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Review

A systematic literature review of climate change research on Europe's threatened commercial fish species

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ABSTRACT

Climate change poses a major challenge for global marine ecosystems and species, leading to a wide range of biological and social-ecological impacts. Fisheries are among the well-known sectors influenced by multiple effects of climate change, with associated impacts highly variable among species and regions. To successfully manage fisheries, scientific evidence about the potential direct and indirect impacts of climate change on the species targeted by fisheries is needed to inform decision-making processes. This is particularly pertinent for fisheries within European seas, as they include some of the fastest warming water bodies globally, and are thus experiencing some of the greatest impacts. Here, we systematically examine the existing scientific climate-related literature of 68 species that are both commercially important in European seas and considered threatened according to the IUCN Red List to understand the extent of information that is available to inform fisheries management and identify critical knowledge gaps that can help to direct future research effort. We also explore the climate and fishing vulnerability indices of species as potential drivers of current scientific attention. We found no literature for most of these species (n = 45), and for many others (n = 19) we found fewer than five papers studying them. Climate change related research was dominated by a few species (i.e., Atlantic salmon, European pilchard, and Atlantic bluefin tuna) and regions, such as the Northeast Atlantic, revealing a highly uneven distribution of research efforts across European seas. Most studies were biologically focused and included how abundance, distribution, and physiology may be affected by warming. Few studies incorporated some level of social-ecological information. Moreover, it appears that research on species with high climate and fishing vulnerabilities is not currently prioritized. These results highlight a gap in our understanding of how climate change can impact already threatened species and the people who depend on them for food and income. Our findings also suggest that future climate-specific adaptation measures will likely suffer from a lack of robust information. More research is needed to include all the species from our list, their relevant geographic regions, and subsequent biological and social-ecological implications.

1. Introduction

The effects of climate change have, and will continue to have, impacts on the structure and function of global marine ecosystems and species, as well as the goods and services they provide (Doney et al., 2012; Sumaila et al., 2019). Direct changes to the physical environment, such as temperature increases or changes in ocean chemistry (Williamson and Guinder, 2021), can lead to a range of biological and social-ecological responses. These may occur through species distribution shifts to find optimal conditions (Dufour et al., 2010; Lima et al., 2022) or community assemblages changing as better-adapted individuals come to dominate marine fish communities (Poulard and Blanchard, 2005). Climate change can also directly affect species' physiology (Friedland et al., 2000; Jonsson et al., 2013), for example via

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changes to their growth rates, diet modifications (Olsvik et al., 2016; Queiros et al., 2019), or increases in their susceptibility to disease and parasites (Vollset, 2019), that in turn can lead to higher mortality rates and loss of biomass (Carozza et al., 2019). Climatic effects can interact with other local stressors to exacerbate impacts on marine ecosystem function through non-linear or synergistic effects (Nash et al., 2017; Schneider, 2004; van der Molen et al., 2013). Climate change is already known to impact fisheries, where species sensitive to environmental variations can experience dramatic declines in stocks or lower yield in some cases (Sumaila et al., 2011). As climatic changes grow stronger, changes in fish landings, and their commercial values are increasingly expected (Allison et al., 2009; Lam et al., 2020). These changes pose substantial challenges to fisheries sectors, which are socially and economically important in many coastal communities (Natale et al., 2013; Teh and Sumaila, 2013). For example, reoccurring extreme weather events may directly impact fishing operations, leading to disruptions on both land and sea, with consequent economic losses (Cheung et al., 2012; Sumaila et al., 2020). With declining fish stocks and increasing fuel prices, countries with high dependency on fishing for their livelihoods are most affected by climate change (Huynh et al., 2021; Lam et al., 2020). However, even in the regions globally ranked as having low economic vulnerabilities to climate change impacts on fisheries, such as Europe (Allison et al., 2009), locally vulnerable areas emerge, as a combination of reduced vessel productivity, low diversity in fisheries target species, and decreased catch prices (Guillen and Maynou, 2016; Payne et al., 2021).

While increasing temperatures are observed across all the world's oceans, climate change impacts vary in different regions. European seas, particularly enclosed or semi-enclosed basins such as the Baltic Sea, North Sea, Mediterranean Sea and Norwegian Sea (Belkin, 2009) are experiencing rapid warming. European seas contribute to more than one-eighth of global fisheries catches, making the EU the second largest trader of fisheries and aquaculture products after China in 2019 (European Commission and Fisheries, 2021; FAO, 2020). Many of the species caught and consumed across European countries are listed on the IUCN Red List (Dureuil et al., 2018) rendering them even more vulnerable due to the combined effects of climate change and fisheries pressure. Understanding responses of threatened fisheries species to climate change across various biological and socio-ecological scales is crucial to provide baseline data for mitigating negative synergistic effects (Harvey et al., 2014a; Hughes et al., 2012; Maina et al., 2016). This knowledge can then, in turn, help to inform targeted management and governance strategies tailored to the unique challenges faced by European fisheries at different scales, enabling a more effective response to the changing climate and promoting long-term sustainability and resilience.

