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Original Article

Risks and adaptation options for the Mediterranean fisheries in the face of multiple climate change drivers and impacts

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The Mediterranean Sea is among the most vulnerable semi-enclosed seas to climate change. Multiple oceanic changes occur besides warming that can generate numerous ecological, social, and economic risks, challenging fisheries management at various spatial scales—from local to international. In this study, we applied a semi-quantitative climate risk assessment (CRA) to the Mediterranean small pelagic and demersal fisheries in relation to a diversity of climate-related drivers and impacts. We assessed the risks of climate change effects on demersal and small pelagic fisheries resources, fishing operations, livelihoods, and wider social and economic implications in seven sub-regions of the Mediterranean Sea. Ocean warming, an increase in extreme weather events, and changes in vertical stratification resulted in the most important climate drivers. Overall, climate drivers present higher risks to fishing resources and livelihoods than to fishing operations and wider social and economic impacts. The study puts into evidence geographic differences in terms of the drivers and impacts, with the south-eastern Mediterranean being the sub-region with higher risk levels for both fisheries, while the north-central Mediterranean also showed important risk levels for the demersal fisheries. The study furthermore discusses the most plausible adaptive measures in management, policy, research, and livelihoods to be potentially applied to address high priority risks, as well as various implementation concerns and technical effectiveness issues. Enhancing adaptive fisheries management needs to be the primary strategy for this region to reverse the high number of overfished stocks and build resilience to climate change.

Keywords: adaptation measures, climate change, climate-related risks, demersal fisheries, Mediterranean Sea, pelagic fisheries.

Introduction

Climate change constitutes an unprecedented threat to the food and economic security of more than three billion people depending on marine ecosystems (e.g. Barange *et al.*, 2018; IPCC, 2021; Free *et al.*, 2022). The ecological processes affected are numerous, with changes in production, phenology, and distribution of living marine resources being reported in numerous studies (e.g. Poloczanska *et al.*, 2013; Pinsky *et al.*, 2018; Free *et al.*, 2019). Although temperate and Arctic ecosystems are more responsive due to the higher sensitivity to warming (Fossheim *et al.*, 2015), semi-enclosed seas worldwide are especially vulnerable. This is because species have fewer options to migrate, and these seas are likely to be heavily impacted by other cumulative threats such as pollution, habitat degradation, and overfishing, which all synergistically interact with climate change, exacerbating its effects (Hoegh-Guldberg *et al.*, 2014).

The Mediterranean Sea, as a landlocked semi-enclosed sea, is the paradigmatic example, showing cumulative anthropogenic impacts, high sensitivity to local climate stressors,

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and a diversity of climate change impacts (e.g. Hidalgo *et al*., 2018; Ramirez *et al*., 2018; Hilmi *et al*., 2021). Climate change risks have been shown to increase elsewhere with generalized delays or lack of implementation of adaptation measures. For these reasons, the Mediterranean Sea needs the application of integrative and regional management and policies urgently, moving from the climate change risks identification to the implementation of adaptation measures (Hidalgo *et al*., 2022).

Predictable climate change drivers such as warming, increasing heatwaves, or changes in the river runoff have been reported to impact the Mediterranean ecosystems across the whole basin (e.g. Adloff *et al*., 2015; Darmaraki *et al*., 2019). Warming, as the most investigated driver, affects several processes such as: favouring pelagic and thermophilic species of smaller size and lower trophic level (e.g. Moullec *et al*., 2019); changes in species and landings composition (Fortibuoni *et al*., 2015; Tsikliras *et al*., 2015; Vasilakopoulos *et al*., 2017); increasing diversity (i.e. species richness) in the eastern Mediterranean while decreasing it in the western (Albouy *et al*., 2013), facilitating the northward extension, colonization, and enhancement of thermophilic species in the colder northern Mediterranean regions (i.e. meridionalization: e.g. Azzurro *et al*., 2019); or the increasing introduction and range extension of thermophilic, non-indigenous species, from the Red Sea and the Indo-Pacific region (tropicalization: Boero *et al*., 2008), with a heterogeneous species risks in the northern and southern countries (Pita *et al*., 2021). Changes in primary production and runoff are also likely to have a negative impact on the optimum habitats for small pelagic fish in the Mediterranean (Tzanatos *et al*., 2014; Pennino *et al*., 2020), particularly in the north-western and eastern Mediterranean and the Adriatic Sea.

At the regional scale, however, the most important drivers affecting fishing resources go far beyond warming and are, in general, hardly predictable. Changes in the vertical mixing affecting primary production regimes (Macias *et al*., 2018), thermohaline circulation and local hydrography (Ser-Giacomi *et al*., 2020), or the strength of winter weather events (Gaertner *et al*., 2018) are expected to impact demersal species that will suffer from more regional and diverse impacts (Hidalgo *et al*., 2018; Murciano *et al*., 2021). Fisheries is thus a primary ecosystem service under a climate risk in the Mediterranean Sea, having important implications on local and regional economies and communities in all surrounding countries (FAO, 2018, 2020).

The identification and qualitative assessment of climate change risks are commonly made through climate vulnerability assessments (CVAs), and more recently called climate risk assessments (CRAs). These have increasingly been used to evaluate the vulnerabilities of marine species and fisheries to climate change over the last decade (e.g. Allison *et al*., 2009; Cinner *et al*., 2012; Gaichas *et al*., 2014; Colburn *et al*., 2016; Hare *et al*., 2016; Pinnegar *et al*., 2019; Payne *et al*., 2021, among others). Most CVAs qualitatively quantify species sensitivities according to trait-based information, thermal preferences, and climate change projections of thermal conditions (e.g. Aragão *et al*., 2022; Pita *et al*., 2021). However, beyond warming and other projectable climate change drivers, less predictable ones are almost always omitted (e.g. extreme weather events, but see Pinnegar *et al*., 2019, vertical stratification or mesoscale circulation). A qualitative expert-knowledge CRA is generally used to circumvent this lack of detailed information over a broad number of species while keeping and assessing a larger diversity of climate-related drivers and impacts.

The Mediterranean Sea is spatially heterogeneous as concerns the environmental, ecological, socio-economic, and geopolitical characteristics among regions. Thus, it is fair to expect that, for instance, fisheries vulnerability to climate change is likely to be higher in southern countries given the higher exposure to warming and the arrival of non-indigenous species, as well as their overall lower socio-economic adaptive capacity (Hidalgo *et al*., 2018). This was recently exemplified by Pita *et al.* (2021) with respect to warming. These sub-regional differences in risks and adaptive capacities need to be considered when developing regional policies to cope with the impacts of climate change on fisheries (e.g. Holsman *et al*., 2019; Sumby *et al*., 2021; Aragão *et al*., 2022; Kleisner *et al*., 2022).

Management approaches, seldom integrated across spatio-temporal scales, have a high risk of being maladapted to unidirectional change and extreme events (Holsman *et al*., 2019), which are both expected to increase in the Mediterranean Sea. The range of spatial and temporal scales of the processes and impacts requires a matching range of adaptation by fishing enterprises, communities, and regional, national, and international bodies (Lindegren and Brander, 2018). Thus, while CRAs in the Mediterranean need to consider socio-ecological differences at regional scales, adaptation responses need to focus on priority impacts considered more relevant to both a given sub-region and the whole Mediterranean Sea.

The Mediterranean Sea, therefore, urgently needs implementing flexible marine management policies to address climate change impacts that allow management and fisheries to progressively adapt to changing and extreme conditions as they arise. Our aim in this study was twofold. We first compared a set of multi-driver CRAs, separately for pelagic and demersal fisheries, performed over seven large sub-regions of the Mediterranean Sea to identify the "priority" impacts. Then, we discussed a set of available and needed adaptation options designed to cope with the identified priorities, considering the technical effectiveness and the implementation issues of each potential measure.

Methods

Climate risk assessments

CRA is a method extensively used to understand, quantify, and synthesize the impacts of climate change on socio-ecological systems. Vulnerability (i.e. risk) is given as a function of the "sensitivity" of the system to a specific climate change driver, the degree of "exposure" to this driver, and the "adaptive capacity" as the ability of different components of the systems (i.e. ecological and social) to face or compensate potential climate damage (IPCC, 2001). The approach is being continuously revised, conceptually and methodologically. One example of this is the recent suggestion of including the uncertainties in simulations of future climate impacts (to consider uncertainties in projections of climatic risk at the regional scale; IPCC, 2014); another is the conceptual change from "vulnerability" to "risk" more broadly used in the recent years (CRA; Cardona *et al*., 2012).

