliency of fishing communities to a changing climate.

2. Methods

2.1. Study area

Located in the northeast Atlantic, the continental Portuguese coast is situated in a transition zone between temperate ecosystems to the north, and subtropical ecosystems, with Mediterranean characteristics, to the south (Cunha, 2001; Bettencourt et al., 2004). In this research, we are specifically working with continental Portugal, thus fisheries in Madeira and the Azores islands were not considered. In the present analysis, the Portuguese coast was split into 3 regions, north, centre, and south, according to oceanographic conditions (Cunha, 2001; Bettencourt et al., 2004) and fish assemblages' composition (Sousa et al., 2005; Leitão et al., 2014; Teixeira et al., 2014). Considering the main fishing ports, the northern region spans from the port of Viana do Castelo until the port of Peniche, and the centre region from the port of Sesimbra until the port of Sines, thus covering the whole Portuguese western coast. The southern region, which encompasses the coast of Algarve, goes from the port of Sagres until the port of Vila Real de Santo António.

2.2. Data source and indicators selection

The ecological and socio-economical components of vulnerability (exposure, sensitivity, and AC) of 17 coastal fishing communities (ports) were evaluated. To measure the ecological and socio-economical components of vulnerability of the Portuguese fishing sector, we developed 32 indicators, categorized in 13 subdimensions (A-M) (see supplementary material (A1) for the full development criteria and categorization of indicators). To develop the indicators, we combined qualitative and quantitative data obtained from available national statistics sources (links for indirect data sources provided in supplementary material A1) and from individual interviews with fishers (direct data sources). Whenever possible, indirect data were obtained at local or regional level. Indicators were defined based on previous studies that applied Climate Vulnerability Assessments (Martins and Gasalla, 2020; Payne et al., 2021). The final list of indicators were selected considering the ecological, socio-economic and cultural context of the Portuguese coastal fishing communities and data availability (see supplementary

Material 1 for the definition and rationale of each indicator).

Direct data from fisheries, for each fishing community along the Portuguese coast, were obtained in two field surveys (Fig. 1). Field surveys were conducted mainly in ports or the port vicinity (< 3 km distance from the port). Interviews were performed individually, with fishers using 2 methods: the snowball sampling method (Bailey, 1982), where fishers or representatives of fisher associations indicate other fishers to be contacted and, by looking for fishers who were present at the location at that specific time (chosen randomly). Surveys were conducted between September 2020 and July 2021 and covered all the ports identified in Fig. 1. No >1 enquiry was performed for a given vessel. The interviews mostly targeted vessel owners/captains, as we considered these to be better positioned to answer specific questions related to the expenditures and benefits of their activities.

Field interviews (supplementary material A1) consisted of 33 questions structured as follows: 29 close-ended questions, where the fisher picked one choice and, 4 open-ended questions, where the fisher could pick >1 option or the answer was a direct reply. This survey intended to cover, for instance: economic and cultural dependencies; current fishing practices and policies; activity perception and ecological/socio-economical knowledge, etc. Information obtained in the interviews was used in the development of indicators. One indicator can use several questions, but the same question is not used twice with the same purpose (supplementary material A1). To define the indicators and sub-dimensions, the step-by-step-process used in previous socio-ecological vulnerability assessment was followed (see supplementary material A1; Johnson et al., 2016; Martins and Gasalla, 2020). All data related to field enquiries was pooled to ensure individual anonymity and confidentiality. All the indicators, vulnerability subdimensions, and vulnerability dimensions (exposure, sensitivity, and AC) were computed, standardized, and combined using R Software (R Core Team, 2021) and the packages "diverse" (Guevara et al., 2016), "dplyr" (Wickham et al., 2023), "ggplot2" (Wickham, 2016), "ggrepel" (Slowikowski, 2022), "ncdf4" (Pierce, 2023), "raster" (Hijmans and Etten, 2012) "sf" (Pebesma and Bivand, 2023) and "vegan" (Oksanen et al., 2022).

2.3. Climate vulnerability assessment framework

The Climate Vulnerability Assessment framework (CVA) (see graphical abstract) was developed based on several sources: the framework proposed in the third and fourth IPCC assessment reports (IPCC, 2007), the modifications proposed in Cinner et al. (2013), and other peer-reviewed scientific literature (Mamauag et al., 2013; Johnson et al., 2016; Nguyen et al., 2016; Pinnegar et al., 2019; Lazzari et al., 2021; Payne et al., 2021).

2.4. Exposure

Exposure is defined as the degree to which a system is likely to experience climatic stress (IPCC, 2019). Depending on the perspective of the analysis to be performed, exposure can be assessed using different types of indicators. When considering ecological vulnerability, oceanographic variables are widely used to compute the exposure component, as they influence the overall productivity of the ecosystems (Allison