With the variety of direct and indirect factors that influence different marine fish species and the uncertainties surrounding climate change impacts, predictions of those impacts become increasingly challenging (Payne et al., 2016; Pörtner and Peck, 2010). Yet, such predictions are important as they can allow for adequate management strategies to be identified and implemented in response to both existing and projected changes (Hobday and Pecl, 2014). One of the emerging fisheries management strategies in many parts of the world is adaptation to climate change (Melnychuk et al., 2014; Ogier et al., 2016; Pinsky and Mantua, 2014). A variety of strategies in fisheries adaptation can be used, such as increasing gear and livelihood diversification, changing fishing locations and incorporating traditional fishing techniques (Galappaththi et al., 2022). In Europe, several regional organizations and policies emerged as adaptation initiatives that address climate change impacts in European marine ecosystems, including fisheries. For example, The Integrated Maritime Policy (IMP) and Common Fisheries Policy (CFP) of the European Union aim to promote the sustainable management of fisheries and marine resources, including incorporating climate change considerations into management decisions and practices. Additionally, the EU has created a comprehensive platform (http://climate-adapt.eea.europa.eu/) for sharing information and best practices on climate change adaptation. However, to be successful, such adaptation initiatives should be informed and supported by scientific knowledge (Cvitanovic et al., 2014; Cvitanovic and Hobday, 2018). Considering potentially diverse impacts of climate change on different species (Sguotti et al., 2016), it is crucial to comprehensively understand the current extent of the scientific knowledge capturing those variations. Identifying and addressing the primary knowledge gaps is essential for informing long-term sustainability strategies for threatened fished species and ensuring their resilience in the face of ongoing environmental changes.

Therefore, the aim of this study is to synthesize the current available climate change species-specific scientific literature to support existing and future adaptation strategies in European seas. In doing so, we assess the current research focus in terms of species that receive more scientific attention, and main topics represented in the literature. Recognizing knowledge gaps can guide future scientific efforts and avoid over-representation of certain topics and species by redirecting effort towards underexplored subjects. We carried out a systematic literature review to quantify the extent of scientific research related to climate change impacts on threatened commercial species in European seas. Specifically, our objectives are to 1) summarize the existing primary scientific literature on threatened commercially important species; 2) identify knowledge gaps in terms of species and topics in the literature; and 3) investigate potential drivers of current research efforts, such as species' vulnerability to climate and fishing pressures. This evaluation of existing knowledge can serve as a roadmap to guide future research, and funding allocation, ultimately informing forthcoming adaptation strategies and enhancing management decisions.

2. Methods

2.1. Focal research species

This study focused on identifying the extent of scientific literature dedicated to climate change impacts and implications in European seas, targeting species that are both threatened and commercially important. The species were chosen based on their appearance both in the list of commercial species in European countries (taken from https://www.seaaroundus.org/) and The European Red List (IUCN 2010 European Red List, downloaded in June 2022). From these two lists, we identified an overlap between all commercial species and species that are critically endangered, endangered, vulnerable, or nearly threatened, which resulted in 68 species in total (Appendix S1). Among our subset of 68 species, 35% (n = 24) were nearly threatened species, 26% were vulnerable (n = 18), 25% were endangered (n = 17), and 13% (n = 9) of species were critically endangered (Appendix S1).

2.2. Data collection

Once the list of focal study species was identified, a systematic literature review, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, Moher et al., 2016, Fig. 1) of climate-related studies for all 68 species was performed. This approach was selected given its comprehensive and prior application to assessing the literature both in relation to fisheries (e.g. Fogarty et al., 2019) and marine social-ecological systems more broadly (e.g. Karcher et al., 2021). Using the platform SCOPUS (accessed on May 27, 2022) the search was performed for each 68 species individually, with the search terms: "scientific name" OR "common name" AND "climat*" (e.g., "*Thunnus thynnus*" OR "*T. thynnus*" OR "Atlantic bluefin tuna" AND "climat*"), following the search string formation used in Fogarty et al. (2019). Search results were restricted to research articles, and only the EU countries (except Romania and Bulgaria), the United Kingdom, Iceland, and Norway were among the selected countries. Studies conducted in Northwest Africa, a region that includes the Canary Islands, were excluded, due to the distance from the rest of the European seas.

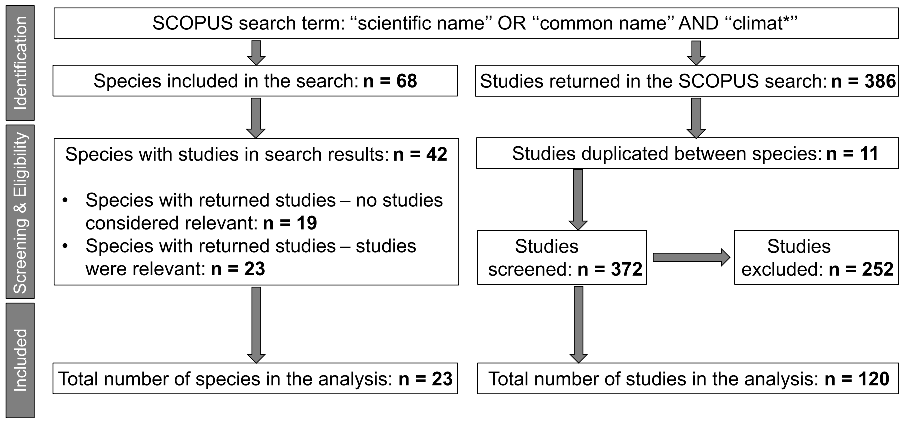

Fig. 1. Flow diagram of the PRISMA (Moher et al., 2016) method both for species and research articles.

In total, the search identified 386 studies, covering 42 species, leaving 26 species without any search results (Fig. 1). Several of those studies (n = 11) included search results for two or more species, leading to 372 unique studies. The bibliographic details (i.e title, authors, abstract, year of publication) for all returned studies were downloaded into Excel and screened on title/abstract level to assess their eligibility. Only peer-reviewed English language articles were included, to ensure high scientific level of data and be logistically possible. Studies about paleontology (fossil data) and studies with no climate-related impacts or implications were excluded. Studies were also excluded if they were conducted outside of the relevant geographical region, or if they were focused on species beyond the list of focal species.

