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How overfishing handicaps resilience of marine resources under climate change

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How overfishing handicaps resilience of marine resources under climate change

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Editorial: How overfishing handicaps resilience of marine resources under climate change

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Editorial on the Research Topic
How overfishing handicaps resilience of marine resources under climate change

It is now clear to most scientists and many non-scientists that Climate Change (CC) is altering ocean physics and chemistry, thereby affecting the ecology and biology of marine life. These changes in turn impact ocean economics and the lives and livelihoods of millions of people who depend on it. Independent and IPCC (Intergovernmental Panel on Climate Change) researchers have been developing this knowledge for decades (e.g., Cheung et al., 2010; Sumaila et al., 2011; Bopp et al., 2013; Pörtner et al., 2019).

In recent years, scientists and the world have come to realise that the interaction between CC and the ocean and its dependent economies are not unidirectional but bidirectional. That is, it is not just that CC impacts ocean life and related economies, but ocean economic activities also contribute to carbon emission and therefore CC. To demonstrate the latter in terms of fish and fisheries, researchers at the University of British Columbia in collaboration with the environmental NGO, Our Fish, launched a Research Topic to see if we could show that addressing overfishing is also in effect climate action. Over 40 scholars collaborated to author nine papers in this Research Topic entitled "*How Overfishing Handicaps Resilience of Marine Resources Under Climate Change*".

We describe here the highlights of each paper with the goal of whetting the appetite of the reader to dig deeper into our findings by reading the papers in full.

In the opening paper in the Research Topic, Sumaila and Tai explain how ending overfishing can increase the resilience of the ocean to CC. The authors conducted a literature review and analysis, and concluded that (i) marine fish stocks are overfished in many parts of our oceans; (ii) CC has significant consequences on ocean life; (iii) ending overfishing could make fish stocks more climate resilient; and (iv) fish and fish stocks are like people and more likely to withstand the impact of an attack (e.g., by CC) when they are in a healthy condition to start with.

Ferrer et al. make the powerful point that overfishing, often caused by large, subsidised fishing fleets (Sumaila et al., 2021; Skerritt et al., 2023), is a double whammy for small-scale fisheries (SSF). First, it forces people to spend more time burning fuel to search for scarcer, overfished resources, which is both costly and risky. Second, the extra carbon emitted to chase fewer fish aggravates the contribution of CC to warming, ocean acidification and deoxygenation, all of which unduly impact fish and fisheries (Sumaila et al., 2019; Lam et al., 2020). The authors used long-term fisheries monitoring data from Northwest Mexico to test the relationship between underlying fishery biomass and fuel intensity observed among several motorised small-scale fisheries (SSF). Their study supports the double whammy conclusion for SSF.

Martin et al. addressed the question: what if depleted fish stocks worldwide were restored, how would this affect the level of carbon emissions? Clearly, this is an important question since, until recently, the literature had mainly concentrated on how much more biomass, catch, and profits would be generated if fish biomass were rebuilt and managed more effectively (Sumaila et al., 2012; World Bank, 2017; Teh and Sumaila, 2020). Using landings and effort data combined with estimates of adult population biomass, Martin et al. explore the potential for lowering emissions intensity and impacts on organic carbon stocks through ending overfishing and rebuilding stocks. Specifically, they use the recent recovery of European hake (*Merluccius merluccius*) stocks in the Northeast Atlantic as a case study. Their results suggest that recovery of the hake stock led to reductions in overall emissions intensity from fuel.

Scotti et al., focused on the western Baltic Sea, exploring how ecosystem-based fisheries management (EBFM) can increase catch and carbon sequestration through recovery of exploited stocks. In a nutshell, they found that by allowing fish stocks that have been overfished to recover, we can enjoy the double dividend of being able to catch more fish sustainably while at the same time increasing the ability of the large fish biomass to sequester more carbon. This study presents the first mass-balanced ecosystem model focused on the western Baltic Sea (WBS), and a more specific result generated by the study is that heavy fishing pressure exerted on the WBS has forced top predators such as harbour porpoise and cod to cover their dietary needs by shifting from forage fish to other prey, or to find food outside of the model area. In addition, they found that the EBFM scenario would allow the recovery of harbour porpoise, forage fish and cod with increases in catch of herring and cod. In addition, EBFM promotes ecosystem resilience to eutrophication and ocean warming, and through the rebuilding of commercial stocks, increases by more than three times carbon sequestration compared to the 'Business as Usual' scenario.

Issifu et al. developed a risk assessment and policy solution framework, which the authors used to evaluate the impact of ocean warming, overfishing and mercury on European fisheries. Their study suggests that the negative impacts of these stressors on European fisheries depend on the type of species being studied, and their mean temperature tolerance (MTT). These negative impacts may limit the capacity of fisheries and marine ecosystems to respond to current climate induced pollution sensitivity. The authors concluded that ongoing global efforts aimed at minimising carbon footprints and mercury emissions need to be enhanced in concert with an extensive drive to reduce fishing intensity. Such an integrated approach to tackling the combined effects of ocean warming, overfishing and mercury is needed to maintain effective conservation measures that promote increased resilience of fisheries to CC and other stressors.

Villasante et al. start by emphasizing the importance of SSF for livelihoods, food security, jobs, and income worldwide. The authors further make the point that these fisheries are facing serious challenges, including the increasing effects of CC that pose significant threats to coastal ecosystems and fishing communities. They carried out a case study based in Galicia (Spain), where they estimated the economic vulnerability of shellfishers and assessed the diversity of social adaptive responses used to deal with CC. Among other things, Villasante and his co-authors found that Galician shellfishers developed a wide range of adaptation strategies to anticipate and respond to CC impacts. These include targeting pricier and more abundant species, reducing household expenses, and increasing social involvement in shellfishery associations. Still, the locally developed adaptive strategies are not enough to insulate the shellfish fishers from the risks they face from CC and other threats.

Macusi et al. sought to determine how vulnerable a selection of SSF and associated fishing communities around the Davao Gulf in the Philippines are to CC. A semi-structured questionnaire was used to gather data on the perceptions of fishers on the impacts of CC on their livelihood and communities. The results of their analysis suggest that coral bleaching, inadequate food, lack of credit access, changes in weather patterns and hotter temperatures contributed highly to the vulnerability of the SSF. The authors report that CC contributes to less seasonality, unclear reproductive patterns, diseases in the catch, invasive species, decrease in catch as well as forcing SSFs to venture farther and deeper in the ocean to fish - aggravating CC as discussed in earlier papers in this Research Topic.

Oostdijk et al. discuss how to govern the open ocean so it can contribute its part to sequestering carbon. They highlight the vital service that fish, and other marine vertebrates provide in the biological pump, a topic that is now receiving more attention by both policy makers and scientists. The authors explored the interest in and possibilities for the establishment of international governance of the open ocean and the role that fish, and other marine vertebrates play as carbon sequesters. The authors used semi-structured interviews involving environmental non-governmental organization (ENGO) representatives, policy makers, and policy experts. This was supplemented by an exploratory review of grey and peer-reviewed literature with two objectives in mind. First, the authors traced the pathway of important key actors, and the strategies they use to influence the governance of ocean carbon. Second, they investigated different frameworks to determine which ones might be used to govern the open ocean and the fish carbon it sequesters. The authors conclude that more viable routes for future governance of the open ocean and the carbon sequestered by fish and other marine animals may lie in international fisheries management and in the negotiations of the treaty on Biodiversity Beyond National Jurisdiction (BBNJ) that were just concluded.

The final paper by Krabbe et al. suggests ideas on how international fisheries laws could be reformed to increase blue carbon sequestration. The authors emphasized the fact that the climate services performed by the ocean can be described as an interaction between a physical and a biological carbon pump, and that the scale of interaction is yet to be fully understood. Currently many species in the open ocean and elsewhere in the marine ecosystem are managed under the international law of the sea and subject to the concept of Maximum Sustainable Yield (MSY). Under MSY-based management, states are not required to consider the climate services represented by different marine organisms, making this regime unable to balance the interest of maximizing fish as a product against the ocean's role in carbon sequestration. The authors argue that in order to make optimal use of the carbon sequestration features of marine organisms, a number of modifications to the current international law are urgently needed. Their top recommendation is that MSY should be complemented with a new management objective, which governs the open ocean to maximize carbon sequestration (MCS) rather than MSY. The authors conclude that reforming international fisheries law to achieve MCS could make an important contribution to the operationalization of the Paris Agreement on Climate Change, as well as the UN Sustainable Development Goals.

These papers taken together are greater than the sum of their parts, and we anticipate that the studies reported in this Research Topic, and the insights they provide, will contribute an important "missing link" to ongoing discussions on CC, marine ecosystems and how we best fish sustainably. Many of the papers alert us to the fact that fisheries are not just victims of CC but also contributors to its aggravation through overfishing. The important conclusion that overfishing contributes to the intensity of CC, which in turn makes fisheries more vulnerable and susceptible to CC, is a very important one for policy makers. Ultimately, this Research Topic also shows that addressing overfishing is a win-win, for ocean health, to address CC, and ultimately for the millions who depend on sustainable fisheries for jobs, food and nutritional security.

Author contributions

US wrote initial draft; CF and MP contributed equally. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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MINI REVIEW
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End Overfishing and Increase the Resilience of the Ocean to Climate Change

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Marine fish stocks and the ecosystems they inhabit are in decline in many parts of our ocean, including in some European waters, because of overfishing and the ecosystem effect of fishing in general. Simultaneously, climate change is disrupting the physics, chemistry and ecology of the ocean, with significant consequences on the life it holds. While the positive effects of mitigating climate change on the ocean and marine life are currently being documented, papers that examine how ending overfishing could increase ocean resilience to climate change are less common. The goal of this paper is to review the current literature and conduct an analysis that demonstrate that ending overfishing and reducing other negative ecosystem effects of fishing would make fish stocks and marine ecosystems more resilient to climate change. Our findings suggest that fish and fish stocks are no different from other living organisms and are more likely to survive external pressures when healthy.

Keywords: food webs, habitat, carbon sequestration, climate change mitigation, sustainable ocean resources

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HIGHLIGHTS

- Marine fish stocks are overfished in many parts of our ocean;
- Climate change is having significant consequences on ocean life;
- We demonstrate that ending overfishing could make fish stocks more climate resilient;
- Fish and fish stocks are no different from other organisms and more likely to survive when healthy.

INTRODUCTION

We know the critical importance of the ocean for planetary function and life on Earth—mediating global weather patterns, cycling of carbon (i.e., biological carbon pump) and carbon sequestration (i.e., carbon sink), contributing almost half of the annual primary production on Earth, to name a few (Brierley and Kingsford, 2009). Marine ecosystem goods and services to human society are dependent on ocean health, yet there are many potential consequences of continuous human population growth and rising per capita consumption, in particular human-accelerated climate change and overfishing to meet global demands.

