Climate-risk to European fisheries and coastal communities

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Abstract

With the majority of the global human population living in coastal regions, identifying the climate risk that ocean-dependent communities and businesses are exposed to is key to prioritising the finite resources available to support adaptation. Here we apply a climate-risk analysis across the European fisheries sector for the first time to identify the most at-risk fleets and sub-national regions. We combine a trait-based approach with ecological niche models to differentiate climate hazards between populations of fish and use them to assess the relative climate risk for 380 fishing fleets and 105 coastal regions in Europe. Countries in SE Europe and the UK have the highest risks to both their fishing fleets and their communities while, in other countries, the risk-profile is greatest at either the fleet or community level. These results reveal the diversity of challenges posed by climate-change to European fisheries: climate adaptation, therefore, needs to be tailored to each country's and even each region's specific situation. Our analysis supports this process by highlighting where adaptation measures are needed and could have the greatest impact.

Manuscript Body

The ocean provides human societies with a wide variety of goods and services, ranging from food and employment to climate regulation and cultural nourishment[1]. Climate change is already shifting the abundance, distribution, productivity and phenology of living marine resources[2–4] and, thereby, many of the ecosystem services that we depend upon[5]. These impacts, however, are not being experienced uniformly by human society but depend on the characteristics and context of the community or business affected. Raising awareness and understanding the risk to human systems is, therefore, a key first step[6] to developing and prioritising appropriate adaptation options in response to the challenges of the climate crisis[7].

Over the past decades, climate risk assessments (CRAs) and climate vulnerability assessments (CVAs) have been developed to support such a prioritisation. The approach, developed by the Intergovernmental Panel on Climate Change (IPCC), has shifted over time from a focus on "vulnerability" to a focus on "risk"[8], in part due to criticisms of the negative framing that "vulnerability" implies[9]. The modern CRA framework considers risk as the intersection of hazard, exposure and vulnerability[10]. CVAs, and more recently CRAs, have been applied widely in the marine realm, for example in coastal communities in northern Vietnam[11], Kenya[12] and the USA[13], at the national level across coastal areas of the USA [14,15] and Australia [16,17], across regions such as Pacific island nations [18,19] and globally[6,20,21]. Several 'best practice' guides have also been developed [7,22].

CRAs and CVAs covering European waters, however, are notable by their absence. The lack of attention to climate risk in European fisheries may arise in part from the results of early global CVAs[6] that ranked European countries as having low vulnerabilities due to their affluence and, therefore, high 'adaptive capacity'. Yet the European region poses unique challenges when assessing climate-risks due to its wide range of species, biogeographical zones and habitats. Fishing techniques and the scale of fisheries vary widely, from large fleets of small vessels in the Mediterranean Sea[23] to some of the largest fishing vessels in the world (e.g. the 144-m long *Annelies Ilena*). Furthermore, although fisheries contribute very little to national GDP, food or income-security for most countries[24], in specific communities and regions fishing is the mainstay of employment[25]. Adapting European fisheries to a changing climate, therefore, requires the development of robust analyses capable of assessing the climate-risk across this extremely diverse continent.

We conducted a detailed CRA across the European marine fisheries sector, estimating the climate risk of both fishing fleets and coastal regions in one integrated analysis. Our analyses span more than 50 degrees of latitude from the Black Sea to the Arctic and encompass the United Kingdom, Norway, Iceland and Turkey in addition to the 22 coastal nations of the European Union. We apply an approach that incorporates fine-scale geographical differences in the climate hazard of fish and shellfish populations and then assess the climate-risk of both European fishing fleets and coastal regions in two separate CRAs. Since both CRAs are based on the same underlying climate hazard, these analyses can be combined to compare the relative importance of climate-hazard to fleets and coastal communities within a country.

Our index of climate hazard is derived from the biological traits of the species being harvested, together with modelled distribution data. Species trait data were gathered for 157 fish and shellfish species harvested in European waters, representing 90.3% of the total value of landings in Europe and at least 78% (and typically more than 90%) of national value. We accounted for the expected large differences in climate hazard throughout a species range (i.e. from the cold to warm edges of the distribution) by focusing on "populations" (i.e. a single species in a single FAO subarea). Population-level climate hazards were then defined based on the thermal-safety margin (TSM) between the temperature in that subregion and the upper thermal tolerance of the species[26,27]. Climate hazards could then be calculated for 556 significant "populations" in 23 FAO subareas, based on the TSM of the population and the inherent traits of the species[15,28,29].

We then calculated the climate risk for 105 coastal regions across 26 countries in the European region (Figure 1). Population-level climate hazards of fish were integrated to regions, weighted by the relative value of landings in that region. We defined exposure metrics based on the diversity[30,31] of these landings, and vulnerability based on regional socio-economic metrics[6]. We focused our analysis on coastal regions, as these are the communities most directly dependent on the ocean: regions far from the sea but within a coastal nation were explicitly excluded (e.g. Bavaria in Germany).

The analysis reveals appreciable variation in the climate risk within the European region and even within a single country. In the United Kingdom, for example, climate risk is greatest in the north of England, while Scotland and the south of England show the least risk. Indeed, six of the 10 regions with the highest climate risk, including the overall top region (Tees Valley & Durham), are part of the UK (Table S8). These results reflect high hazard scores for the species landed in these regions, together with high vulnerability due to low GDP per capita in some of these regions.

