Global Change Biology
November 2021, Volume 27, Issue 22, Pages 5920-5933
https://doi.org/10.1111/gcb.15814
https://archimer.ifremer.fr/doc/00708/82034/

Contrasted patterns in climate change risk for Mediterranean fisheries

Pita Ignacio [1,*], Mouillot David [1,2], Moullec Fabien [3], Shin Yunne-Jai [1]

[1] Marine Biodiversity, Exploitation and Conservation (MARBEC) Université Montpellier, Institut de Recherche pour le Développement (IRD), Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), CNRS 34000 Montpellier ,France
[2] Institut Universitaire de France Paris ,France
[3] Royal Netherlands Institute for Sea Research, Coastal Systems (COS) Den Burg Noord-Holland, NL, The Netherland

* Corresponding author : Ignacio Pita, email address : ignacio.pita-vaca@ird.fr

Abstract :

Climate change is rapidly becoming one of the biggest threats to marine life, and its impacts have the potential to strongly affect fisheries upon which millions of people rely. This is particularly crucial for the Mediterranean Sea, which is one of the world's biodiversity hotspots, one of the world's most overfished regions, and where temperatures are rising 25% faster than in the rest of the ocean on average. In this study, we calculated a vulnerability index for 100 species that compose 95% of the Mediterranean catches, through a trait-based approach. The Climate Risk Assessment (CRA) methodology was subsequently used to assess the risks due to climate change of Mediterranean fisheries. We found that the northern Mediterranean fisheries target more vulnerable species than their southern counterparts. However, when combining this catch-based vulnerability with a suite of socio-economic parameters, north African countries stand out as the most vulnerable to climate change impacts. Indeed, considering countries' exposure of the fisheries sector and their vulnerability to climate change, a sharp contrast between northern and southern Mediterranean appears, with Egypt and Tunisia scoring the highest risk. By integrating a trait-based approach on targeted marine species with socio-economic features, our analysis helps to better understand the ramifications of climate change consequences on Mediterranean fisheries and highlights the regions that could potentially be particularly affected.

I- Introduction

Covering 71% of the earth's surface, the ocean is vital to human society, providing essential resources and sustaining food security (Costello et al., 2020; Duarte et al., 2020). With growing human populations, marine fish consumption has increased by more than 60% from 1990 to 2018, while the proportion of fish stocks within biological sustainable levels has dropped from 90% to 65% during the same period (FAO, 2020). In addition to direct anthropogenic pressure, the oceans are under severe and multiple climate change impacts (Hastings et al., 2020; IPCC, 2014). As a matter of fact, 93% of the heat excess caused by green-house gases accumulates in the ocean, affecting its physical properties and dynamics (Cheng, Abraham, Hausfather, & Trenberth, 2019; Oschlies, 2021). Changing ocean conditions have repercussions on biological traits of marine organisms affecting, for example, their growth and reproduction, resulting in shifts of their biogeography and trophic interactions (Cheung 2018; Lotze et al. 2019). The unprecedented rate at which climate is changing will inevitably redistribute oceanic habitats and species, even faster than on land (Lenoir et al., 2020; Pecl et al., 2017; Weatherdon, Magnan, Rogers, Sumaila, & Cheung, 2016). Consequently, fisheries production patterns are expected to be modified in the near future as a direct consequence of climate change (Cheung 2018; Holsman et al. 2020). Global primary production, but also that of top predators, is expected to decrease significantly whatever the scenario (Bopp et al. 2013; Lam et al. 2016; Schwalm, Glendon, and Duffy 2020), with an average decrease of 17% of fish biomass projected by the end of the century using an ensemble of ecosystem models (Lotze et al., 2019).

The combined consequences of fisheries overexploitation and climate change are highly heterogeneous among species and regions (Cheung 2018; Holsman et al. 2020). The Mediterranean Sea is one of the fastest warming areas of the planet with temperatures rising at a rate two to three times faster than the global ocean (Cramer et al., 2018; Marbà, Jordà, Agustí, Girard, & Duarte, 2015; Vargas-yáñez, Jesús, Salat, García-martínez, & Pascual, 2008). The marked gradient, from the arid climate of North Africa to the temperate climate of central Europe, exacerbates the consequences of minor modifications in the general circulation and warming trends (Giorgi & Lionello, 2008). Furthermore, species movements are geographically limited by the semi-enclosed configuration of the Mediterranean Sea with no escape towards colder waters beyond the northern limit (Albouy, Guilhaumon, Araújo, Mouillot, & Leprieur, 2012; Ben Rais Lasram et al., 2010; Marbà et al., 2015). As a world biodiversity hotspot with more than 17 000 marine species (650 fish species), of which over 20% are endemic (Coll et al., 2010, 2015), global warming is projected to have a considerable impact on the Mediterranean Sea (Albouy et al., 2013; Moullec, Barrier, et al., 2019) including fish geographic redistribution (Azzurro et al., 2019). This is particularly alarming knowing that it represents 7% of the world's biodiversity within merely 0.82% of the ocean's surface (Coll et al., 2010).

Yet, the socio-economic consequences of these rapid shifts in the distribution of Mediterranean fishes are still unclear while millions of people rely on fisheries for their livelihood (Lotze, Coll, & Dunne, 2011) and about 75% of the Mediterranean and Black Sea fish stocks are being overexploited (FAO, 2020b). Therefore, assessing the vulnerability to climate change of the different marine exploited species and fisheries over the Mediterranean is essential to support an effective management plan towards sustainable resource exploitation.

In this study, we used the Climate Risk Assessment (CRA) Framework, a re-designed version of the Climate Vulnerability Assessment (CVA) (IPCC-AR4, 2007) that has been proposed by the Intergovernmental Panel on Climate Change (IPCC-AR5 2014), and used in a number of studies for both species and fisheries risks due to climate change (Albouy et al., 2020; Allison et al., 2009; Blasiak et al., 2017; Hare et al., 2016; Payne, Kudahl, Engelhard, Peck, & Pinnegar, 2021; Pinnegar, Engelhard, Norris, Theophille, & Sebastien, 2019; Thiault et al., 2019; Williams, Shoo, Isaac, Hoffmann, & Langham, 2008). By considering both the environmental and socio-economic context of each country, this framework aims to identify which marine species and fisheries are likely to be the most at risk due to climate change across the Mediterranean.

II- Materials and Methods

1) Study area and species selection

The objective of this CRA was to determine the species and nations most at risk in the Mediterranean Sea, i.e., those that would experience the strongest impacts from climate change. The studied species were taken from recent modelling studies on marine biodiversity in the Mediterranean Sea (Moullec, Barrier, et al., 2019; Moullec, Velez, et al., 2019). This selection was composed of 86 fish species among the 635 species included in the FishMed database (Albouy et al., 2015), chosen based on data availability (i.e. growth and reproduction), but also 10 crustaceans and 5 cephalopods that were added for their commercial value and contribution to total biomass in the Mediterranean Sea. Availability of traits, abundance and spatial distribution data were key to this selection since these were necessary to determine species' sensitivity and their geographic shifts due to climate change. Together, these species represent 95 % of the declared fisheries catches in the Mediterranean Sea between 2006 and 2013 and play major roles in food web dynamics and ecosystem functioning (FAO, 2006-2017; Moullec, Velez, et al., 2019). The Mediterranean coast is composed of 22 countries. Gibraltar, Monaco, Slovenia and Bosnia and Herzegovina were excluded from the study because of their very small coastlines and fishing effort compared to the other countries. Syria and Montenegro's data on socio-economic factors were unavailable and therefore these countries were also excluded. Fisheries risk was consequently calculated for 16 countries.

2) Climate Risk Assessment (CRA)

The CRA developed by the IPCC (2014), is multi-faceted and can be analyzed at different scales (individual, community, ecosystem, country, continent)(Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2014; FAO, 2015). The CRA methodology evaluates the risks posed to a system due to climate change using three components: hazard, exposure and vulnerability (IPCC, 2014). The hazard is the prospect of a physical event, related to climate change, causing harm to an individual, ecosystem, or service. It can refer to the biophysical, social, or economic attributes that are likely to be impacted by climate change (Monnereau et al., 2017; Morrison et al., 2015). Exposure is defined as the presence of said individual, ecosystem, service, resource or economic, social, or cultural assets in a position that could be affected (e.g., species distribution area, infrastructure, income…). Finally, vulnerability refers to the individual or sector's ability to cope and adapt to the environmental threat which is context specific. It is determined by a diversity of concepts that range from the factors directly affected by the consequences of a hazard to the ability to prepare for and respond to climate change impacts. Integrating these three parameters for the Mediterranean countries, we built a CRA of national fisheries from an ecological, economic, and social perspective (Figure 1).