Fish are an important part of marine ecosystems and are a central part of the marine food web where predator-prey relations both within different fish species and between fish and other marine life keep the ocean thriving. An ocean full of life is also important as a source of food and livelihood for hundreds of millions of people worldwide. Unfortunately, fish and life in the ocean in general are facing a multitude of threats, two of the biggest being overfishing and climate change.

Here, we ask and address the question: How would the reduction of overfishing as broadly defined herein increase the ability of fish stocks to withstand the impacts of climate change, making the ocean more resilient to such changes. We conduct a selected literature review and carry out an analysis that reveals the links between reducing overfishing, improvements in fish stock and marine ecosystem health and increased resilience of marine ecosystems to the effects of climate change. We use fish stocks of the European Union as an example throughout.

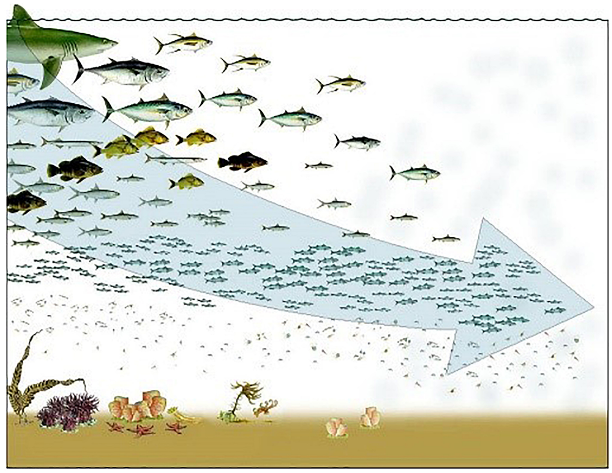

FIGURE 1 | Overfishing truncates the food web and simulates the same effects of "fishing down food webs." Figure adopted from Pauly et al. (2005).

A BROAD DEFINITION OF OVERFISHING

We adopt a dynamic and broad concept of overfishing as captured by the concept of fishing down marine food web of Pauly et al. (2005). This concept does not only capture the fact that we are taking too many fish than nature can sustainably yield annually, we are also taking too many high tropic level and valuable fish species thereby truncating the food web (**Figure 1**). While both of these are happening, we are also disturbing and, in some cases, destroying ocean habitats through the use of harmful fishing gears (Chuenpagdee et al., 2003). All of these three aspects of overfishing combine to weaken the health of both fish stocks and the marine ecosystem as a whole. According to the FAO, overfishing and habitat destruction have resulted in the depletion of a third of fish stocks worldwide. Academic research has reported even higher levels of overfished stocks (e.g., Pauly et al., 2005). For fisheries in the European Union (EU), estimates suggest that "at least 40% of fish stocks in the North East Atlantic and 87% in the Mediterranean and Black Seas, are currently subject to unsustainable fishing practices (STECF, 2019)." It should be noted that these numbers are averages and that some Atlantic EU stocks have seen improvements during the past decade. At the same time the situation in other European waters are worse than the averages.

Human society has had considerable and far-reaching impacts on the global ocean (Halpern et al., 2015), and overfishing has had lasting effects on marine ecosystems and continues to be one of the greatest threats to ocean health (Pauly et al., 2005; Jackson et al., 2007; Le Quesne and Jennings, 2012; Halpern et al., 2015; Gattuso et al., 2018). Overfishing often has major ecosystem effects (Coll et al., 2008; Sumaila et al., 2019) and has even been identified as a driver of ecosystem regime shifts (Daskalov et al., 2007). As a stressor, overfishing will have negative effects on many indicators of ocean health, including biodiversity, food security, and coastal livelihoods and economies (Halpern et al., 2012). The direct impacts of overfishing can reduce fish biomass, affecting biodiversity and the sustainability of fisheries, as well as exacerbate the impacts of destructive fishing gear on marine ecosystems (e.g., bottom trawls). Furthermore, where overfishing is a result of illegal, unreported, or unregulated fishing, these fishing operations are often also conducted with highly impacting fishing gears—e.g., bottom trawls—that negatively affect benthic substrate (Bailey and Sumaila, 2015).

In European waters, recent reports estimate that between 40 and70% of fish stocks are currently at an unsustainable level—either overfished or at their lower biomass limits (Froese et al., 2018; STECF, 2019). In the Mediterranean Sea, it is estimated that over 90% of stocks are overexploited (Colloca et al., 2017). Similarly, the Black Sea also sees high levels of exploitation, with continuing declines in catch (Tsikliras et al., 2015). In contrast, some northern European fish stocks are faring better, e.g., those in the Norwegian Sea and Barents Sea—due to historically well-managed fisheries some fish stocks in these waters are at maximum sustainable yield (MSY) (Gullestad et al., 2014; Froese et al., 2018). The January 1, 2020 deadline for the proposed plan to end overfishing in the EU is approaching. While there are some trends heading in the right direction, the EU is far from eliminating overfishing in its waters. In fact, on August 30, 2019, the EU proposed to continue overfishing past the deadline for January 1 2020, https://twitter.com/SeasAtRisk/status/1167458264566706176.

CLIMATE CHANGE IMPACTS ON FISH AND OCEAN LIFE

Climate-related impacts on marine environments are already impacting species, populations, and ecosystems (Pörtner et al., 2014). **Figure 2** provides a quick summary of the channels through which climate change can impact marine ecosystems and life. Responses to environmental change for marine organisms is largely determined by physiological tolerance, and they respond

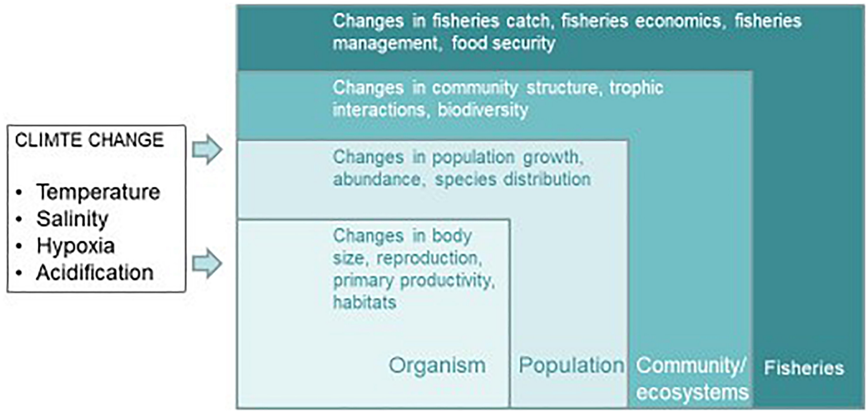

FIGURE 2 | Climate change impacts on marine ecosystems and goods and services provided to human society. Figure adopted from Sumaila et al. (2019).

with changes to physiological function and behavior shaped by their evolutionary history (Doney et al., 2012; Somero, 2012). For example, changes in temperature—e.g., ocean warming—that go beyond an organism's optimal range will initiate physiological responses that may affect biological performance including growth, reproduction, and survival. Climate-related impacts may also lead to shifts in phenology (timing of seasonal biological events). For example, in European waters we have observed shifts in the timing of zooplankton biomass formation in the North Sea (Schlüter et al., 2010), juvenile Atlantic salmon migration (Kennedy and Crozier, 2010; Otero et al., 2014), and general widespread ecosystem shifts across all major taxonomic groups in the United Kingdom (Thackeray et al., 2010). These direct effects may translate into higher levels of biological organization, affecting population dynamics, and ecosystem structure, function, and diversity [e.g., tropicalisation of temperate reefs (Vergés et al., 2019), localized species invasions and extinctions (Philippart et al., 2011)].

The onset of rapid climate-related changes in these ecosystems is increasing pressure on fish stocks, with the potential of extinction for some fish species. Evidence of large-scale shifts in species' distributions to deeper and higher latitudinal waters has already been documented extensively in the past two decades (e.g., Parmesan and Yohe, 2003; Perry et al., 2005; Dulvy et al., 2008), and these climate effects have continued to manifest at the species (Montero-Serra et al., 2015), ecosystem (Frainer et al., 2017), and fisheries levels (Cheung et al., 2013). Swift action is critical at this stage to ensure the long-term sustainability of marine ecosystems and fisheries (Gattuso et al., 2018) and the varied and crucial benefits they provide (Rogers et al., 2014).

HOW ENDING OVERFISHING CAN INCREASE FISH STOCK RESILIENCE UNDER CLIMATE CHANGE

Ending overfishing results in: the reduction of fishing effort to ensure sustainable levels of fish catch and yield given the management structure in place (e.g., MSY); a healthier, richer ocean with more diverse fish populations; a more complete marine food web with fish of all trophic levels well represented; and a marine ecosystem with healthier, more varied and more complete marine habitats. Based on these four consequences of ending overfishing, we see at least 5 ways in which ending overfishing can increase the resilience of fish stocks and the marine ecosystem in the face of climate change. Three of these increase resilience by leaving more fish in the ocean; maintaining the structure of marine food webs; and ensuring rich and diverse marine habitats and ecosystems. The remaining two help fish stocks and the marine ecosystem by reducing the amount of CO_2 in the atmosphere through the (i) emission of less CO_2 by the fishing sector itself; and (ii) sequestration of higher levels of CO_2 that more fish in the ocean that ending overfishing entails.

End Overfishing, Increase Fish Abundance of Commercial Stocks

Overfishing takes too much fish out of a renewable natural capital just like withdrawing more money out of a bank account than the savings can generate annually. And just like a bank account, taking more than the annual yield that a fish stock can generate makes the system more vulnerable; the fish stocks and the marine ecosystem would be more vulnerable to change even without a stressor such as climate change. Overfishing has been widely accepted as a direct pressure and major risk to marine environments and ocean health, drastically reducing fish biomass in the ocean (Pauly et al., 2005; Halpern et al., 2015).

End Overfishing, Protect the Integrity of Marine Food Webs

Overfishing has already done considerable damage to ecosystems and has resulted in trophic cascades (i.e., restructuring of the food chain). It takes too many large individuals from higher trophic levels and high value fish out of the marine ecosystem, going from the highest trophic level and most valuable species at the time they are fishing resulting in serial depletion and fishing down marine food webs (Pauly et al., 2005). These all serve to weaken fish stocks and make them vulnerable to all sorts of stressors including climate change. Climate-related impacts on marine ecosystems affect natural and human elements of ocean health. Changes in species' distribution and abundance will increase local invasions and extinctions, redistributing marine biodiversity and its composition (Cheung et al., 2009; Pecl et al., 2017; Sunday et al., 2017). Subsequently, this will affect marine ecosystem goods and services, including food security and dependent coastal communities (Halpern et al., 2012; Lam et al., 2014; Sumaila et al., 2019). Furthermore, the increased variability of environmental change will also increase the variability—and decrease the predictability and reliability—of goods and services to human society (IPCC, 2014).