The CRA applied in this study focused on the two main fisheries: small pelagic and demersal fisheries. Sardine (*Sardina*

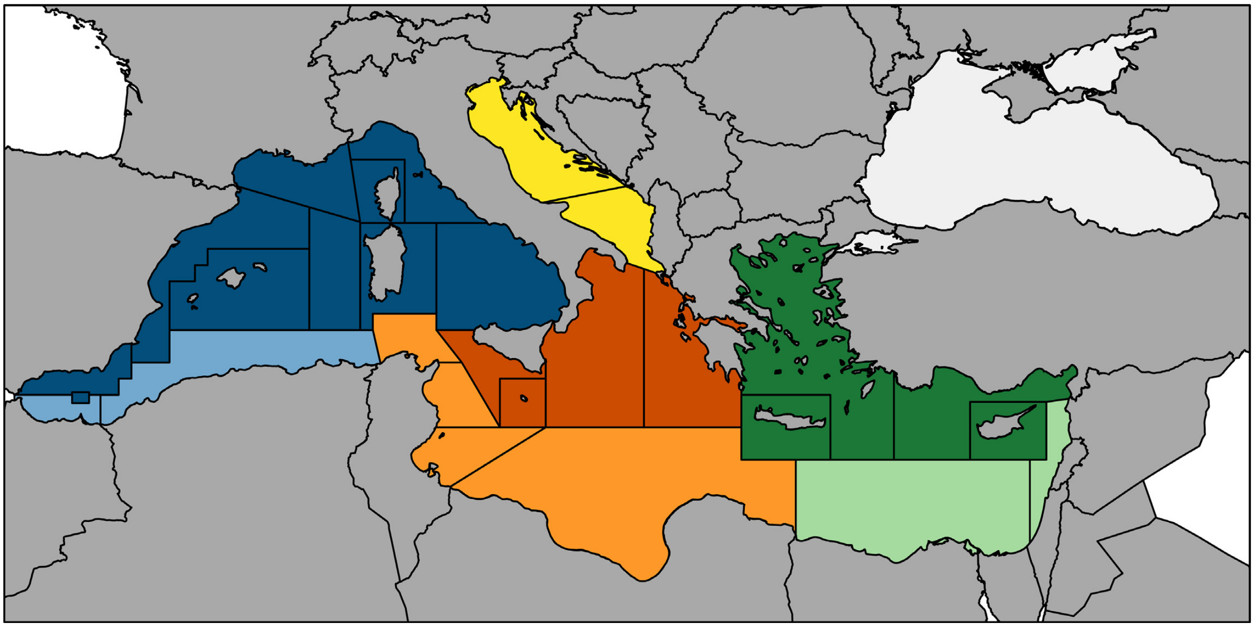

Figure 1. The Mediterranean Sea map displays the sub-regions considered in the CRA: north and southwestern (dark and light blue respectively), north and southcentral (dark and light orange respectively), Adriatic (yellow) and north and southeastern (dark and light green respectively).

pilchardus) and anchovy (*Engraulis encrasicolus*) are the main target species of the small pelagic fisheries that operate in the Mediterranean Sea. Other small pelagic species are also captured, sometimes representing a high percentage of the catch, such as round sardinella (*Sardinella aurita*), horse mackerels (*Trachurus* spp.), and mackerels (*Scomber* spp.). Sardine and anchovy account on average for >50% of the total landings, with sardine being the most important species (FAO, 2020). Purse seiners and pelagic trawlers are the main targeting vessels, although small-scale fisheries also make a high contribution. Demersal fisheries are, in contrast, multi-species and multi-fleet in the Mediterranean Sea. The most important demersal species are European hake (*Merluccius merluccius*), red mullets (*Mullus* spp.), deep-water rose shrimp (*Parapenaeus longirostris*), and the deep-water red shrimp (*Aristaeomorpha foliacea* and *Aristeus antennatus*), including some cephalopods (*Octopus* spp. and *Eledone* spp.). Although these species are mainly captured by trawlers, small-scale fisheries also contribute substantially, particularly in the south and the eastern Mediterranean (FAO, 2020).

To obtain risk scores over a range of different expected impacts, the CRA was applied for the four main sub-regions in the Mediterranean Sea corresponding to General Fisheries Commission for the Mediterranean (GFCM) sub-regions: western, central, and eastern Mediterranean, and the Adriatic Sea. In addition, in order to capture differences in environmental, socio-economic, and governance conditions within these sub-regions as already reported (FAO, 2018; Hidalgo *et al.*, 2018), the CRA for the eastern, central, and western Mediterranean was further divided into north and south sub-regions (Figure 1). This division to develop the CRA was selected as a compromise between a spatial scale representing similar ecological and social exposure, sensitivity, and adaptive capacity and a reasonable scale at which adaptation measures can be implemented to respond to the identified priorities (also acknowledging that some adaptation measures can be implemented at a national, sub-regional, or even regional level). The Adriatic sub-region has been treated as a single area because it is a more homogeneous zone in terms of exposure to climate change despite the differences in adaptive capacity between eastern and western Adriatic (FAO, 2018).

The CRAs were carried out using a common matrix of climate drivers and observed/expected impacts of climate change on fisheries based on literature review and expert consultation mainly held in a dedicated workshop (FAO, 2018). While numerous CRAs apply quantitative risk scores associated with the life history traits more sensitive to sea warming, important climate change impacts, which are not associated with any trait, are often omitted. Therefore, in this study, the climate drivers considered were extended beyond warming to include a diversity of climate change-related drivers, for which there is evidence of their impacts on fishing resources and their related activities (Hidalgo *et al.*, 2018; Figure 2): increase in sea surface temperature; increase in salinity; increase in frequency (and intensity) of heatwaves; changes in the precipitation and runoff; sea-level rise; changes in vertical mixing and stratification; increase in frequency (and intensity) of extreme weather events; and changes in mesoscale circulation. In terms of expected impacts, 27 potential impacts were considered and grouped into four categories: (i) Fisheries resources (10), (ii) Fishing operations (5), (iii) Communities and livelihoods (7), and (iv) Wider society and economic implications (5) (Figure 2, and all defined in Table 1).

For each combination of driver-impact, the climatic risk of fisheries to a given characteristic was assessed in terms of risk levels (FAO, 2015, 2018). Risk levels are computed as the product of (i) the level of expected impacts or *consequences* of the driver/threat and (ii) the *likelihood* of the impact occurring. The scoring of *consequence levels* (C) considered information about the sensitivity of the system to the driver/threat and the presumed adaptive capacity to cope with the effects of the driver/threat. C was scored from 1 to 4 (minor, moderate, major, and extreme; see scoring criteria in Supplementary Table 1). On the other hand, the scoring