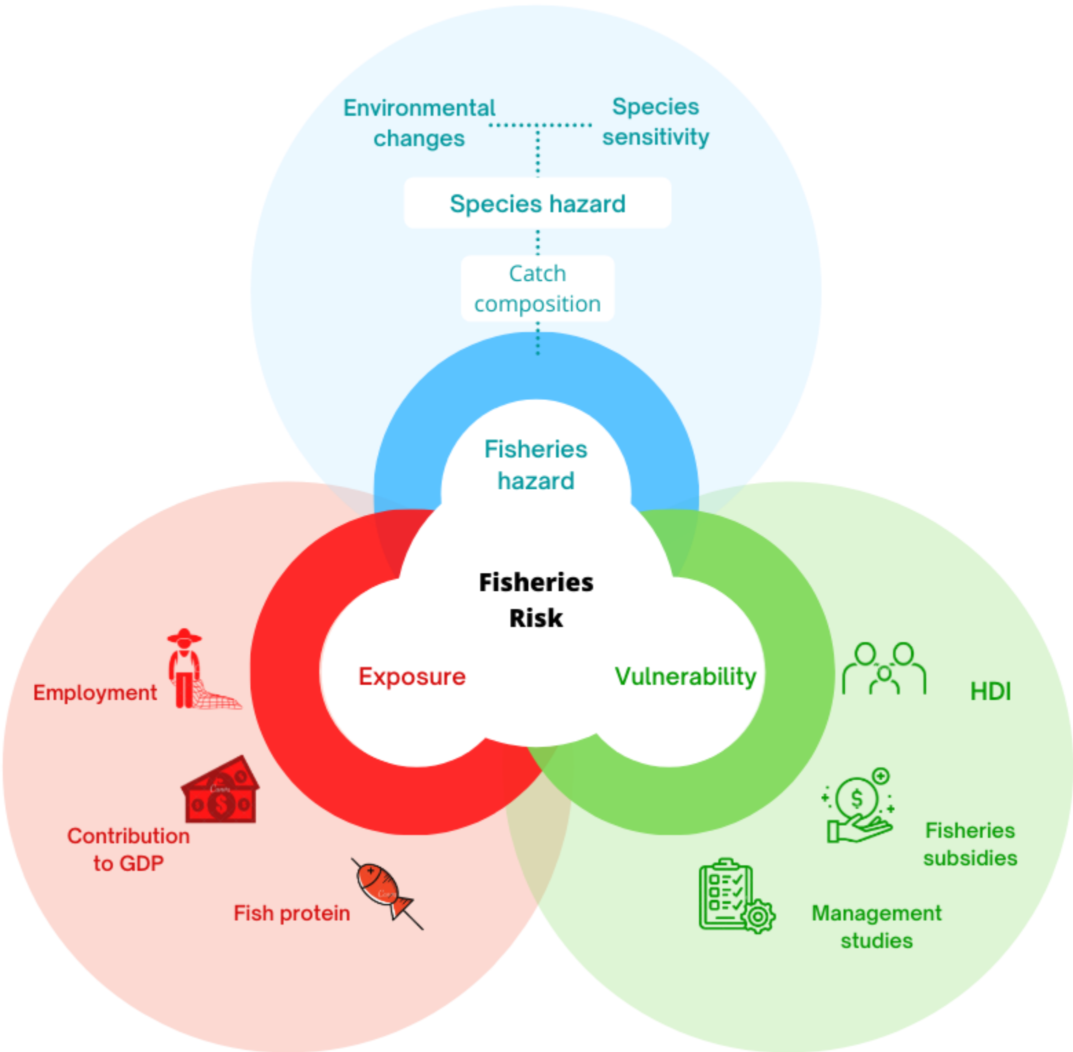

Figure 1: Conceptual schematic drawing of the CRA framework applied to our specific study. Firstly, fisheries hazard was determined through species hazard due to climate change. Secondly, fisheries risk was obtained based on hazard, exposure, and vulnerability.

3) Species Hazard

a) Environmental changes

Based on species geographical range derived from Species Distribution Models (SDM) that were fitted at global scale using environmental and species' occurrence data and projected at the Mediterranean scale (Moullec, Velez, et al., 2019), we were able to estimate the magnitude of the environmental changes that are likely to impact each species. In our study, temperature and salinity were chosen as they were shown to drive distributional shifts of marine organisms in the current climate change context (Albouy et al. 2020; Cheung, Watson, and Pauly 2013; Moullec, Barrier, et al. 2019) and are available in output of any global climate models. By assessing changes in these two variables, we quantified the potential impacts on the species' life cycle. Environmental changes were recorded between the "historical" 1975 – 2012 period, extracted from the World Ocean Atlas 2013 version 2 (https://www.nodc.noaa.gov/OC5/woa13/woa13data.html), and the "near-future" 2021 – 2050 period. Projections are based on the ocean component NEMOMED8 of the regional climate CNRM-RCSM4 model (Beuvier et al. 2010), under the RCP8.5 high emission scenario from the IPCC AR5, regarded as a "no mitigation scenario" (Riahi et al., 2011; Schwalm et al., 2020). Mean changes in temperature and salinity from each species' geographical range were calculated and standardized between 0 and 1. An environmental change score was then calculated as the average of the two standardized values. A species that faces a strong variation (increase or decrease) in the physical parameters over a large part of its geographical range will be categorized as being highly exposed whereas a small variation within the majority of its range will categorize the species as less exposed (Albouy et al., 2020; Hare et al., 2016; Morrison et al., 2015).

b) Trait-based sensitivity analysis

To assess species sensitivity to climate change, we compiled information on biological traits, that are suggested to shape species' responses to climate change (Hare et al., 2016; Spencer, Nelson, Hollowed, Sigler, & Hermann, 2019). We focused on quantifiable parameters that can be related to temperature preference and tolerance, habitat specificity, mobility and population growth rate (Pinnegar et al., 2019). Extending the methodology of (Albouy et al., 2020), each trait was scored on a four-point scale from 0 (the least sensitive) to 3 (the most sensitive) that was determined from the quartiles of the trait distribution. Species sensitivity was then calculated by summing all scores. Finally, we divided the resulting values by the maximum overall sensitivity across species to standardize the species-specific sensitivity index between 0 and 1.

Temperature Tolerance Range. Climate change is projected to increase sea temperature mean and variability (Hayashida, Matear, & Strutton, 2020; Hurd, Lenton, Tilbrook, & Boyd, 2018). Consequently, species with narrower temperature tolerance are more likely to be negatively impacted by these environmental changes (Perry, Low, Ellis, & Reynolds, 2005; Sunday, Bates, & Dulvy, 2012).Species temperature preferences were derived by overlaying species geographical range based on Spatial Distribution Models (Moullec, Velez, et al., 2019) and a long-term mean sea temperature extracted from the World Ocean Atlas 2013 version 2 over the 1975 – 2012 period. These distribution maps were built from the environmental conditions of species occurrences compiled from several data sources (OBIS, GBIF, FAO, FishMed). Information on temperature in different parts of the water column was available and taken into consideration according to species' vertical habitat documented in FishMed and SeaLifeBase databases (Albouy et al., 2015; Palomares & Pauly, 2019). The temperature tolerance for a given species is then estimated by calculating the difference between the maximum and minimum temperature, defined as the 10^{th} and 90^{th} percentile, found in a species' range (Pinnegar et al., 2019).

High temperature tolerance. The 90^{th} percentile of temperatures within a species' geographical range was used as a proxy for species tolerance to high temperatures.

Habitat specificity. The capacity to inhabit a variety of environments is an important advantage when facing climate change. Habitat generalists are assumed to be less threatened by global warming compared to species with specific and spatially restricted habitats (Burgess, Garcia, & Ara, 2014; Johnson & Welch, 2010; Perry et al., 2005; Peters, Darling, Peters, & Darling, 1985). Compiling data from FishMed and SeaLifeBase (Albouy et al., 2015; Palomares & Pauly, 2019), habitat specificity was assessed by distinguishing the vertical habitat of a species (namely its position in the water column, i.e. pelagic, benthic or demersal), and its horizontal habitat (i.e. coastal, shelf, slope and oceanic), (Albouy et al., 2020; Pinnegar et al., 2019). In addition, species depending on soft substrate, rocky reefs or Posidonia meadows, were considered as habitat specialists. Habitat specificity score was derived by combining Habitat with a possible specific substrate (rocky, soft or Posidonia as stated on the FishMed database) when specified, for each species (Table 2 in Supplementary material).

Population growth rate. Here, we used population growth rate as a proxy for species reproductive capacity or turnover rate. We used the intrinsic rate of increase *r* when reliable, which can be understood as the number of births minus the number of deaths per generation time (Froese & Pauly, 2019; Palomares & Pauly, 2019). Otherwise, the von Bertalanffy growth parameter K was used (Cheung, Pitcher, and Pauly 2005; Froese et al. 2017; Musick 1999) as available in a standardized way in Fishbase and SeaLifeBase (Froese and Pauly 2019; Palomares and Pauly 2019; accessed March-August 2020). A lower population doubling time corresponds to a greater reproductive potential, thus a greater resilience to climate change (Le Bris et al., 2018). This metric is also key to determine species' resilience to fishing (Le Bris, Pershing, Hernandez, Mills, & Sherwood, 2015; Pinnegar et al., 2019), as exploitation impacts abundance, age, and size distribution, and as a result limits adaptability to climate change.

c) Species hazard score

The Hazard (H) to a species i was calculated as the product of its environmental changes (E) and sensitivity (S) scores.

$$H_i = E_i \times S_i$$

As a result, a species with high sensitivity to climate change but with no significant changes in temperature or salinity within its geographical range will not necessarily rank highly in hazard. Conversely, a species with large projected changes in temperature and salinity within its geographical range, but with low sensitivity to climate change will not be considered highly hazard-prone either.

4) Fisheries Risk

a) Fisheries hazard

We first compiled data from the SeaAroundUs project (Pauly, Zeller, & Palomares, 2020) on the Mediterranean LME (Large Marine Ecosystem) catches. By considering the proportion of each species in the yearly catches from 2000 to 2014, we calculated a weighted average species vulnerability per country (catch vulnerability [*Cv*]). Most catches are listed by species, however, in some cases they are listed under a family (e.g., *Eledonidae*), order (e.g., *Octopoda*) or even class level (e.g., *Cephalopoda*). 67 species were reported individually in the catch data, but 5 fishing categories were composed of three or more species (the maximum being 6 for *Decapoda*). Yet, species vulnerability scores from the same fishing category varied relatively little, therefore in these cases the mean score in the fishing category was used (Fig 9 in Supplementary material). With $Catch_{i,j}$ being the yearly landing in tons of species i for country j, fisheries hazard (Hf_j) was calculated as follows:

$$Hf_j = \sum_i^{H_i} \times Catch_{i,j} / \sum_i Catch_{i,j}$$

Since species hazard scores ranged from 0 to 1, the fisheries hazard was also in the same range. Combined with fisheries exposure and vulnerability, it determined the overall fisheries risk for each country.

b) Exposure

Metrics quantifying a country's exposure to hazards have often been used to determine its sensitivity to climate change impacts (Allison et al., 2009; Blasiak et al., 2017; Thiault et al., 2019). Adopting the methodology from previous studies, we used the factors "Percentage of workforce in fisheries", "Percentage of GDP contributed by seafood landings" and "Fish protein as proportion of all animal protein", to build the fisheries exposure indicator. Scores were attributed by standardizing values from 0 to 1 after dividing by the maximum value across countries.