End Overfishing, Avoid Marine Habitat Degradation

Indirect pressures of overfishing include habitat degradation (from destructive fishing gear) and pollution (i.e., plastic, oil). Overfishing has already resulted in habitat loss (Daskalov et al., 2007; Halpern et al., 2015). Improving aspects of ocean health such as the condition of marine habitats (corals, seamounts, mangroves and seagrass) can benefit other components of the ecosystem including fish stocks and increase resilience to other pressures—in particular, climate change (Gaines et al., 2018). While pressures and stressors will decrease fish stock abundance and marine ecosystem health, resilience counteracts these negative effects (Halpern et al., 2012).

Habitat loss has implications for marine life, but will also affect other aspects of ocean health such as coastal protection and carbon storage. Hence, the reduction of habitat degradation due to the elimination of overfishing would increase the health of marine ecosystems and the fish stocks they sustain.

End Overfishing, Decrease CO_2 Emissions by the Fishing Sector

The world is awash with fishing vessels. According to the FAO there are currently 4.6 million vessels of various sizes (FAO, 2018). It is estimated that the fishing capacity and effort currently being used to catch fish is between 40 and 60% of what is needed to fish at MSY. Ending overfishing and rebuilding depleted fish stocks will entail cutting overcapacity by a significant amount. Less fishing vessels chasing few fish in the ocean will mean the fishing sector, which is credited with emitting at least 1% of global CO_2 emissions could cut its emissions by at least 50%, thereby contributing to mitigating climate change. This will in turn benefit fish stocks and the marine ecosystem.

End Overfishing, Increase Fish Biomass and CO_2 Sequestration by Marine Life

Maintaining healthier fish stocks imbedded in a full functioning ocean ecosystem and habitat is important for planetary function—e.g., carbon storage, coastal protection/erosion. The role of the oceans in the regulation of the global carbon cycle is well known (Rogers et al., 2014). It is estimated that the ocean contains about 38,000 Gigatonnes (Gt) of carbon, and this is by far the largest reservoir of carbon in the Earth system (Houghton, 2007). Approximately 6,000 Gt of carbon also lies in marine sediments (Houghton, 2007). Estimates of the flux

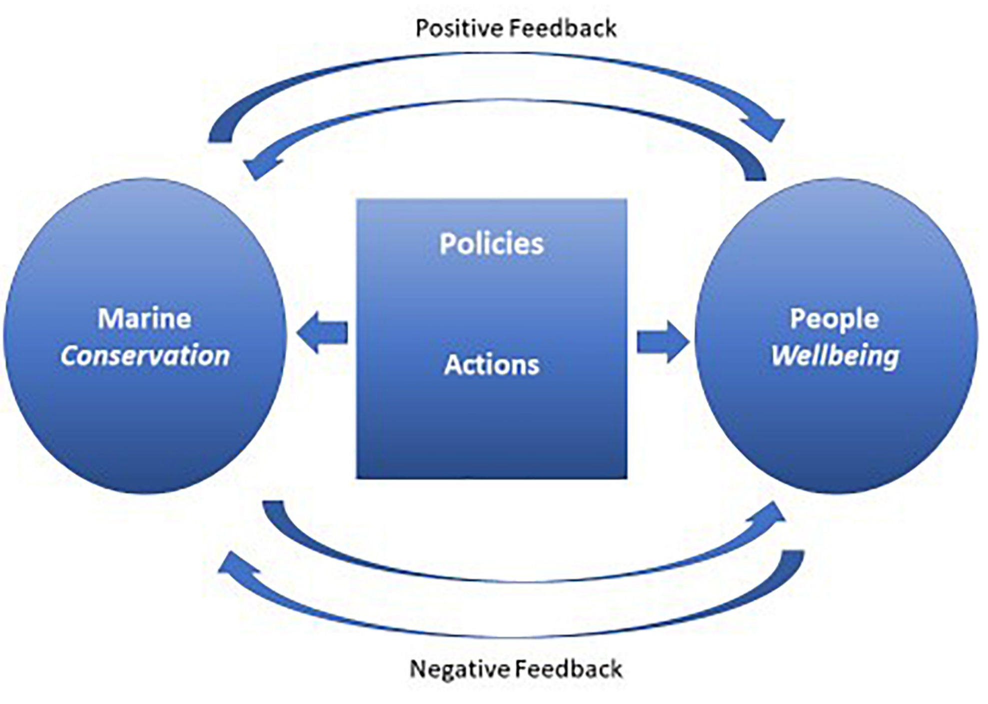

FIGURE 3 | Ending overfishing requires positive feedback between people and the ocean.

of carbon from the surface ocean to intermediate depths and the deep ocean vary but come from both vertical mixing and the sinking of organic primary production (Houghton, 2007). The oceans are thought to have been the only net sink of human CO_2 emissions over the last 200 years with terrestrial ecosystems likely to have been a net emitter (Sabine et al., 2004). By capturing and storing carbon that would otherwise enter the atmosphere and contribute to climate change (Rogers et al., 2014), healthy fish stocks and marine ecosystems can help to mitigate global warming, which in turn protects the ocean and makes marine life more resilient, in a cyclic positive feedback loop (**Figure 3**).

Climate change and overfishing are working together to accelerate the decline of ocean health putting marine ecosystems and the goods and services provided to society at risk. Ending overfishing would reduce the cumulative pressures on the ocean and increase its resilience, partly mitigating the effects of climate change. Current literature suggests that many possible mechanisms and solutions to adjust the current structure and narrative of fisheries to reduce the pressures on marine ecosystems as a mitigation tool against climate change (Cheung et al., 2017, 2018; Gaines et al., 2018; Gattuso et al., 2018).

Cheung et al. (2018) explored the extinction risk of overfishing and climate change using IUCN categories and species distribution models. The authors found very high extinction risk for 60% of assessed species with high emissions scenarios and no fisheries management change. With improved fisheries management and climate change mitigation the number of species with very high extinction risk is reduced by 63%. Gaines et al. (2018) set out to understand whether reducing overfishing through fisheries management reform will increase fisheries catch, even under high climate change. They found that despite the negative effects of climate change on fish stocks, reducing fishing effort to ensure MSY will result in gains in catch based on the current state of overfished stocks. Efforts to improve management and the health of fish stocks are best met with ocean solutions that combine global and local solutions, and prioritize fully comprehensive assessments that evaluate trade-offs, benefits

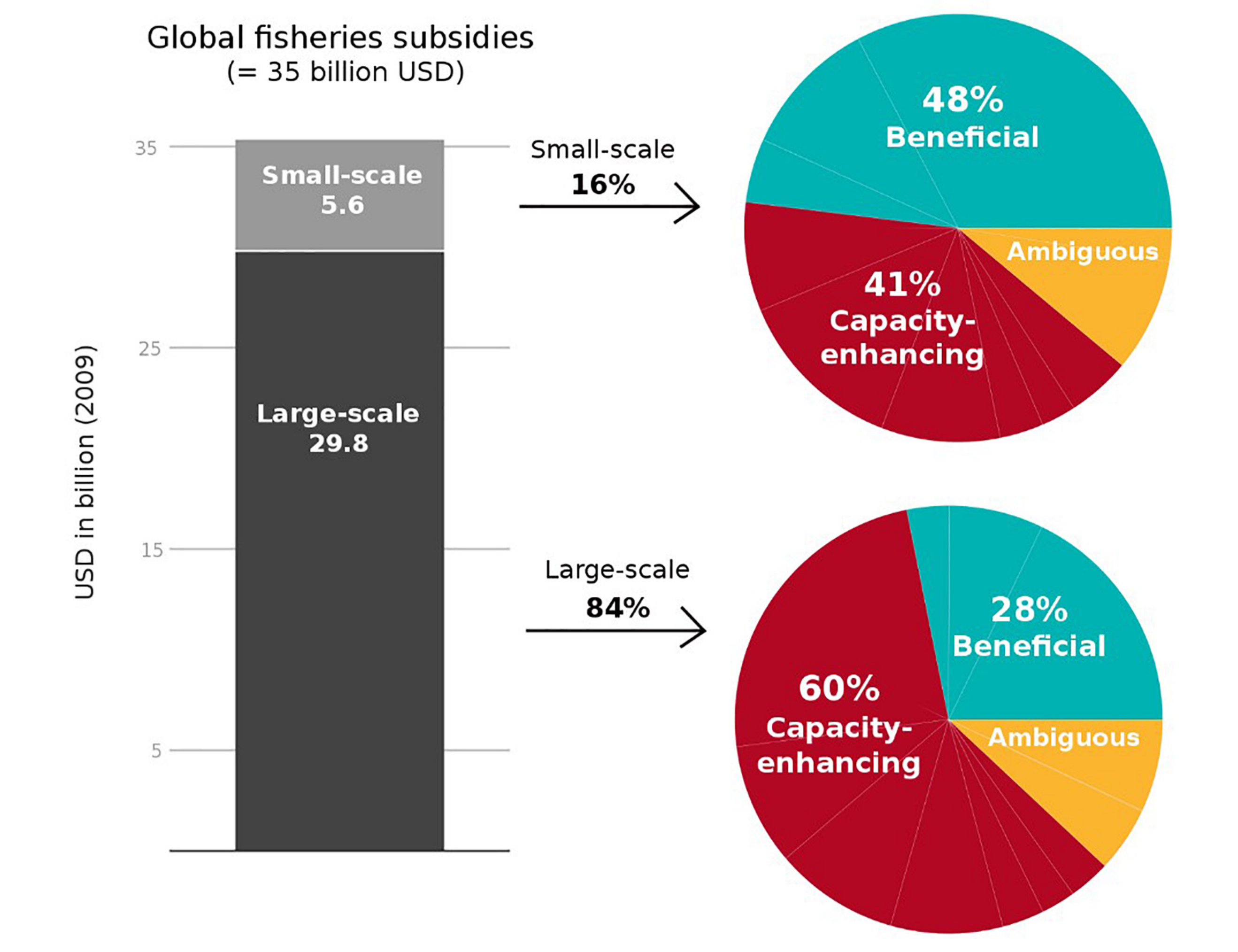

FIGURE 4 | Subsidies that stimulate overcapacity in large-scale industrial fisheries can lead to overfishing. Figure adopted from Schuhbauer et al. (2017).

and costs, and the effectiveness of management measures in consideration (Gattuso et al., 2018).

POLICIES AND ACTIONS TO END OVERFISHING

In general, people overfish because it pays to do so. Hence, the solution to overfishing is to remove the incentive to overfish by making it unprofitable to do so. The organizing framework we propose for ending overfishing is depicted in **Figure 3**. We assert that the key to successfully ending overfishing is to design policies and take actions that promote positive feedback while dampening negative feedback between people and the ocean. Our discussion of specific solutions is couched within this framework.