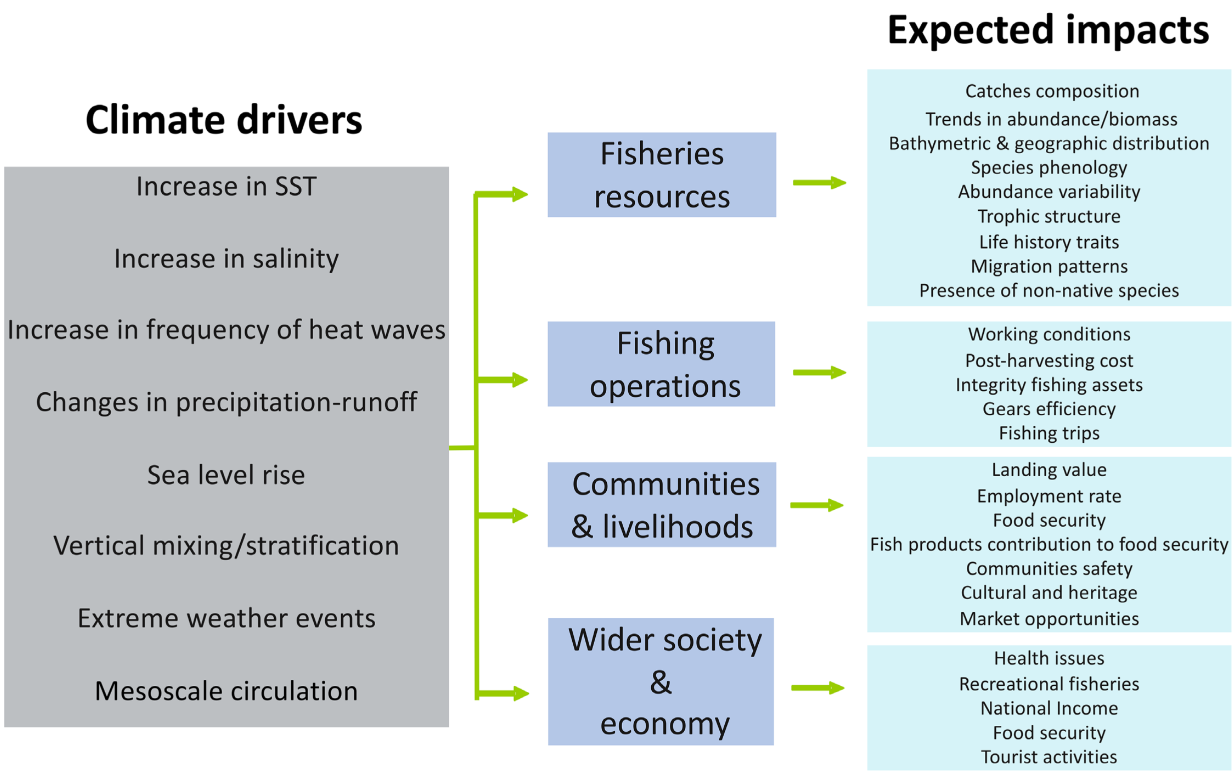

Figure 2. The schematic diagram below shows the CRA developed with the climate drivers considered (left) and the expected impacts (right) grouped into four categories (centre) (adapted from Badjeck *et al.*, 2010). Note that geographic and bathymetric distribution are treated as separate impacts in the analysis, as well as employment rate for males and females (Table 1).

of the *likelihood* (L) of an impact occurring considered the level of exposure of the system to the driver/threat, the likelihood of the predicted changes in the driver, and any available evidence that the impacts were occurring; the L was scored from 1 to 4 (remote, unlikely, possible, and likely; see scoring criteria in Supplementary Table 2). The resulting risk levels, computed as the product of C and L, varied from negligible (1–2), low (3–4), medium (5–8), and high (9–16). The scoring of C and L and the categorization of risk level was done in consultation with local experts and supported by the available literature, where the availability of published information was considered as a part of the scoring process following the established criteria (Supplementary Tables 1 and 2; FAO, 2018). In the Adriatic and the central Mediterranean, local experts with multi-disciplinary backgrounds were consulted through a close-ended questionnaire, and the resulting scores were the averaged risk values (Supplementary Material—Text). In the western and eastern Mediterranean, the scoring was done by consensus among a multi-disciplinary team of experts, followed by a review by local experts. These approaches were selected based on the contrasting composition of the group of experts between regions, and they were equally standardized as they were based on the same framework (drivers, impacts, and risk assessment categories).

Climatic risk scores are here presented from two perspectives: drivers and impacts, using independent statistical approaches and plots. To do that, statistical geographic differences in the scores were assessed first for the different types of drivers and then, in independent plots and analyses, for the different groups of impacts. Statistical analyses applied in each case were two-way ANOVA. These analyses and plots were independently performed for the demersal and pelagic fisheries.

Climate drivers can affect fisheries in different ways, and adaptation responses need to focus on priority impacts that are considered the most relevant to both a given sub-region and the whole Mediterranean Sea. To identify these priority impacts, which were used to define the most plausible adaptation measures, we calculated cumulative frequency curves for each sub-region in order to select them in a comparative way among all sub-regions and connect them to the most efficient adaptive measures. To do that, cumulative risk score curves were calculated for each area and type of fishing using the mean risk value for each impact. From those, all impacts with >75% of cumulated probability were considered relevant and deemed "priorities". This is consistent with the risk assessment methodology adopted by FAO (2015, 2018). Using a cumulative probability threshold, the sub-region priorities were also made more comparable.

Adaptation measures

Different types of adaptation measures can be employed to cope with the identified priorities. The adaptation measures need to be commensurate with the realities and capacities of the countries in each sub-region to be effective. The recent FAO toolbox for climate adaptation in fisheries was used as the baseline, which operates with three categories of measures: institutional and management, livelihoods, and risk reduction (Poulain *et al.*, 2018). However, other various examples of good practices for fisheries management adaptation to climate change are also available in the literature and they are also considered (Holsman *et al.*, 2020; Ogier *et al.*, 2020; Bahri *et al.*, 2021; Bryndum-Buchholz *et al.*, 2021).

Table 1. Definition of the 27 impacts considered in the CRA grouped in four categories (also illustrated in Figure 2).

Category of impact	Impact	Definition
Fisheries resources	Catches composition	Species composition in the catch
	Species geographic distribution	Range of geographic distribution covered by the species
	Species bathymetric distribution	Range of bathymetric distribution covered by the species
	Trends in abundance/biomass	Increasing or decreasing patterns observe in fisheries production
	Abundance variability/changes year-class strength	Degree of fluctuating variability of annual indices of fisheries production
	Species phenology	Seasonal timing of recurring biological events
	Trophic structure	Partitioning of biomass between marine trophic levels
	Life history traits (growth, reproduction)	Characteristics and critical life events affect the life table of an organism
	Migration patterns of targets species	Routes and timing of migration of migratory species
	Presence of non-indigenous species	Occurrence of non-indigenous species entering the Mediterranean through the Suez canal, the Gibraltar strait, ballast waters, etc.
Fishing operations	Fishers working conditions/number of accidents at sea	Level of working and security conditions of fishers at sea
	Cost of post-harvesting (preservation)	Level of cost on all the post-fishing processes
	Integrity of fishing assets (gears, vessels)	Level preservation of all tools used in the fishing process
	Efficiency of gears	Capacity of fishing gears to maximize the level of catches
	Fishing trips/days at sea	Time spent by fishers at sea
Community and livelihoods	Landing value	Commercial value of catches
	Employment rate female	Level of employment of females in all activities related to fishing
	Employment rate male	Level of employment of males in all activities related to fishing
	Contribution of fish products to food security	Level of importance of fisheries catches to the access to a sufficient quantity of affordable and nutritious food
	Safety of (coastal) communities	Degree of security and protection of coastal areas against extreme and progressive natural events
	Cultural heritage	Legacy of tangible and intangible heritage assets of a group or society that is inherited from past generations
	Market opportunities (non-native species)	Degree of new species being potential fished and offered to the market
Wider society and economy implications	Health issues	Any element (pollutant, pathogen, or other means) that can cause a health problem
	Food security	The state of having reliable access to a sufficient quantity of affordable and nutritious food
	Recreational fisheries	Fishing for pleasure or competition
	National income	The total amount of money earned within a country
	Tourism activities	All commercial activity associated with meeting the needs of people who are travelling for pleasure or on business to coastal areas

Building on all these previous initiatives, we identified in this study the adaptation options and measures that could be used to address the main priorities, grouped into four types: management options, policy, research, and livelihoods. We focused on adaptation measures that could be considered "low or no-regret", i.e. low-cost measures that provide relatively large benefits, and/or "win–win" or "lose–win", i.e. adaptation that yields large long-term benefits under relatively low short-term risks (Grafton, 2010; Poulain *et al.*, 2018). In terms of cost-benefit, almost all measures considered were lose–win and low-regret. The adequacy of the proposed measures is discussed in terms of their likely technical effectiveness to address the identified priority impacts and any expected issues with their implementation.

Results

Risks associated to different drivers

The risk values obtained indicated that all the climate drivers considered are expected to impact fisheries in all the Mediterranean Sea sub-regions (Figure 3). However, their importance significantly varies according to the type of driver and sub-region for the pelagic (ANOVA, $F = 8.45$, $p < 0.05$ for the type of driver; $F = 6.71$, $p < 0.05$ for the sub-region; Figure 3a) and demersal fisheries (ANOVA, $F = 13.93$, $p < 0.05$ for the type of driver; $F = 15.9$, $p < 0.05$ for the sub-region; Figure 3b).