Percentage of workforce in fisheries. This parameter represents the contribution of fisheries to the national economically active population. Data on the number of workers, directly or indirectly, employed in the marine capture fisheries sector were compiled (Teh & Sumaila, 2013). These numbers were then compared to each country's total number of active workers (International Labor Organization, 2020), resulting in the percentage of workforce in fisheries.

Percentage of GDP contributed by seafood. To calculate countries' yearly catch values, we averaged the landed values in dollars compiled from SeaAroundUs (Pauly et al., 2020) from 2000 to 2014. Similarly, GDP data were averaged in the same period to make both values comparable (Roser, 2020) thus resulting in the percentage of GDP contributed by seafood landings per country.

Fish protein as proportion of all animal protein. We obtained all information on consumed animal protein for each country, from 2000 to 2013, from the FAOSTAT food supply dataset (FAO, 2020a).

c) Vulnerability

Fisheries ability to cope with environmental threats has been commonly assessed in previous CVA frameworks (Allison et al., 2009; FAO, 2015; Johnson & Welch, 2010; Thiault et al., 2019). It modulates a country's vulnerability to changing conditions by accounting for the potential of a given system or sector, in our case fisheries, to adapt to a changing environment. We estimated this component by taking into account some aspects of human and economic development, effectiveness of governmental structures and knowledge on the fisheries' status (Allison et al., 2009; Blasiak et al., 2017; Cinner et al., 2018). Under the assumption that countries with high human and economic development have more resources to mitigate and adapt to climate change impacts (Cinner et al. 2019; Cinner and Barnes 2019), we based our vulnerability indicator on three socio-economic factors: Human Development Index, fisheries subsidies as a percentage of total landings value and the number of scientific publications related to fisheries management in proportion to the country's landed tonnage. Scores were attributed by standardizing values from 0 to 1, after dividing by the maximum value across countries.

Human Development Index (HDI). HDI assesses the development of a country by incorporating health (life expectancy), education (years of schooling) and standard of living (GNI per capita) into one index. This index may vary at a sub-national level. To account for this variability, we used spatially gridded data at resolutions going from NUTS level 0 (Country) to 3 (region) (Kummu, Taka, & Guillaume, 2018). We selected the Mediterranean coastal regions of each country and calculated a mean local HDI. GDP was also available at this fine scale and was considered for this study. However, it was strongly correlated to HDI (Pearson's $\rho = 0.91$) and significantly correlated to the subsidies as a percentage of total landings (Pearson's $\rho = 0.74$). HDI already integrates GNI. Adding GDP alongside it would give an unbalanced weight towards the economic situation of the countries so it was subsequently removed from analyses.

Fisheries subsidies as a percentage of total landings. Information on total subsidies to the fisheries sector was compiled from the SeaAroundUs project (Pauly et al., 2020). We assessed the support of government structures in proportion to the sector's landings by calculating each country's subsidies as a proportion of the total landings value.

Scientific publications on fisheries management. Effective fisheries management has been shown to be essential for marine ecosystem's health and stocks status (Bundy et al., 2017; Hilborn, Oscar, Anderson, Baum, & Branch, 2020). Stock health and abundance are important parameters of a species' resilience to environmental changes (Johnson & Welch, 2010; Sumaila & Tai, 2020), therefore fisheries management undermines vulnerability. A country's research on fisheries management has been shown to be strongly correlated to its fisheries management effectiveness (Melnychuk, Peterson, Elliott, & Hilborn, 2017). To quantify the scientific literature on fisheries management as a proxy for the management effort in a given country, we searched the ISI Web of Knowledge for all publications from 1990 to 2020 with the terms: "Fisheries management" AND [Country]. In an effort to include the grey literature and national languages, the same was done for each country on Google Scholar using the official language. To put into perspective the number of scientific publications with the country's fishing effort, the total number was divided by the annual landed tonnage compiled from SeaAroundUs.

d) Fisheries Risk

By combining hazard, exposure, and vulnerability for Mediterranean countries, we calculated the fisheries risk ultimately considering species sensitivity, environmental changes due to climate change, the country's catch composition, its exposure of the fisheries sector and its potential to adapt to climate change. To integrate the risk components, several methods can be used that have very similar optimum solutions in most cases (Kolios, Mytilinou, Lozano-Minguez, & Salonitis, 2016). The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) aggregation method has been used in recent CVA studies (Leclerc, Courchamp, & Bellard, 2020; Thiault et al., 2019). It seemed the more suitable here since when one of the components has an extreme score, it does not imbalance the final score like in the multiplicative framework. Yet, TOPSIS gives more weight to these extreme scores than with the additive method that does not consider each component as a distinct entity. TOPSIS establishes a score based on the geometrical distance of a scenario to the theoretical positive ideal alternative and the negative ideal alternative (Parravacini et al., 2014). By having three criteria, this allows a simple and understandable application (Figure 2):

$$R_j = d_j^+ / (d_j^+ + d_j^-)$$

Where R_j represents the risk of the Country j, d_i^+ the distance to the positive ideal solution and d_i^- is the distance to the negative ideal solution. The ideal solution for a country is therefore minimum fisheries hazard, exposure and vulnerability.

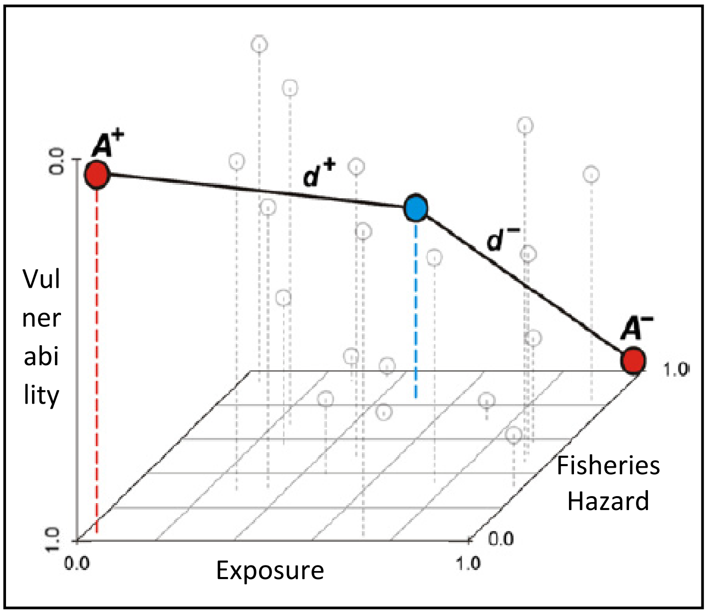

Figure 2: Conceptual model of the TOPSIS method.
adapted from Parravacini et al. 2014.
"A+ "represents the positive ideal solution
"A- "represents the negative ideal solution
"d" depicts the distance between the assessed country (in blue) and both positive and negative solutions.

III- Results

1) Species hazard

Environmental changes. Environmental changes were calculated based on the difference in both sea temperature and salinity between present and future projections under RCP8.5 (exposure scores for all studied species, as well as salinity and temperature evolution projections can be found in appendix 1). Regarding salinity, Flathead grey mullet (*Mugil cephalus*) stood out as the most exposed species of our list due to the highest difference in salinity by far, followed by Garfish (*Belone belone*) for which exposure score was 0.87. Concerning sea temperature, Bluefin tuna (*Thunnus thynnus*) came out as the most exposed to changes, followed closely by Albacore tuna (*Thunnus alalunga)* and Swordfish (*Xiphias gladius*) (respectively scoring 0.997 and 0.990). However, as they were among the species expected to experience the lowest changes in salinity, their overall Exposure score put them in the middle of the gradient, scoring approximately 0.82.

Sensitivity. Cumulated and standardized between 0 and 1, all sensitivity attributes are combined to provide scores of the overall species sensitivity to climate change (distribution of sensitivity attributes for all studied species can be found in appendix 1). A vast majority of species (84 out of 100 species) scored between 0.4 and 0.8, with over half of the species (55 species) scoring between 0.6 and 0.8. Only 8 species had a sensitivity score above 0.8, with blacktail comber (*Serranus atricauda)* and common prawn (*Palaemon serratus)* on the top of the list, both scoring 1. On the other end, 8 species scored below 0.4, giant red shrimp (*Aristaemorpha foliacea)* standing out with a null score, qualifying into the “0” category in all four of the sensitivity attributes.

Species hazard. When combining environmental changes and sensitivity, we found that species having scored highly in sensitivity were also among the most vulnerable species. The top four most vulnerable species (pouting (*Trisopterus luscus),* common prawn (*Palaemon serratus),* blacktail comber *(Serranus atricauda)* and smooth-hound *(Mustelus mustelus)*) were among the most sensitive species (Figure 3 and appendix 1). At the other end of the vulnerability scale, giant red shrimp (*Aristaemorpha foliacea)* having scored 0 in overall sensitivity had a vulnerability score equal to 0, making it the least vulnerable species to climate change. However, there were some combinations of sensitivity and exposure scores that reshuffled species ranking. For instance, caramote prawn (*Penaeus kerathurus)* stood among the top five most exposed species with a 0.97 score but was eventually classified among the least vulnerable species because of its very low sensitivity score of 0.4.