National, regional and global fisheries management is not anywhere close to fully effective (Pitcher et al., 2009). Ineffective management reinforces negative feedback from people to nature because our tendency to race for the fish is not managed effectively resulting in overfishing, which makes fish more scarce, aggravating the need to race for the fish even harder with time. While national management is important, regional and global management is also critical because many fish stocks are shared, transboundary, and highly migratory, straddling both EEZs and the high seas. A recent example of ineffective management was provided at last December's AGRIFISH Council in Brussels. This is an annual gathering where EU fishing quotas are allocated behind closed-door. At this particular meeting fisheries ministers agreed to quotas that were a whopping 300,000 t above scientific advice for the North East Atlantic in 2019. Such an action will not be taken in a well-managed fishery. Clearly, improving fisheries management by avoiding such actions would address current overfishing in many fisheries in the EU (and around the world).

Currently most fisheries subsidies are harmful in that they stimulate overcapacity and overfishing (Sumaila et al., 2019), which reinforces negative feedback from nature to people and vice versa. As fish stocks get depleted partly due to subsidies, the fish available to feed people diminishes making people more desperate to catch whatever they can—further aggravating the depletion and desperations. What is more, most of the subsidies provided to fishing sector go to large-scale industrial fisheries to the detriment of small-scale fishers (Schuhbauer et al., 2017; **Figure 4**).

Designating adequate and high quality marine protected areas is a viable and effective strategy for tackling overfishing, and also provides many ancillary benefits to ocean health. Marine reserves that prevent fishing activities can protect important habitat refuges for fish populations and reducing the probability of overfishing (e.g., Afonso et al., 2011). Furthermore, it protects habitats from destructive fishing gear (McLeod et al., 2009; Green et al., 2014), improving overall biodiversity and fisheries-related indicators of ocean health. Subsequently, marine reserves will improve other aspects of ocean health that directly address climate change mitigation (Roberts et al., 2017), specifically: carbon sequestration and storage by protecting critical habitat (e.g., reefs, seagrass beds, kelp); and reducing coastal erosion due to sea level rise by preserving safeguarding habitats.

CONCLUDING REMARKS

The combination of overfishing and climate change is deadly for fish stocks and marine ecosystems, and just like climate change mitigation will help the long term sustainability of the marine ecosystem. Ending overfishing would enable more effective conservation and sustainable use of marine fish and ecosystems, making it more resilient to climate change.

Reducing exploitation rates to end overfishing has been widely discussed as a viable climate change mitigation strategy. The MSY of fisheries is projected to generally decrease with climate change, yet some areas will face increases (i.e., temperate and polar regions) while others will see major declines (i.e., tropical regions) (Cheung et al., 2010). Despite the historical global spatial expansion of fisheries and its extensive footprint on marine ecosystems (Halpern et al., 2008; Swartz et al., 2010), current fisheries catch are estimated to be underperforming due to inefficiencies with management, regulation, and compliance. Due to the current inefficiencies and operating at below MSY, improvements in management to achieve MSY would not only increase long-term catch, but actually offset some of the negative effects of climate change on catch (Gaines et al., 2018). For overfished EU fish stocks, this could prove extremely valuable to increase catch by improving management as a climate change adaptation strategy.

Implementing policies, strategies and actions that reinforce positive feedback from people to nature and vice versa would help end overfishing, increasing resilience to climate change as it has been found to help with recovery from extreme climate impacts (O'Leary et al., 2017; Roberts et al., 2017). Therefore, ending overfishing will not only provide more seafood over time but it will also increase fish stock and ocean resilience by helping to reduce CO_2 in the atmosphere via the emission of less CO_2 by the fishing sector and sequestration of carbon in the deep ocean, strengthening the health and abundance of life in the ocean.

AUTHOR CONTRIBUTIONS

US conceived the manuscript. US and TT wrote the manuscript. Both authors contributed to the manuscript and approved the submitted version.

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Perceived Vulnerability and Climate Change Impacts on Small-Scale Fisheries in Davao Gulf, Philippines

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The small-scale fisheries play a critical role in food security and income of coastal fishing communities. However, climate variability and its impacts are affecting fishers, their communities, and fishing grounds. This study aimed to determine the perceived impacts of climate change and vulnerability of small-scale fisheries in selected fishing communities around the Davao Gulf. A semi-structured questionnaire was used to gather data on the perceptions of fishers (N = 220) on the impacts of climate change on their livelihood and communities. Seven focus groups corroborated the collected data and conclusions reached (N = 15). Principal component analysis (PCA) was used to reduce the sources of vulnerability and number of impacts of climate change. Regression was used to determine factors influencing the catch per unit effort (CPUE). The PCA results showed that for the vulnerability, the sources, coral bleaching, inadequate food, lack of credit access, changes in weather pattern and hotter temperature contributed highly. For the climate change impacts, the factors, less seasonality, unclear reproductive patterns, diseases in the catch, invasive species, decrease in catch and venturing farther to fish offshore were substantially influential. Further analysis showed that disease and invasive species, decrease in fish catch, fishing farther offshore, and monthly income affected the CPUE of the fisheries. Recommendations for climate change vulnerability reduction based on the conclusions reached in this study include more financial credit access, apprehension of illegal fishers, increased capacity building and technical skills for coastal communities, supplemental livelihoods, and information dissemination on climate change adaptation strategies.

Keywords: adaptation, climate change impacts, Davao Gulf, Mindanao, Philippines, small-scale fisheries, vulnerability

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INTRODUCTION

Climate change is projected to affect the distribution and abundances of several finfish species in the Philippines (Geronimo, 2018; Tan et al., 2018) and other species worldwide (IPBES, 2019). This gives high uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems (IPCC, 2014). Because of this, there is an urgent need to locally assess the vulnerability of the fisheries to climate change impacts. This was no less than recommended in the case of the Philippine fisheries in recent publications discussing climate change impacts in the Philippines (Sales, 2009;

Mamauag et al., 2013; Jacinto et al., 2015; Macusi et al., 2020) and economic modeling on impacts of climate change on marine capture fisheries (Suh and Pomeroy, 2020). The municipal fisheries of the Philippines mainly consist of small fishing boats that weigh less than three gross tons, manned by individual fishers or has a crew of two or three fishers. Fishers use a variety of fishing gears like fish traps, handline, small hook-and-line, longlines, multiple hook-and-lines, gillnets, liftnets and modified bagnets, and ringnets that land a decreasing volume of fish in Davao Gulf (Muallil et al., 2014a; Anticamara and Go, 2016). The municipal fisheries are very important for the food security and livelihood of the coastal fishing villages and the growing population of the country. It is also considered as a small-scale fisheries (Drury O'Neill et al., 2019). In 2018, the fishing industry contributed more than 16% (Php 122 billion; U$2.32 billion) to the agricultural sector and 1.3% to the GDP generating over Php 265 billion (U$5.03 billion) to the country's economy with its 4.35 million metric tons of production (BFAR, 2019). However, this economic contribution is now threatened by climate change impacts, marine pollution, overexploitation and declining fish catches as a result of negligence on fisheries management and human impacts to the environment (Nañola et al., 2011; Macusi et al., 2020; Onda et al., 2020; Suh and Pomeroy, 2020). Assessing the vulnerability of small-scale fisheries to climate change impacts will therefore provide an evidence-based policy decision making that can be formulated by members of the local, regional and national government. The recent Intergovernmental Panel on Climate Change (IPCC) report defines vulnerability to climate change as: "The propensity or predisposition to be adversely affected and vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014). According to this definition, the vulnerability of small-scale fisheries can be dependent on factors, or situations that could be exposing them to harm, and the presence of or lack of capacity to cope and adapt to these factors or situations. Given that the small-scale fisheries provide food and livelihood to fishers that are dependent on natural marine resources, they can be vulnerable to climatic variabilities. Previous studies have already demonstrated and analyzed the vulnerability of small-scale fisheries to climate change in developing countries and focused their assessment on fishing communities (Daw et al., 2009; Sales, 2009; Mamauag et al., 2013; Blair and Momtaz, 2018; Macusi et al., 2020). Some have provided insights on the vulnerability of the fisheries at a global scale (Allison et al., 2009), including making projections of catch redistribution under various climate change scenarios (Cheung et al., 2010), focused on environmental hazards namely flooding, rainfall and volcanism (Pati and Cruz, 2017; Cabrera and Lee, 2020; Yumul et al., 2011). Other studies delved on increasing frequency of floods, typhoons and warmer weather which were seen as evidence for the direct results of a changing climate with corresponding socioeconomic impacts (Cinco et al., 2016; de Lara-Tuprio et al., 2018).

In addition, there have been increasing concern over the consequences of climate change impacts to the fisheries sector and marine ecosystems (Brander, 2007; Perry et al., 2010). For instance, coastal and floodplain fisheries were subject to flooding and tsunamis while inland fisheries can be significantly affected by droughts and floods (Guerrero, 1999; Macusi et al., 2015a). Heavy unpredictable rains have been increasing in frequency and can increase nutrient inputs, affecting the oxygen levels of different water bodies (Vista et al., 2006; Macandog et al., 2014). Heavy rains through flooding can also introduce non-native species into new areas due to pond or reservoir overflow (Copp et al., 2007; Cunico and Vitule, 2014). Extreme climate events particularly high magnitude super-typhoons and increasing sea surface temperatures can impact productive coral reef ecosystems and the fish communities that depend on them (Eisner et al., 2008; Madin et al., 2012; Anticamara and Go, 2017). Due to a changing climate, typhoons have now become stronger in magnitude, longer in duration, more frequent in occurrence, and larger in scale (Faustino-Eslava et al., 2013; Lagmay et al., 2015). Their impacts on the goods and services provided by coral reefs, seagrass, and mangrove ecosystems are important to understand because the reduction of their abundance also affects fisheries productivity (Hoegh-Guldberg, 1999; Graham et al., 2007; Licuanan et al., 2019). Hence, by conducting vulnerability assessments in the different fisheries sectors, this can provide solutions in minimizing the impacts of climate change to ecosystem services provided by the marine ecosystem. Also, by identifying the linkages and evaluating the drivers of social and ecological vulnerability to climate change this could reduce climate change impacts on the fisheries sector (Kittinger et al., 2015; McClanahan et al., 2015; Macusi et al., 2020). Our study will first describe the current status of the fisheries, followed by perceptions of small-scale fishers in the Davao Gulf on the different sources of vulnerability and perceived fisheries impacts of climate change. From this collected data, we will explore the relationship between CPUE and vulnerability and impacts of climate change.

MATERIALS AND METHODS

Description of Study Area

The study was conducted in the small-scale fishing communities of Governor Generoso and Lupon in Davao Oriental, Malita, and Don Marcelino in Davao Occidental and in Davao City (**Figure 1**). The municipality of Governor Generoso has a population of 55,109 with a land area 365.75 km^2, and a poverty incidence of 34%. Lupon has a population of 65,785 with an area of 886.39 km^2, and a poverty incidence of 25%. The third study site is Malita in Davao Occidental, with a population of 117,746 with an area of 883.37 km^2. It has a poverty incidence of 57%. The fourth study site was Don Marcelino, Davao Occidental, with a population of 44,554 with an area of 407.30 km^2 and has a poverty incidence of 60%. The last site was Davao City, considered as a highly urbanized city with a population of 1.62 million and an area of 2443.61 km^2. It has a poverty incidence of 9%. The whole Davao region has an area of 20,357 km^2, and 20% of the population of the island of Mindanao resides in this area. Its weather and climate pattern are considered fair, with rain scattered throughout the year, although December to April are considered as generally drier months. The months of March and April are considered as the hottest and driest months.