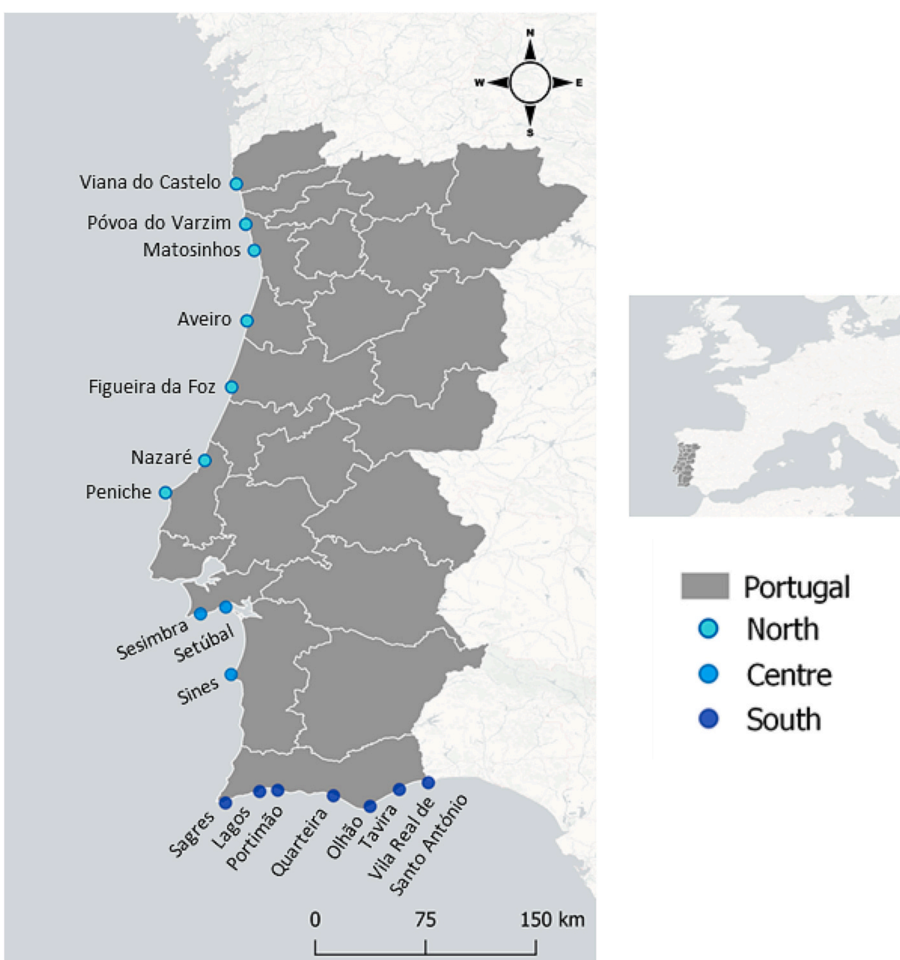

Fig. 1. Division of the Portuguese continental coast. Location of the main Portuguese fishing ports are indicated with dots, with their colour indicating the region, with ports in the north region in light blue, centre in blue, and south in dark blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2009; Pinnegar et al., 2019). When addressing socio-economic vulnerability, we must account for two different sources of exposure: the exposure of the catch, which consists of the above-mentioned ecological vulnerability (Cinner et al., 2013), and the environmental exposure of fishers, where physical variables directly impact the fishing activity through impacting fishing infrastructures, such as ports, or limiting the number of days with good weather conditions (Heck et al., 2020).

In the present framework, exposure was computed from a combination of 4 indicators grouped in 2 subdimensions: ecological exposure (A, 2 indicators) and environmental exposure (B, 2 indicators). Ecological exposure indicators included the vulnerability and the potential distribution changes of the fisheries landings of each fleet and port (Bueno-Pardo et al., 2021; Albo-Puigserver et al., 2022). Environmental exposure was based on available projection maps of coastal vulnerability to sea level rise (Antunes et al., 2017; Antunes, 2019; Antunes et al., 2019; Rocha et al., 2020) and changes in the frequency of extreme winds (see supplementary material (A1) for the detailed procedure used to estimate exposure indicators).

2.5. Sensitivity

Sensitivity is described as the extent to which a system can be impacted by CC, either adversely or beneficially (IPCC, 2019). The effect of sensitivity can be estimated considering both intrinsic and external characteristics of the unit of analysis (IPCC, 2001), with sensitivity indicators ranging from political status to economic and cultural dependencies (Cinner et al., 2013; Barnes et al., 2020), and including various trends of fisheries landings (Pinnegar et al., 2019)

In this framework, to account for the general sensitivity to CC, we used a combination of 13 indicators, grouped into 5 subdimensions: Social dependence on fishing (C, 2 indicators); Economic dependence on fishing (D, 3 indicators); Cultural importance of fishing (E, 1 indicator); Trends and characteristics of the fisheries portfolio (F, 5 indicators) and Fishing policy and management (G, 2 indicators) (see supplementary material (A1) for the detailed procedure used to estimate sensitivity indicators).

2.6. Adaptive capacity

Adaptive capacity (AC) encompasses the inherent ability of a given system to withstand or cope with potential damages (moderate or extreme) derived from CC (IPCC, 2019). When estimating AC, factors such as human capital (Allison et al., 2009), economic performance of communities and countries (Allison et al., 2009; Pinnegar et al., 2019), government performance (Heck et al., 2020), and livelihood diversification (Mamauag et al., 2013; Lazzari et al., 2021; Aragão et al., 2022) should be considered.

In this framework, to calculate the AC of Portuguese fisheries to CC, we used a combination of 15 indicators, grouped into 6 subdimensions, as follows: Human capital (H, 1 indicator); Occupational flexibility (I, 3 indicators); Attitude, perception and personal flexibility (J, 4 indicators); Institutional presence and performance (K, 2 indicators); Economic performance (L, 4 indicators); and Local ecological and socio-economical knowledge (M, 1 indicator). The detailed procedure used to estimate AC indicators and data sources are provided in supplementary material (A1).

2.7. Vulnerability estimation

In the present CVA, we divided the fisheries sector into three different fleets, for which vulnerability was calculated separately: 1) the multigear fleet, which mostly coincides with artisanal fisheries (includes gears such as longlines, gill nets, traps, etc.); 2) the seine fleet which is also an artisanal fishery in Portugal and operates purse-seine nets exclusively and, 3) the trawl fleet which is an industrial fishery which operates bottom trawl only.

Vulnerability was calculated at port level for the multigear fleet. In the cases of seine and trawl, data were not always available by port and these fleets present a high mobility, so vulnerability was calculated at the region level (north, centre, and south, see Fig. 1). Vulnerability comprises the combination of exposure, sensitivity, and AC as described in the equation bellow:

Vulnerability = Exposure + Sensitivity – Adaptive Capacity

Since each subdimension is standardized between 0 and 1 prior to the calculation of the vulnerability, the initial vulnerability values can range from − 1 to 2. Nevertheless, the final vulnerability score of each port or region is provided between 0 and 1 after standardization. Finally, to facilitate the communication of results, we assigned different categorical values to the vulnerability score following these criteria: **very low – [0–0.2 [; low – [0.2–0.4 [; moderate – [0.4–0.6 [; high – [0.6–0.8 [and very high – [0.8–1]**

2.8. Data analysis

Pearson correlation was used to test the influence of each dimension (exposure, sensitivity, and AC) on vulnerability. Correlations were considered significant when *p*-value <0.05. To visualize similarities among areas (seine and trawl fleets) and among ports (multigear fleet) regarding vulnerability subdimensions, we performed a cluster analysis based on a Euclidean similarity matrix, grouping the data based on the association of each pair of samples. Euclidian distance was computed using the Paired group (UPGMA) algorithm.