The risks observed for the two fisheries were, in general, highly heterogeneous across sub-regions, representing

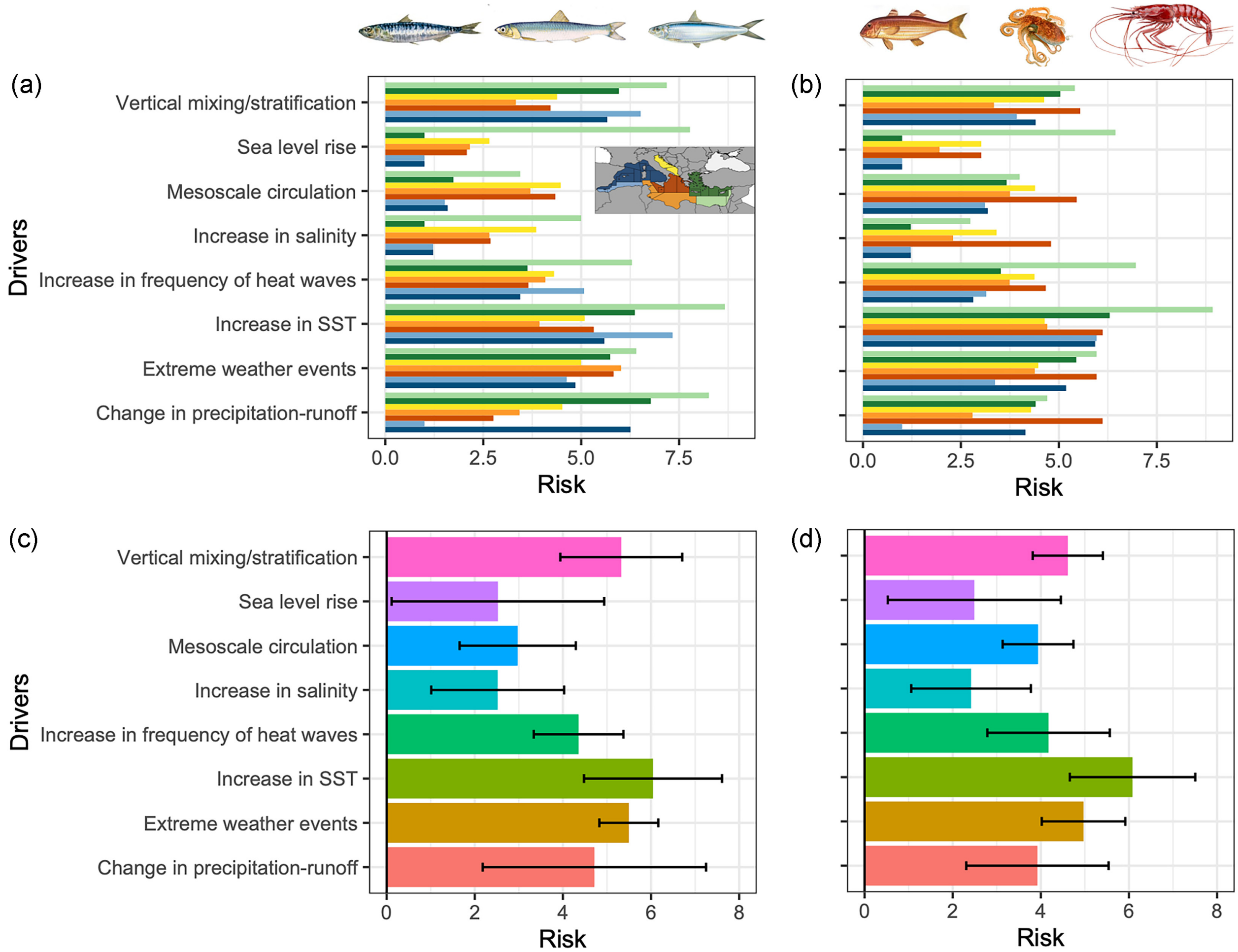

Figure 3. Mean risk scores for each driver and sub-region (colour coding from Figure 1 (a, b) and, mean risk and *SD* per driver (c, d) for small pelagic (left) and demersal (right) fisheries calculated over the values presented in panels (a) and (b).

the different perceptions of risks and the specificity of some species and fisheries to certain drivers, often geographically constrained. The most important drivers in the pelagic fisheries were the "*increase in SST*", "*extreme weather events*", and changes in "*vertical mixing/stratification*" with a similar pattern for demersal fisheries (Figure 3c and d). "*Changes in precipitation-runoff*" and "*vertical mixing/stratification*" were important secondary drivers (i.e. the next highest risk scores). They were also the most heterogeneous (i.e. region-specific) of the two fisheries. For instance, the "*changes in precipitation-runoff*" were important in the north-western and eastern sub-regions due to the key role of river runoff, while "*mesoscale circulation*" was considered more relevant for the Adriatic and the north-central Mediterranean, particularly for demersal fisheries, as these are sub-regions with narrow transboundary areas and/or high hydrodynamic activity (Figure 3b and d). The "*increase in frequency of heatwaves*" was considered relevant mainly in the south-eastern and Adriatic sub-regions. For the demersal fisheries, a generally higher and more consistent score within areas was better observed in the north-central sub-region and the Adriatic, where many drivers had a strong influence (Figure 3b). Some drivers were considered as a reduced risk attending to the type of fishing or sub-region such as "*sea-level rise*" or "*increase in salinity*", except in the Adriatic Sea and the south-eastern Mediterranean (Figure 3).

Risks in terms of the most relevant impacts

Figure 4 provides mean risk values by impact category and sub-region, while Figure 5 illustrates the mean value per specific impact and fishery (presented for each sub-region in Supplementary Figures 1 and 2 for pelagic and demersal fisheries, respectively) . The risk levels significantly vary according to the group of impacts and sub-region for the pelagic (ANOVA, $F = 27.36$, $p < 0.05$ for the group of impacts; $F = 13.31$, $p < 0.05$ for the sub-region; Figure 4a) and demersal fisheries (ANOVA, $F = 44.4$, $p < 0.05$ for the type of driver; $F = 17.52$, $p < 0.05$ for the sub-region; Figure 4b). The highest risks were associated with impacts on "*fisheries resources*" compared to the other three categories, particularly for the Adriatic and the south-eastern sub-region and the north-central sub-region for demersal fisheries (Figure 4). Within this category, "*abundance variability/changes year-class strength*", "*catches composition*", distribution changes, and "*trends in abundance/biomass*" were the more relevant impacts (Figure 5a and b). "*Communities and livelihoods*" group shows high variability with the south-eastern sub-region being the most impacted, for both pelagic and demersal species (Figure 4a and b). Within this category of impacts, "*landing value*" was the most relevant in the two fisheries, followed by "*cultural heritage*" and "*market opportunities*". In the case of small pelagic fisheries, the assessment also