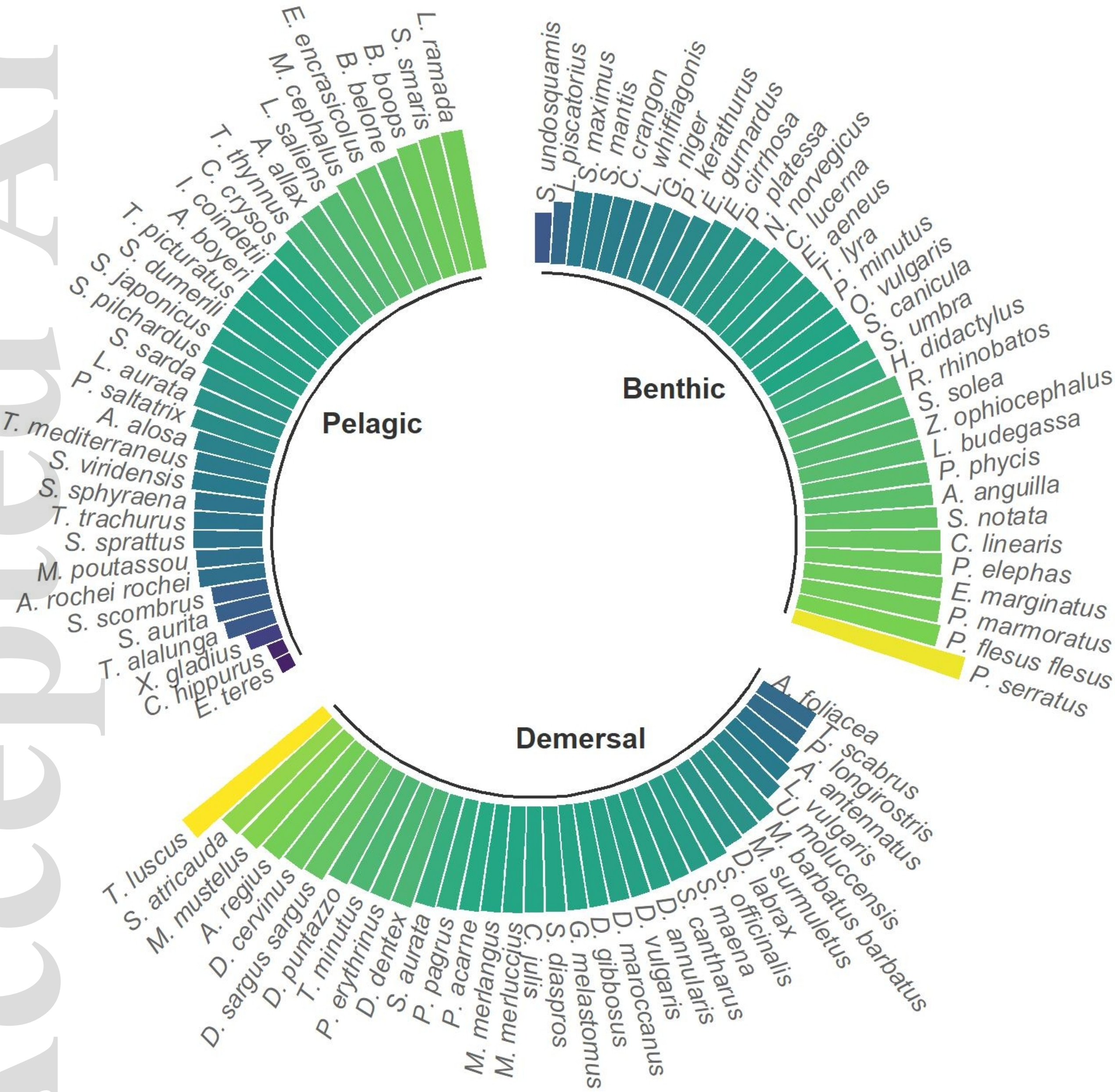

Figure 3: Species Hazard scores grouped by habitat, under the RCP8.5 climate change scenario by 2050.

2) Fisheries risk

Fisheries Hazard. Averaging the species vulnerability scores, weighted by their importance in the yearly national catches, we were able to determine which countries are most likely to see their catches affected by climate change. Countries on the northern part of the Mediterranean seem to be targeting more hazard-prone species than their southern counterparts (Figure 4.C, scores distribution in appendix 2), with Croatia having the highest average fisheries hazard (0.61). By contrast, African countries and Malta have the lowest fisheries hazard values, with scores averaging around 0.5 and below. Nevertheless, apart from Malta that showed a particularly low score (0.32), all average scores were found between 0.5 (Tunisia) and 0.61 (Croatia), with no country standing out as being significantly more hazard-prone than others.

Exposure. Combining the percentage of workforce in fisheries, the percentage of GDP contributed by landings and fish protein as a proportion of all animal protein, three countries stood out as the most exposed to fisheries hazards (Figure 4.A). Egypt, Tunisia, and Morocco, all three scoring above 0.77 after standardization between 0 and 1, are followed by Greece with a score of 0.53 (scores distribution can be found in appendix 2). Egypt came out as the most exposed country being ranked first for fisheries employment in proportion to the countries' total employment and for fish protein consumption in proportion to all animal protein consumption. Tunisia ranked second, being by far the most dependent on fisheries revenue relative to its GDP. Northern Africa appears to be the most exposed region taking up five of the top six exposure scores. Greece (0.53), Spain (0.46) and Malta (0.46) are the top-ranked European countries regarding exposure. Data showed that the income fisheries produced in Greece, in proportion to its GDP, was remarkably high in comparison to the other European countries. Spain and Malta scored highly in exposure particularly because of the large proportion of fish in their diets. On the other end of the spectrum, Israel and Albania appear to have the lowest exposure to fisheries hazard. Albania has the lowest fish protein intake in proportion to all animal protein, and Israel's landings values represent a very small proportion of the Gross Domestic Product.

Vulnerability. Combining the Human Development Index, fisheries subsidies as a percentage of total landings and scientific publications on fisheries management, European countries came out as the least vulnerable particularly thanks to their high HDI scores and considerable subsidies with Spain and Cyprus providing subsidies over 80% of landings value to the fisheries sector (Figure 4.B, scores distribution in appendix 2). Israel is also found among the least vulnerable countries with a very high HDI and the highest number of scientific papers on fisheries management in proportion to its yearly landings. African countries appear to be in the worst position to cope and adapt to climate change, with low subsidies, low numbers of scientific studies and HDI scores significantly lower than their European counterparts.

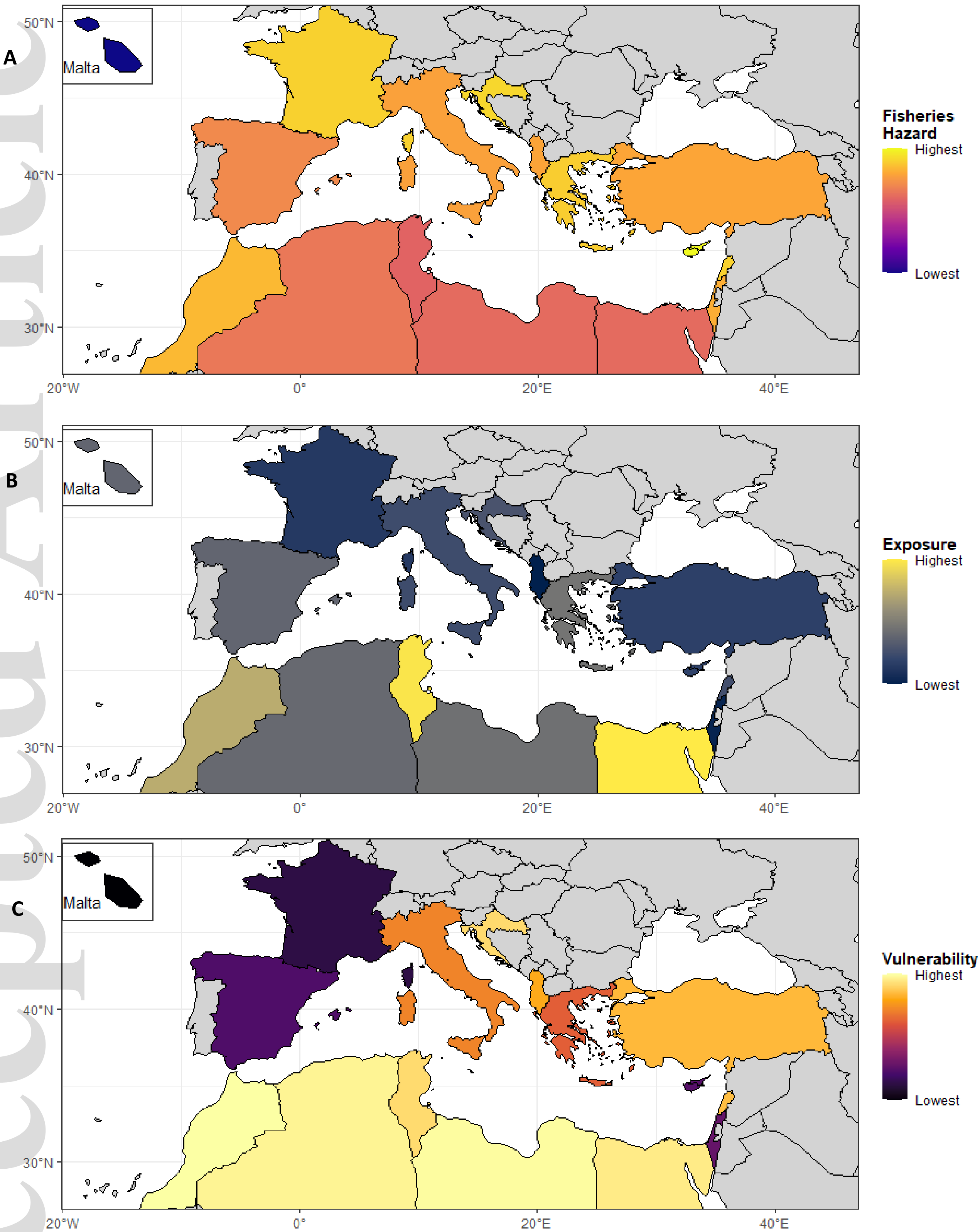

Figure 4: Geographical distribution of the studied Mediterranean countries for the three components of fisheries risk. Lighter yellowish colors represent the highest risk in all three components. Fisheries hazard is determined under the RCP8.5 climate change scenario, by 2050.