Larger-scale patterns are also apparent. South-east Europe stands out with consistently high climate risk, with coastal Romania and Croatia in the top five. Both countries have high vulnerability scores due to low GDP per capita of their coastal communities, and high exposure scores due to fisheries that target only a few species (e.g. the value of Romania's fisheries is more than 70% veined rapa whelk, *Rapana venosa*). Many northern European countries, including Belgium, the Netherlands and Scandinavian nations have relatively low climate risks due to their wealth (high GDP per capita), diverse fisheries and the relatively low climate hazard of the fish populations landed.

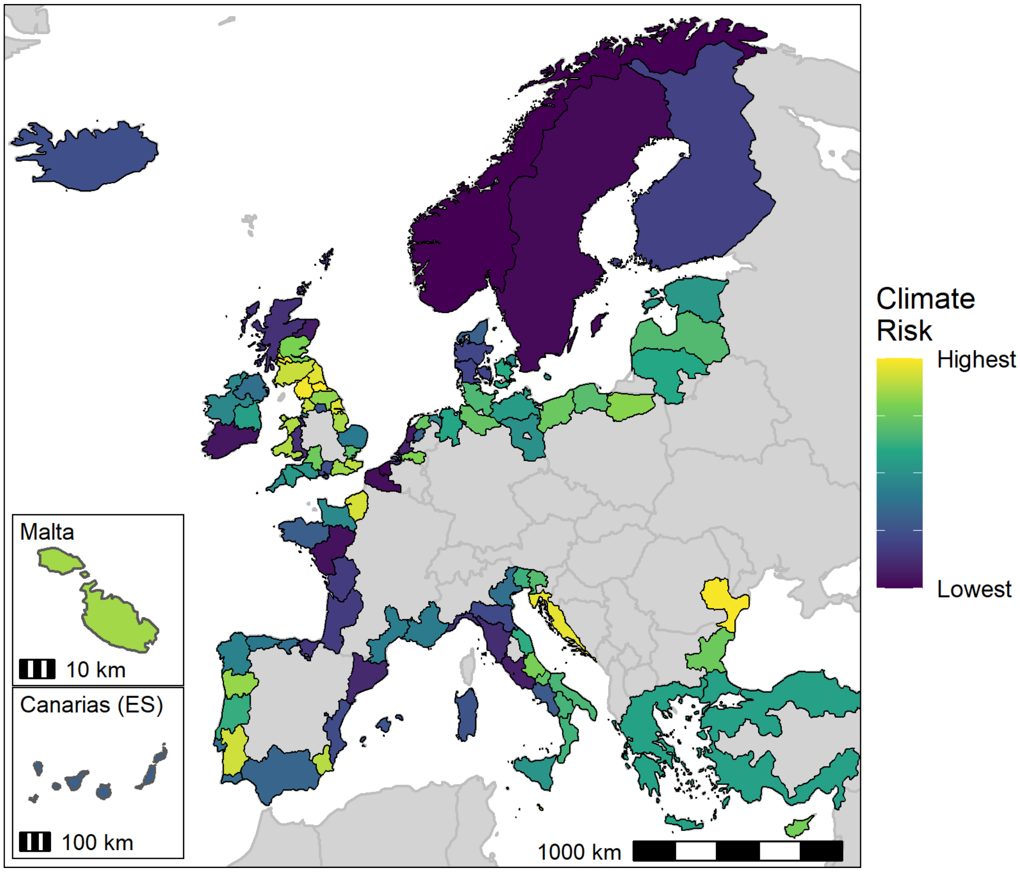

Figure 1 Map of the regional climate risk. Colour scale is linear in the value of the corresponding score, but is presented without values, as they have little direct meaning. National-level borders are shown for reference. Insets at bottom-left show small regions.

The risks associated with climate change will also be felt by the individual fishing vessels and fleets whose fishers' livelihoods depend on the ocean. We therefore performed a second CRA to examine the climate risk of European fishing fleets. As the basis for this analysis, we followed the EU definition of a "fleet segment" based on the size classes of the vessels, the country of registration, the gear being used and the geographical region being fished (Atlantic or Mediterranean)[23]. We scaled fish population-level climate hazards up to the fleet segment level based on the composition of landings by value of that fleet, while we based exposure on the diversity and dominance of landings and vulnerability on the profitability of the fleet. Coverage of our analysis at this fleet segment level was poorer than at the national level: nevertheless, we still cover 75% or more of total fishery catch value for more than 70% of the 380 fleet segments within the EU and UK.

The smallest class of vessels (0-6m) had an appreciably higher climate risk than all other size classes (Figure 2a). For the most part, these fleets operated in the Mediterranean region, particularly in Croatia, Bulgaria, France, Malta and Greece (Table S9). This result reflects, in part, the higher climate risk of stocks in this area, but is also driven by the poor profitability (and therefore higher vulnerability) of these fleets. On the other hand, the high catch diversity of these fleets reduces exposure and helps to reduce the net climate-risk.