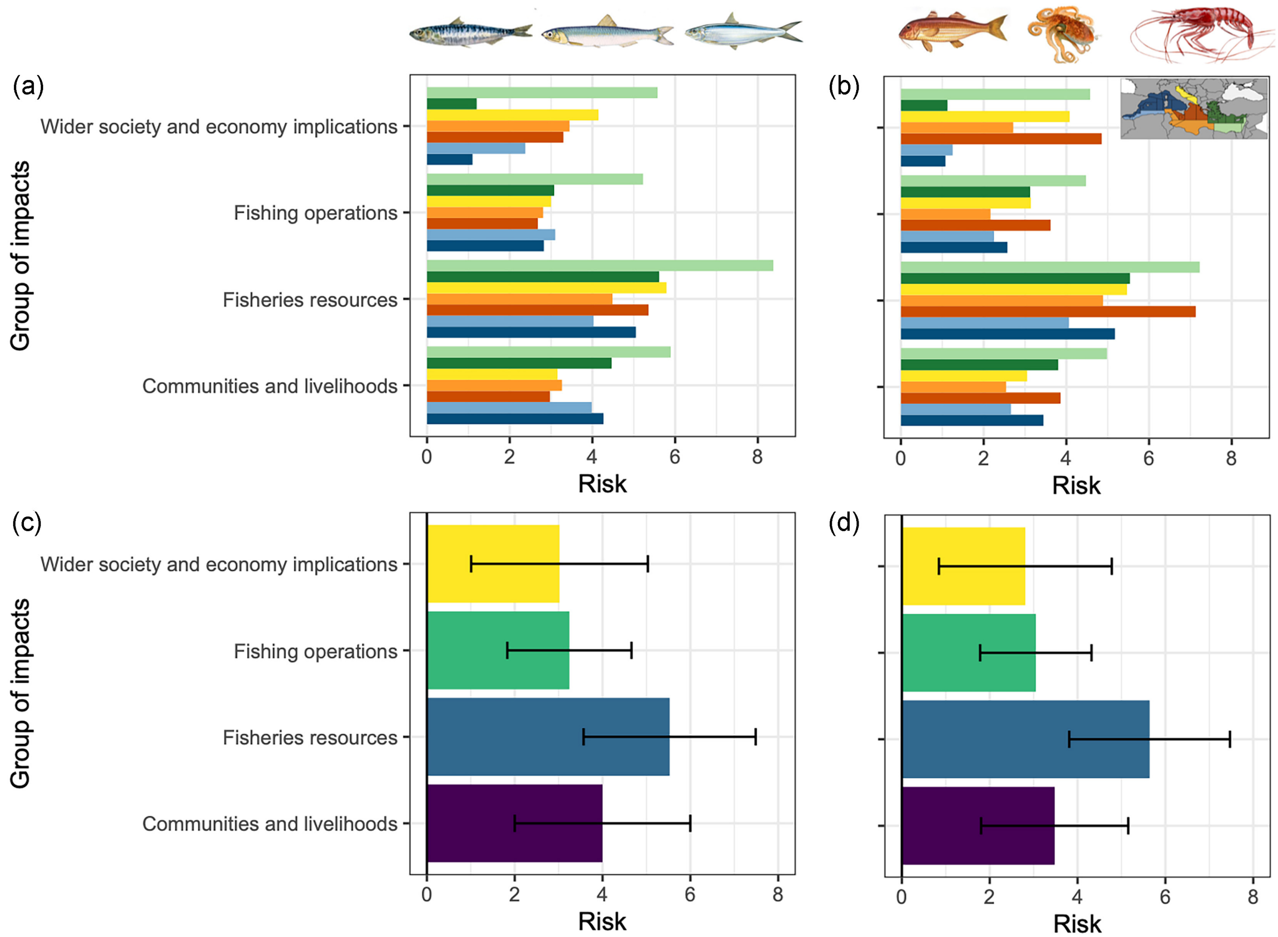

Figure 4. Mean risk scores for each group of impacts and sub-region (colour coding from Figure 1)(a, b) and mean risk and *SD* per group of impact (c, d) for small pelagic (left) and demersal (right) fisheries were calculated over the values presented in panels (a) and (b). Supplementary Figures 1 and 2 provide scores for each impact, region, and fishery.

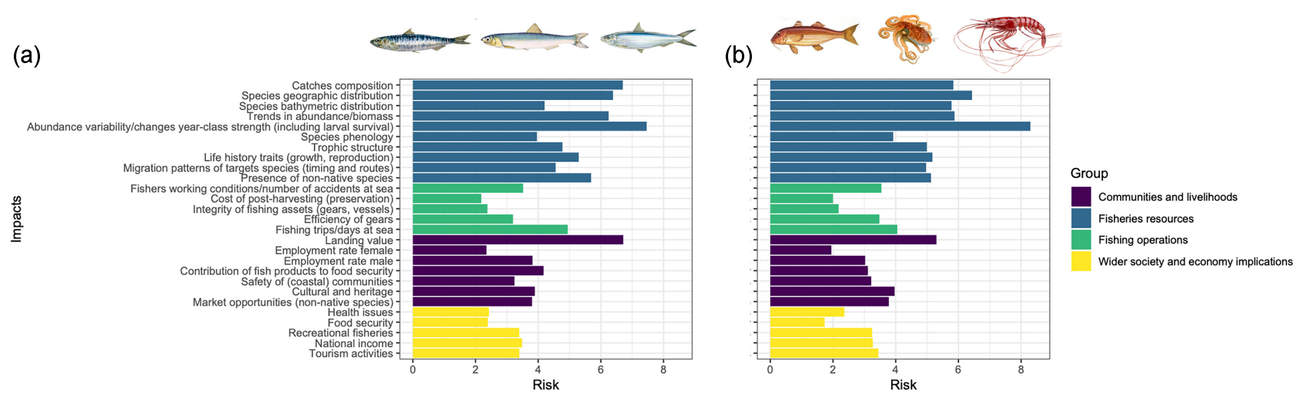

Figure 5. Mean risk scores for each expected impact are averaged over all sub-regions for small pelagic (a) and demersal fisheries (b). Bar colour code for the four categories of impact. Supplementary Figures 1 and 2 provide scores for each impact, region, and fishery.

highlighted the risks to the "*contribution of fish products to food security*" (Figure 5a and b). Impacts grouped under "*fishing operations*" and "*wider society and economy implications*" were deemed as higher risk in the Adriatic and south-eastern sub-regions and, for demersal fisheries, in the north-central sub-region (Figure 4a and b). Within the "*fishing operations*" category, "*fishing trips/days at sea*" received higher risk scores, followed by "*fishers working conditions*" and "*efficiency of gears*". "*Tourism activities*", "*national income*", and "*recreational fisheries*" were the wider impacts considered somehow relevant, but with generally lower risk levels than those impacting "*fisheries resources*" impacts. Sub-regional specific differences are shown in Supplementary Figures 1 and 2.

Table 2. Selected priorities by fishery type attending to cumulative probability curves (Supplementary Figures 1 and 2) and the sub-regions in which priority (i.e. impact) was above the threshold selected.

Priorities	Small pelagics	Demersal
Fisheries resources		
Abundance variability/changes year-class strength	NC, SC, NE, SE, AD	NW, SW, NC, SC, NE, SE, AD
Catches composition	NW, SW, NC, SC, NE, SE, AD	NW, SW, NC SC, NE, SE, AD
Life history traits (growth, reproduction)	NC, SE, AD	NC, SC, SE, AD
Migration patterns of target species	NC, SC, AD	NC, SC, SE, AD
Presence of non-indigenous species	NC, NE	NW, SW, NE, SE
Species bathymetric distribution	SC	NW, SW, NC, SC, NE, SE, SE
Species geographic distribution	NW, SW, NC, SC, NE, SE, AD	NW, SW, SC, NE, SE, AD
Trends in abundance/biomass	NW, SW, NC, NE, SE, AD	NW, SW, NC, SC, SE, AD
Trophic structure	NC, SE	SC, SE
Fishing operations		
Fishing trips/days at sea	NE	
Communities and livelihoods		
Contribution of fish products to food security	SW, SC	
Cultural heritage	NE	NW, NE
Employment rate (men)	NW, SW	SW
Landing value	NW, SW, NE	NW, NC, NE, SE
Market opportunities (non-indigenous species)	NW	
Wider society and economy implications		
Food security	SW	
National income	SC	
Recreational fisheries	SC	AD
Tourism activities	AD	NC, AD

NW: North-western; SC: South-western; NC: North-central; SC: South-central; AD: Adriatic; NE: North-eastern; SE: South-eastern.

Table 2 summarizes the main impacts (i.e. "priorities") reported in Supplemenatry Figures 1 and 2 for pelagic and demersal fisheries, respectively, considering a sub-region specific threshold associated with the 75% cumulative probability over all scores impact for each sub-region. This threshold value allowed a balanced selection of a similar number of priorities between 6 and 9 impacts per sub-region.

Likelihood, consequences, and geographic risks patterns

The relative contribution of consequences and likelihood differs for each sub-region, while it is generally consistent (except in the Adriatic) between fisheries for each sub-region (Figure 6a and b; Supplemenatry Figure 3 for the geographical variation of consequences and likelihood). The western and north-eastern sub-regions have a relatively equal contribution of the two components, compared to central sub-regions that display a high level of likelihood with lower consequences, particularly in the northern-central Mediterranean. The Adriatic shows a contrasting scenario between fisheries with a high level of likelihood in the small pelagic fisheries and the high level of consequences in the demersal fisheries. The south-eastern Mediterranean displays the highest levels of both consequences and likelihood in the pelagic fisheries and the highest level of consequences in the demersal fisheries. Overall, the global risk was the highest in the eastern Mediterranean, particularly for the small pelagic fisheries, followed by the demersal fisheries of the northern-central Mediterranean and the Adriatic (Figure 6c and d). The lowest risks were observed in the western sub-regions and the south-central Mediterranean.

Most plausible adaptation measures

Attending to the list of priorities identified across the seven Mediterranean regions (Table 2), we identified 13 potential adaptive measures that specifically respond to the list of priorities. Table 3 displays the list of these 13 potential measures and how they are related to the impacts prioritized in the CRAs of small pelagic and demersal Mediterranean fisheries. They are grouped into four types of adaptation options: management options, policy, research, and livelihoods (Table 3 and defined in Supplementary Table 3). These measures are expected to be relevant for the two types of fisheries and all sub-regions, with most of them useful for three or more priorities, and a few more specific. Each measure is accompanied by the more relevant characteristics in terms of technical effectiveness and implementation considerations (Table 3).