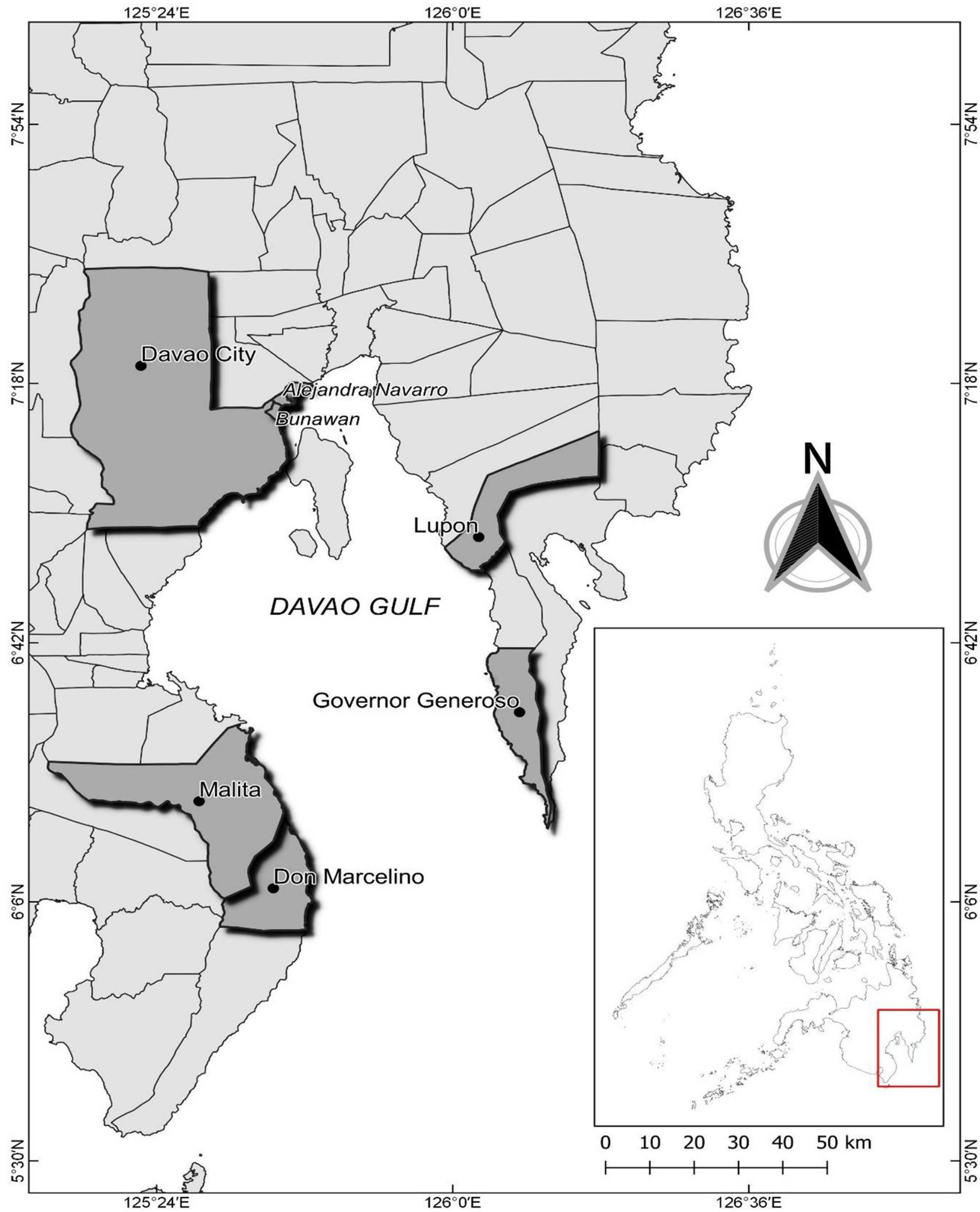

FIGURE 1 | Map of the coastal study sites (municipalities) in dark gray around the Davao gulf.

The fishing communities in the study sites are largely composed of small-scale municipal fishers. They own boats that weigh less than 3 tons and fish within the municipal waters (10–15 km from the shoreline). Common fishing gears used are small hooks and line, multiple handline, long line, gillnet, scoopnets, fishtraps, liftnets, squid jiggers, and spear fishing (Villanueva, 2018). Boats are commonly made of laminated marine plywood, 12 ft long, with bamboo stabilizers, and powered by a single motor engine of 7–10 HP. The Davao Gulf is located in the southeastern part of Mindanao island and is one of the most productive fishing zones in the country, hosting about 47,000 fishers. It ranks as a high priority conservation area because of its status as a biodiversity hotspot (Ambal et al., 2012). It is known as a breeding and nursery ground for small and large pelagic species mainly bigeye scad, roundscads, dolphinfish, rainbow runners, flying fish, moonfish, frigate tuna, skipjack tuna, yellowfin tuna, sardines, and anchovies. There are also frequent sightings of whale sharks, dugongs and leatherback turtles which are endangered species. Unfortunately, commercial developments in many coastal areas, particularly in Tagum, Panabo, Davao and Digos cities have contributed to increasing marine pollution in the gulf (Abreo et al., 2016a,b).

The Questionnaire

The semi-structured questionnaire interview targeted 30 respondents per fishing village in the five study sites. The thirty respondents per fishing village, although a limited number, was sufficient to represent the subject population in the area (Mason, 2010; Dworkin, 2012). We have conducted similar studies with fishers in the past taking this minimum number of 30 respondents per barangay and using it for quantitative analyses in our previous studies (Macusi et al., 2015a,b, 2019, 2020). With this number, we found that the data can already reach saturation and redundancy of responses during the interviews. The survey was conducted on various dates in January 2020 in Governor Generoso, Lupon, in Davao Oriental; Bunawan and Lasang in Davao City and Malita and Don Marcelino in Davao Occidental with small-scale fishers. There was a total of $N = 245$ respondents that were encoded but after inspection of the data, some entries were removed because these fishers were considered as commercial fishers. Commercial fishers in the Philippines use active fishing gears like purse seine, ringnet and bagnet and have boats that weigh more than 3 tons under government classification. Their gears are focused on catching non-reef fish species offshore. Fishers fitting their criteria were therefore not included (the total number of analyzed respondents was reduced to $N = 220$). The questionnaire used in this study is made up of several parts, a socio-demographic profile of the respondents, income levels, fishing characteristics, catch characteristics and their sources of vulnerability and management aspects (see Macusi et al., 2020). The main aspects of the demographic profile included age, number of years fishing, number of years staying in the community, household size, educational and income levels from different sources and on different months. For the fishing characteristics the information gathered included principal and alternative fishing gear used, boat types, boat power, boat ownership, travel time, average fishing time, total fishing costs, catch of fishers, and species composition. Various ecological, financial and social vulnerability aspects were assessed using yes or no questions pertaining to the main sources of vulnerability including coral bleaching, inadequate food, typhoons, generally hotter weather, flooding and sea-level change. To further understand management tactics, questions on government fisheries resource planning and other aspects of management were asked. The research was carried out by sampling small-scale fishers found at landing sites, at home or in their *barangays* (villages). The interviews were conducted by the researchers in Cebuano, the local language of the fishers, and lasted for 30 min per respondent.

Focus Group Discussion

Focus group discussion (FGD) was used to validate the data gathered from the semi-structured interview. There were seven focus groups that were conducted in the various study sites from February 12 to 13, 2020 in Bunawan and Lasang in Davao City, and from February 19 to 21, 2020 in Sta. Maria, Malita and Don Marcelino, and Lupon and Governor Generoso with average attendance of 15 individuals. The objective of the FGD was to further elicit answers on the present problems of the fisheries in the area, as well as their solutions to these problems. Questions on common impacts of climate change were also asked, and what adaptation practices had the fishers applied. Various stakeholders participated in the focus groups mainly from the women's association, fishers, barangay chairmen of the fisheries and farming associations, barangay captains, and some of the fish and farming produce vendors. We expected that the additional information from these stakeholders could provide further insights on climate change impacts and adaptation.

Data Analysis

After quantitative and qualitative data were compiled using Microsoft Excel (2016), factors were encoded in order to organize and review the data. To compare the sociodemographic characteristics of the respondents, data was summarized into statistical components and frequency tables. The different indicators of vulnerability (eight factors) such as ecological e.g., coral bleaching, social e.g., inadequate food, financial e.g., lack of credit source for livelihood (money to be used for a fishing operation i.e., fuel, bait, food, replacement of damaged fishing gear); natural disasters e.g., typhoons, flooding, sea level change, changing weather patterns and generally hotter temperatures were coded as 0 or 1 for negative and positive responses in order to be processed for statistical analysis. The impacts of climate change to the fisheries (nine factors), included, less seasonality (inconsistent seasonal changes for instance monsoon winds), changes in species distribution (spatial distribution within Davao Gulf) and reproductive patterns (this refers to the spawning of fish and its gravid stages which has been observed by fishers first hand through their catches, the processing of products, and consumption), and species composition (various species caught by the fishers), vessel gear replacement, diseases of the catch, increased number of invasive species, decrease in catch, and venturing farther offshore to catch fish etc. The same data coding was done for the impacts of climate change to the fisheries. These different indicators of vulnerability and climate change impacts to the fisheries were surveyed, whether they have experienced or observed such impacts to be happening in their environment or in their livelihoods. The data was analyzed using principal component analysis (PCA) and three factors were identified from each of the sources of vulnerability and impacts of climate change to the fisheries. These factors were summarized in table form and their factor loadings and variance were explained in the results. The extracted scores from the PCA was used for regression analysis together with the other fisheries variables that were selected. All PCA analyses for the vulnerability and climate change impacts were done using SPSS version 21 (IBM, Armonk, New York).

Only the following quantitative fisheries data, household size, age, number of years in the community, number of years fishing, boat power, price value, monthly income, and fishing costs (costs of fuel, food, bait, and ice) were included in the final analysis. The fisheries data collected from the interviews have values that were similar to the previous study in Mati (Davao Oriental) and Cantilan (Surigao del Sur) (Macusi et al., 2020). The values of a normal daily catch was 6 and 7 kg/trip, and fish price of Php 133 ($2.77) and Php 147 ($3.06) were comparable to the catches found in the previous study of 5.3 kg/trip and fish price of

Php 90 ($1.87), consistent with decreases in decadal catch when compared to previous studies (Muallil et al., 2014a,b).