To be included, studies had to i) focus on the species from the search term, ii) be a peer-reviewed research article, iii) be conducted in the relevant geographic area, and iv) directly (e.g., the effect of temperature changes on fish growth rates) or indirectly (e.g., fish distribution changes in different regions that experienced climate change effects) measure the effects or implications of climate change. During the screening, it was evident that a lot of studies (n = 195 from initial search results) focused on Atlantic salmon (*Salmo salar*) compared to any other species. However, many studies on Atlantic salmon were conducted in freshwater (n = 82) or not eligible (n = 68), leading to an exclusion of 150 research articles focused on that species (Appendix S2). Cases where Atlantic salmon studies focused both on the fresh water and the marine environment were included if considered relevant based on the other criteria (n = 23).

To measure the level of agreement and consistency of the interpretation of inclusion criteria, a subsample of 50 random studies was screened by two authors separately (M.P. and D.B.K.), on title/abstract level. Individual decisions were compared by performing kappa analysis that resulted in a relative mutual agreement of 92% representing a kappa of 0.83, rated as "almost perfect" agreement between the authors (Landis and Koch, 1977). Where minor differences in screening were present between the authors, the reasons were discussed until mutual agreement on classification was obtained. Following this, the lead author completed the title/abstract screen to determine the final sample for analysis. Based on title/abstract screening, the articles that could not be excluded with certainty remained for full-text screening. For this step, full texts were accessed online and screened regarding the inclusion criteria (i-iv) by M.P. In cases of doubt (n ≈ 40), respective studies were screened by both M.P. and D.B.K. and discussed until mutual agreement was reached. Once all studies were screened, 120 remained for full analysis (Fig. 1).

2.3. Data analysis

Full texts of the remaining articles were downloaded for further analysis (n = 120). The final set of studies that were eligible for inclusion was listed in Excel and classified into several categories and subcategories based on their topic and type of research. First, the studies were classified based on the region they were conducted in. The regions included Northeast Atlantic, Mediterranean, Norwegian waters (seas within Norwegian EEZ), Baltic Sea, and in case of several regions at once, "Multiple regions". Next, the studies were classified into two main categories based on their focus: biological or social-ecological. The biological category was then divided into six subcategories: abundance, diet, distribution, genetics, physiology, and reproduction. To limit the number of biological subcategories, "abundance" also included research related to recruitment, biomass, survival, and population, "distribution" included studies on larval dispersal and migration, "physiology" included research on growth rates, life history, disease, body functions, metabolism, and mortality, while "reproduction" included studies on settlement and spawning. The social-ecological category was further divided into fisheries, management, and marine protected area (MPA). Finally, all research articles were separated into either observed (use of past and current data) or projected (data projected in the future). If the study complied with more than one category or subcategory, all of them were separately recorded, which resulted in a higher number of topics (subcategories) than the total number of studies. Similarly, if a single study focused on more than one species from our list, it was recorded separately for each species to capture the number of studies per species.

2.4. Scientific knowledge vs. climate and fishing vulnerability

For each of the 68 focal species, we compared the number of studies with the species' estimated climate and fishing vulnerability index and plotted regression lines in R (R Core Team, 2022). The estimates of climate and fishing vulnerabilities follow a fuzzy-logic expert approach, by using intrinsic species information (Cheung et al., 2005; Jones and Cheung, 2018). These indices were extracted from FishBase where each species was assigned a value on a scale of 0–100 representing their climate and fishing vulnerability with the following classification: 0–25 = low, 26–35 = low to moderate, 36–45 = moderate, 46–55 = moderate to high, 56–65 = high, 66–74 = high to very high, 75–100 = very high. Fishing vulnerability was available for all species included in this study, whereas climate vulnerability data was missing for five species (i.e. *Bodianus scrofa, Dipturus nidarosiensis, Mycteroperca fusca, Odontaspis ferox,* and *Rostroraja alba*).

3. Results

3.1. Temporal and spatial distribution of published literature

Studies included in this review (n = 120) were published between

1974 and 2022, peaking in 2016 with 14 published studies (Fig. 2). Most studies were published after 2007 (n = 102), with at least two publications every year. Before that, in the period between 1997 and 2007, a small number of studies (n = 1–3) were published per year (except 1999, 2002 and 2007) accounting for 13 studies in total. Only five studies were published before 1997 with several years between some publications. Half of the studies (50%, n = 60) were conducted in the Northeast Atlantic region, followed by 23% (n = 27) in the Mediterranean, and 14% (n = 17) in Norwegian waters. Few studies (3%, n = 4) were conducted in the Baltic Sea. Several studies (10%, n = 12) focused on more than one region (Fig. 2, A). Among those, three studies covered all regions, four studies focused on Northeast Atlantic and the Mediterranean, two studies focused on all the regions except the Baltic Sea, one study was conducted in the Baltic Sea and Northeast Atlantic, one study covered all regions except the Mediterranean, and one study was a model that could be applied to all regions. Over the years, there has been a greater focus on biological topics, with abundance being a primary subject of research across the majority of the publishing years. Social-ecological studies, although limited in number, have emerged since the early 2000s (Fig. 2, B).

3.2. Representation of focal species in the literature

Out of the 68 initial species, we found only 23 species (34% of focal species, Figs. 1 and 3) with relevant studies examining the effects of climate change. The most studied species was Atlantic Salmon (*Salmo salar*, n = 45/120), accounting for more than a third (38%) of all the included studies (Fig. 3, Appendix S2). Most of the Atlantic salmon studies (n = 30) were focused on wild salmon, two studies focused on both farmed and wild Atlantic salmon, and n = 13 studies focused only on farmed salmon. The most studied region for Atlantic salmon was Norwegian waters (n = 31).

Other highly represented species included European pilchard (*Sardina pilchardus*, n = 24) and Atlantic bluefin tuna (*Thunnus thynnus*, n = 11). Most studies (n = 17) focused on European pilchard were conducted either in the Mediterranean or Iberian Peninsula, and only a few (n = 6) included countries such as the UK or Norway. In the case of Atlantic bluefin tuna, most studies (n = 9) were conducted in the Mediterranean. For all other species, we found five (*Cetorhinus maximus*) or fewer studies, and 10 species had only one study each. A lot of species (66%, n = 45) resulted either in no relevant studies or no studies in search results at all (Fig. 3).