Fisheries Risk. Combining fisheries hazard, exposure and vulnerability, we calculated overall fisheries risk ranging from 0 to 1 (Figure 5, scores distribution for all countries in appendix 2) using the TOPSIS method to assess each country's distance to the ideal solution (fisheries hazard=0, exposure=0, vulnerability=0). Most indicators from exposure and vulnerability show a marked contrast between northern and southern Mediterranean countries, respectively the least and most vulnerable to climate change. Egypt, Morocco, and Tunisia particularly stand out having the highest distances to the positive ideal solution so being most at risk (scoring respectively 0.91, 0.90 and 0.90). On the other end, Malta and Israel came out as the least at-risk countries both having a very low vulnerability that gives them fisheries risk scores of 0.07 and 0.11 respectively.

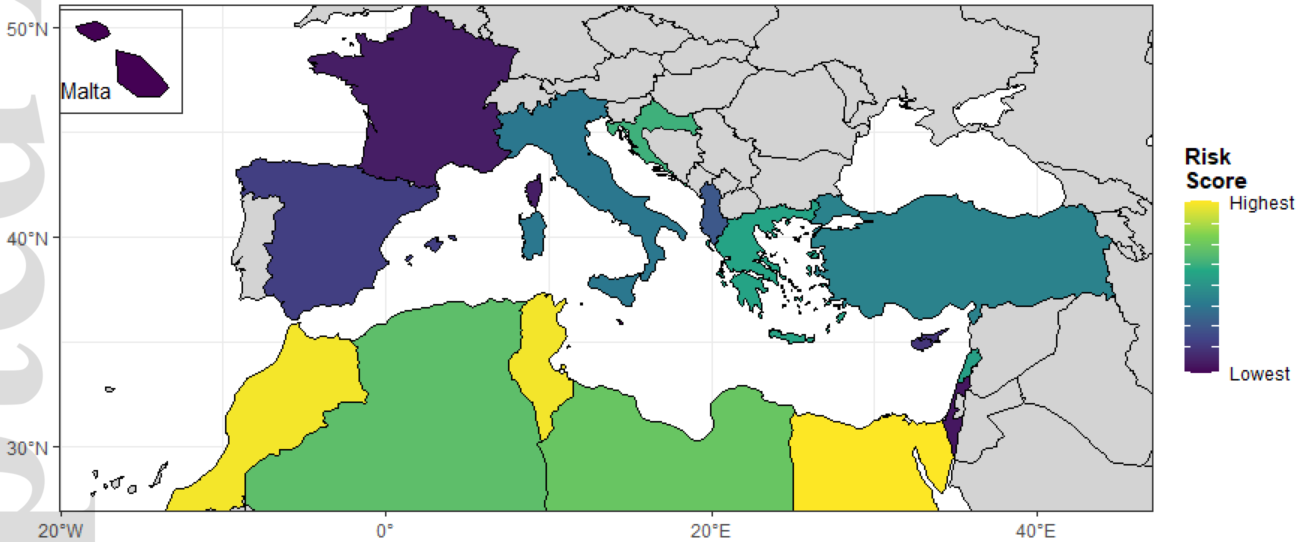

Figure 5: Fisheries risk scores amongst the 16 studied Mediterranean countries under the RCP8.5 climate change scenario by 2050.

IV- Discussion

1) Species hazard

Most species presented a hazard score of 0.5 or higher, however a distinction could be made between pelagic species and demersal or benthic species: pelagic species had overall a lower hazard score (13 out of the 15 most at-risk species are either benthic or demersal). Likewise, all countries presented a high risk to climate change, based solely on the species composition of the catches. Climate change hazard appeared to impact more strongly the catches of countries that border the northern Mediterranean (Figure 4.A).

To provide some perspective and robustness to our results, we compared them to two recent studies on species' response to climate change. Firstly, a vulnerability assessment based on the AR4 IPCC framework, but with a different mathematical approach (fuzzy logic) and additional sensitivity attributes (maximum body length, taxonomic group), (Jones & Cheung, 2017). Secondly, an integrated end-to-end ecosystem model considering the species' spatial dynamics, trophic interactions, and species' full life cycle (Moullec, Barrier, et al., 2019). All three assessments seem to generally agree on low vulnerability species such as *Etrumeus teres, Saurida undosquamis* and *Spratttus spratus,* as well as high vulnerability species such as *Belone belone, Mugil cephalus, Phycis phycis* and *Thunnus thynnus*. A few species' assessment aligns better with Moullec et al. (2019) (e.g., *Aristeus antennatus* and *Parapeneaeus longirostris'* low vulnerability and *Palinurus elephas* and *Serranus atricauda's* high vulnerability). Nevertheless, our study particularly concurs with Jones and Cheung's assessment, with most species having an analogous score, within maximum 20 ranks of each other. These similarities suggest that despite some differences in the attributes used for the vulnerability assessment, common attributes such as: "temperature tolerance", "habitat specificity" and life-history traits, seem determinant in ranking species' risk to climate change impacts. This raises the idea that the modification of traits, be it via phenotypic plasticity or evolution, will be an important aspect of the adaptation of marine populations to climate change. In some cases, a decade to half a century is a long enough time-span to start seeing significant changes in some species' biological traits (Crozier & Hutchings, 2013; Lescak et al., 2015). This potential for adaptation could be considered for a subset of species for which data on traits intra-population variability are available. The comparisons thus help nuance our vulnerability assessment, the major addition of Moullec et al. (2019a) lying in the feedbacks due to species predator/prey and competition interactions as well as explicit ontogenic dynamics. One clear advantage of our CVA approach is to be much simpler than the end-to-end modelling in Moullec et al. (2019a), but comparisons across studies help to determine where uncertainties lie. In addition, in contrast with Moullec et al. (2019a), the CVA approach does not allow to provide any projections of species or biodiversity status in the future, but rather an indication of where to prioritize conservation actions today.

Fishing pressure, as a factor of hazard related to species and climate change, would definitely deserve further analyses, as it has been shown that fish stocks are more likely to adapt and survive when healthy (Sumaila & Tai, 2020). Notably, fishing is likely to negatively impact the growth rate of exploited species, thus potentially reducing their resilience (Jones & Cheung, 2017). By contrast, marine protected areas could help buffer climate change impacts and increase species resilience (Gattuso et al., 2018; Leclerc et al., 2020) and thus could as well be considered as an additional factor to complement the climate risk assessment. However, our proposed analysis was deliberately parsimonious given available data. This does not preclude refinements based on several other aspects, directly linked to species biology and behavior. For example, mobility is an important factor when looking at the species habitat specificity based on the assumption that mobile fish are more likely to move more easily towards suitable habitats when their environmental conditions shift. However, as climate-induced habitat changes occur over several years, low mobility does not prevent species migration when facing climate changes (Gaines, Gaylord, Gerber, Hastings, & Kinlan, 2007). As a matter of fact, several sedentary species can have very rapid colonization strategies with high larval dispersal, and therefore may not be disadvantaged compared to more mobile species (Albouy et al., 2015). The question still remains for coping with heatwaves that occur on shorter time scales with frequency and intensity expected to increase with climate change (Hayashida et al., 2020; Oliver et al., 2019).

Furthermore, it is interesting to point out some counterintuitive results, for example the high hazard score of the European anchovy *Engraulis encrasicolus* compared to other species. Indeed, we would have expected small pelagic fishes to have low hazard scores due to their high reproductive capacities and mobility. However, mobility was not considered as a factor of habitat specificity while the wide geographical range of this species provides a high score in environmental changes. This, paired to a relatively low temperature tolerance range and thus a medium sensitivity score, places anchovy among the most vulnerable species. When looking at the recent history of small pelagic fish dynamics, and particularly *Engraulis encrasicolus*, it can be noted that their abundance and stock status declined at an alarming rate in the last few years (Borja, Fontán, Sáenz, & Valencia, 2008; Saraux et al., 2019). In the case of the Bay of Biscay, anchovy fishing was completely banned from 2005 to 2010 to allow population recovery. Although anchovy biomass remained low until 2010, the fishery closure allowed the population's replenishment after a while. Biomass has remained high since 2010 with the implementation of conservative Harvest Control Rules set in 2009 (Doray et al., 2018). This raises the question of the synergistic impacts of direct anthropogenic stressors and climate change that can influence species resilience (Fu et al., 2018).