In this study, the catch per unit effort (CPUE) was computed based on a day's normal (average) catch and the average number of hours of a fishing trip. Since CPUE was calculated in this manner, revenue was not included in the final computation as this would have increased the possibility for multicollinearity in the regression analysis. The number of fishing hours was not also included in the regression since this was already used as effort data for the computation of the CPUE). Only the following data were included in the multiple regression analysis: age of fisher, boat power (HP), fishing cost (Php), price of fish (Php), income of fisher (Php), and the six derived variables from the PCA scores. The derived variables were renamed as weathertemp, foodaccesscredit, coralbleach, speciescompodist, decatcshore, and seasonrep. Normality was checked using plotted graphs for the catch data and probability plots (pplots) for the CPUE prior to conducting multiple linear regression analysis. If data output was not normally distributed then a $\log_{10}$ transformation was applied to sustain a normal distribution and homogeneous response variable. Analyses were performed using Minitab version 17.0 (State College, Pennsylvania, United States). Qualitative data coming from the FGD were organized and coded into themes based on the issues highlighted and their frequencies of mention.

RESULTS

Fishers' Characteristics

Based on the survey, fishers have an average age of 45 years and ranged from 18 to 73 years old. Their mean household size was five, and ranged from 1 to 13 individuals including young children. Fishers lived in their communities for an average of 33 years, staying anywhere between 1 and 69 years. They also have an average fishing experience of 24 years that ranged from 1 to 64 years. Their boats are powered by 8 HP engines, normally spending 7 h per fishing trip. In addition, the cost of fishing mainly came from fuel expenses during travel to the fishing ground and cost an average of Php 372 (U$7.75) per fishing trip although it can go as high as Php 1,735 (U$36.15). The average price of fish was Php 148 (U$3.08) and could go from Php 40 to Php 300. Fish catch was divided into worst, normal, and best catches. The worst reported catch was 3 kg and ranged from 0.7 to 15 kg while the normal catch was 7 kg and ranged from 0.3 to 30 kg. On the other hand, the best catch was 20 kg and ranged from 3 to 220 kg. On a per day basis, fishers obtained an average revenue of Php 958 which could range from Php 75 (U$1.56) to Php 5,400 (U$113). While their income per month could average Php 5,359 (U$111.64) and ranged from Php 500 (U$10.42) to Php 15,000 (U$313). The sociodemographic characteristics of fishers and descriptions of criteria were summarized in **Table 1**.

Fishers' Perception of Climate Change

When statements concerning climate change (shown in **Table 2**), were presented to the fishers, most of them replied that they have observed a change in weather patterns and increase in sea-level rise due to higher frequency and intensity (87%). This was followed by an increased prevalence of typhoons (86%) that bring flooding and destruction. A generally hotter temperature (83%) was also observed. This was perceived as an impact especially during summer months and less frequent during the onset of the rainy season. In contrast, flooding (76%) is considered unpredictable when there is sudden prolonged rain even in the summer. The lack of credit access (59%) also affects the fishers because they need financial assistance for vessel and gear replacement as well as for starting capital during fishing days. When the onset of rainy days or typhoons occur, some could not fish causing them to experience inadequate food (45%). Only 41% of the respondents mentioned observing destruction and bleaching of coral reefs.

Fishers' Perception on Climate Change Impacts to the Fisheries

The majority of fishers observed that their usual catch has decreased (94%) as a recognized impact of climate change (**Table 3**). This was the main reason why many fishers tend to venture farther offshore (88%) in order to catch

TABLE 1 | Sociodemographic profile of the respondents including a brief description.

Factors	Description of the factors	Mean (S.E.)	Min	Max
Household size	The number of individual household numbers including children	4.67 (0.14)	1	13
Age	Age of fisher interviewed	44.86 (0.89)	18	73
No. of years fishing	The number of years that the fisherman consider as his fishing years	24.46 (0.95)	1	64
No. of years in the community	Number of years in the community	33.22 (1.07)	1	69
Boat power (HP)	Boat engine power in horse power	7.78 (0.30)	0	22
Hours fishing per trip	Number of hours that the fisher normally fishes and returns to port	7.29 (0.56)	1	48
Fishing cost (Php)	Amount of money spent by fisher to operate on a daily basis in the fishing ground	372.45 (24.04)	0.00	1,735.00
Fish price value (Php/kg)	The average cost of a fish	147.78 (3.09)	40.00	300.00
Worst catch (kg)	The minimum catch of a fisher on a fishing trip	3.37 (0.20)	0.17	15
Normal catch (kg)	The usual catch of a fisher	6.76 (0.35)	0.30	30
Best catch (kg)	The maximum catch possible by a fisher on a fishing trip	19.88 (1.57)	3	220
Revenue (Php)	The average cost of a fish and the weight of a fish catch	957.93 (51.07)	75.00	5,400.00
CPUE/hr	Catch of the fisher per fishing trip	3.10 (0.31)	0.07	30
Income (Php)	Monthly income of the fisher	5359.07 (213.26)	500.00	15,0000.00

more fish. They have also observed less seasonality (78%) in their target species which includes moonfish (*Mene maculata*), bigeye scad (*Selar crumenopthalmus*), mackerel scad (*Decapterus macarellus*), shortfin scad (*Decapterus macrosoma*), island mackerel (*Rastrelliger faughni*), *short mackerel* (*Rastrelliger brachysoma*), Indian mackerel (*Rastrelliger kanagurta*), yellowfin tuna (*Thunnus albacares*), skipjack tuna (*Katsuwonus pelamis*), bullet tuna (*Auxis rochei*), frigate tuna (*Auxis thazard*), golden trevally (*Gnathanodon speciosus*), common dolphinfish (*Coryphaena hippurus*), spotfin flyingfish (*Cheilopogon furcatus*), and rainbow runner (*Elagatis bipinnulata*) (Macusi et al., 2017a; Villanueva, 2018). Whenever typhoons affect the Davao Gulf, the fishers use that free time to repair worn-out fishing gears and vessels (69%). According to their narratives, there have been changes in reproductive patterns (64%), distribution patterns (52%), and species composition (48%). There was also an increased number of invasive species (27%) and diseased fish in the catches (22%), though this was less frequently mentioned in comparison to other factors.

Vulnerability and Climate Change Impacts

PCA reduced the eight different sources of vulnerability factors and identified three components that mainly indicated change in weather, inadequate food, and ecological destruction. The analysis mainly points to hotter temperature noticed in the area (0.889) as indicated by weather changes (0.846). The next most significant component was the lack of opportunities for fishers to gain access to government banks or other microfinance institutions (0.827) which results in inadequate food (0.819). It is difficult to fish without a starting capital for fuel, bait and food costs. Lastly, the bleaching of corals (0.913) is an observation that is somehow clear to fishers and results in the destruction of fish habitat (**Table 4**). These components summarize the main sources of vulnerability in the surveyed areas as a warmer environment (1) and explains 36% of the variance of data in component 1; followed by lack of financial stability (2) that explains 18% of the variance of data in component 2; and, ecological destruction (3) that explains 14% of the variance of the data in component 3. Hotter temperature can affect coral reefs which leads to bleaching that can cause death in reef fish in the area. Changes in weather patterns can cause illness e.g., cold and/or cough to fishers and which may prevent them from fishing, leading to inadequate food. The lack of credit access can restrict purchasing ability for fishers preventing them from fishing which can also result in inadequate food for fishing families.

Another three components were extracted from the PCA of the nine factors of direct impact of climate change on fisheries listed in **Table 5**, invasive species (0.884) and diseases in the catch (0.860) both contribute highly and positively to component 1 and they explained data variance by 33%. Subsequently, less seasonality (0.902) and species reproductive pattern (0.842) explain the variation of the data by 25%. While the third component was greatly affected by venturing farther to catch fish (0.907) and the decrease in catch (0.837) that explains the variation in the data by 18% (see **Table 5**).

Relationships Between CPUE, Vulnerability and Climate Change Impacts

Further analysis was conducted using the factor scores from the different variables of various sources of vulnerability (hotter temperature, lack of credit and coral bleaching) and climate change impacts (invasive species, less seasonality and venturing farther to catch fish). Factor scores of these variables, other fisheries factors selected, and the calculated CPUE based on the self-reported normal catch per fishing trip were further analyzed using multiple regression analysis. The results were highly significant (df = 3, MS = 3.47, F = 12.84, p < 0.001; see **Table 6**). One fisheries variable, monthly income (df = 1, MS = 1.92, F = 7.08, p = 0.009); two variables from climate

TABLE 2 | Perceived changes in the climate.

Perceived changes	Frequency	Percentage
Coral bleaching	91	41.4
Inadequate food	99	45.0
Lack of credit access	129	58.6
Flooding	167	75.9
Generally hotter temperature	182	82.7
Typhoons	190	86.4
Changing weather patterns	191	86.8
Sea level change	191	86.8

TABLE 3 | Perceived impacts to fishers.

Perceived fisheries impacts	Frequency	Percentage
Increased in disease among the catch	49	22.3
Increased in invasive species	60	27.3
Changes in species composition	106	48.2
Changes in distribution patterns	115	52.3
Changes in reproductive patterns	141	64.1
Vessel/gear replacement due to storm events	152	69.1
Less seasonality	171	77.7
Venturing farther to catch fish	194	88.2
Decrease in catch	207	94.1

TABLE 4 | Factors loadings of the PCA results of variables related to climate change vulnerability (numbers in bold contribute highly and positively to a component).

Sources of vulnerability	Component		
	1	2	3
Coral bleaching	0.013	–0.050	**0.913**
Inadequate food	–0.095	**0.819**	–0.276
Lack of credit	0.031	**0.827**	0.207
Typhoons	0.748	0.099	0.174
Flooding	0.757	0.169	–0.174
Sea level change	0.474	–0.121	–0.308
Changes in weather pattern	**0.846**	–0.188	0.057
Hotter temperature	**0.889**	–0.116	0.005
% Variance explained	36.15	18.30	13.58

TABLE 5 | Factors loadings of the PCA result of the various variables related to climate change impacts (numbers in bold contribute highly and positively to a component).

Impacts of climate change	Component		
	1	2	3
Less seasonality	0.051	**0.902**	0.160
Species distribution pattern	0.636	0.545	–0.001
Species reproductive pattern	0.170	**0.842**	0.088
Species composition	0.643	0.538	0.134
Gear replacement	0.754	0.004	0.122
Diseases in the catch	**0.860**	0.172	0.050
Invasive species	**0.884**	0.092	–0.010
Decrease in catch	0.059	0.276	**0.837**
Venturing farther to catch	0.077	–0.012	**0.907**
% Variance explained	32.8	24.7	17.7

TABLE 6 | Results of the regression between the dependent variable (cpue) and various predictor variables.