3.3. Representation of the IUCN categories in the literature

All IUCN categories included in this study (critically endangered, endangered, vulnerable, or nearly threatened) were represented to some extent (Fig. 3). Critically endangered species (n = 9) had the lowest number of species covered by the literature (n = 2), and a high number of species with no studies at all (n = 7, 78% of critically endangered species). Endangered species (n = 17) had three represented species (n = 3) and an even higher number of species with no studies (n = 14, 82% of endangered species). Vulnerable species (n = 18) had eight species (n = 8) in the literature and ten species (n = 10, 55% of vulnerable species) with no studies. Nearly threatened species (n = 24) were the most represented in the literature (n = 10), but still had a high number of non-represented species (n = 14, 58% of nearly threatened species). In terms of number of studies, vulnerable species had the most representation (n = 57/120 studies) mainly due to the high representation of the Atlantic salmon (n = 45) from that group. Nearly threatened species were second most represented (n = 51/120) thanks to the number of studies devoted to the European pilchard (n = 24) and Atlantic bluefin tuna (n = 11). A small number of studies covered endangered (n = 7/120) and critically endangered (n = 5/120) species (Fig. 3).

3.4. Topics covered by the literature

Biological impacts of climate change on fish species were the focus of most studies (n = 109/120, Fig. 4). Only one (n = 1) targeted social-ecological implications and a small number (n = 10) covered both biological and social-ecological aspects of climate change. Under biological subcategories, the most frequent was abundance (n = 69), followed by physiology (n = 43), then distribution (n = 35). Diet (n = 13), genetics (n = 7), and reproduction (n = 6) were among the less-represented topics in all biological studies. Social-ecological studies were underrepresented, with few studies on fisheries (n = 6), management (n = 5), and MPA (n = 1). Most studies (except the study on MPA) focused on current (observed data), however, each topic (subcategory) had at least one study using projected data, with physiology having the most (n = 15, Fig. 4).

3.5. Topics covered by the literature per species and IUCN group

Breaking down the studies and topics by species showed that most species (n = 17/23) had a low number of topics covered (n ≤ 3) from biological and social-ecological categories combined (Fig. 5). Some species covered four topics, mostly in biological subcategories. Those include one critically endangered species (*Dipturus batis*), one endangered (*Cetorhinus maximus*), and two nearly threatened species (*Thunnus thynnus* and *Pomatomus saltatrix*). Studies focused on nearly threatened European pilchard (*Sardina pilchardus*) and vulnerable Atlantic salmon (*Salmo salar*), covered seven topics for each species. In both cases, these included all biological subcategories and one social-ecological category (fisheries). The most frequently studied topics for Atlantic salmon were physiology (n = 31) and abundance (n = 17), whereas for European pilchard those were abundance (n = 17) and distribution (n = 9).

Six species (three vulnerable and three nearly threatened) had only one topic covered. In all cases, they were only biological topics (n = 4

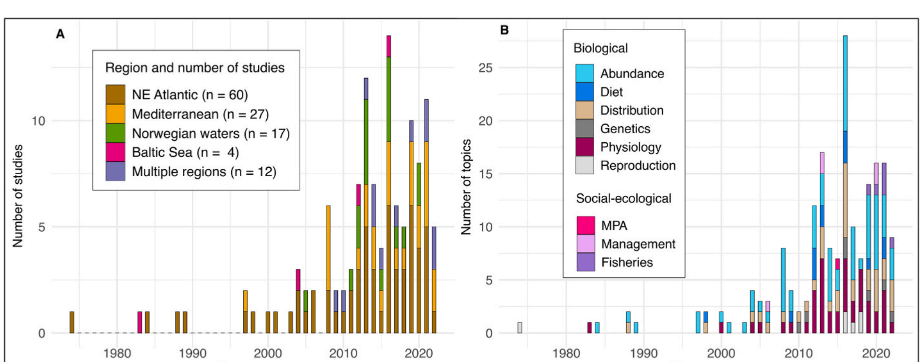

Fig. 2. Number of studies (A) and topics (B) per publication year. Studies were categorized into study regions. Multiple regions means that a study was based in two or more listed regions. NE = Northeast. Topics were categorized into biological and social-ecological subcategories. MPA = marine protected areas.