2) Fisheries risk due to climate change

The results of the climate risk assessment show a sharp contrast between northern and southern Mediterranean countries. Fisheries from northern countries appear to be affected by climate change mainly through the hazard to the species they catch, with French fisheries catching the most hazard-prone composition of species. A difference in the main small pelagic fish captured can be observed with very high *Sardinella aurita* catches in the southern Mediterranean whereas the hazard-prone *Engraulis encrasicolus* is reported in large proportion in the catches of the northern Mediterranean fisheries. Interestingly, when exposure and vulnerability are added to the equation, the pattern shifts, and an opposite contrasted picture emerges where the southern countries' stand out as being the most at risk due to climate change, with both parameters strongly influencing the risk score (Appendix 2, Figure 14). Northern Mediterranean countries with lower vulnerability seem to target more hazard-prone species than their southern counterparts as shown by the fisheries hazard score. Nevertheless, exposure, and particularly vulnerability seem to have the opposite trend, thus creating the contrast between countries' risk based solely on fisheries hazard and their actual fisheries risk. Malta, Israel, and France eventually show the lowest risk highlighting the importance of the vulnerability component which scores very low for these three countries. European countries' fisheries seem to pose the lowest risks with socio-economic factors compensating for their high fisheries hazard. It is important to note that, although subsidies are known to be detrimental to sustainable fisheries (Munro & Sumaila, 2002), they are used in our study as a proxy for the available resources invested in fisheries and therefore considered as a positive asset in adaptive capacity. Consequently, establishing suitable adaptation actions is a key challenge (Green et al., 2014; Lédée, Sutton, Tobin, & De Freitas, 2012; Miller, Ota, Sumaila, Cisneros-Montemayor, & Cheung, 2018; Ojea, Lester, & Salgueiro-Otero, 2020).

These results imply that different adaptation strategies suitable for their particular needs can compensate for climate change detrimental impacts on Mediterranean countries (Comte, 2020; Ojea et al., 2020). In doing so, climate risk and vulnerability assessments represent important tools for identifying priorities and establishing strategies (Free et al., 2020; Lindegren & Brander, 2018). This highlights the importance of taking into account not only the biophysical threats of climate change that will impact marine ecosystems (Foden et al., 2019), but also the different socio-economic facets that might exacerbate, or mitigate, their consequences on fishing communities (Allison et al., 2009; Blasiak et al., 2017).

Our study is limited by data availability and resolution. There is a recurrent data contrast between northern and southern Mediterranean countries. For example, northern countries' catch data are significantly more precise regarding the species and quantities caught whereas the catch data compiled from SeaAroundUs (Pauly et al., 2020) for the southern countries tend to be aggregated within taxonomic groups. Similarly, socio-economic factors, such as HDI or number of employees in the fisheries sector, have a finer spatial resolution and lower uncertainty in northern countries (Kummu et al., 2018; Teh & Sumaila, 2013). There is also a bias in the way we assess the effort put into fisheries management, something which would need to be improved in the future. Research capacity has been shown to be strongly correlated with fisheries management effectiveness (Melnychuk et al., 2017). Therefore, we used the number of scientific publications found in the ISI web of knowledge as a proxy, but this database does not accurately consider grey literature or publications in languages other than English. We attempted to address this issue by including Google Scholar results in the native languages. Although scarce for the southern Mediterranean countries, results were more conclusive with this search engine, which allowed us to have a better representation of this literature in our results. Nevertheless, understanding local fisheries management procedures could be essential in order to more reliably address the socio-economic facet of climate vulnerability (Ojea, Pearlman, Gaines, & Lester, 2017). Taking a socio-ecological systems approach and directly engaging with the fisheries communities could be a possibility to gather this data (Galappaththi, Ford, & Bennett, 2020). Another possible improvement concerns the exposure facet, for which we would need to consider seafood import when looking at the importance of fish protein in diets (EUMOFA, 2019). These limits present opportunities on possible finer assessments. Taking into consideration these factors with a more accurate inclusion of the grey literature and on-site analysis on fisheries management and governance would allow a better understanding of local specifics and reduce the bias in favor of European Mediterranean countries. Nevertheless, this is an interesting first step towards building an integrated analysis of the climate change risk across Mediterranean countries. With the challenge of representing the combined influence of all anthropogenic stressors to ecosystems, researchers' effort to produce assessments following established frameworks will allow us to gradually obtain more accurate and comprehensive results.

REFERENCES

Albouy, C., Delattre, V., Donati, G., Frölicher, T. L., Albouy-Boyer, S., Rufino, M., … Leprieur, F. (2020). Global vulnerability of marine mammals to global warming. *Nature Research*, *10*(1), 1–12. https://doi.org/10.1038/s41598-019-57280-3

Albouy, C., Guilhaumon, F., Araújo, M. B., Mouillot, D., & Leprieur, F. (2012). Combining projected changes in species richness and composition reveals climate change impacts on coastal Mediterranean fish assemblages. *Global Change Biology*, *18*(10), 2995–3003. https://doi.org/10.1111/j.1365-2486.2012.02772.x

Albouy, C., Guilhaumon, F., Leprieur, F., Lasram, F. B. R., Somot, S., Aznar, R., … Mouillot, D. (2013). Projected climate change and the changing biogeography of coastal Mediterranean fishes. *Journal of Biogeography*, *40*(3), 534–547. https://doi.org/10.1111/jbi.12013

Albouy, C., Lasram, F. B. R., Velez, L., Guilhaumon, F., Meynard, C. N., Boyer, S., … Mouillot, D. (2015). FishMed : traits , phylogeny , current and projected species distribution of Mediterranean fishes , and environmental data. *Ecology*, *96*(8), 2312. https://doi.org/10.1890/14-2279.1

Allison, E. H., Perry, A. L., Badjeck, M., Adger, W. N., Brown, K., Halls, A. S., … Dulvy, N. K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 1–24. https://doi.org/10.1111/j.1467-2979.2008.00310.x

Azzurro, E., Sbragaglia, V., Cerri, J., Bariche, M., Bolognini, L., Ben Souissi, J., … Moschella, P. (2019). Climate change, biological invasions, and the shifting distribution of Mediterranean fishes: A large-scale survey based on local ecological knowledge. *Global Change Biology*, *25*(8), 2779–2792. https://doi.org/10.1111/gcb.14670

Ben Rais Lasram, F., Guilhaumon, F., Albouy, C., Somot, S., Thuiller, W., & Mouillot, D. (2010). The Mediterranean Sea as a ‘ cul-de-sac ’ for endemic fishes facing climate change. *Global Change Biology*, 3233–3245. https://doi.org/10.1111/j.1365-2486.2010.02224.x

Blasiak, R., Spijkers, J., Tokunaga, K., Pittman, J., Yagi, N., Henrik, O., & Österblom, H. (2017).

Climate change and marine fisheries : Least developed countries top global index of vulnerability. *PLoS ONE*, *12*(6), 1–15. https://doi.org/10.1371/journal.pone.0179632

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., … Vichi, M. (2013). Multiple stressors of ocean ecosystems in the 21st century : projections with CMIP5 models. *Biogeosciences*, 6225–6245. https://doi.org/10.5194/bg-10-6225-2013

Borja, A., Fontán, A., Sáenz, J., & Valencia, V. (2008). Climate, oceanography, and recruitment: The case of the Bay of Biscay anchovy (Engraulis encrasicolus). *Fisheries Oceanography*, *17*(6), 477–493. https://doi.org/10.1111/j.1365-2419.2008.00494.x

Bundy, A., Chuenpagdee, R., Boldt, J. L., Borges, M. D. F., Camara, M. L., Coll, M., … Jarre, A. (2017). Strong fisheries management and governance positively impact ecosystem status. *Fish and Fisheries*, (18), 412–439. https://doi.org/10.1111/faf.12184

Burgess, N. D., Garcia, R. A., & Ara, M. B. (2014). Matching species traits to projected threats and opportunities from climate change. *Journal of Biogeography*, 724–735. https://doi.org/10.1111/jbi.12257

Cheng, L., Abraham, J., Hausfather, Z., & Trenberth, K. E. (2019). How fast are the oceans warming? *Science*, *363*(6423), 128–129. https://doi.org/10.1126/science.aav7619

Cheung, W. W. L. (2018). The future of fishes and fisheries in the changing oceans. *Journal of Fish Biology*, (92), 790–803. https://doi.org/10.1111/jfb.13558

Cheung, W. W. L., Pitcher, T. J., & Pauly, D. (2005). A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biological Conservation*, *124*(1), 97–111. https://doi.org/10.1016/j.biocon.2005.01.017

Cheung, W. W. L., Watson, R., & Pauly, D. (2013). Signature of ocean warming in global fisheries catch. *Nature*, 1–5. https://doi.org/10.1038/nature12156

Cinner, J. E., Adger, W. N., Allison, E. H., Barnes, M. L., Brown, K., Cohen, P. J., … Morrison, T. H. (2018). Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, *8*(February), 117–123. https://doi.org/10.1038/s41558-017-0065-x

Cinner, J. E., & Barnes, M. L. (2019). Social Dimensions of Resilience in Social-Ecological Systems. *One Earth*, *1*(Figure 2), 51–56. https://doi.org/10.1016/j.oneear.2019.08.003

Cinner, J. E., Lau, J. D., Bauman, A. G., Feary, D. A., Januchowski-hartley, F. A., Rojas, C. A., & Barnes, M. L. (2019). Sixteen years of social and ecological dynamics reveal challenges and opportunities for adaptive management in sustaining the commons. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1914812116

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben, F., Lasram, R., … Voultsiadou, E. (2010). The Biodiversity of the Mediterranean Sea : Estimates , Patterns , and Threats. *PLoS ONE*, *5*(8). https://doi.org/10.1371/journal.pone.0011842

Coll, M., Steenbeek, J., Ben, F., Lasram, R., Mouillot, D., & Cury, P. (2015). ' Low-hanging fruit ' for conservation of marine vertebrate species at risk in the Mediterranean Sea. *Global Ecology and Biogeography*, (24), 226–239. https://doi.org/10.1111/geb.12250

Comte, A. (2020). Structuring the Discussion on the Multiple Threats of Climate Change to Fisheries around Impact Pathways and Adaptation Pathways. *One Earth*, *2*(6), 528–529. https://doi.org/10.1016/j.oneear.2020.05.017

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. Á., Free, C. M., Froehlich, H. E., … Lubchenco, J. (2020). The future of food from the sea. *Nature*. https://doi.org/10.1038/s41586-020-2616-y

Cramer, W., Guiot, J., Fader, M., Garrabou, J., Gattuso, J., Iglesias, A., … Paz, S. (2018). Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change*, *8*(November). https://doi.org/10.1038/s41558-018-0299-2

Crozier, L. G., & Hutchings, J. A. (2013). Plastic and evolutionary responses to climate change in fish. *Evolutionary Applications*. https://doi.org/10.1111/eva.12135

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). (2014). *A framework for climate change vulnerability assessments*. Retrieved from https://www.ccardesa.org/knowledge-products/framework-climate-change-vulnerability-assessments

Doray, M., Petitgas, P., Romagnan, J. B., Huret, M., Duhamel, E., Dupuy, C., … Massé, J. (2018).