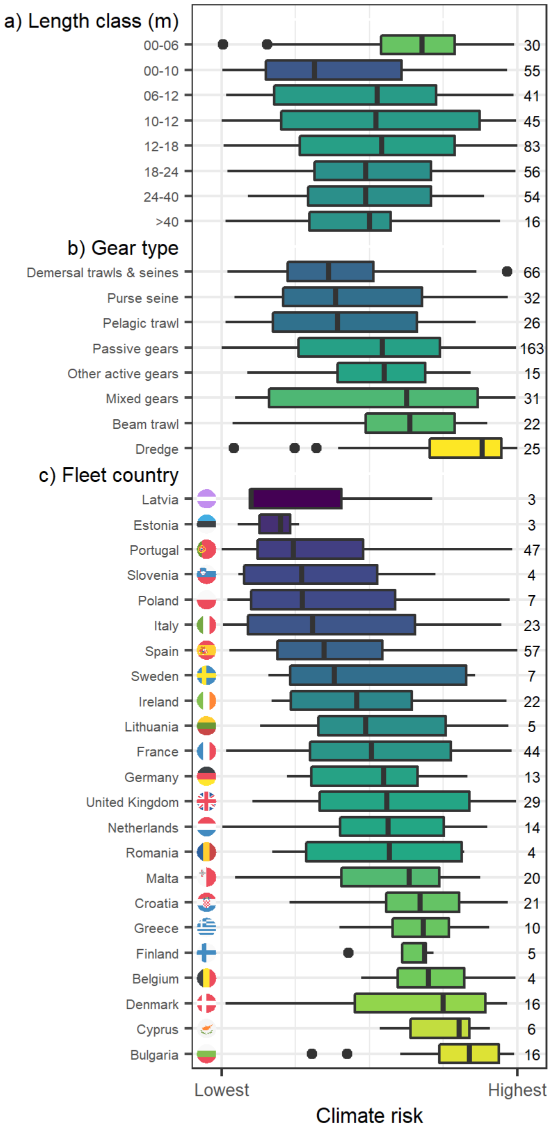

Figure 2 Climate risk of European fleet segments. The climate risk across 380 fleet segments is plotted as a function of a) the size range of the vessels (m), b) the gear type employed (sorted by median risk) and c) the country of origin of the fleet (sorted by median risk). Risk is represented on a linear scale from highest to lowest: the absolute values are not shown, as they have little direct meaning. The distribution of risk is shown as a boxplot, where the vertical line is the median, the box corresponds to the interquartile range (IQR), and the whiskers cover all points less than 1.5 times the IQR from the box. Outliers are plotted as points. Boxes are coloured based on the median climate risk for that category. The number of fleet segments in each class is shown at right. Note that the STECF definitions of small length classes (less than 12m) vary between countries and therefore have a degree of overlap. STECF gear codes are aggregated to our "Gear Types" to ensure comparability between Atlantic and Mediterranean fisheries (Table S4).

Systematic differences in climate-risk were revealed among gear types (Figure 2b), with dredgers having the highest climate risk. These fleets generally target populations with high climate hazards and have low species diversity in their catches (giving high exposure): good profitability, on the other hand, lowers their vulnerability and somewhat reduces overall risk (Table S9). Fleets using pelagic and demersal trawls together with purse seines have the lowest climate risks, primarily due to the low hazard associated with the species on which they fish.

The strongest differentiation in climate risk amongst fleet segments, however, is at the national level (Figure 2c). A clear cluster of high climate-risk fleet segments can be seen in south-east Europe, particularly in Croatia, Greece, Bulgaria, Cyprus and Romania (Figure S1). The risk profiles underlying each of these cases, however, are quite different, emphasising the need to understand the components in detail. Greek and Cypriot fleets have high climate risks due to poor profitability and, therefore, high vulnerability, while Bulgarian and Romanian fleets active in the Black Sea have extremely low catch diversities, giving them unusually high exposures (Table S9). It is also important to note that there is substantial variation among fleets within a country. For example, two of the five most at-risk fleets (including the most at risk) are Spanish (Table S9), even though the national level median for Spain is amongst the lowest in Europe. A detailed examination of the individual elements of the risk-profile is therefore critical to understanding the underlying factors responsible for these results.

A strength of the analysis performed here is that the results of the fleet and region CRAs can be directly compared. While the fleets and regions are all exposed to the same base set of hazards, the relative importance of each fish or shellfish population (and therefore hazard) differs. Each region and fleet also has its own intrinsic exposure and vulnerability profiles, further modulating the climate risk. However, as the base set of hazards that our analysis starts from is the same in both CRAs, a direct comparison of the two cases is possible, allowing the relative importance of climate risk to fleets and regions to be gauged.

Systematic differences in risk between fleets and regions can be seen among European countries (Figure 3) with several characteristic types of responses apparent. Countries in south-eastern Europe, together with the United Kingdom, have consistently the highest risk across both fleets and regions. The regional climate risk scores of states on the south coast of the Baltic (Latvia, Lithuania, Estonia and Poland) are higher than their fleet level scores, while the high fleet-risk of NW European states is moderated by their relative affluence and therefore low regional risk. Spain and Sweden generally have low climate risks in both sectors.