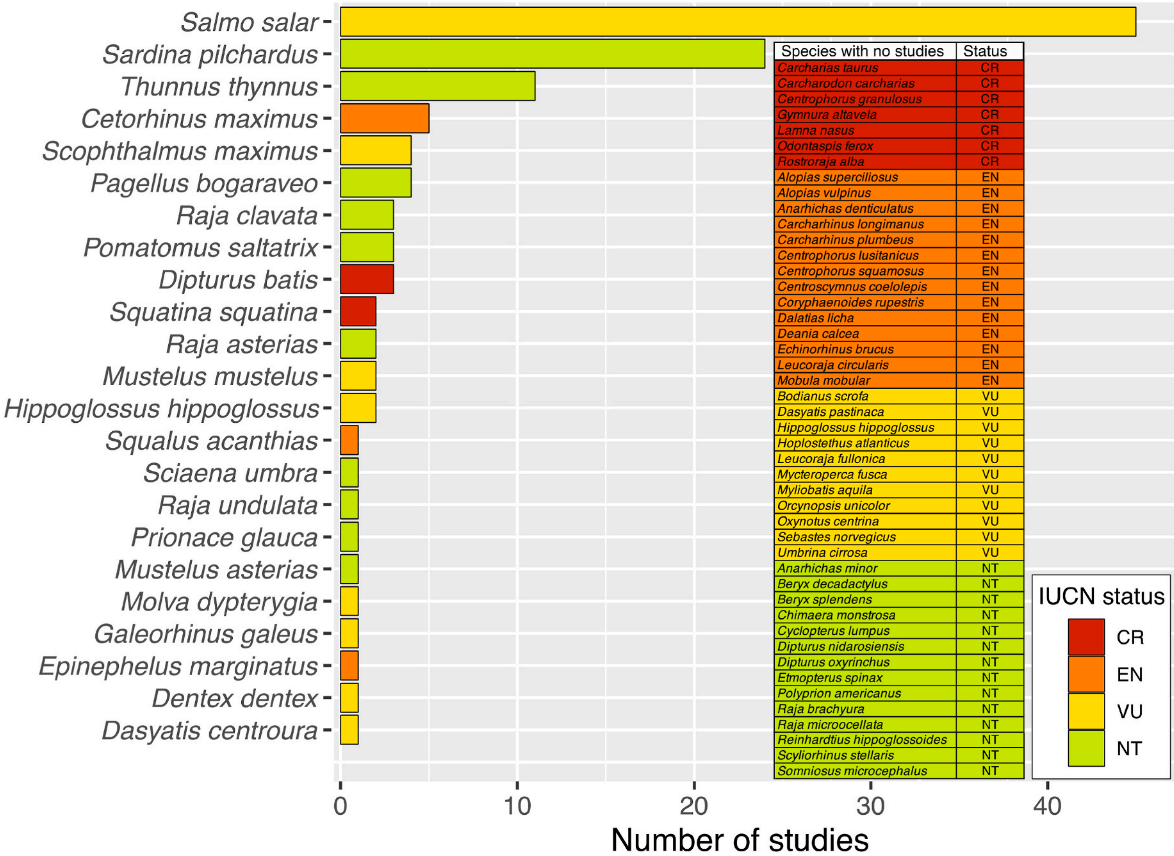

Fig. 3. Number of studies included in the analyses per species and the list of species with no relevant studies, or no studies at all from the search result. The color indicates each species' IUCN status (CR = critically endangered, EN = endangered, VU = vulnerable, NT = nearly threatened).

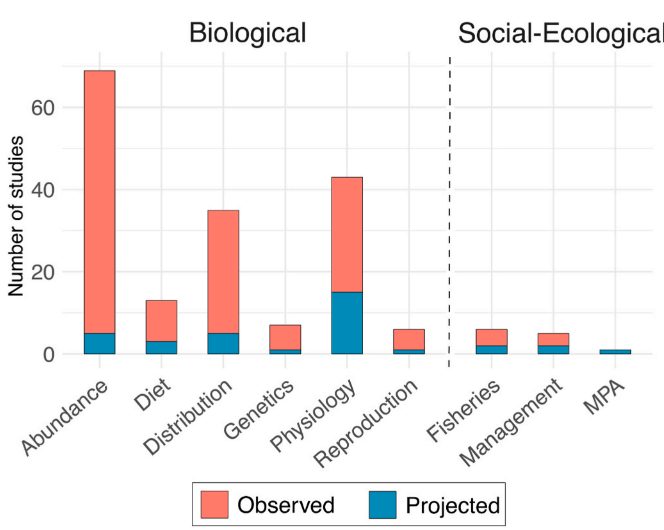

Fig. 4. Number of studies covering different biological and social-ecological topics classified into observed and projected studies (MPA = marine protected area).

abundance, and n = 2 distribution). Less than half the species (n = 9) had studies that included social-ecological topics. In most cases (n = 5 species), the covered topic was management. Only one endangered species (*Epinephelus marginatus*) had a single study focusing on the social-ecological MPA subcategory (Fig. 5).

3.6. Climate and fishing vulnerability of species as drivers of research effort

Climate vulnerability of all 68 focal species in this study spanned from low to very high, with most species concentrated between moderate (38/100) and high to very high (75/100, Fig. 6 (A)). Linear relationship between species' climate vulnerability and number of studies was not significant ($p = 0.3$, $df = 61$, Fig. 6 (A)). The three species with the highest climate vulnerability were *Raja microocellata* (88/100), *Carcharhinus longimanus* (76/100), and *Umbrina cirrosa* (70/100, Appendix S1). Overall fishing vulnerability of most species fell between moderate to high (50/100) and very high (90/100, Fig. 6 (B)). Among the three most represented species in the literature, *Thunnus thynnus* had the highest fishing vulnerability index (82/100), followed by *Salmo salar* (45/100) and *Sardina pilchardus* (30/100, Appendix S1). Many species (n = 39) had high or very high fishing vulnerability, among which ten species had the highest value (90/100): *Centrophorus lusitanicus, Dasyatis centroura, Dipturus nidarosiensis, Dipturus oxyrinchus, Echinorhinus brucus, Odontaspis ferox, Oxynotus centrina, Rostroraja alba, Somniosus microcephalus, Squatina squatina* (Appendix S1). There was a weak but significant negative relationship between fishing vulnerability and number of studies ($R^2 = 0.12$, $p = 0.004$, $df = 66$, Fig. 6 (B)).