Discussion

Oceanic changes resulting from climate change will generate numerous ecological, social, and economic risks related to food security, sustainability, and ecological integrity in the Mediterranean Sea. This will challenge fisheries management at all scales—from local to international (Bryndum-Buchholz *et al*., 2021). In this study, common drivers, impacts, and priorities have been consistently identified across sub-regions, evidencing that the Mediterranean Sea is in dire straits. Urgent action must be taken, but important geographic differences must be considered when choosing appropriate adaptive measures.

Drivers, impacts, and main priorities

Beyond warming, other considerable climate-related drivers, in particular "*extreme weather events*" and changes in "*vertical mixing/stratification*", may seriously threaten the Mediterranean fisheries. While climatic models have, in general, lower predictive capability (spatial and temporal) over these impacts, recent studies prove that primary production dynamics will change in response to different directional changes in the stratification in the basin (increasing and decreasing in the western and eastern, respectively, Macías

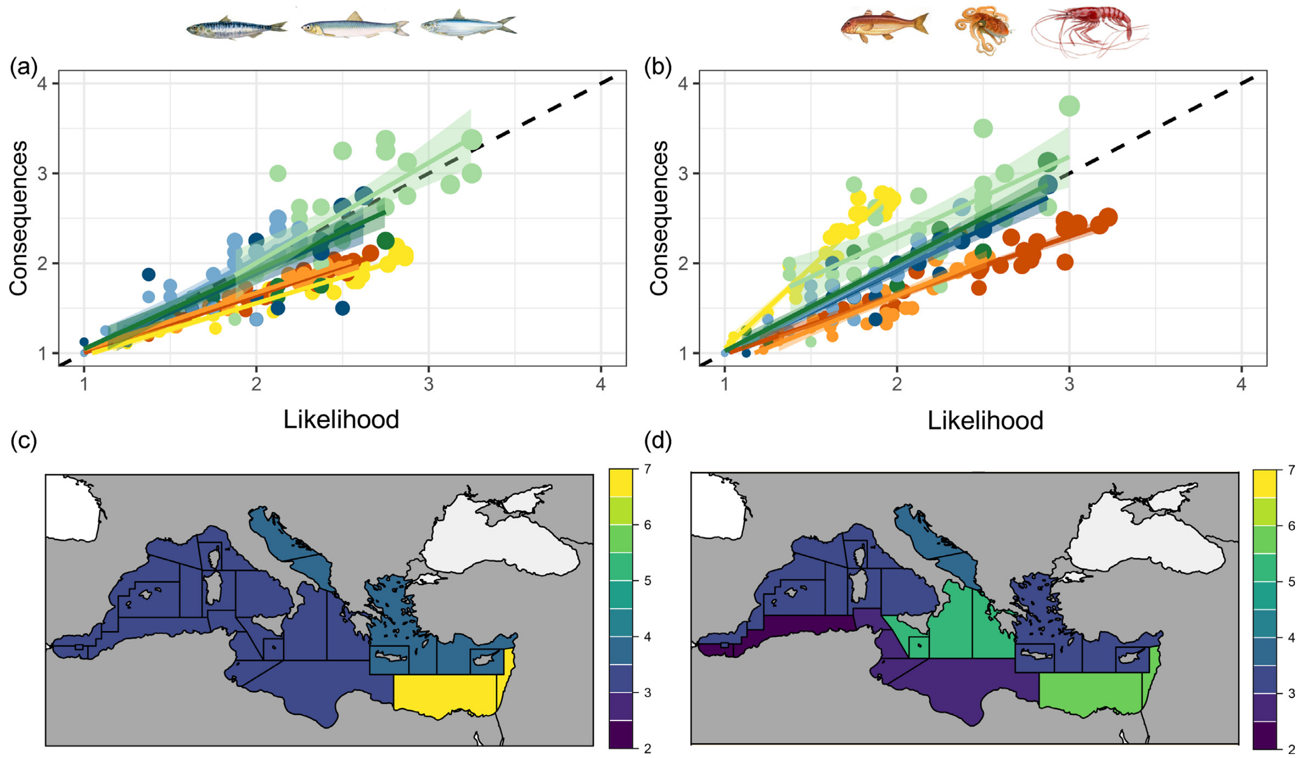

Figure 6. Relationship between mean likelihood and consequence scores for all impacts in the sub-regions (colour coding from Figure 1) and with risk values represented by the size of the bubble for the small pelagic (a) and demersal (b) fisheries. Mean risk scores for each sub-region for small pelagic (c) and demersal (d) fisheries.

et al., 2015), and also at regional scales critical for feeding and nursery areas (Macías *et al.*, 2018). Besides the growing evidence of a climate-induced rise in extreme weather events (Gaertner *et al.*, 2018), few studies report direct mechanistic effects on fishing resources (e.g. Hidalgo *et al.*, 2019). However, the fishers' perception of the expected risks associated with extreme weather events is very high and has been reported both in western and eastern regions (Murciano *et al.*, 2021). Another important hazard is the expected decrease in river runoff. This will act as a driver of the decline of primary production in many regions (Macias *et al.*, 2018), exacerbated by its synergy with warming (Coll *et al.*, 2019; Moullec *et al.*, 2019). This will be critical for pelagic fisheries in many areas of the Mediterranean (north Adriatic, river mouths in the north-western, and the Nile in the eastern Mediterranean; e.g. Pennino *et al.*, 2020). The "*increase frequency of heatwaves*" is a climate change impact with very likely projections at a temporal scale in the Mediterranean (Adloff *et al.*, 2015; Darmaraki *et al.*, 2019). Although reports have yet to come in, it is expected that direct impacts on fishing resources will soon be in evidence in the Mediterranean in the same way as in other affected areas in the world (e.g. Cheung and Frölicher, 2020).

Similarly, numerous studies have also demonstrated that "*mesoscale circulation*" will change due to climate change (e.g. Adloff *et al.*, 2015; Ser-Giacomi *et al.*, 2020). However, specific scenarios are both elusive and highly uncertain due to the complexity associated with oceanographic processes (Adloff *et al.*, 2015). Nevertheless, several modelling and empirical studies have demonstrated the importance of this driver in terms of dispersion, connectivity, transport-mediated early life survival, and the ultimate influence on recruitment success (e.g. Andrello *et al.*, 2015; Gargano *et al.*, 2017; Hidalgo *et al.*, 2019). The perception of this risk is, as such, highly region-specific.

In sum, climate-related drivers that pose a serious threat to the Mediterranean fisheries can be divided into three groups: (i) those with well-understood dynamics in climatic simulations where available knowledge exists on the likely ecological and fisheries impacts (e.g. warming and vertical stratification); (ii) those with well-understood dynamics but where only moderate knowledge on the impacts (heatwaves or extreme weather events) exists; and (iii) those with good and increasing knowledge on the ecological impacts but where moderate and relatively uncertain physical dynamics apply (mesoscale circulation).

Most studies (empirical and modelling) related to the effects of climate change on fisheries focus on small pelagic fisheries (e.g. Tzanatos *et al.*, 2014; Coll *et al.*, 2018; Alheit *et al.*, 2019; Peck *et al.*, 2021). They show general geographic agreement on the effects and their direction but mention that some specific drivers are more important in certain areas. For instance, river discharge impacts are meaningful in areas with rivers with enough flow runoff and associated primary production dynamics. This biogeographic relevance is evident also in the central Mediterranean and Adriatic demersal fisheries, which are more affected by mesoscale circulation than other areas and could easily affect the distribution and structure of the transboundary stocks (Gargano *et al.*, 2017). In general, heterogeneity in demersal fisheries can be considered higher beyond warming. The high diversity of physical drivers impacting demersal species and the geographic variation of their effects, including the direction of the effect, make regional projections by climate change models difficult and hinder the assessment of future directional changes (Hidalgo *et al.*, 2018).

Table 3. List of 13 potential adaptation measures for the identified priorities and important elements regarding technical effectiveness and implementation considerations.