Using the statistical software PRIMER, a One-Way Similarity Percentages (SIMPER) test was performed to identify the vulnerability subdimensions that most explain differences among areas and fishing fleets. A 90% cut off was applied for SIMPER analyses.

3. Results

A total of 542 interviews were conducted between October 2020 and July 2021, distributed across fleets and ports, as follows: (Supplementary Table B1): 383 (70.66%) interviews performed in the multigear fleet, 92 (16.97%) interviews performed in the seine fleet, and 67 (12.36%) interviews performed in the trawl fleet. According to the fisheries statistics for 2021 (INE 2021), the multigear fleet is composed of 5995 fishing vessels, the seine fleet is composed of 195 fishing vessels, while the trawl fleet is composed of 82 vessels. As such, the surveys covered a considerable proportion of the population of Portuguese fishing vessels: 6.39% of the multigear fleet, 52.87% of the seine fleet, and 81.70% of the trawl fleet. More surveys were performed in the northern area than in the central or southern areas, regardless of the fleet, which also reflects the reality of the country regarding fleet distribution, with more vessels registered in the northern ports than in the central and southern ports.

3.1. Vulnerability

CC vulnerability of the Portuguese fisheries sector presented no clear latitudinal north-south trend, and the estimated values were similar across different ports/areas (Fig. 2). For all fleets (multigear, trawl and seine) and areas (north, centre and south), vulnerability scores were low to moderate (Fig. 2). The multigear fleet vulnerability scores ranged between 0.35 at the port of Figueira da Foz, and 0.46 at the port of Sagres, with an average vulnerability score of 0.41 (Fig. 2). In the seine fleet, vulnerability scores ranged between 0.36 in the north, and 0.45 in the centre, with an average vulnerability score of 0.40 (Fig. 2). In the trawl fleet, vulnerability scores ranged from 0.38 in the south to 0.42 in the centre, with an average vulnerability score of 0.39 (Fig. 2).

Vulnerability was negatively correlated with AC and positively correlated with exposure, while correlations between vulnerability and sensitivity were not significant (Table 1). The correlation between AC

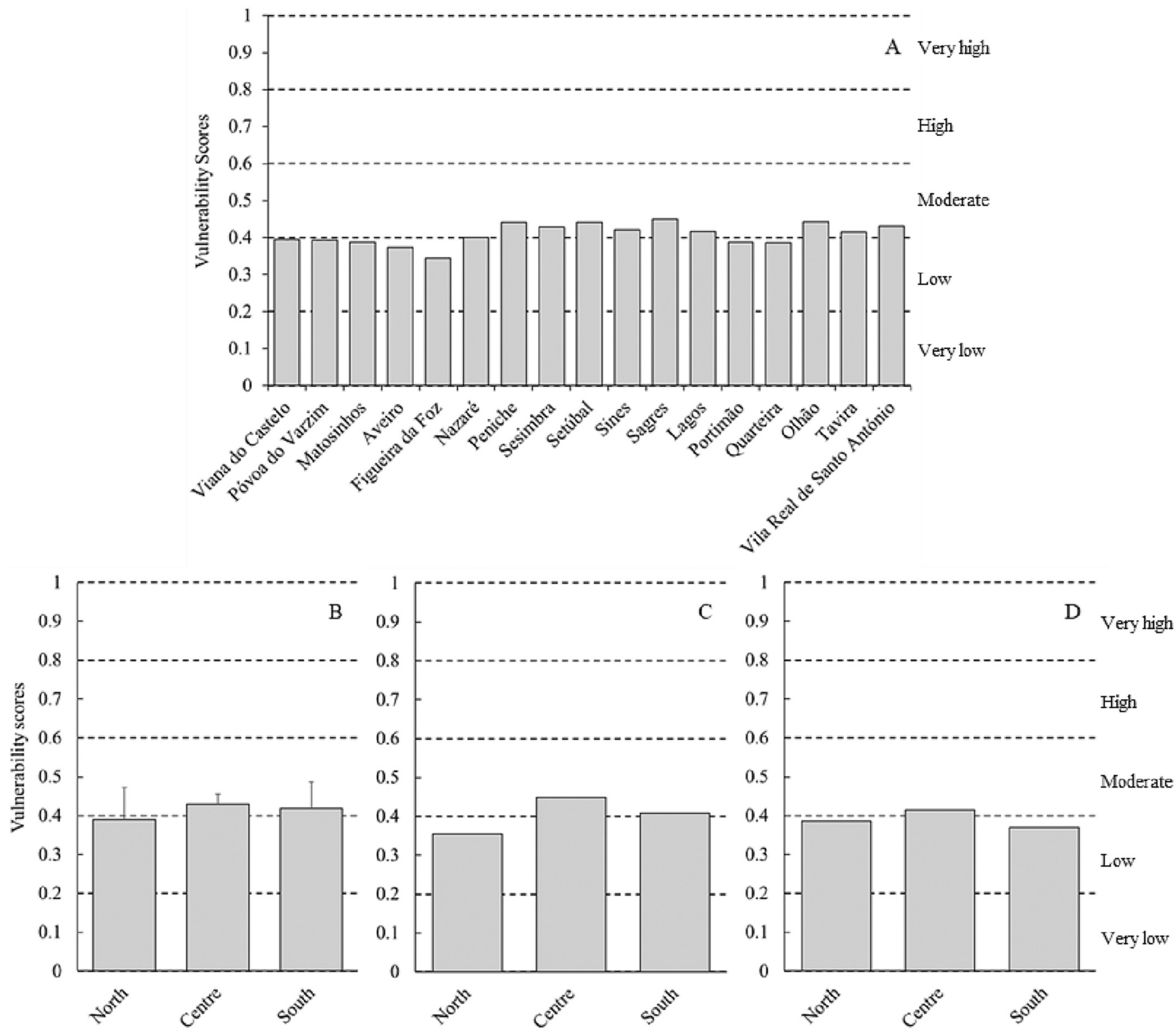

Fig. 2. Vulnerability of the Portuguese fisheries sector estimated for each port for multigear (A) and by area, for multigear (averaged) (B), seine (C) and trawl (D). Vulnerability is presented in a 0–1 scale, where 1 represents the most vulnerable ports/areas and 0 represents less vulnerable ports/areas. Bars represent standard deviation and dotted lines separate the following vulnerability categories: very low – [0–0.2[; low – [0.2–0.4[; moderate – [0.4–0.6[; high – [0.6–0.8[and very high – [0.8–1].

and vulnerability is stronger than the correlation between exposure and vulnerability (Table 1).