4. Discussion

4.1. Limited knowledge on focal species: implications for climate-adaptive management

This study offers the first extensive review of the current scientific literature on the climate-driven biological and social-ecological effects on marine fish species in European waters, which are under combined

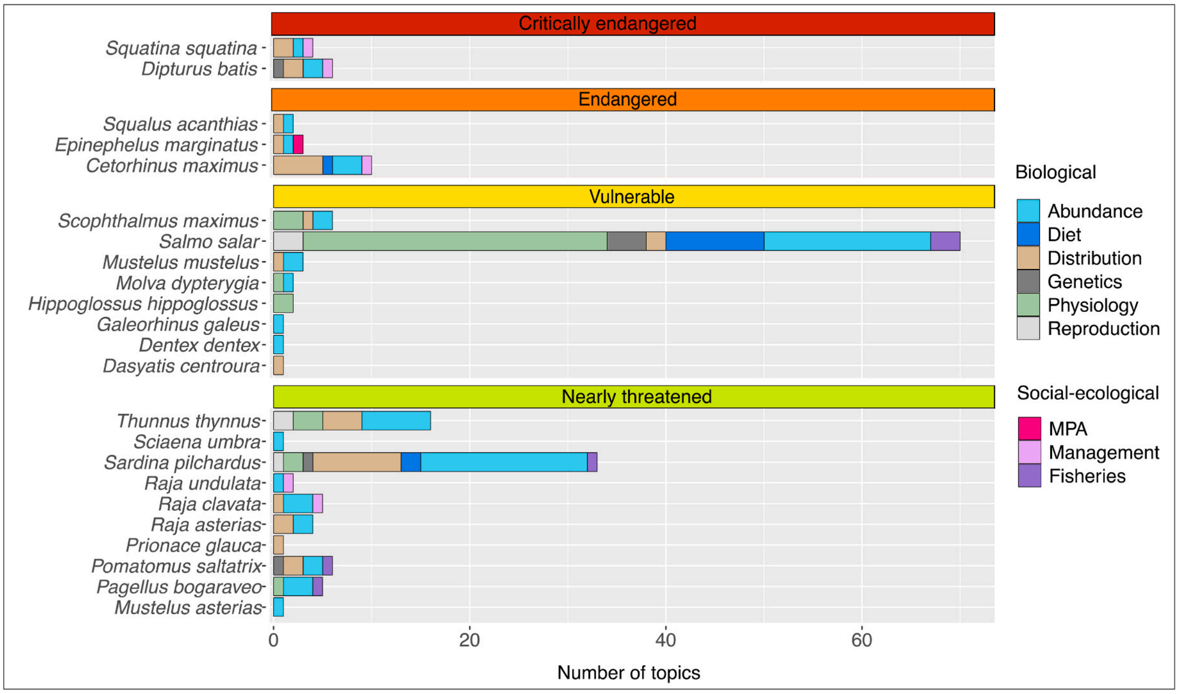

Fig. 5. The number of biological and social-ecological topics covered for each species individually. The species are sorted based on their IUCN status (MPA = marine protected area).

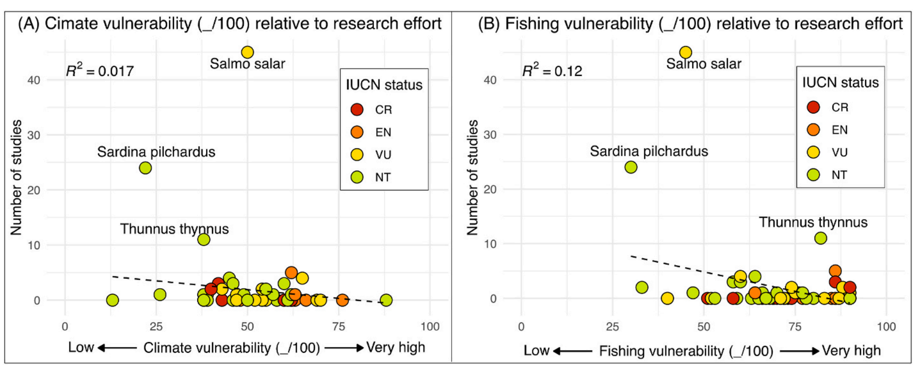

Fig. 6. Species climate vulnerability index (A) and fishing vulnerability index (B) relative to the number of studies (for all 68 species). The color indicates each species' IUCN status (CR = critically endangered, EN = endangered, VU = vulnerable, NT = nearly threatened), the dotted line is the regression line.

threats from climate change and fishing pressure. Our findings reveal a significant gap in knowledge, with nearly two-thirds of species not represented in the literature. For the species covered, the majority have only a handful of relevant studies. This lack of scientific knowledge has critical implications for governance and management decisions, as it undermines the ability to make evidence-based decisions about how to manage these species under climate change (Cvitanovic et al., 2014). The potential disconnect between the limited research and the pressing management needs jeopardizes the long-term survival of these species and the livelihoods of those who rely on them (Sutherland et al., 2004). Moreover, many of the species without climate-related research are classified by the IUCN as critically endangered or endangered, suggesting that the IUCN status of the species may not be a driving factor for scientific attention. The absence of research on these vulnerable species is concerning as it can limit the effectiveness of adaption strategies and interventions, for example, by causing delays in management actions (Brown et al., 2012).

The findings of this study can play a crucial role in informing existing initiatives aimed at sustainable management of marine fish species in European waters. Organizations such as the International Council for the Exploration of the Sea (ICES) could benefit from the insights derived from our analysis, as they seek to provide evidence-based advice on marine ecosystem management (Cvitanovic et al., 2021). By incorporating our findings into their assessments, ICES can better understand the extent of knowledge gaps for various fish species and prioritize research areas accordingly. Likewise, the Integrated Maritime Policy (IMP) and Common Fisheries Policy (CFP) of the European Union, which aim to promote sustainable fisheries and protect marine ecosystems, can utilize our study to identify underrepresented species and the challenges they face due to climate change. This knowledge can then be translated into more targeted and effective management measures, such as adaptive harvest strategies and marine protected area design that account for species' climate-driven range shifts (Andrello et al., 2015). The European Maritime and Fisheries Fund (EMFF) is another initiative that can benefit from our study, as it strives to support the sustainable development of fisheries and coastal communities. By recognizing the species and regions with limited research, the EMFF can allocate its resources more strategically, fostering initiatives that fill knowledge gaps and promote climate-adaptive management strategies.