Source	df	MS	*F*	*P*
Regression	3	3.47	12.84	0.000
Disease and invasive species in catch	1	1.68	6.2	0.014
Decrease in catch and farther offshore	1	7.06	26.07	0.000
Monthly income	1	1.92	7.08	0.009
Error	155	42.01	0.271	
Total	158	52.44		

change impacts to the fisheries, diseases in the catch and invasive species ($df = 1$, $MS = 1.68$, $F = 6.2$, $p = 0.014$) and decrease in catch and venturing farther offshore to catch fish ($df = 1$, $MS = 7.06$, $F = 26.07$, $p < 0.001$) were found to highly influence the dependent variable (CPUE).

The CPUE was then modeled together with other fisheries factors based on the survey data shown in **Figure 2**. The results showed that age and the number of years fishing, did not predict higher CPUEs as they are similar to the CPUEs of fishers in the age brackets of 25–30. Those who were 33–60 years of age did seem to have higher CPUEs compared to other age brackets (see **Figure 2A**). For the number of years fishing, those with experience of 15–32 years in fishing showed higher CPUE than the other groups (**Figure 2B**). Those with 7–10 HP boats can have similar CPUEs as those with 16–20 HP, although having 16–20 HP is more advantageous because they can travel farther and catch more (**Figure 2C**). The number of fishing hours showed that fishing for 6–12 h could be sufficient. Going longer did not necessarily predict higher CPUEs but a declining one instead (**Figure 2D**). Most of the revenues (**Figure 2E**) of the catches averaged Php 2,000 (U$42) per fishing trip while fishing costs (**Figure 2F**) averaged Php 750 (U$15.63). Corresponding with climate change impact perceptions on diseases in the catch, invasive species and the decrease in fish catch result in fishers having to venture farther, to be profitable in their fishing livelihoods.

TABLE 7 | Summary of perceived climate change impacts (FGD).

A. Fishers and fishing communities
Health risks such as coughs, colds, fever
Age determines whether or not a fisher can tolerate harsh weather
Weather can be too hot; summer season is hotter compared to previous years
Unpredictability of weather
Fish prices rising due to lack of fish supply
More frequent bad weather days have been observed
Strong winds generate big waves as observed during a bad weather
Typhoons can damage boats and fishing materials
Typhoons do not allow fishers to go fishing resulting to less income for the family
Because of the scarcity of fish in nearshores, fishers are forced to go farther offshore
Fishers may disappear and become missing due to typhoons
B. To fishes
Hot weather forces fish to go deeper into the sea, resulting to lower fish catch
Fishes are more difficult to find because of warmer water
Sometimes fishes also die due to warmer water
Fishes swim with undersea currents
Decline in fish population
During times of flooding the waters are muddy which affects fishing
The emergence of factories, banana plantations caused fish to decline

Focus Groups Results on Climate Change Impacts to Fish, Fishers, and the Fisheries

There were two main climate change impacts mentioned by the participants and this was with regards to fishers and fisheries, and to the fish. For example, the participants have mentioned on the dimension of health, their age and the weather which seems to be getting hotter, and unpredictable making them prone to sickness. During bad weather days, since fishers cannot get out to fish, local market vendors take advantage and increase the fish prices. According to the fishers, typhoons have also been increasing in areas that it affects, including Mindanao which was rarely being hit in the past. Whenever it passes by, it can generate big waves, erode beaches and damage boats and houses. In terms of direct impacts to fish, a hotter weather, according to the fishers can force fishes to dive and stay deeper, resulting to lower fish catch. They are also more difficult to find due to the warmer water. There are instances that fish die also because of warmer water. During times of flooding the murky water also makes it difficult for fishers to catch a fish, including the perceived waste residues coming from banana plantations. All of these, the hotter weather, the pesticides, coral die offs or bleaching are perceived by fishers to be contributing to their catch decline (**Table 7**).

Threats and Vulnerability of Small-Scale Fisheries

Results of the focus groups conducted in the various fishing communities around the Davao gulf have indicated a decreasing catch highly affected by climate change variabilities. The identified threats mentioned that affect the local fisheries include: illegal fishing (compressor, poison, and triple/double net fishing gear, trammel net, with fine-meshed nets having less than 3 cm of mesh size), intrusion of commercial fishers (boats > 3 t) into municipal waters, agricultural wastes and pesticide residues coming from nearby banana plantations in the coastal area. It is highly likely that compressor fishers who capture large

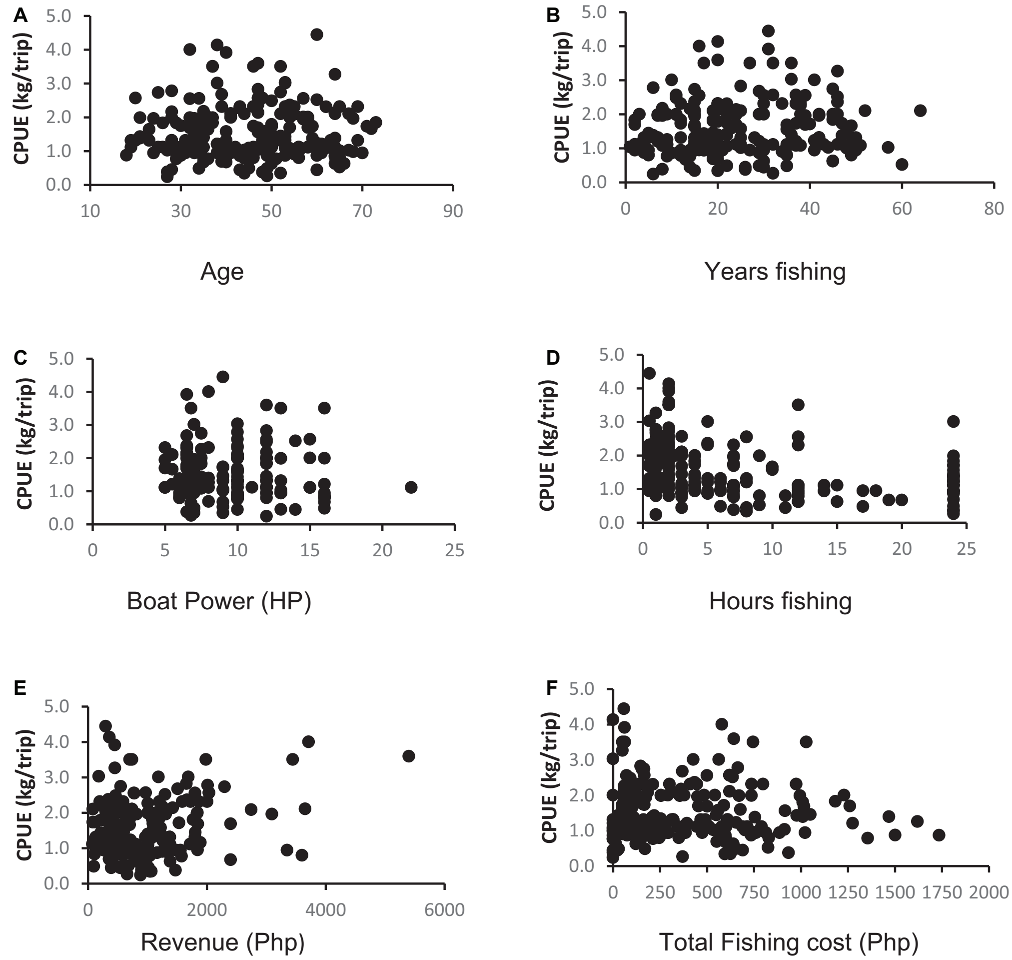

FIGURE 2 | CPUE per trip based on the regression model and the modeled data from the survey. The age and number of years of fishing show that the data is bell-shaped, thick at the center and tapered at both ends **(A,B)** with ages between 40 and 60 showing that they can have higher cpues while the number of years fishing show that longer fishing experience may not matter. While for the boat power and the number of hours fishing **(C,D)** a horse power of 6 can get as much as those on 12 and 16 and fishing longer hours do not yield more fish. The revenue and fishing costs are skewed to the left, showing that most of the trips yield on average a revenue of Php 1,000.00 at an average fishing cost of Php 400.00 **(E,F)**.

bodied fish found in coral reef areas contribute to coral reef fish catch decline. Some of the illegal fishers also make use of a plant-based poison and cyanide to stun the fish and then scoop them afterward. Commercial fishers are also known to harvest 200–1,000 kg/trip, leaving the smaller fishers with less catch. Most of the identified community vulnerability by the participants are experiences of hotter summers, coral reef bleaching, seagrass die off, sea-level change (beach erosions), typhoons, flooding and decline in fish catch (see **Figures 3**, **4**). Whenever typhoons pass by, advisories are given to fishers to not go fishing, however, some difficult fishers persist and drowning or persons missing are not uncommon to be reported.

Problems Mentioned and Adaptation Strategies by Small-Scale Fishers

Most of the issues and problems mentioned by key informants during the focus groups revolved around how their nearby environment, living areas, and livelihoods have been impacted (**Figure 4**). For instance, problems concerning land reclamation focused on the construction of jetties and coastal defense structures that have been completed without prior consultation with local fishers and residents in Lupon, Bunawan and Lasang, and Malita. Industrial wastes were also reported by participants to be a common problem in Bunawan and Lasang which was compounded by flooding events caused by extended rainfall or typhoons. The lack of financial access to most small-scale fishers was also a problem for their start-up capital for fishing. Easy access to loans were not available for most of them. For their adaptation strategies, respondents suggested crop production, gleaning, alternative livelihoods through cacao, coconut, banana, corn, and vegetable production were suggested. During bad weather days, short-term labor contracts on construction and repair activities were sought by the participants, including boat building. There was

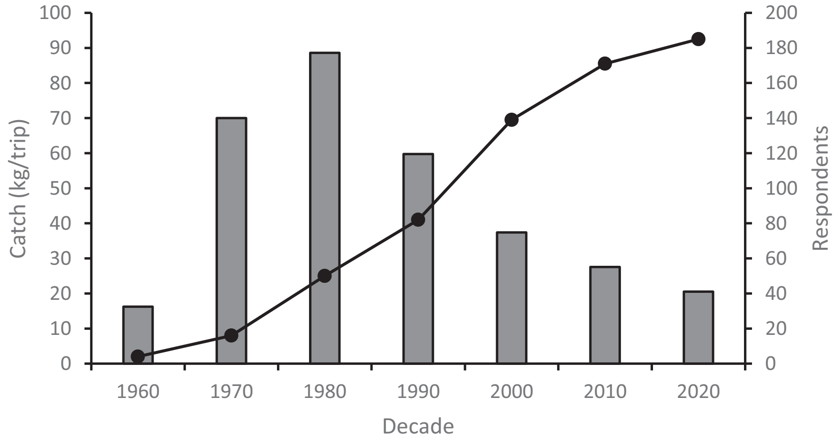

FIGURE 3 | Decadal catch of the fishers based on the survey with the number of respondents on the secondary *y*-axis (*N* = 220).