3.1.1. Vulnerability subdimensions

For each dimension, the subdimensions with the highest contributions to vulnerability were: Ecological exposure within exposure, Economic dependence on fishing within sensitivity, and Attitude, perception, and personal flexibility within AC (Fig. 3). Considering that vulnerability equals exposure plus sensitivity minus adaptive capacity, values of AC close to 0 have the highest contribution to vulnerability.

Considering the different fleets separately, in the case of the multigear fleet, exposure scores were highest for the ecological exposure in the south area, while the highest sensitivity scores were registered for economic dependence on fishing in the centre area. The highest AC scores were registered for local knowledge in the south area.

In the seine fleet, the highest exposure scores were registered for ecological exposure in the centre area, while the highest sensitivity scores were registered for economic dependence on fishing in the centre area. The highest AC scores were registered for human capital, in the north area.

For the trawl fleet, exposure scores were highest in the ecological exposure in the north area, while economic dependency on fisheries, also in the north, registered the highest sensitivity scores. Human capital in the north and south areas registered the highest AC scores.

For the multigear sector, the cluster analysis grouped ports into two main groups based on the scores of the vulnerability subdimensions (Fig. 4). However, none of these groups included ports exclusively from a single region (north, centre or south). For the seine and trawl fleets, the cluster analysis also created two different groups. For the seine north fleet, vulnerability structure differed from the centre and south by a 0.8 distance. For trawl centre fleet, vulnerability structure differed from the north and south by a 0.8 distance.

The SIMPER analysis revealed that subdimensions who contributed the most to the dissimilarities among areas, regardless of the fleet, were

Table 1
Distribution of performed field surveys by fleet and port (multigear) / area (seine and trawl).

Multigear	N° of surveys	Seine	N° of surveys
Viana do Castelo	50	North	55
Póvoa do Varzim	17	Centre	20
Matosinhos	15	South	17
Aveiro	31	Total	92
Figueira da Foz	20		
Nazaré	20		
Peniche	40		
Sesimbra	36		
Setúbal	9	**Trawl**	**N° of surveys**
Sines	28	North	43
Sagres	17	Centre	15
Lagos	13	South	9
Portimão	20	Total	67
Quarteira	17		
Olhão	20		
Tavira	8		
Vila Real de Santo António	22		
Total	383	**Total survey N°**	**542**

human capital and economic performance subdimensions (Supplementary Material B, Table B2). The only exception was verified in the seine fleet, where most differences between the centre and south areas were derived from economic dependency on fisheries.

For the multigear fleet, human capital (71%), and economic performance (15%) were the vulnerability subdimensions most contributing to the differences observed between the north and centre areas.

For the seine fleet, dissimilarities between the north and south areas were explained mostly by human capital (76%), which also explained most of the differences between the north and centre areas (80%). Economic dependency on fishing (56%) was the main source of dissimilarity between the centre and south areas for seine.

For the trawl fleet human capital (92%) was the subdimension that explained most dissimilarities between the south and centre.

3.2. Vulnerability dimensions

The exposure dimension presented the overall lowest values, with the only exception being the seine fleet (Fig. 5). In contrast, AC presented the highest values regardless of the fishing fleet (Fig. 5). The lowest exposure scores were registered in the multigear fleet, contrasting with the seine fleet, which registered the highest scores. Opposite to this, in the seine fleet sensitivity, scores were lowest while in the multigear fleet, sensitivity scores were highest. AC registered the highest scores for the trawl fleet and the lowest scores in the seine fleet.

3.2.1. Multigear

For the multigear fleet (Fig. 6A), exposure presented low scores, sensitivity presented moderate scores, while adaptative capacity values were moderate in the centre and south areas and high in the north. Exposure was highest in the south area (0.36) and lowest in the north (0.31). Considering CC sensitivity, the highest scores were registered in the north area (0.49), while the lowest scores were registered in the south area (0.46). Considering the AC of the multigear fleet, it was lowest in the centre area (0.50) and highest in the north area (0.64).

3.2.2. Seine

In the seine fleet (Fig. 6B), AC scored the highest values in all areas. The seine fleet is most exposed to CC in the north area (0.43) and least exposed in the south area (0.38). Its sensitivity is lowest in the centre area (0.33) and highest in the north area (0.43). Highest AC was registered in the south area (0.68) and lowest AC in the northern area (0.51).

3.2.3. Trawl

For the trawl fleet (Fig. 6C), AC was the highest scoring dimension in all areas. Exposure was similar in the three areas (0.38) and sensitivity was lowest in the centre area (0.39) and highest in the north (0.48). AC was highest in the south area (0.69) and lowest in the north (0.51).

4. Discussion

Research on vulnerability assessments has been performed for large scale geographical areas mostly using large-scale data (see Allison et al., 2009; Ding et al., 2017; Payne et al., 2021). In Europe, most assessments do not estimate socio-economic and ecological vulnerability at local scales (Aragão et al., 2022) with some studies underlining the need to downscale large-scale assessments to local-regional scales to provide accurate and efficient support for policy making (Payne et al., 2021; Aragão et al., 2022). In the present Climate Vulnerability Assessment (CVA) we evaluated vulnerability at a port/area level, based on 32