4.2. Few species and regions dominate the literature

We identified a large imbalance in species representation, driven by three species dominating most published studies, Atlantic salmon (*Salmo salar*), European pilchard (*Sardina pilchardus*), and Atlantic bluefin tuna (*Thunnus thynnus*), with the majority focusing on the Atlantic salmon. This bias could exist because these three species are some of the most commercially important species in Europe, both in terms of production, consumption, and in the case of salmon and tuna, export (European Commission and Fisheries, 2021). There was also a regional bias for each of these species that seems to be driven by regional production and consumption. Many studies on Atlantic salmon occurred in Norway, a leading producer of salmon, mostly by aquaculture (Misund and Nygård, 2018). Besides its high economic value, Atlantic salmon holds great social and cultural importance for locals (Myrvold et al., 2019). Due to its anadromous life cycle, many studies investigated climate change effects on the Atlantic salmon's freshwater life stage. These included already observed climate change effects on migration behavior (Arevalo et al., 2021), projected decreased range and distribution shifts (Kärcher et al., 2021), and examples of natural resilience to variations in the environment in some cases (Härkönen et al., 2021). While these studies were out of scope for this review, they offer valuable knowledge that should be considered for a holistic understanding of climate change effects on Atlantic salmon.

The European pilchard was largely studied in the Mediterranean and Iberian Peninsula, in line with the countries that consume it the most, such as Portugal, Spain, and France (European Commission and Fisheries, 2021), and the Atlantic bluefin tuna was mostly studied in the Mediterranean. For both species, important geographic areas remain understudied, such as the Northeast Atlantic and Baltic Sea. For example, climate change is already affecting regional abundance and distribution of the Atlantic bluefin tuna throughout the Northeast Atlantic (Dufour et al., 2010; Faillettaz et al., 2019). Climatic variations coupled with large catch volumes of this species in the Northeast Atlantic (Havice et al., 2022) highlight the need for the expansion of scientific efforts beyond the Mediterranean waters.

Our results revealed that the least represented region in terms of species-specific climate change studies is the Baltic Sea. This region received minor scientific attention, which is alarming considering that it is one of the fastest-warming seas in the world (Belkin, 2009) and that climate change effects on the few studied species in that region are evident (Huusko and Hyvärinen, 2012; Jokinen et al., 2016). While extensive monitoring efforts have been undertaken for commercially important species in the Baltic Sea, such as herring, sprat, and sea trout (Ojaveer et al., 2010), these efforts were not reflected in our study due to the absence of these species from the European IUCN Red List. The limited representation of the Baltic Sea in our research may be attributed to the distribution patterns of our focal species, which primarily occur in regions outside of the Baltic.

4.3. Lack of social-ecological studies

Our results also highlighted knowledge gaps in terms of topics covered by the studies included in this review. This was true, even within the small group of well-represented species. Most studies were focused on climate-driven biological effects across all species, with uneven distribution among subcategories reflecting these gaps. While these topics certainly offer valuable insight into species performance under climate change (Frost et al., 2020; Guisande et al., 2004), there are missed opportunities to learn about species' reproduction, diet, and genetics. These are very important aspects of species' life cycle that might suffer negative impacts under climate change, potentially impairing populations' persistence (Baltazar-Soares et al., 2021; Queiros et al., 2019; Reglero et al., 2018). Biological studies are important since they allow for a better understanding of species' responses to climate change (Harvey et al., 2014a), and can inform management decisions that enhance species' resilience, for example, redistributing fishing pressure (Ramírez et al., 2021). However, our results show that research regarding the social-ecological implications of climate change on fisheries in European Seas, for example the response of fishers and fishing fleets, is frequently overlooked, despite its importance for informing fisheries management (Fulton et al., 2011).

Here, we found that social-ecological climate change implications related to fisheries, management, and MPA studies were largely lacking for all focal species. Since implementing adequate conservation measures in the face of climate change involves some form of social-ecological transformations to adapt to the changes (Mcclanahan et al., 2008), it is imperative to fill in the knowledge gaps in those areas. Among the very few social-ecological studies identified in this review, only one was exclusively focused on that topic. It directly assessed the effects of climate change at social and economic levels, by projecting expected changes of profitability in the European aquaculture sector, finding high sensitivity to costs of feeding, fish price on the market, and marketing options (Kreiss et al., 2020). All other studies examined social-ecological dimensions by connecting them with the biological effects of climate change. For example, suggestions of fishing redistribution to increase species' resilience to climate change (Ramírez et al., 2021) or projections of climate change impacts on farmed fish physiology that can lead to economic consequences (Cubillo et al., 2021). While these studies undoubtedly offer valuable information with clear management implications and can help identify where current management practices are succeeding and falling short (Elliott et al., 2020; Southall et al., 2006), they are still lacking data, for example, about human behavior, interactions with focal species, and possible social consequences of climate change.

However, one study did incorporate human perceptions and behavior, by analyzing YouTube videos of recreational anglers and spearfishers in Italy, targeting bluefish (*Pomatomus saltatrix,* Sbragaglia et al., 2022). This nearly threatened species is native to the southern and eastern Mediterranean (Fisher et al., 1987), but in recent years has migrated northward, likely due to increased local temperatures (Sabats et al., 2012). The authors determined that local fishers had both positive and negative perceptions of this species and argued this could be leveraged to support regional bluefish management. Similar types of studies, focused on other focal species in this review, could help choose which management strategies for conservation could be most effective (e.g. seasonal bans).

There was also only one study focusing on climate change implications in MPAs, that projected climate change effects on the connectivity and effectiveness of MPA networks in the Mediterranean, in terms of larval supply to fished areas (Andrello et al., 2015). Globally, MPAs have long been used as effective management tools to support fisheries (Medoff et al., 2022), but are also known to be under climate change threats (Bruno et al., 2018), as protected areas typically remain static while shifting environmental conditions do not. This can change the conditions within an MPA affecting the distribution of species within boundaries (Lima et al., 2022) leading to a mismatch between MPA goals and reality. While future research should be directed towards improving our knowledge of how MPAs will be affected by climate change, this research should be multi-faceted to incorporate all dimensions of the social-ecological spectrum (Mangubhai et al., 2015).