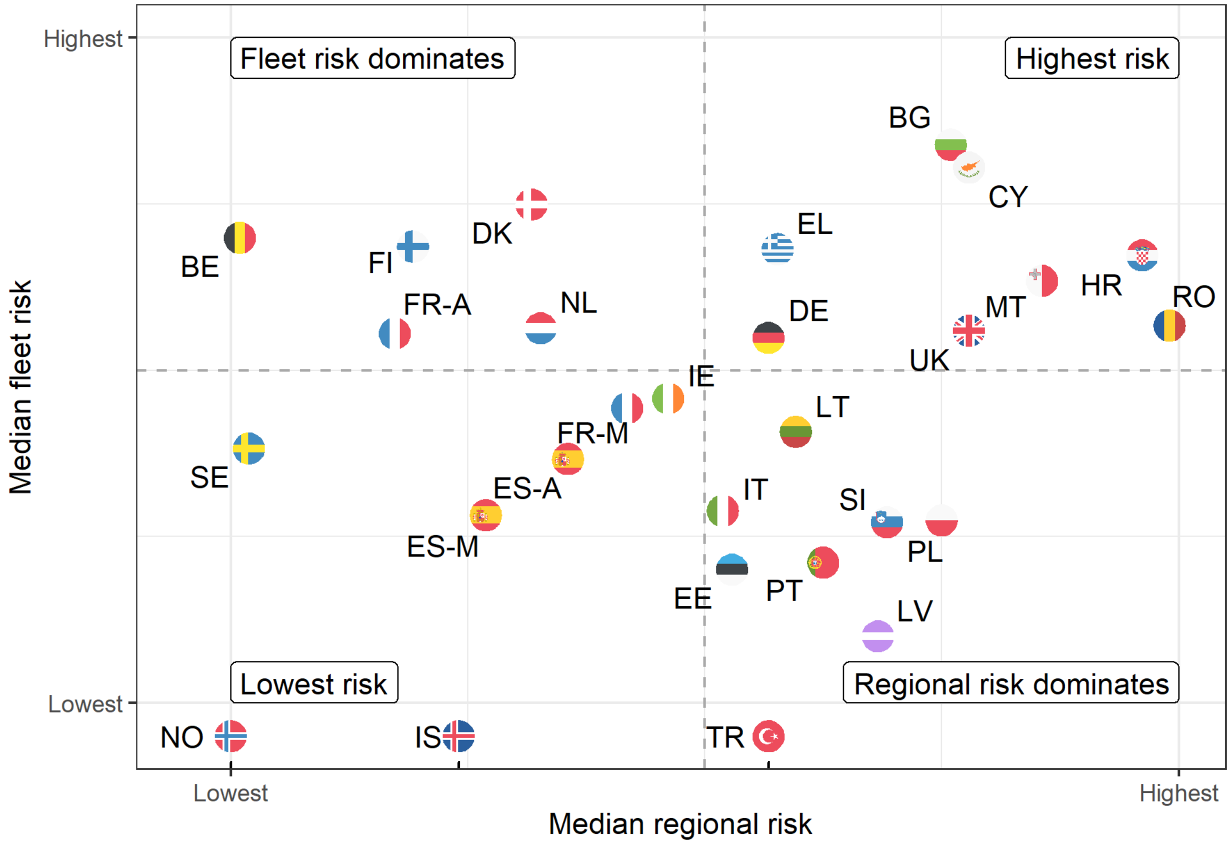

Figure 3 Comparison of the median fleet- and region-based risks for European countries. Labels indicate the country code. In addition, France (FR) and Spain (ES) are split into their Atlantic (-A suffix) and Mediterranean (-M suffix) seaboards. As the fleet-segment analysis only covers fleets from the EU and UK, no data are available for Turkey, Norway and Iceland: their regional risk results are plotted in the horizontal margin. Dashed lines divide the coordinate system into quarters. Country codes: BE: Belgium. BG: Bulgaria. CY: Cyprus. DE: Germany. DK: Denmark. EE: Estonia. EL: Greece. ES: Spain. FI: Finland. FR: France. HR: Croatia. IE: Ireland. IS: Iceland. IT: Italy. LT: Lithuania. LV: Latvia. MT: Malta. NL: Netherlands. NO: Norway. PL: Poland. PT: Portugal. RO: Romania. SE: Sweden. SI: Slovenia. TR: Turkey. UK: United Kingdom.

Our analysis highlights the wide variety of challenges facing European countries and regions with adapting their fisheries sectors to a changing climate. In some cases, such as in the southern-Baltic states, a focus on strengthening the resilience of local regions and communities would be of most benefit e.g. by creating alternative employment opportunities. In other regions, fleet risks dominate, and therefore increasing the efficiency and diversity of the fleet would appear to be a priority. However, some areas, such as the UK and south-east Europe appear to require both types of intervention, and therefore present the greatest adaptation challenges. There is, however, no “one-size-fits-all” solution that can be applied across all European waters or even, in some cases, across a country (e.g. the UK): climate adaptation plans therefore need to be tailored to these realities.

Climate risk and vulnerability analyses do, however, have a key role to play in shaping the development of such plans. By increasing awareness of the elements that contribute to a fleet or region’s risk[6], CVAs and CRAs can help prioritise adaptation actions to mitigate this risk[32] and thereby maximise the effectiveness of limited resources. Previous socio-economic linked analyses have focused on adaptive capacity (in the CVA framework) as a focal point for action[6,12]. However, the diversity of European risk profiles found here highlights the need and potential for adaptation actions across all components of the risk portfolio.

First and foremost of these actions is ensuring sustainable management of the living marine resources upon which the sector rests. The future impact of over-exploitation of these resources can be more important than that stemming from climate change, particularly in the heavily fished North Atlantic region[33]. Maintaining these stocks at a higher abundance leads to increases in genetic diversity, meta-population complexity, and age structure, all of which make stocks more resilient to the challenges of a changing environment[34,35]. The ensuing increase in productivity and incomes will simultaneously benefit both fishing fleets and regions, generating a “win-win” effect[36]. Fisheries scientists already have many of the tools necessary to ensure that management systems are robust to climate change and climate variability[37], while emerging tools, such as seasonal-to-decadal marine ecological forecasts[38], can potentially provide the basis for further coping strategies[39]. A focus on sustainable management will therefore reduce the climate risk that both fleets and regions are exposed to.