Adaptation measure	Type	Priority (climate change impact)	Technical effectiveness	Implementation considerations
Transboundary stock management	**Management options**	Species geographic distribution. Trends in abundance/biomass. Abundance variability/changes year-class strength.	Long-term regulation. Changes in availability to national fleets.	Aligned with current international initiatives. Increased complexity of decision-making.
Adaptive spatial planning	**Management options**	Species bathymetric distribution. Species geographic distribution. Abundance variability/changes year-class strength.	Flexible: able to combine short and long-term regulation. Studies support effectiveness in dealing with species distribution and abundance trends. Abundance variability is highly dependent on the environment, which does not ensure effectiveness.	Aligned with current initiatives and projects and international commitment.
Adaptive and collaborative control of fishing pressure	**Management options**	Species geographic distribution. Trends in abundance/biomass.	Available remote sensing tools. Sensitive information with potential restrictions to be shared among countries.	Requires enhanced cooperation among countries. It can create discrimination (countries winners and losers in terms of increase/decrease of fishing yields). Potential lack of transparency.
Diversifying patterns of fishing activities with respect to exploited species	**Management options**	Abundance variability/changes year-class strength.	Flexibility: allow spatial-temporal variation in access to the resource.	Implementation must be aligned with adaptive spatial management.
Policy product value addition and value development	**Policies**	Landing value. Catches composition. Presence of non-indigenous species.	Effectiveness not guaranteed and dependent on social acceptance. Not equally applicable to northern and southern countries.	Strong country dependence in the implementation, policy procedures and interaction with other activities. The effective implementation is only ensured if it is accompanied by public investment in communication and awareness.
Address poverty and food insecurity	**Policies**	Food security. Employment rate male.	Effectiveness proved. Probably more relevant for coastal areas in southern countries.	Rapidly mobilized and implemented as needed when conditions change. Implementation requires institutional coordination (national and international).
Public investment (communication and awareness)	**Policies**	Cultural heritage. Presence of non-indigenous species. Catches composition.	Effectiveness not ensured and dependent on cultural and social acceptance.	Acceptance and support required from fishers, communities, and other stakeholders. High short-term costs can be an impediment for some countries. Long-term positive effects not guaranteed.
Diversification of markets and (new) fish products	**Livelihoods**	Landing value. Presence of non-indigenous species. Catches composition. Contribution of fish products to food security. Cultural heritage.	Effectiveness for landing value not guaranteed. Flexible, as NIS will need a portfolio of options to be socially acceptable. Effectiveness not necessarily ensured to face food security (social acceptance).	Strong country dependence and different application in the north and south countries. Social acceptance is not ensured to facilitate successful implementation. Acceptance and support required from fishers, communities and stakeholders. Potential of being successful in the short term but uncertain long-term benefits. Relative high cost for some countries and may not ensure long-term positive effects.

Table 3. Continued

Adaptation measure	Type	Priority (climate change impact)	Technical effectiveness	Implementation considerations
Exit strategies for fishers to leave fishing	**Livelihoods**	Employment rate male. Food security.	Flexible, effective, adaptive and highly responsive to impacts.	The effectiveness is only ensured if it is accompanied by policy compromise and public investment.
Livelihood diversification	**Livelihoods**	Food security. Contribution of fish products to food security. Employment rate male.	It provides flexibility and broader opportunities. Effectiveness proved. Effective and responsive once implemented.	Acceptance and support required from fishers, communities, and other stakeholders. Rapidly mobilized and implemented as needed when conditions change.
Research and monitoring of stock productivity and distribution and its relationship with environmental conditions	**Research**	Abundance variability/changes year-class strength. Trends in abundance/biomass. Changes in the geographic distribution. Changes in the bathymetric distribution.	Flexible, adaptive, highly responsive to impacts.	Aligned with current initiatives and international commitment.
Investment and research in adapting fishing operations	**Research**	Presence of non-indigenous species. Fishing trips/days at sea. Species geographic distribution. Species bathymetric distribution.	The most plausible solution to face damages by harmful NIS on gears. Effectiveness proved with new technologies and more selective gears.	Implementation will depend on the cost and the acceptance by all stakeholders. Relative high cost for some countries, and particularly for fishers.
Early-warning forecasting	**Research**	Catches composition	Studies support effectiveness. Flexibility: allow country dependence estimation and assessment.	The effectiveness is only ensured if it is accompanied by other management measures in the long term. Likely contrasting signals for different species and systems.

As expected, impacts on "*fisheries resources*" were the group with higher risk values. The most recurrent impacts were related to changes in abundance variability, species composition, and biomass trends, which are the key elements that sustain the stability and productivity of fisheries, and were identified as priorities in the present study. These findings are consistent with studies elsewhere, including a recent quantitative climatic risk assessment of Mediterranean warming (Pita *et al.*, 2021). Beyond those impacts, the role of non-indigenous species is also of paramount importance in the Mediterranean Sea, particularly in the eastern Mediterranean despite the progressively increasing in the western sub-regions, all requiring specific measures (e.g. Tsikliras *et al.*, 2015; Azzurro *et al.*, 2019; Gücü *et al.*, 2021). Non-indigenous species present a higher risk for artisanal fisheries, but their impact is increasing in the small pelagic fisheries and demersal fisheries as well. They cause numerous adverse ecological effects, health, and fishing asset damage (e.g. pufferfishes), while they are becoming a fishing resource opportunity in some cases (e.g. rapa whelk or blue crab) (Öztürk, 2021).

In this study, "*communities and livelihoods*" were associated with moderate risk values, in which mainly landing value but also employment rate, market opportunities, food security, and cultural heritage issues were found relevant depending on the fishery and sub-region. Twenty-two species represent >70% of the total landing value in the Mediterranean, and just six species represent >50%, which are mainly small and medium pelagic fish and especially important in the Adriatic and western Mediterranean sub-regions (FAO, 2020). The central and eastern regions display a more diverse portfolio of catches, mainly demersal and from small-scale fisheries. This is known to constitute a key advantage in the face of climate change impacts (González-Mon *et al.*, 2021; Short *et al.*, 2021), but may represent a higher sensitivity to losses in employment opportunities. The southern sub-regions are, in general, more at risk due to the higher contribution of fisheries to food security, mainly where small pelagic species are a primary source of protein (Ding *et al.*, 2017; Karmaoui, 2018). Conversely, countries in the northern areas are more sensitive to cultural heritage issues and have a greater capacity to increase imports under local or seasonal demands (Hidalgo *et al.*, 2018).

The eastern Mediterranean is especially vulnerable and at risk (Payne *et al.*, 2021; Pita *et al.*, 2021), because of its higher exposure to several drivers (i.e. likelihood) and a higher number of highly scored consequences. Notably, the unprecedented increase of non-indigenous species is much higher in this sub-region than elsewhere (Gücü *et al.*, 2021; Öztürk, 2021), and this, in combination with other anthropogenic pressures, may explain the area's high climate risk status. In the case of demersal fisheries, the northern-central Mediterranean also displays high-risk values due to the high diversity of drivers and high impacts in all groups. In contrast to the south-eastern Mediterranean, the northern-central sub-region also received higher likelihood scores, reflecting an expected higher exposure to different drivers, predicted changes in drivers, and the degree to which impacts are being observed. This may also be due to the higher perception of the adaptive capacities in this region, which may trigger lower consequences scoring.

While a similar pattern was observed in the south-central Mediterranean for the two fisheries, the Adriatic shows an interesting opposite pattern in the demersal fisheries. This may be associated with the perception that the high diversity of drivers in the demersal fisheries will likely result in stronger consequences due to the lower preparedness of adaptive measures for demersal species to cope with a variable environment in the region. Although we expected to find a more evident difference between northern and southern sub-regions (e.g. Pita *et al.*, 2021), our study did not detect such differences except in the south-eastern Mediterranean. This is likely due to the combination of several factors, such as the high number of drivers assessed in the study or the lower availability of comparable studies needed to assess and score the level of likelihood and consequences in some of the southern sub-regions.

Adaptation actions: the need for combining international and national efforts

It has long been clear that the performance of Mediterranean management systems needs improvement (e.g. Cardinale and Scarcella, 2017). The resilience of fisheries needs strengthening to reduce their vulnerability to climate change, and Mediterranean managers must be given the ability to respond promptly to the projected changes in the dynamics of marine resources and ecosystems. To address these goals, a selection of integrative and holistic adaptive approaches has been selected. These all draw upon previous experiences and toolboxes (e.g. Few *et al.*, 2017; Poulain *et al.*, 2018; Bahri *et al.*, 2021; Galappaththi *et al.*, 2021). Those actions are intended to be deliberate interventions or processes with the objective of bringing about major changes in the Mediterranean fisheries as they have been particularly selected to respond to one or several of the priorities identified (Table 3). The measures here proposed are intended to combine regional and national level tools with internationally designed measures to inform fishing management performed by the FAO regional fisheries body in the Mediterranean, the GFCM, and with the European Commission and national governments as main policymakers. It is, however, worth noticing that all measures have implementation considerations and technical effectiveness issues that may differ across sub-regions and countries.