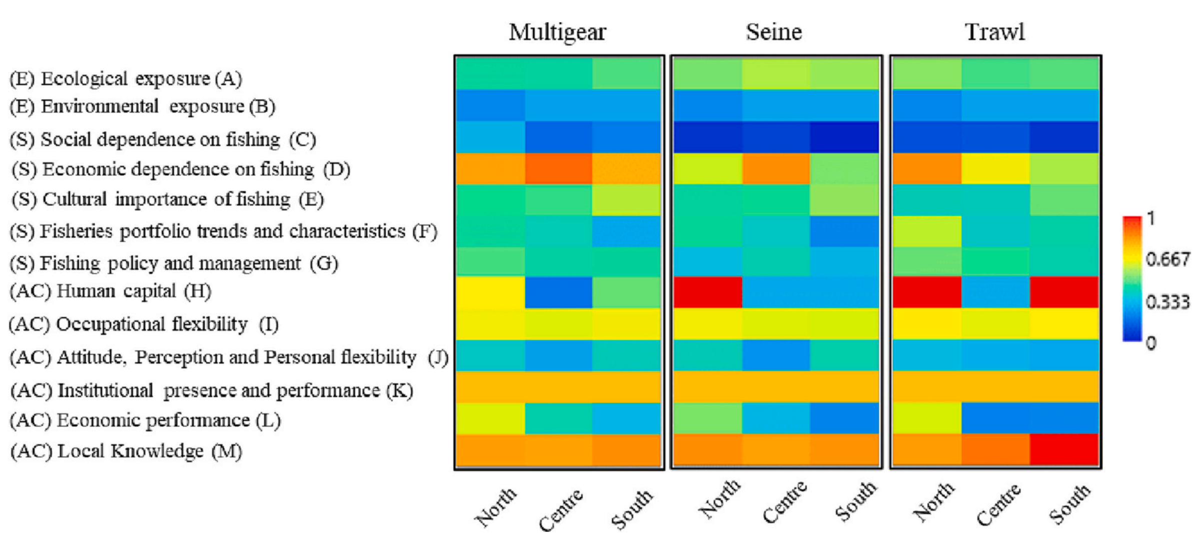

Fig. 3. Vulnerability subdimensions scores of each dimension (exposure, sensitivity and AC) and for each fleet (multigear, seine and trawl) and area (north, entre and south). All subdimension scores range from 0 to 1. Considering that vulnerability is equal to E + S-AC, values of AC close to 0 will increase the final vulnerability score.

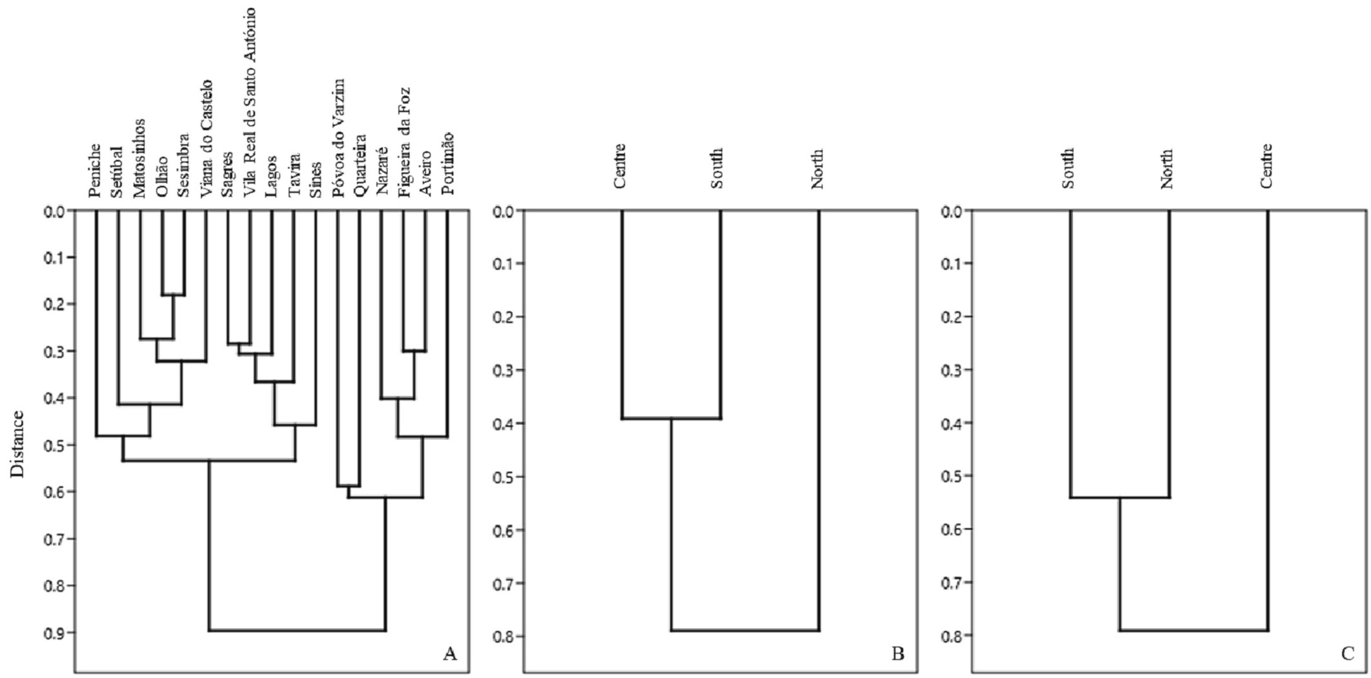

Fig. 4. Euclidian matrix-based cluster analysis, performed at the port scale (multigear (A)) and area scale (seine (B) and trawl (C)), using vulnerability subdimension data. Ports and areas are grouped based on how closely associated they are.

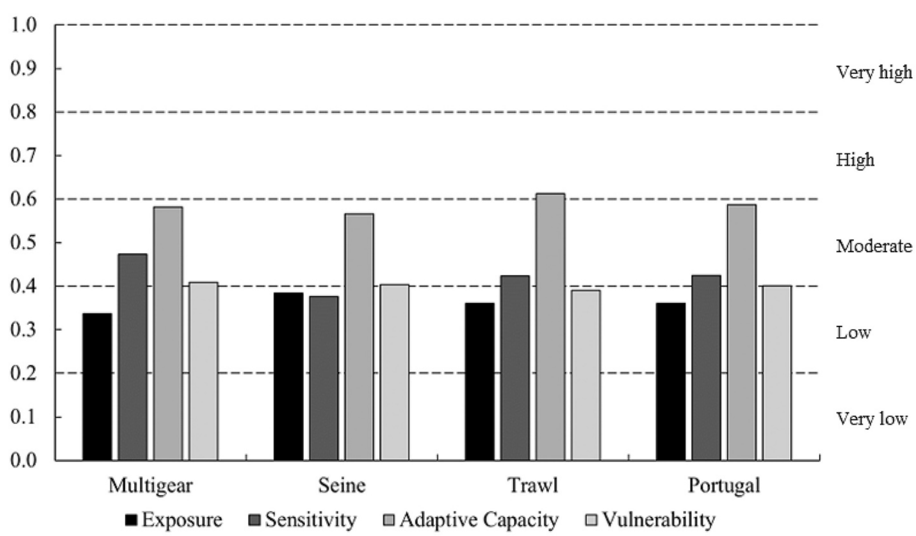

Fig. 5. Averages of the vulnerability dimensions of the Portuguese fisheries sector for each fleet (multigear, seine and trawl) and regardless of the fleet (Portugal).

indicators, drawing information compiled through direct and indirect multiple data sources. Our results point to vulnerability scores ranging from low to moderate in all gears and areas, with similarities between these resulting from different sources (different subdimensions of vulnerability), which offset each other at larger scales.