Diversification of the sector is a second key tool to reduce climate risk. Fishing fleets and regions relying on only a few species have an elevated risk of climate impacts: increasing this spread reduces exposure and therefore buffers fleets and communities against climate risk[31,40,41]. Diversification of catches and landings can take place autonomously as fishers respond to changes in the abundance and distribution of the fish they depend on[32,37]. For example, changes in the distribution of fish species in surrounding waters[42–44] have led to the development of new fisheries in the UK for squid, seabass and red mullet, amongst others[45]. There are, however, barriers to diversification[31,41], most notably in the form of the variety of resources available: the limited catch diversity and therefore high exposure of fleets and regions adjoining the Black Sea, for example, arises at least in part from the relatively low biodiversity of this region. The ability to diversify may also be limited by existing quota agreements[46], a particularly challenging issue under the “relative stability” agreements of the EU Common Fisheries Policy.

Thirdly, governance can coordinate and drive actions to reduce the vulnerability of fleets and regions. Investments and support for developing new, and switching between, fishing, storage, transport and processing technologies can increase the efficiency of fleet operations and, therefore, reduce vulnerability[18,37,47]. Increasing regional development, including employment opportunities outside the fisheries sector, reduces regional vulnerability and risk[6,48]. Furthermore, both fishing fleets and regions can also potentially benefit from governance-led actions that increase the flexibility, ability to learn, social organisation and the power and freedom to respond to challenges[49]. Regional, national and European governments therefore have a critical role to play in adapting fisheries and ocean-dependent regions to the risks presented by climate change.

Several key caveats of these results need to be highlighted. Our analysis focused solely on the sensitivity to ocean warming, ignoring other climate-driven processes, such as ocean acidification, deoxygenation, and changes in storms or circulation patterns[5,30] that, while important, are viewed as second order effects. Spatial differences in warming across European regional seas were also not accounted for here but these differences (1 to 2°C by 2050) are much less than the variability in thermal safety margins between populations (range 15°C). The treatment of uncertainty in CVAs and CRAs varies greatly between studies[15,50] but in such a semi-quantitative analysis the choice of metrics is usually the most important aspect[51]. We believe that such “structural uncertainty”[52] is best addressed by focusing on a limited, but transparent and readily interpretable set of indicators, rather than by quantifying uncertainties or increasing complexity. Finally, while we have considered European fisheries on fish stocks in the Mediterranean Sea, we have not incorporated coastal communities in African countries that also fish on these same stocks. The relatively low GDP per capita of these communities suggests that they would have correspondingly high regional vulnerabilities and therefore climate risks but it is not possible to draw robust conclusions in the absence of appropriate data sets: the population-level hazards generated here (Table S7) could be readily applied to aid such analyses in the future.

This study has shown that even though climate-risk to European countries is, on average, moderate compared to many other countries across the globe[6,21], major differences exist across the European region. This is not only true for coastal regions, where especially south-east European and various UK coastal regions were found to be subject to the greatest climate-risk, but also for the different European fishing fleets, with (small-sized) fleet segments in south-east Europe at greatest risk. This corroborates with fine-scale spatial differences among fishing communities documented in eastern North America[13,53] and the Caribbean[30,54], each requiring very different adaptation actions. Our detailed analyses allow a distinction between climate hazard, exposure and vulnerability as key sources of climate-risk, and highlight where (and which) adaptation measures can have greatest impact in increasing resilience.

Acknowledgements

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 678193 (CERES – Climate change and European Aquatic Resources). The results generated by this analysis can be explored using an online tool available at https://markpayne.shinyapps.io/CERES_climate_risk/ Source code is available at https://github.com/markpayneatwork/CERES_vulnerability. "Fishing Boat", "Urban" and "Thermometer" icons in Figure 4 by smalllikeart from www.flaticon.com.

Methods

General approach

We have applied an integrated approach to a climate risk assessment (CRA) across the European fisheries sector. The CRA has three major components (Figure 4; Figure S2). The first and most fundamental of these is the *population hazard* component, where the hazard associated with climate-change impacts on both species and individual fish populations is quantified. We then use these hazard metrics as inputs into two parallel climate-risk assessments focussing on coastal regions and fishing fleets in turn. In each of these cases, the population hazard is integrated up to the region or fleet level based on information about the relative importance of each fish population to that unit, to form the region- or fleet-specific hazards. These hazard data are then complemented with region- and fleet-focused *exposure* and *vulnerability* metrics to produce a *climate-risk* for each.