Consistent with international good practices, we emphasize that the enhancement of adaptive fisheries management should be the primary overarching strategy to cope with climate effects in the Mediterranean fisheries. For several years, the Mediterranean Sea has experienced high levels of overfishing, and now around 75% of priority commercial stocks are considered below sustainable fishing levels (FAO, 2020). It is well known that stocks under high fishing pressure and depleted spawning biomass are more susceptible to external drivers, with abundance variability and trends being among the top risk factors (i.e. priorities) identified for all sub-regions in the present study. Those adaptive measures related to management options are: "*transboundary stock management*", "*adaptive spatial planning*", "*adaptive and collaborative control of fishing pressure*", and "*diversifying patterns of fishing activities with respect to exploited species*", which would principally respond to the priorities of the *Fisheries Resources* category (Table 3). Assessment of transboundary stocks and management of their exploitation are increasing challenges in the context of climate change (e.g. Pinsky *et al.*, 2018; Palacios-Abrantes *et al.*, 2020). Given the interconnectedness and semi-enclosed nature of the Mediterranean, cross-boundary collaboration is paramount for addressing the ongoing and expected impacts of climate change, particularly the impacts on species distribution. Transboundary can also encompass schemes for tradable fishing rights and catch and effort allocations to allow flexibility in response to stocks shifting across national jurisdictions (Bahri *et al.*, 2021). This measure must also be aligned with adaptive and collaborative control of fishing pressure, for which there are currently various ongoing initiatives to note, such as the international joint inspection and surveillance scheme outside the waters under national jurisdiction in the Strait of Sicily (GFCM/41/2017/8, amended by Rec. GFCM/42/2018/6). Several other measures are also listed in the "diversification" category from a different perspective (e.g. Gamito *et al.*, 2016; González-Mon *et al.*, 2021): diverse and flexible allocation of fishing grounds; varying targeting species (including new opportunities for non-indigenous species: Gücü *et al.*, 2021; Öztürk, 2021); favouring polyvalent vessels or promoting new flexible gears able to catch different species better adapted to changed conditions.

Three measures were deemed relevant in terms of policies: "*policy product value addition and value development*", "*address poverty and food insecurity*", and "*public investment (communication and awareness)*", which would principally respond to a selection of priorities in the *Fisheries Resources* and *Communities and Livelihood* categories (Table 3). Policies on value addition may help enforce practices such as ecolabelling, reduction of post-harvest losses, or the valorization and utilization of non-indigenous species (e.g. FAO, 2018; Rotter *et al.*, 2020; Öztürk, 2021). This necessitates alignment with the public investments that may focus on research, sharing best practices, and communication to raise awareness and increase capacity building to integrate climate change into research, management, policy, rules, and society's priorities. This may also promote the diversification of citizens' demands and preferences. Climate change can also exacerbate poverty and food insecurity issues by affecting food and fishers' livelihoods. Impacts on food supplies are expected to be more severe for populations living in coastal areas in the southern countries (Karmaoui, 2018), and a call for specific actions in these countries may therefore be required. All this suggests that the implementation consideration and technical effectiveness highlighted for these measures in Table 3 may be a higher impediment for their application in the southern countries, while a country-based specific assessment is further required, including more detailed socio-economic information.

In terms of livelihoods, three measures were identified: "*diversification of markets and fish products*", "*livelihood diversification*", and "*exit strategies for fishers to leave fishing*", which would principally respond to a selection of priorities of the *Communities and Livelihood* along with few priorities of the rest of categories (Table 3). Diversification of markets and fish products may be addressed by access to high-value markets and supporting the diversification of citizens' demands and preferences. This is a feasible measure with a reasonable likelihood of success in the northern countries due to their higher capacities to access new markets, their higher dynamism, and their structural portfolio. However, it might be more challenging in the southern sub-region, where it may focus on the arrival of new species, some of which may have high commercial value and create new but low-accessible market opportunities. This measure must be well aligned to livelihood diversification where both intra- and inter-sectorial options could be explored, such as: diverting fishing activities to alternative resources, aquaculture-related activities, tourism, or agricultural-related activities (Deb and Hanke, 2016; Galappaththi *et al.*, 2021). However, it is worth noting that, in many regions, there may be a "cultural resistance" to job-changes and/or limited alternative job opportunities. An evaluation of the success and effectiveness of this measure may be thus assessed once implemented (Bahri *et al.*, 2021). The same can occur with exit strategies, in which fisheries subsidies can provide a cushion to the sector and help fishers change activity (Blasiak *et al.*, 2017). In the northern Mediterranean countries, this could be effectively applied to deal with the employment rate, while in the south, it would also aid in coping with periods of food insecurity in coastal areas.

Finally, as concerns research, we here highlight: "*research and monitoring of stock productivity and distribution and its relationship with environmental conditions*", "*investment and research in adapting fishing operations*", and "*early-warning forecasting*", which would respond to the reduced selection of priorities of the *Fisheries Resources* and *Fisheries Operations* categories (Table 3). The next generation of fisheries assessment calls for a better consideration of several ecological processes such as the spatial structure of stocks, potential changes in the spatial distribution related to productivity and climate change, changes in species phenology (e.g. a temporal shift in recruitment or spawning), and the incorporation of environmental-dependent processes in the assessment of stocks and management advice, among others (e.g. Skern-Mauritzen *et al.*, 2016; Punt *et al.*, 2019, 2021). Good practices applied in some fisheries should rely on "climate-change conditioned" advice, which indicates how fishing pressure can be adjusted to maintain a similar probability of achieving objectives at the acceptable risk level given by climate change impacts on the stock (Sharma *et al.*, 2021). Changes in migratory routes and fish distributions will affect travel time, increasing or decreasing fuel and ice costs. The heavy dependence of a fishery on old vessels with fossil fuels is undesirable and the fisheries sector, like other sectors of the economy, ought to be required to mitigate its carbon footprint, including investments for adapting fleets and fishing technologies affecting fisheries operations. Such changes would be beneficial to society at large but costly to fishing enterprises in the short term (Sumaila *et al.*, 2011), particularly in developing countries with more limited economic resources such as those of the southern Mediterranean. Finally, advanced warnings in a broad sense (i.e. early warning systems) can contribute to mitigating shocks and could be used to adopt timely decisions to minimize the damage and loss to fisheries, particularly in periods with unstable or low yields and in relation to the expansion of some non-indigenous species (e.g. Defeo *et al.*, 2021; Bastardie *et al.*, 2022).

Future work and concluding remarks

This study, combining a multi-driver risk assessment with the most plausible adaptive measures, provides the GFCM with well-funded support for the future development of the Mediterranean Sea strategy to face climate change and non-indigenous species impacts in the near and far future as a part of the GFCM 2030 Strategy (FAO, 2021). However, limits, barriers, and constraints to adaptation will restrict the adaptive responses of fisheries systems and their ability to address the negative impacts of climate change (Galappaththi *et al.*, 2021). Implementing climate-adaptive fishing management and evaluating its success and effectiveness in real-world situations are generally lacking and have been consistently highlighted in recent literature (e.g. Bell *et al.*, 2020; Magnan *et al.*, 2020; Bahri *et al.*, 2021; Galappaththi *et al.*, 2021). In addition, "readiness" (actual stage of the measure's technical and technological development), "lead time until full effectiveness" and "duration of the benefits" are also important elements that need further research (Magnan *et al.*, 2020), but these will also depend on the regional or national context (Aragão *et al.*, 2022; Kleisner *et al.*, 2022). "Societal acceptability" is also a pending task challenging to assess without full implementation of adaptive measures, which is a key element if a profound transformation is to be attempted.

An effective transformation of the world's oceans' sustainability still requires an improved understanding of how to introduce flexibility into the fishing management cycle to foster and consolidate adaptation to climate change (Hidalgo *et al.*, 2022), and complement the needed reform in capture fisheries with an expansion of sustainable mariculture operations (Free *et al.*, 2022). In the context of the Mediterranean fisheries, it urges to act as soon as possible by enhancing adaptive fisheries management as the primary strategy for this region, along with the proposed measures.

Supplementary data

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

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Data availability statement

Data supporting Climate Risk Assessment developed in this study are available at https://doi.org/10.5281/zenodo.7101382.

Author contributions

MH and MV conceived the manuscript framework, designed the Climate Risk Assessments (CRAs) and the structure of the manuscript. MH, AEE, EMT, TF, FR, VL, OB, EA, LC, NM, SL, and PH, conducted and cross-revised the CRAs of all areas. MH analysed the results of all CRAs and wrote the original version of the manuscript. All authors contributed to the writing and editing of the manuscript. MV and MB coordinated the project in which CRAs were conducted.

Conflict of interest statement

The authors declare no conflict of interest.

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