4.1. Overall vulnerability estimates

We identified areas/ports that are less capable to withstand disturbances by CC and thus prioritize management interventions aiming to increase resilience (Adger, 2006; Lazzari et al., 2021). The estimates of climate-vulnerability for the Portuguese fisheries sector present moderate values – in the range of 0.4 – for all three sectors of the fishing fleet. Moderate vulnerability to CC was expected since previous CVAs and climate risk assessments (CRA) for European countries have consistently reported low – moderate vulnerability to CC (Allison et al., 2009; Ding et al., 2017; Payne et al., 2021), a likely reason being the variable environmental conditions found in temperate regions (Bueno-Pardo et al., 2021). However, within the socio-economic vulnerability assessment framework, ecological vulnerability represents only one subdimension (Cinner et al., 2013) of the framework, allowing other socio-economic factors to influence the overall vulnerability of social groups. Such are the cases of sea level rise or fisheries dependency, which do not directly affect fishing resources but do have potential social impacts.

Results do not exhibit clear latitudinal trends in port vulnerability (multigear) or area (seine and trawl). In the north of Portugal, vulnerability to CC appears to be similar to what was reported for Galicia (Spain) (see Aragão et al., 2022), which directly borders the northern coast of Portugal. Applying this comparison to southern Iberia, vulnerability in the south region of Portugal appears to be lower than that

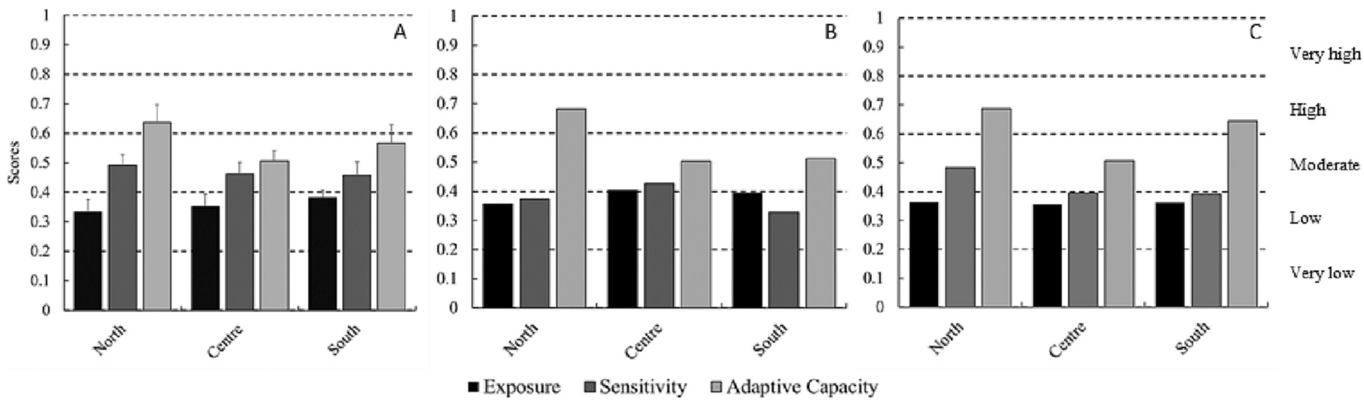

Fig. 6. Vulnerability dimensions (exposure, sensitivity, and AC) of the Portuguese fisheries sector by area for each fleet: multigear (A), seine (B) and trawl (C) fleets.

reported for Andalusia (south of Spain) (see Aragão et al., 2022). Despite fleets operating in a similar manner and targeting similar species in this fishing area, lower vulnerability for the south of Portugal is explained by the nonexistence of Mediterranean fisheries which are more vulnerable than Atlantic fisheries (Aragão et al., 2022).

In the present study, we verified that the CC vulnerability in the Portuguese fisheries sector is mainly driven by the AC dimension, evidenced by the strong negative correlations between AC and vulnerability. The high AC values are in accordance with previous research, reporting moderate vulnerability for European countries due to higher-than-average AC (Allison et al., 2009; Ding et al., 2017; Payne et al., 2021), which often derives from high GDP per capita and governmental stability (Allison et al., 2009; Ding et al., 2017), especially in comparison with developing African (Cinner et al., 2013) or South American countries (Martins and Gasalla, 2020), which present a limited AC often linked to developing economies (Stanford et al., 2013).

In the present study, similar vulnerability scores across areas or fleets are explained by the contribution of different subdimensions, as revealed by the SIMPER and cluster analysis. Overall, two important results are unravelled regarding the role of subdimensions in explaining vulnerability: 1) subdimensions contributing to decrease vulnerability (i.e., very low to low exposure and sensitivity and high to very high AC) are generally transversal between fleets and areas and, 2) subdimensions contributing to increase vulnerability (i.e., high to very high exposure and sensitivity and very low to low AC) differ between fleets and areas.