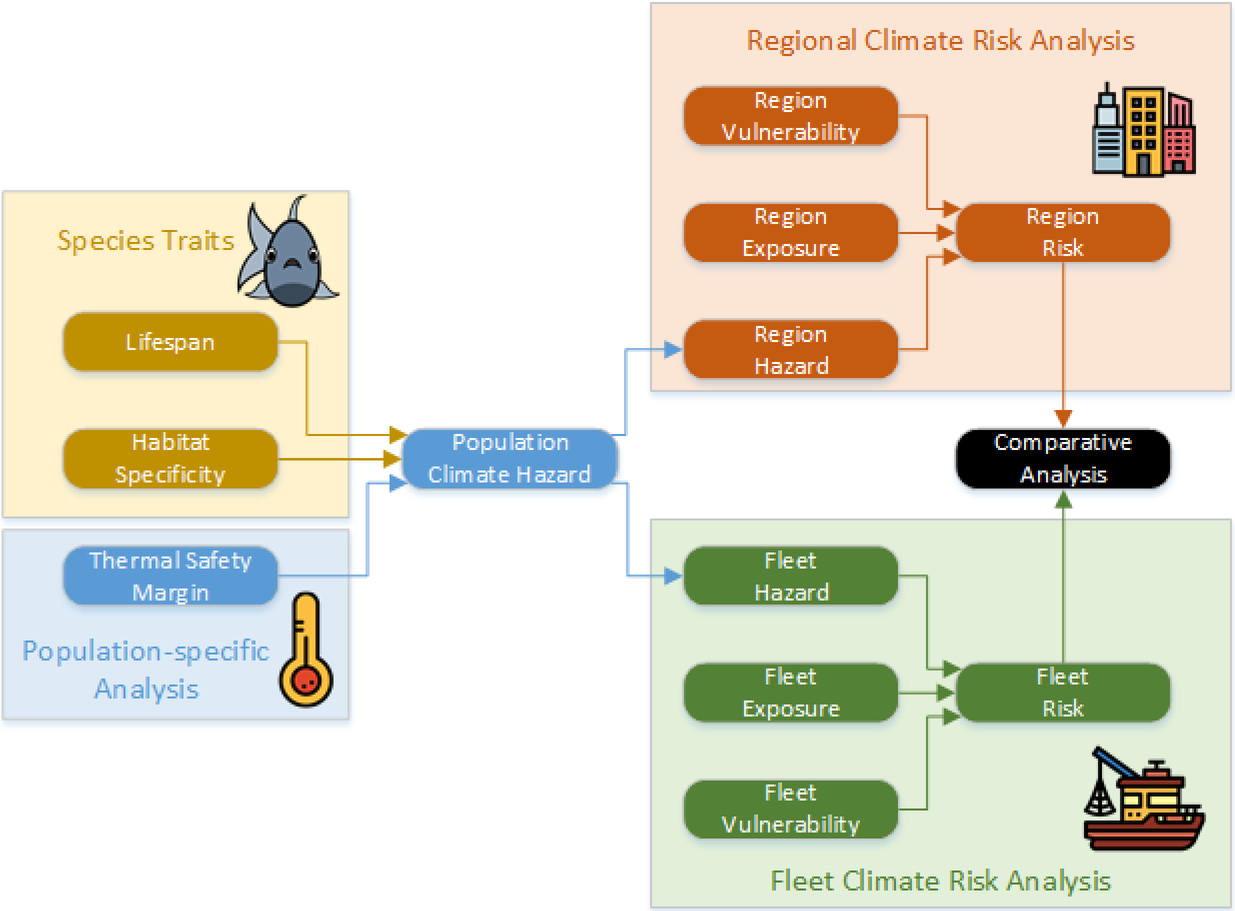

Figure 4 Schematic diagram illustrating the approach used here to estimate climate risk in European fishery-dependent communities and fishing fleets. Species traits and population specific analyses of the thermal safety margin are combined to give a population-specific climate hazard. This hazard then forms the basis for the regional and fleet level CRAs, based on the combination of hazard, exposure and vulnerability. Finally, the regional and fleet risks are combined again into a comparative analysis. A detailed flow diagram is presented in the supplementary material (Figure S2).

Scope and Data Sources

We aimed to assess the climate risk for the European marine fisheries sector, including all 22 EU countries with marine borders, the United Kingdom, Norway, Iceland and Turkey. We based our analysis primarily on catch data from FAO Areas 21, 27, 34 and 37 held in the EUROSTAT database (Table S1), excluding distant water fleets. While this database covers more than 1200 species, many of these are economically minor. We therefore aimed to cover the largest 90% of the value of the marine fish and shellfish sector in each country and across Europe as a whole. Two species predominately inhabiting freshwater, European perch (*Perca fluviatilis*) and pike-perch (*Sander lucioperca*), were removed from the database. Alternative (or misspelled) scientific names were corrected where we could identify these (following World Register of Marine Species, WoRMS) (Table S3).

Regional analyses were performed for European coastal regions based on NUTS2 statistical units. Sub-national indicators of landings composition were derived from monthly harbour-level "first-sales" data from the EU Market Observatory for Fisheries and Aquaculture (EUMOFA) (Table S1). In cases where this data covered more than one NUTS2 unit within a country (10 countries), the harbour data was aggregated up to NUTS2 units based on the geographical coordinates of the harbours. Where EUMOFA data coverage was insufficient, the coastal NUTS2 units of that country were merged into one "region" (Table S5) and EUROSTAT national landings data were assigned to it (Table S1). Socio-economic data for the NUTS2 units was also obtained from EUROSTAT and integrated up to our "regions", if relevant.

The Annual Economic Report (AER) provided by the EU Scientific, Technical and Economic Committee for Fisheries (STECF)[23] formed the basis of the fishing fleet analysis (Table S1). This dataset has the advantage of providing a single coherent dataset for fleet segments (the combination of fishing technique and a vessel length category) across all of the European Union and United Kingdom: however, it does not include data on fleets from Norway, Iceland or Turkey, and in the absence of comparable datasets, these countries were not included in this part of the analysis.

All data was averaged over the period 2010-2018, where available.

Hazard Metrics

The *hazard* dimension of our CRA measures the strength and severity of climate change on the unit of interest: in this case, fish populations in European waters. Many previous CVAs and CRAs do not distinguish between the positive and negative effects of climate change, and simply highlight elements of their study system that will change, making interpretation difficult. In contrast, we made a conscious decision to focus on "negative" impacts in order to have an unambiguous interpretation. We consider the hazard due to climate change impacts on living marine resources as being the combination of both species-specific and population-specific processes, as follows.