The PELGAS survey: Ship-based integrated monitoring of the Bay of Biscay pelagic ecosystem. *Progress in Oceanography*, *166*(October 2017), 15–29. https://doi.org/10.1016/j.pocean.2017.09.015

Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J. P., … Worm, B. (2020). Rebuilding marine life. *Nature*, *580*(7801), 39–51. https://doi.org/10.1038/s41586-020-2146-7

EUMOFA. (2019). *The EU Fish Market Yearly Report - 2019 Edition*. https://doi.org/10.2771/168390

FAO. (2006). Fisheries and aquaculture software. FishStat Plus - Universal software for fishery statistical time series. Retrieved from http://www.fao.org/fishery/statistics/software/fishstat/en

FAO. (2015). *Assessing climate change vulnerability in fisheries and aquaculture: Available methodologies and their relevance for the sector, by Cecile Brugère and Cassandra De Young. FAO Fisheries and Aquaculture Technical Paper No. 597. Rome, Italy.*

FAO. (2020a). FAOSTAT Statistical Database. Retrieved May 31, 2020, from http://www.fao.org/faostat/en/#data/FBSH

FAO. (2020b). The State of Mediterranean and Black Sea Fisheries 2020. In *The State of Mediterranean and Black Sea Fisheries 2020*. https://doi.org/10.4060/cb2429en

FAO. (2020c). The State of World Fisheries and Aquaculture 2020. Sustainability in action. In *FAO*. https://doi.org/https://doi.org/10.4060/ca9229en

Foden, W. B., Young, B. E., Akçakaya, H. R., Garcia, R. A., Hoffmann, A. A., Stein, B. A., … Huntley, B. (2019). Climate change vulnerability assessment of species. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(1), 1–36. https://doi.org/10.1002/wcc.551

Free, C. M., Mangin, T., Molinos, J. G., Ojea, E., Burden, M., Costello, C., & Gaines, S. D. (2020). Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLoS ONE*, *15*(3), 1–21. https://doi.org/10.1371/journal.pone.0224347

Froese, R., Demirel, N., Coro, G., Kleisner, K. M., & Winker, H. (2017). Estimating fisheries reference points from catch and resilience. *Fish and Fisheries*, *18*(3), 506–526. https://doi.org/10.1111/faf.12190

Froese, R., & Pauly, D. (2019). FishBase. Retrieved from World Wide Web electronic publication website: www.fishbase.org

Fu, C., Travers-trolet, M., Velez, L., Grüss, A., Bundy, A., Shannon, L. J., … John, E. (2018). Risky business : The combined effects of fishing and changes in primary productivity on fish communities. *Ecological Modelling*, *368*, 265–276. https://doi.org/10.1016/j.ecolmodel.2017.12.003

Gaines, S. D., Gaylord, B., Gerber, L. R., Hastings, A., & Kinlan, B. P. (2007). Connecting Places: The Ecological Consequences of Dispersal in the Sea. *Oceanography*, *20*(No. 3, SPECIAL ISSUE ON Marine Population Connectivity), 90–99. https://doi.org/10.5670/oceanog.2007.32

Galappaththi, E. K., Ford, J. D., & Bennett, E. M. (2020). Climate change and adaptation to social-ecological change: the case of indigenous people and culture-based fisheries in Sri Lanka. *Climatic Change*, 279–300. https://doi.org/10.1007/s10584-020-02716-3

Gattuso, J., Magnan, A. K., Bopp, L., Cheung, W. W. L., Duarte, C. M., Hinkel, J., & Mcleod, E. (2018). Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. *Frontiers in Marine Science*, *5*(October). https://doi.org/10.3389/fmars.2018.00337

Giorgi, F., & Lionello, P. (2008). Climate change projections for the Mediterranean region. *Global and Planetary Change*, *63*, 90–104. https://doi.org/10.1016/j.gloplacha.2007.09.005

Green, A. L., Fernandes, L., Almany, G., Abesamis, R., McLeod, E., Aliño, P. M., … Pressey, R. L. (2014). Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation. *Coastal Management*, *42*(2), 143–159. https://doi.org/10.1080/08920753.2014.877763

Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, J., Griffis, R. B., … Mcmanus, M. C. (2016). Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U . S . Continental Shelf. *PLoS ONE*, 1–30.

https://doi.org/10.1371/journal.pone.0146756

Hastings, R. A., Rutterford, L. A., Freer, J. J., Collins, R. A., Simpson, S. D., & Genner, M. J. (2020). Climate Change Drives Poleward Increases and Equatoward Declines in Marine Species. *Current Biology*, *30*(8), 1572–1577. https://doi.org/10.1016/j.cub.2020.02.043

Hayashida, H., Matear, R. J., & Strutton, P. G. (2020). Insights into projected changes in marine heatwaves from a high-resolution ocean circulation model. *Nature Communications*, 1–9. https://doi.org/10.1038/s41467-020-18241-x

Hilborn, R., Oscar, R., Anderson, C. M., Baum, J. K., & Branch, T. A. (2020). Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(4), 2218–2224. https://doi.org/10.1073/pnas.1909726116

Holsman, K. K., Haynie, A. C., Hollowed, A. B., Reum, J. C. P., Aydin, K., Hermann, A. J., … Punt, A. E. (2020). Ecosystem-based fisheries management forestalls climate-driven collapse. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-18300-3

Hurd, C. L., Lenton, A., Tilbrook, B., & Boyd, P. W. (2018). Current understanding and challenges for oceans in a higher CO2 world. *Nature Climate Change*, 686–694.

International Labor Organization. (2020). Employment by sex and age — ILO modelled estimates. Retrieved May 31, 2020, from ILOSTAT database website: https://ilostat.ilo.org/data

IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In R. K. Pachauri & L. Meyer (Eds.), *Ipcc*. IPCC.

Johnson, J. E., & Welch, D. J. (2010). Marine Fisheries Management in a Changing Climate : A Review of Vulnerability and Future Options Marine Fisheries Management in a Changing Climate : A Review of. *Reviews in Fisheries Science*, *1262*, 106–124. https://doi.org/10.1080/10641260903434557

Jones, M. C., & Cheung, W. W. L. (2017). *Using fuzzy logic to determine the vulnerability of marine species to climate change*. (August). https://doi.org/10.1111/gcb.13869

Kolios, A., Mytilinou, V., Lozano-Minguez, E., & Salonitis, K. (2016). A comparative study of multiple-criteria decision-making methods under stochastic inputs. *Energies*, *9*(7), 1–21. https://doi.org/10.3390/en9070566

Kummu, M., Taka, M., & Guillaume, J. H. A. A. (2018). Data Descriptor : Gridded global datasets for Gross Domestic Product and Human Development Index over 1990 – 2015. *Nature Scientific Data*, *5*(1), 1–15. https://doi.org/10.1038/sdata.2018.4

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., & Sumaila, U. R. (2016). Projected change in global fisheries revenues under climate change. *Nature Publishing Group*, 6–13. https://doi.org/10.1038/srep32607

Le Bris, A., Mills, K. E., Wahle, R. A., Chen, Y., Alexander, M. A., Allyn, A. J., … Pershing, A. J. (2018). Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(8), 1831–1836. https://doi.org/10.1073/pnas.1711122115

Le Bris, A., Pershing, A. J., Hernandez, C. M., Mills, K. E., & Sherwood, G. D. (2015). Modelling the effects of variation in reproductive traits on fish population resilience. *ICES Journal of Marine Science*, *72*(9), 2590–2599. https://doi.org/10.1093/icesjms/fsv154

Leclerc, C., Courchamp, F., & Bellard, C. (2020). Future climate change vulnerability of endemic island mammals. *Nature Communications*, *11*(1), 1–9. https://doi.org/10.1038/s41467-020-18740-x

Lédée, E. J. I., Sutton, S. G., Tobin, R. C., & De Freitas, D. M. (2012). Responses and adaptation strategies of commercial and charter fishers to zoning changes in the Great Barrier Reef Marine Park. *Marine Policy*, *36*(1), 226–234. https://doi.org/10.1016/j.marpol.2011.05.009

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J., & Grenouillet, G. (2020). Species better track climate warming in the oceans than on land. *Nature Ecology & Evolution*, *4*(August). https://doi.org/10.1038/s41559-020-1198-2

Lescak, E. A., Bassham, S. L., Catchen, J., Gelmond, O., Sherbick, M. L., Van Hippel, F. A., & Cresko, W. A. (2015). Evolution of stickleback in 50 years on earthquake-uplifted islands.