The low levels of vulnerability were partially explained by low exposure and high AC scores. Low exposure scores were derived mostly from the low scores obtained for the extreme winds indicator (physical exposure) in all areas. Such finding is in accordance with previous research which identified no changes in storminess trends, in south Portugal (Almeida et al., 2011), but are opposite to the increase in northerly winds observed on Portugal in recent decades (1988–2009); (Leitão et al., 2019). The role of north winds favours upwelling in western coast (Leitao et al., UPW North Winf). Considering that this indicator is based on the comparison of past data and future projection (see supplementary material A1, indicator 4), it is possible that extreme wind events (wind strength resulting from west and north wind vectors) are not well captured yet in future scenarios, impairing our capacity to well evaluate this indicator. In any case, wind strength is a fundamental factor to understand the ability of fishers to go to the sea (strong winds are the main environmental factor causing the ports to close in Portugal), and hence, it must be considered as a potential driver of change in the future from the perspective of fishers. Social dependency on fishing (sensitivity subdimension) also presented low to very low scores for all fleets and areas, reflecting Portugal as a diverse economy, since such dependency is often associated with less developed economies (Stanford et al., 2013; Lam et al., 2016). Local knowledge (AC subdimension) accounted solely for the knowledge of the survey respondent and, since the surveys targeted vessel captains over regular fishers, this indicator reflects the ability of vessel captains to retain knowledge derived from the inherently more advanced courses/training they had to undertake to be eligible to pilot fishing vessels. This evidences education as an important tool to enhance AC and in effect reduce CC vulnerability. Institutional presence and performance (AC subdimension) was similar across areas and fleets, since on one hand it comprises an indicator operating at the national scale and, on the other hand every area of the country has elaborated an adaptation plan to CC, as every municipality is required by the climate basis law (Law n° 98/202, December 31st, 2021) to have a CC adaptation plan. These scores reflect the importance of well executed governmental plans in increasing the AC of fishers (Allison et al., 2009; Ding et al., 2017). Nonetheless, we believe that the implementation of these plans is still in an early phase so these results should be regarded with caution.

The second result, linked to the subdimensions that increase overall vulnerability, is explained by the following subdimensions: Economic dependency on fishing (sensitivity subdimension) and Economic performance (AC subdimension). According to the obtained results, Economic dependency on fishing plays an important role in defining the sensitivity to CC of the Portuguese fisheries sector, as demonstrated by its high scores, namely in the multigear sector. The higher levels of fisheries economic dependency in the multigear sector are likely related to multigear fishers' lower wages relative to the seine or trawl sectors. Considering the Economic performance of the Portuguese fisheries sector, it is stronger in the north of the country than in the centre our southern areas (moderate scores in the north of the country and low scores in the centre and south areas) for all three fleets. The economic performance was estimated considering several indicators: fish imports and exports, fishing effort (in gross tonnage), fisheries gross value added (GVA), and presence of canning and freezing industry. Better economic performance was registered for the northern area, a result tied to the better GVA trends registered in this area, which provides higher AC when compared to the centre and south areas.

There is another result which affects vulnerability estimations differently across areas and fleets which was highlighted by the SIMPER analysis, that being human capital. Human capital (AC subdimension) explained most of the dissimilarities found in vulnerability subdimension analysis made between fleets and areas. According to fishers, the recruitment of young people into the fisheries scene has been a major difficulty. During the field surveys, comments such as "I don't know who is going to fish when I retire" were commonplace, providing further evidence for the thesis that barely any young people are entering the sector. This creates a situation where (i) knowledge transference from older generations to the younger ones can be impaired and, (ii) the lack of young people can aggravate the dependency on migrant manpower to fill the working positions left by older fishers who enter retirement age. Furthermore, the Portuguese population presents, much like most of EU countries, an aging population, suggesting that fisheries will have to increasingly compete with other sectors of the job market to attract young people.

4.2. Vulnerability dimensions

4.2.1. Exposure

Exposure presented no clear latitudinal trend, not even when addressing its subdimensions, and affected all fleets in a similar manner. Despite the moderate to low scores, Ecological exposure was the main driver of CC exposure for the Portuguese fisheries sector. This is explained by the high ecological AC that temperate species that inhabit the Portuguese coast present (Bueno-Pardo et al., 2021). These characteristics reduce exposure of the sector and society to CC. Concerning species distribution changes, while already happening in the North Sea (ICES, 2016), in Portugal, such phenomena relate mostly to species entering Portuguese waters coming from the south or changes inside territorial waters (Gamito et al., 2013, 2016; Teixeira et al., 2014; Leitão et al., 2018a; Lima et al., 2022).

The number of days with extreme winds reflects on the number of days available for fishing, thus influencing fishing efforts, which is an important metric in fisheries management (Leitão, 2015; Carvalho et al., 2017; Melnychuk et al., 2017; Hamon et al., 2021). As previously discussed, no significant temporal changes in wind regimes are forecasted for the Portuguese coast (Almeida et al., 2011). Instead, Almeida et al., (2011) suggests that the cyclical wind pattern is expected to continue into the near future, with steady conditions and stronger but shorter extreme events. This evidences that more days are available for fishers to work, which will have to be accounted for to mitigate future impacts from potential increase in fishing efforts. For instance, in the south of Portugal, higher fishing pressure levels result from fair sea conditions, something that is considered as a reason to develop artificial reefs and MPAs, which aim at alleviating the fishing effort of the fleet (Leitão et al., 2008; Leitão et al., 2009). Considering fisheries' vulnerability to sea level rise for the middle of the century (Supplementary Material B, Fig. 2), exposure to submersion will occur during the equinox tides in the spring and autumn potentially leading to 9 h of submersion per year (Antunes et al., 2017; 2019). Despite the low frequency occurrence expected year-round these events are enough to critically damage unprepared electrical, water, gas and infrastructural facilities in ports. Submersion adaptation requires large investments (i.e., raise port structures, isolate electric facilities, etc.). Furthermore, smaller ports with less vessels which in turn generate less revenue may be deemed as not worth of adaption, resulting in them being progressively abandoned in favor of bigger or better prepared ports and thus affecting, socio-economically, local communities. Changes in wave height and direction are also threats to ports or boat navigation (Izaguirre et al., 2021; Wiegel et al., 2021) and can also be considered for future analysis.

The adopted approach to exposure allowed to discern between the contributions of ecological and physical exposure to CC, which are usually not separated or one or the other are not considered in the components of exposure, in large scale socio-economic CVA (Allison et al., 2009; Ding et al., 2017). Future adaptation measures aiming at lowering exposure to CC in the Portuguese fisheries sector should focus primarily on the management of marine species, although modernization of port infrastructures should not be negligible in most exposed areas in the coming decades.