Species-specific processes

A trait-based approach was employed to characterise the hazard of a species to climate change. Such an approach is well established in climate-risk and vulnerability analyses[15,17,28], due to its ability to draw on general understanding of the response of species to climate change. Trait data was collated from previously published databases [55–58] and complemented with data from Fishbase [59] and Sealifebase [60] (accessed April-July 2019) (Table S1). Of the original set of species from EUROSTAT, 24 taxa were only at the genus level, and appropriate trait sets were therefore identified based on 'exemplar species': in some cases different exemplar species were used for the North Atlantic (FAO Area 27) and Mediterranean regions

(FAO Area 37) (Table S2). Barnacles (*Pollicipes pollicipes*) and solen razor clams (*Solen* spp.) were also removed owing to a lack of biological traits data and difficulties identifying suitable exemplar species.

Trait selection aimed to avoid double-counting information due to inclusion of correlated traits, a commonly overlooked issue[56] that impacts many published analyses[15,28,29,33]. For example, smaller fish are typically planktivorous, live shorter and grow faster, giving a high correlation between maximum length, lifespan, growth rates and trophic level. Lifespan is the most commonly available of these metrics and was therefore chosen as an exemplar for this set of traits. Shorter lifespans are associated with seasonal and variable environments[56], implying robustness to change and variability, paralleling the approach used in other studies[15,28,29,33].

A "*habitat specificity"* hazard metric was also developed. Species with spatially restricted habitat requirements during part or all of their life-history are recognised as being more sensitive to disruption [61,62]. In addition, mobile species have the ability to move rapidly to avoid unfavourable conditions in a way that sedentary species do not, and are therefore at less climate risk [30]. Traits defining the mobility, and vertical and horizontal habitats were therefore collated into a single "habitat-specificity score" (Table 1). The final set of traits is included as supplementary material (Table S6).

Table 1 Combination of mobility, vertical and horizontal habitat traits to generate a habitat specificity score. Definitions of traits follow the scheme of Engelhard *et al*[55].

Habitat Score	***Mobility***	***Vertical habitat***	***Horizontal habitat***
Low (0.00)	Highly migratory species	Any	Any
	Mobile	Any	Oceanic
	Mobile	Bathydemersal Mesopelagic	Slope
Medium (0.33)	Mobile Unknown	Benthopelagic Demersal Pelagic Epipelagic	Slope Shelf Outer shelf
	Unknown	Bathydemersal	Slope
	Mobile	Bathydemersal	Outer shelf
High (0.67)	Mobile (catadromous/anadromous)	Pelagic	Any
	Mobile	Demersal	Inner shelf
	Mobile	Benthopelagic	Coastal
Very high (1.00)	Sedentary	Any	Any
	Mobile	Reef-associated	Any

Population-specific processes

The stress a fish population experiences as the ocean warms depends on the amount of warming, a commonly employed metric of exposure in CVAs [6,15]. However, the physiological context of this warming is also critical but often overlooked. For example, cod (*Gadus morhua*) in the North Sea are close to their upper thermal limit, and will therefore experience negative impacts of warming, while cod in the Barents Sea are far from this limit and will experience little or no negative effects of the same amount of warming[63]. Such a spatial and physiological context of warming is often overlooked in many CRAs and CVAs, yet is critical to differentiate the climate hazard between different populations of the same species.

We resolve this problem in two ways. We first perform our analysis at the "population" level, defined as the combination of species and FAO subarea e.g., cod in subarea 27.4 (North Sea), similar to the approach used to manage many European fish stocks: populations comprising less than 5% of the total catch of the species were excluded from the analysis. Note that we explicitly avoid the use of the term "stock" to refer to this unit of analysis, as this has clear implications in fisheries management but is not entirely the same as our definition "population". Secondly, we place the degree of warming experienced by these populations in a physiological context using thermal-safety margins (TSM)[26,27,64,65]. TSM is defined as the difference between the maximum temperature that the species can sustain and the temperature of the environment: high TSMs indicate a high capacity to tolerate warming. Population-specific TSMs therefore permit a fine-grained measure of the hazard from warming.

We derived population-specific TSM metrics from the habitat models, parameters and maps provided by Aquamaps www.aquamaps.org[66] (Table S1). We downloaded "native distribution maps" from the Aquamaps website for the species selected above: where multiple maps were available, choice was guided by the internal map quality ranking system. For the invasive species purple whelk (*Rapana venosa*), originally from waters around Japan, Korea and China but now supporting a large fishery in the Black Sea, the "Suitable Habitat map" was used. From each map we used the "90th percentile" parameter for the temperature response for each species as an estimate of its upper thermal tolerance. Temperatures in a subarea were based on the data underpinning the Aquamaps model (NOAA NCEP Climatology, 1982-1999)[66], ensuring congruence between the tolerance parameters and the temperature data. Sea-surface or -bottom temperature data, as appropriate for the species and used in the Aquamap, were masked using the habitat model to eliminate unsuitable habitat for each individual species (Figure 5). Population-specific TSM was then calculated as the median difference between the species' "90th percentile" parameter and temperature across all valid pixels in that subarea.