Proceedings of the National Academy of Sciences of the United States of America, *112*(52), E7204–E7212. https://doi.org/10.1073/pnas.1512020112

Lindegren, M., & Brander, K. (2018). Adapting Fisheries and Their Management To Climate Change: A Review of Concepts, Tools, Frameworks, and Current Progress Toward Implementation. *Reviews in Fisheries Science and Aquaculture*, *26*(3), 400–415. https://doi.org/10.1080/23308249.2018.1445980

Lotze, H. K., Coll, M., & Dunne, J. A. (2011). Historical Changes in Marine Resources , Food-web Structure and Ecosystem Functioning in the Adriatic Sea , Mediterranean. *Ecosystems*, (14), 198–222. https://doi.org/10.1007/s10021-010-9404-8

Lotze, H. K., Tittensor, D. P., Bryndum-buchholz, A., Eddy, T. D., & Cheung, W. W. L. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences*, *116*(26). https://doi.org/10.1073/pnas.1900194116

Marbà, N., Jordà, G., Agustí, S., Girard, C., & Duarte, C. M. (2015). Footprints of climate change on Mediterranean Sea biota. *Frontiers in Marine Science*, *2*(August), 1–11. https://doi.org/10.3389/fmars.2015.00056

Melnychuk, M. C., Peterson, E., Elliott, M., & Hilborn, R. (2017). *Fisheries management impacts on target species status*. *114*(1). https://doi.org/10.1073/pnas.1609915114

Miller, D. D., Ota, Y., Sumaila, U. R., Cisneros-Montemayor, A. M., & Cheung, W. W. L. (2018). Adaptation strategies to climate change in marine systems. *Global Change Biology*, *24*(1), e1–e14. https://doi.org/10.1111/gcb.13829

Monnereau, I., Mahon, R., Mcconney, P., Nurse, L., Turner, R., & Vallès, H. (2017). The impact of methodological choices on the outcome of level climate change vulnerability assessments : An example from the global fisheries sector. *Fish and Fisheries*, (January 2016), 717–731. https://doi.org/10.1111/faf.12199

Morrison, W. E., Nelson, M. W., Howard, J. F., Teeters, E. J., Hare, J. A., Griffis, R. B., … Scott, J. D. (2015). Methodology for Assessing the Vulnerability of Marine Fish and Shellfish Species to a

Changing Climate. *NOAA Technical Memorandum*, (October). https://doi.org/10.7289/V54X55TC

Moullec, F., Barrier, N., Drira, S., Guilhaumon, F., Marsaleix, P., Somot, S., … Fulton, E. (2019). An End-to-End Model Reveals Losers and Winners in a Warming Mediterranean Sea. *Frontiers in Marine Science*, *6*(June), 1–19. https://doi.org/10.3389/fmars.2019.00345

Moullec, F., Velez, L., Verley, P., Barrier, N., Ulses, C., Carbonara, P., … Shin, Y. J. (2019). Capturing the big picture of Mediterranean marine biodiversity with an end-to-end model of climate and fishing impacts. *Progress in Oceanography*, *178*, 102179. https://doi.org/10.1016/j.pocean.2019.102179

Munro, G., & Sumaila, U. R. (2002). The impact of subsidies upon fisheries management and sustainability: The case of the North Atlantic. *Fish and Fisheries*, *3*(4), 233–250. https://doi.org/10.1046/j.1467-2979.2002.00081.x

Musick, J. A. (1999). Criteria to Define Extinction Risk in Marine Fishes: The American Fisheries Society Initiative. *Fisheries*, *24*(12), 6–14. https://doi.org/10.1577/1548-8446(1999)024<0006:ctderi>2.0.co;2

Ojea, E., Lester, S. E., & Salgueiro-Otero, D. (2020). Adaptation of Fishing Communities to Climate-Driven Shifts in Target Species. *One Earth*, *2*(6), 544–556. https://doi.org/10.1016/j.oneear.2020.05.012

Ojea, E., Pearlman, I., Gaines, S. D., & Lester, S. E. (2017). Fisheries regulatory regimes and resilience to climate change. *Ambio*, *46*(4), 399–412. https://doi.org/10.1007/s13280-016-0850-1

Oliver, E. C. J., Burrows, M. T., Donat, M. G., Gupta, A. Sen, Alexander, L. V, Perkins-kirkpatrick, S. E., … Alexander, M. A. (2019). Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Frontiers in Marine Science*, *6*(December), 1–12. https://doi.org/10.3389/fmars.2019.00734

Oschlies, A. (2021). A committed fourfold increase in ocean oxygen loss. *Nature Communications*. https://doi.org/10.1038/s41467-021-22584-4

Palomares, M. L. ., & Pauly, D. (2019). SeaLifeBase. Retrieved from World Wide Web electronic publication website: www.sealifebase.org

Parravacini, V., Villéger, S., Mcclanahan, T. R., Arias-González, J. E., Bellwood, D. R., Belmaker, J., … Mouillot, D. (2014). Global mismatch between species richness and vulnerability of reef fish assemblages. *Ecology Letters*. https://doi.org/10.1111/ele.12316

Pauly, D., Zeller, D., & Palomares, M. L. . (2020). Sea Around Us Concepts, Design and data. *(Seaaroundus.Org)*.

Payne, M. R., Kudahl, M., Engelhard, G. H., Peck, M. A., & Pinnegar, J. K. (2021). *Climate risk to European fisheries and coastal communities*. https://doi.org/10.1101/2020.08.03.234401

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I., … Tuanmu, M. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Climate Change*, *9214*. https://doi.org/10.1126/science.aai9214

Perry, A. L., Low, P. J., Ellis, J. R., & Reynolds, J. D. (2005). Climate Change and Distribution Shifts in Marine Fishes. *Science*, *308*(June), 1912–1916. https://doi.org/10.1126/science.1111322

Peters, R. L., Darling, J. D. S. S., Peters, R. L., & Darling, J. D. S. S. (1985). The Greenhouse Effect and Nature Reserves extinctions among reserve species. *BioScience*, *35*(11), 707–717. https://doi.org/10.2307/1310052

Pinnegar, J. K., Engelhard, G. H., Norris, N. J., Theophille, D., & Sebastien, R. D. (2019). Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica : long-term climate change and catastrophic hurricanes. *ICES Journal of Marine Science*, *0*. https://doi.org/10.1093/icesjms/fsz052

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., & Fischer, G. (2011). RCP 8 . 5 — A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 33–57. https://doi.org/10.1007/s10584-011-0149-y

Roser, M. (2020). Economic Growth. Retrieved May 31, 2020, from Published online at OurWorldInData.org website: https://ourworldindata.org/economic-growth

Saraux, C., Van Beveren, E., Brosset, P., Queiros, Q., Bourdeix, J.-H. H., Dutto, G., … Fromentin, J.-M. M. (2019). Small pelagic fish dynamics: A review of mechanisms in the Gulf of Lions. *Deep Research Part II: Topical Studies in Oceanography*, *159*, 52–61. https://doi.org/10.1016/j.dsr2.2018.02.010

Schwalm, C. R., Glendon, S., & Duffy, P. B. (2020). RCP8.5 tracks cumulative CO 2 emissions . *Proceedings of the National Academy of Sciences*, *2020*, 202007117. https://doi.org/10.1073/pnas.2007117117

Spencer, P. D., Nelson, M. W., Hollowed, A. B., Sigler, M. F., & Hermann, A. J. (2019). Trait - based climate vulnerability assessments in data - rich systems : An application to eastern Bering Sea fish and invertebrate stocks. *Global Change Biology*, (June), 3954–3971. https://doi.org/10.1111/gcb.14763

Sumaila, U. R., & Tai, T. (2020). End Overfishing and Increase the Resilience of the Ocean to Climate Change. *Frontiers in Marine Science*, *7*(July), 1–8. https://doi.org/10.3389/fmars.2020.00523

Sunday, J. M., Bates, A. E., & Dulvy, N. K. (2012). Thermal tolerance and the global redistribution of animals. *Nature Climate Change*, *2*(September). https://doi.org/10.1038/nclimate1539

Teh, L. C. L., & Sumaila, U. R. (2013). Contribution of marine fisheries to worldwide employment. *Fish and Fisheries*, (14), 77–88. https://doi.org/10.1111/j.1467-2979.2011.00450.x

Thiault, L., Mora, C., Cinner, J. E., Cheung, W. W. L., Graham, N. A. J. J., Januchowski-hartley, F. A., … Claudet, J. (2019). Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. *Science Advances*, *5*(November), 1–10. https://doi.org/10.1126/sciadv.aaw9976

Vargas-yáñez, M., Jesús, M., Salat, J., García-martínez, M. C., & Pascual, J. (2008). Warming trends and decadal variability in the Western Mediterranean shelf. *Global and Planetary Change*, *63*, 177–184. https://doi.org/10.1016/j.gloplacha.2007.09.001

Weatherdon, L. V, Magnan, A. K., Rogers, A. D., Sumaila, U. R., & Cheung, W. W. L. (2016). Observed and Projected Impacts of Climate Change on Marine Fisheries , Aquaculture , Coastal Tourism , and Human Health : An Update. *Frontiers in Marine Science*, *3*(April). https://doi.org/10.3389/fmars.2016.00048

Williams, S. E., Shoo, L. P., Isaac, J. L., Hoffmann, A. A., & Langham, G. (2008). Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. *PLoS Biology*, *6*(12). https://doi.org/10.1371/journal.pbio.0060325

Acknowledgements

This work was financially supported by the European Union's Horizon 2020 research and innovation program under the grant agreement No 869300 (FutureMARES). YJS and FM acknowledges funding from the Biodiversa and Belmont Forum project SOMBEE (BiodivScen ERA-Net COFUND program, ANR contract n°ANR-18-EBI4-0003-01). YJS acknowledges support from the Pew marine fellows' program.