4.2.2. Sensitivity

Fisheries-dependence is a concept used by the EU to estimate social vulnerabilities, as areas deemed fisheries-dependent are eligible to benefit from EU funds as well as redevelopment programmes (Brookfield et al., 2005). Fisheries dependency is often defined via employment figures (Lindkvist, 2000), wherein areas that have a high proportion of the workforce employed in the catching and downstream industries, are fisheries dependant (Ross, 2013; Stanford et al., 2013). In our study, CC sensitivity varied between fleets and areas. Additionally, as revealed by our results, economic dependency on fishing is one of the most important sources of CC sensitivity, contrasting with social dependency on fishing, which was one of the lower contributors to the sensitivity of the Portuguese fisheries sector. Such results suggest that across Portuguese ports, there is an evenness in fisheries dependency that contributes to lower sensibility scores, where economic dependency contributes to increase the sensitivity, whereas the social dependency contributes to lower sensitivity.

Diversification of income sources is often suggested as a measure to lower fisheries dependency (namely economical dependency) (Ross, 2013; Lazzari et al., 2021; Aragão et al., 2022). The objective of income diversification is to create alternative employment opportunities as well as providing an economic "safety net" (Payne et al., 2021) and thus, rather than attempting to shift people out of fishing, policies should acknowledge the social and cultural aspects of fisheries dependency and find ways to support the strong relationships and specialisation of the industry (Ross, 2013). In effect, the aim is to attenuate fisheries dependency (Ross, 2013). This diversification could include exploring already well-established industries in Portugal, diminishing sensitivity and vulnerability in fisheries through indirect activities such as tourism (Aragão et al., 2022), growing industries such as aquaculture (Brookfield et al., 2005), or even less-established industries such as algae harvesting. In Portugal, algae harvesting only has an important presence in the town of São Martinho do Porto (near Nazaré).

Fisheries bad practices and how involved fishers are in the decision-making process were considered to assess the effectiveness of management and policies. Considering the effectiveness of fisheries management and policy subdimensions, the moderate scores evidence that, across all fleets and areas, there is an important margin for improvement. We deemed that these factors are crucial towards development, planning, and implementation of successful adaptation plans, since they give fishers an opportunity to input their practical and local knowledge, as well as increases the chance that fishers accept proposals they contributed to. These scores also reflect the difficulties of managing Portuguese fisheries, not only due to the multispecies nature of the fisheries, but also due to technical difficulties, i.e. inadequate monitoring, data recording systems (Leitão and Baptista, 2017), and large discard rates (Leitão et al., 2014; Leitão et al., 2018b).

4.2.3. Adaptive Capacity

As the Portuguese population ages (Mota-Pinto et al., 2011), the fisher population is expected to follow the same trend. There are already reports from local fishers claiming that the recruitment of young people into the sector is becoming increasingly more difficult. Human capital was an important factor contributing towards vulnerability (confers low or high AC, depending on fleet and area), and as such this is an issue that needs to be closely monitored to ensure the continuous availability of workforce in the fisheries sector. According to the 2021 INE led census, the trend of population movement from the interior to the coast continues (INE, 2021). This tendency can have two effects: 1) more people become available to enter the workforce, alleviating problems related to population aging and increasing AC; 2) more people moving to coastal areas may place further strain on them and in effect create new challenges (i.e., increase in living costs and more resource demands, namely food), hence decreasing AC. If the proper data is available, future assessments of socio-economic vulnerability should consider the inclusion of this issue, particularly at local scales.

Between 2012 and 2015 the average fleet age increased by one year per year, while for the period of 2008 to 2011, it aged by 0.5 years per year (PSOEMN – 2019 Volume III-C/PCE). Although it was not included in the present research, fleet age is also an issue for the Portuguese fleet, which is generally aging at a faster rate. To increase AC, fleet modernization and renovation will be essential, not only to increase efficiency, i.e., less fuel spent (Knittweis et al., 2016; Aragão et al., 2022) but also to ensure better and safer working conditions. Indeed, increasing fuel efficiency will play an important role in reducing risk and vulnerability (Hamon et al., 2021). Engine efficiency not only lowers emissions but also offers the possibility of tackling future changes in species distribution by increasing fishers' capacity to navigate and access new fishing grounds. Currently, Portuguese fisheries focus mostly on depths of up to 400 m (PSOEMN – 2019 Volume III-C/PCE, n.d.); fleet modernization can "open up" new fishing grounds deeper or further than previously exploited, which can alleviate fishing effort in specific fishing grounds. When translated into improvements to working conditions, fleet modernization is likely to contribute towards increasing youth recruitment to the sector.

Alternatively, increased AC can derive from promotion and exploration of new fisheries related products (Leitão and Baptista, 2017). This is something that would increase the economic performance of the fisheries sector, which is one of the "weak points" in the central and southern areas of the country in all three fishing fleets. Indeed, Economic performance is one of the reasons for AC being higher in the north of the country, according to our results. As an example, this could be done via promoting the use of species who typically have lower commercial value or even by finding market niches for fisheries discards (Leitão and Baptista, 2017).

5. Conclusion

Vulnerability analysis can play a key role in shaping adaptation plans, increasing public awareness towards CC, finding adaptation solutions, and maximizing the effectiveness of limited resources. In Portugal, one of the reasons for the low-moderate vulnerabilities was the high Adaptive Capacity (AC) (regardless of areas/gears). AC can be improved by investing in Human capital as well as Education with the latter being especially important in equipping societies to deal with the effects of CC. While the local scale analysis unravelled differences at area and port level, at the national scale, these offset each other resulting in similar vulnerabilities across the country. Still, it should be noted that these values can change in the future should climate projections change. Regardless of the area or fishing community, fisheries vulnerability to CC should be considered as low risk if, at maximum, vulnerability ranges between low to very low, which would assure more resilience to CC. Therefore, some communities where vulnerability values are close to moderate or, are moderate, require attention.

According to our results, decreasing fisheries vulnerability to CC should consider the improvement of fisheries management, the diversification of income sources, as well as the promotion of fisheries-based products and education of fishers. Results obtained can now be shared with fisheries stakeholders to inform future CC impacts in fisheries and adaptation measures discussed at local level with fishing communities.

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Declaration of Competing Interest

The authors declare that they have no known competing interests that appear to have influenced the research reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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