4.4. Climate and fishing vulnerabilities are not driving scientific attention

We found a weak negative relationship between the number of studies and species' fishing vulnerability and no relationship with their climate vulnerability. These results mean that the species with high vulnerabilities are not currently prioritized in the literature. Several critically endangered and endangered species showed very high values of intrinsic fishing vulnerability. This index captures species' features such as slow growth, late maturity, longevity, and fecundity contributing to high sensitivity to fishing pressures (Cheung et al., 2005).

Among some of the species with the highest fishing vulnerability were three elasmobranches, Angelshark (*Squatina squatina*), Smalltooth sand tiger (*Odontaspis ferox*), and White skate (*Rostroraja alba*). While fishing of all three of these predators was prohibited in many European waters in the past decades (IUCN 2010 European Red List, downloaded in June 2022), they are still susceptible to bycatch (Dulvy et al., 2021) and can be at risk of local extinction even at low capture rates (Fergusson et al., 2008). While discard rates and survivorship after the release remain unknown (James et al., 2016), these species may be illegally fished or even targeted and mislabeled (Alvarenga et al., 2021; Pazartzi et al., 2019). Risks of local extinctions coupled with recent decreases of cold-water skates and sharks followed by increases of warm-water species in some European regions (Sguotti et al., 2016) highlight the need for more investigation of species-specific responses to changing climates. Moreover, it shows the need for informed and effective management measures, considering human behavior and future adaptation scenarios (Fulton et al., 2011).

4.5. Observed climate change effects are more studied

Generally, there was a higher number of studies with observed climate change effects compared to projected changes. This might reflect the fact that currently, similarly to other regions, such as Australia (Fogarty et al., 2019), the scientific community investigating biological climate change effects on marine fish species in European seas is focused mainly on understanding changes that have already happened, before making predictions about the future. However, incorporating future projections into available scientific knowledge would provide useful insights into possible ways to prepare timely management responses. This is especially true considering that management actions take time to be implemented and are not revised very often, so adaptation strategies would benefit from accounting for projected changes. Although the present study focused only on peer-reviewed studies, previous research also found that management plans (e.g. of MPAs) poorly address future climate changes (O'Regan et al., 2021). Anticipation and preparedness are key to coping with and adapting to changes that are likely to induce cultural and economic disruptions (Galappaththi et al., 2022).

4.6. Future research needs

After examining the current extent of scientific knowledge on the impact of climate change on Europe's threatened commercial fish species, we have identified several critical areas for future research. Firstly, future studies should aim to increase climate-related knowledge across all focal species, with a particular emphasis on critically endangered and endangered species. This includes expanding research into understudied topics such as diet, reproduction, and genetics in the context of climate change. Secondly, there is an urgent need for more scientific attention to the social-ecological aspects of climate change, particularly in relation to focal species within marine protected areas, fisheries, and management. Addressing this knowledge gap will be crucial for informing effective policies and management strategies (Cvitanovic et al., 2014; Roux et al., 2006). Expanding the scope of research to encompass broader geographical areas, such as the Baltic Sea, is crucial for a comprehensive understanding of climate change impacts on marine ecosystems. The Baltic Sea is known as one of the fastest warming seas, with substantial consequences already observed within its ecosystems (Huusko and Hyvärinen, 2012; Mackenzie and Schiedek, 2007; Niiranen et al., 2013). Further research should consider the inclusion of species relevant to the Baltic Sea to provide a more comprehensive understanding of climate change impacts on this unique ecosystem.

Although this study primarily focused on peer-reviewed publications to ensure data quality and reliability, future research could benefit from analyzing grey literature and existing management plans related to these species. Doing so would help identify the sources of information that inform decision-making processes. For instance, examining reports and documents from organizations like the International Council for the Exploration of the Sea (ICES), the Helsinki Commission (HELCOM), The Mediterranean Science Commission (CIESM), OSPAR Commission, and the Barcelona Convention, which harness expert knowledge through regional networks, may yield valuable insights not readily available in peer-reviewed literature. Given the extensive research and collaborations of these regional conventions, their resources could significantly enhance our understanding of the impacts of climate change on threatened commercial fish species in different regions. Incorporating such information would provide a more comprehensive understanding of the factors shaping management decisions and contribute to more effective conservation strategies. In addition, as fishing pressure may have a more significant impact on commercial fish species than climate change alone (Dulvy et al., 2021; Pinsky and Fogarty, 2012), it should be incorporated into future studies. Investigating the interaction between fishing pressure and climate change will help to develop a more comprehensive understanding of the factors affecting the resilience and adaptability of these species. Finally, future research could also explore summarizing and synthesizing the known climate change effects on focal species, to better understand the potential impacts and inform targeted management strategies.

As climate change continues to pose challenges to the sustainability of fisheries and the livelihoods of those who depend on them (Barange et al., 2014), addressing these research gaps is essential for developing evidence-informed policies and practices that support the long-term resilience of Europe's endangered commercial fish species. Consequently, future research and funding should prioritize filling these knowledge gaps, which would enable more robust and informed governance and management decisions in the context of climate change (Hobday and Cvitanovic, 2017). However, gathering information is just a first step on the path of adaptation to climate change. Adequate knowledge exchange and science-based management decisions are crucial for successful management actions (Roux et al., 2006), but often difficult to achieve (Cvitanovic et al., 2015a, 2015b). More scientific knowledge is certainly necessary to better understand how climate change will affect species under cumulative threats in Europe, but unfortunately, there may be limited time for research on some of these species. Implementing management actions with the best available data, in parallel with improving knowledge-exchange and knowledge expansion would provide the most effective means to successfully cope with climate change in European seas.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Milica Predragovic reports financial support was provided by la caixa Foundation.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106719.

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