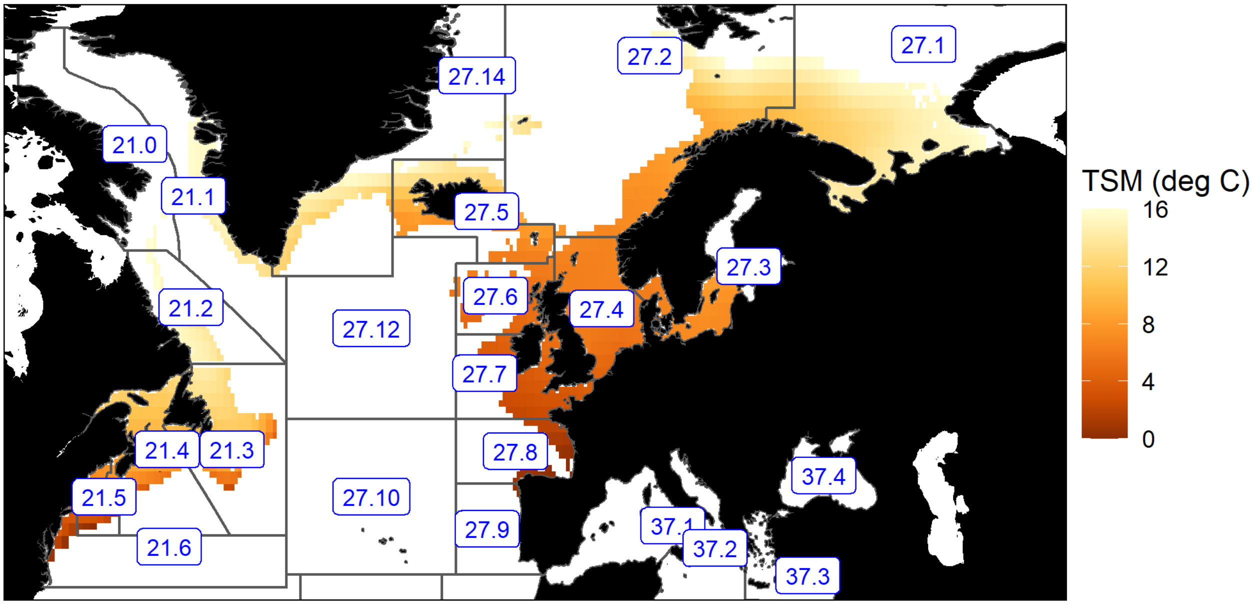

Figure 5 Example of the use of Aquamaps to calculate TSM metrics. Atlantic cod (*Gadus morhua*) as an example. Environmental data and species thermal tolerance data from Aquamaps are used to calculate the thermal safety margin (TSM) for this species (coloured pixels) and masked using the habitat model to limit data to modelled regions of occurrence. Median TSM values are then calculated within each FAO subarea defining a population (grey polygons, blue labels).

Population-level hazard

Hazard metrics were combined based on their relative ranking for each population. The metrics employed here have little quantitative meaning: rather, it is their relative values that are important. Each metric was therefore converted to a rank percentile, and then combined using a weighted average, with a weight of 0.5 for the population TSM (high TSMs give a low hazard), 0.25 for the species' lifespan (shorter-lifespans give a low hazard) and 0.25 for the species' habitat-specificity (low specificity gives a low hazard).

Population-level hazard scores were integrated up to fishing fleet and regional levels. In the case of the fleet analysis, this was based on the relative composition (by value) of the populations that each fleet fishes on, while in the case of the regional analysis it was based on the composition (by value) of landings in that region (Figure 4, Figure S2).

Exposure metrics

We define *exposure* as an indicator of how sensitive a community or fishing fleet is to changes in the fish populations it is dependent on. Fleets or fishing communities have lower exposure (higher resilience) if they catch a wide range of different fish species, rather than concentrating on a specific resource [30,31,41]. If one species is reduced or lost due to the effects of climate change, the impact of that loss is relatively less severe for fleets and communities that are dependent on a broad portfolio of species. We therefore defined our exposure metrics following this logic, using two different metrics to characterise diversity of catch or landings: i) the Shannon diversity index, one of the most commonly used diversity indices in ecology and ii) Simpson's dominance index, a statistic that emphasizes the relative abundance of the most common species in the sample[30].

For European regions, exposure metrics were based on the value of landings data from EUMOFA and EUROSTAT (Table S1; Figure S2). While EUROSTAT data is species resolved, EUMOFA data is organised in approximately 100 "main commercial species" (MCS) groupings: we therefore harmonised the two datasets by aggregating EUROSTAT data to the MCS groupings based on correlation keys provided by EUMOFA. The Shannon and Simpson metrics were then calculated to estimate the diversity of MCS groups.

For fleet segments, the value of landings is available by species code from the STECF Annual Economic Report[23]. The two diversity indices could therefore be calculated directly to quantify the diversity of species.

In both cases, the exposure index was produced as a composite index of the two indices described above by averaging the percentile ranks.

Vulnerability metrics

Vulnerability in this setting refers to the resilience of the analysis unit (either a region or a fleet) and its ability to mitigate the hazard via adaptation.

The regional vulnerability metric was based on the gross-domestic product per capita of the region, as calculated from EUROSTAT data at the NUTS2 level (Table S1). Regions with high GDP per capita were viewed as having a high adaptive capacity and therefore low vulnerability. Regional vulnerability was calculated as the percentile rank of this statistic.

Fleet segment vulnerability was based on the net profit margin (NPM). This is a standard economic metric, defined as net profit (i.e. revenue minus fixed and variable costs and opportunity cost) divided by the total revenue: it therefore represents how much of the total income generated by the fleet is profit [23]. NPM has the feature of taking into account many of the different factors that influence the profitability of the fleet, and is also scale independent (as profitability is divided by the revenue), allowing comparison of both large and small segments. NPM was calculated for each fleet segment based on economic data from the STECF Annual Economic Report[23] (Table S1), and the vulnerability score generated based on percentile rank. Fleet segments with high profitability were viewed as being less vulnerable to the effects of climate change, as they could absorb the anticipated loss associated with any potential negative change in their target species.

Climate risk metrics

For each of the geographic regions, and for each of the fleet segments, the overall *climate risk* was calculated as the unweighted mean of the hazard, exposure and vulnerability percentile ranks.

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