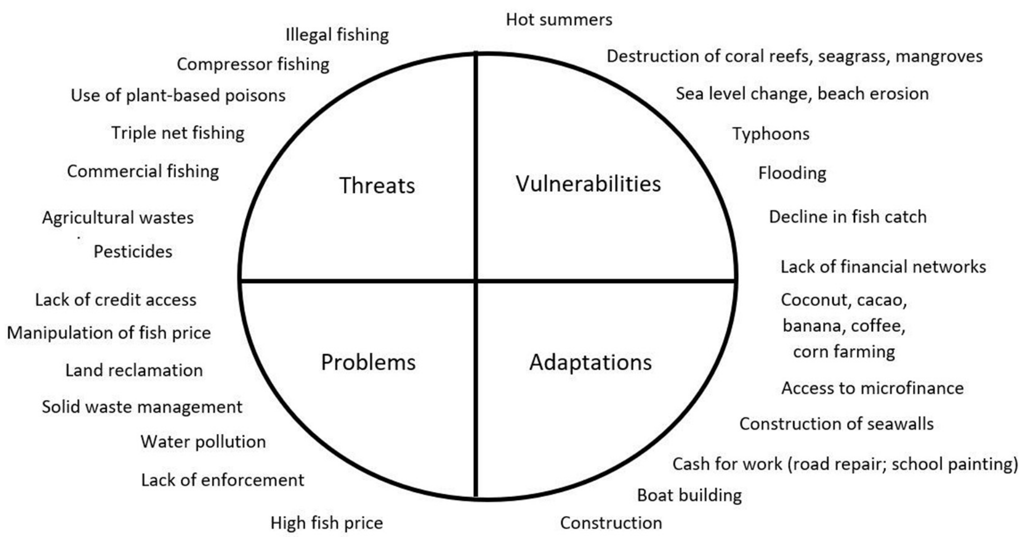

FIGURE 4 | Perceived threats, vulnerabilities, problems and adaptation strategies of fishers to climate change (based on FGD).

also a suggestion asking for easier access to financial capital which would be beneficial to most of their fishing and post-fishing activities.

DISCUSSION

Results from the survey has shown that fishers were aging (>45 years old), while others were aged 70 and still fishing. Those 60 years old and above are some of the most physically vulnerable in their livelihood as they have less stamina to endure when fishing. With fishers growing older over the next decade and fewer young men entering the fisheries, it is possible that this might have an impact on the food security of the nation (Macusi et al., 2020). This was similar to the findings in the rice farming sector in the Philippines, with farmers growing older (53 years old) and less younger farmers replacing them as reported by Palis (2020). The shortage of labor in the fisheries could result to decreased fish supply, higher market fish food prices and eventually resulting to importing fish food instead of catching them (Israel and Briones, 2012; Foale et al., 2013). Despite the taxing labor and hard work that many fishers endure daily, fisheries together with the farming sector remain the lowest paid in the agriculture sector. With low revenue for fishers, this creates a domino effect of several other socioeconomic consequences including low economic standing, non-existent social welfare or pension systems for fishers, and poor health and living standards for their families (Béné, 2009; Muallil et al., 2013). This has caused one fisher from Lupon to describe their struggle as a daily grind, *"we have to borrow money from informal lenders and financiers so that we can go and fish daily. We need money to buy gasoline and to buy our daily needs. Our stomachs are* *intertwined with them, as a result."* With restricted financial access to credit, this compounds their problems as there are many fishers with insufficient food, clothing and shelter. This effect deters fishers from passing the same type of livelihood to their children (Béné, 2009; Muallil et al., 2011; Katikiro et al., 2015). *"During my return to the port, I need to sell off my catch in order to pay my debts, bought at a low price by the same financier I owed money earlier,"* added another fisher from Governor Generoso.

Apart from their being vulnerable financially, socially, ecologically, and being constantly exposed to natural disasters, small-scale fishers also face problems with the intrusion of commercial fishers (boats > 3 *t*) into their fishing grounds (Pomeroy et al., 2007). This may keep the small-scale fishers from getting a bigger share in catches as one ringnet fishing boat can catch as much as 1,000 kg (Muallil et al., 2014b; Macusi, 2017). In another instance of illegal fishing, a fisher from Governor Generoso quipped, *"the local government is doing nothing when it comes to penalizing illegal fishers, so we are also left with nothing when it comes to fish catches."* Although this could be exaggerated, the claims of lack of law enforcement tend to be frequent. In the worst situations, some fishers relied on using plant-based poisons (locally called *lagtang*) to stun and weaken the fish and then to catch. Since these were not being addressed properly one fisher admitted that they have resigned to their fates, *"our local government lack courage in confronting commercial fishers because they are being paid with money to remain silent."*

Some of the study sites have marine protected areas (MPA) established in partnership with the local community, as a way to conserve fish stocks but they lack fish wardens (*bantay dagat*). An example of this includes an MPA from Bunawan and Lasang (Davao City) which according to key informants during the focus group discussion need fish wardens for vigilance and apprehend illegal fishers. One of them narrated, *"how can we keep protecting this MPA when our lives are put in danger after apprehending some of the illegal fishers. Some of these compressor fishers have guns, they also have financiers as their protectors."* Their cases are also settled by some barangay officials that sentence, with no charges. This is an issue that can cause vulnerability to fishers' livelihoods, including the intrusion of commercial fishers to municipal waters (Horigue et al., 2014). By having weak law enforcement, this can endanger the lives of willing and cooperative fishers who want to implement conservation initiatives in their area (Cabral et al., 2013). Other issues mentioned are land reclamation projects in private ports of companies. These companies buy coastal lands for the purpose of having a warehouse, but eventually extend these by reclaiming their adjacent coastal sites, eventually destroying the coastal habitats of juvenile fish. Plastic and chemical wastes are also dumped in coastal areas despite regular coastal clean-up drives and activities. Some of which may contain chemical pesticides used by banana farms and industrial wastes left by factories. If left unchecked, this may lead to increasing marine pollution in Bunawan and Lasang.

Climate change impacts can manifest at multiple spatial scales in coastal fishing communities. These are usually in the form of invasive species, disease among the catch, changes in fish distribution patterns, including reproductive patterns, less seasonality, decrease in catch and venturing farther offshore. The sources of vulnerability as perceived by fishers were varied: floods from rising sea levels, unpredictable rainfall, experience of hotter weather, loss of coral reefs, seagrass cover, inadequate food and lack of credit access. Inevitably, these factors can lead to various socioeconomic problems from job loss to damaged fishing gears and destroyed or flooded houses affecting the fishers and their communities. To help resolve these issues, the development of effective policies that can confront climate change impacts in small-scale fisheries are needed (Sales, 2009; Mamauag et al., 2013). The solution can start by addressing the catch decline due to a combination of reasons previously mentioned by the respondents, one fishery at a time which was done in the sardine fishery in Zamboanga Peninsula (Brillo et al., 2019). Then the ecological component can be addressed, which includes spatial management and strict implementation of marine protected areas (MPAs), coastal zonation and building community partnerships by empowering locals to manage their resources (Horigue et al., 2015; Katikiro et al., 2015). MPAs will continue to be useful as they provide a clearly defined geographical space managed by communities or the government dedicated toward long-term conservation of marine and fisheries resources (Cabral et al., 2014). Admittedly, to mitigate climate change impacts with economic and ecological effects there need to be development assistance in protecting fishers' well-being, prioritizing alternative livelihoods, technical skills trainings and increasing value to their fisheries products to enhance their resilience to external shocks (Islam et al., 2020; Suh and Pomeroy, 2020). This would be in addition to the on-going work of conservation of coral reefs, seagrass, mangroves and coastal wetlands which are known to protect coastal communities during extreme events (McClanahan et al., 2008; Lee et al., 2014; Sun and Carson, 2020). Some recommendations based on the outcome of our study are to make financial credit widely available to fishers and provide technical trainings, and seminars regarding climate change impacts, conduct of vulnerability assessments for local governments directly involved in managing the fisheries as well as promote income diversification through alternative livelihoods. The fisherfolk may need to be trained on fish processing, packaging and marketing their fisheries products. Suitable livelihoods easily identifiable and culturally appropriate for the fishers should be encouraged by local government to promote income diversification. In addition, better enforcement of fisheries laws by the government can be facilitate through fisher's active participation through reporting illegal fishing activities. Finally, wider and more inclusive dissemination of information regarding climate change impacts, and strategies for adaptation must be prioritized by research and government bodies.

CONCLUSION

Globally, small-scale fisheries are affected by the combined impacts of overfishing, degradation of ecosystems and climate change impacts (Cinner et al., 2012; Daw et al., 2012). Conclusions from the surveyed fishers indicated that many coastal communities in Davao Gulf are already experiencing various levels of climate change impacts. The perceptions of ecological change such as unpredictable weather, less seasonality, coral bleaching, changes in spawning seasons and their socioeconomic impacts as perceived by fishers can assist the local governments in formulating policies that will increase their resilience against climate change impacts. Apart from the 3 months of closed fishing season, a comprehensive conservation strategy is also lacking in the Davao Gulf. This perception survey may not be equivalent to a quantitative and predictive approach that use decadal observations based on catch log sheets and other environmental parameters but in a data-poor fisheries, the use of surveys allows insight into the status of marine resource (Silvano and Begossi, 2010). Due to data scarcity, the conventional methods of fish stock assessment are also not easily available for many tropical areas, species and multiple gear fisheries which impedes on further research and collaboration in fisheries management and climate change impacts.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants, in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

EDM helped in the conceptualization, conduct, analysis, and writing of the study. KC helped in the conceptualization, data gathering, analysis, and writing. AB and ESM helped in the data gathering, analysis, and writing of the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.597385/full#supplementary-material

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Impact of Ocean Warming, Overfishing and Mercury on European Fisheries: A Risk Assessment and Policy Solution Framework

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Previous studies have shown that multiple-environmental stressors are expected to have significant and geographically differential impacts on the health and abundance of marine species. In this paper, we analyze the combined impacts of ocean warming, overfishing and mercury pollution in European waters by projecting the impacts of climatic and non-climate drivers on marine species in European waters. Our findings suggest that the impacts vary widely depending on different species and their mean temperature tolerance (MTT). We find for instance, that more than 5 temperate benthopelagic species including, bobtail squids (*Sepiida)* frogfishes (*Lophius)* great Atlantic scallop (*Pecten maximus)* red mullet (*Mullus barbatus barbatus)* and common octopus (*Octopus vulgaris)* are affected (i.e., weakens their resilience to climate change) by the increase in sea surface temperature (SST) under RCP 8.5 in 2050 and 2100. Mercury contamination was estimated to increase in some species (e.g., ∼50% in swordfish), exceeding mercury consumption guideline thresholds (>1 mg/kg). This negative impact may limit the capacity of fisheries and marine ecosystem to respond to the current climate induced pollution sensitivity. An implication of our study is that the international community should strengthen a global ban on mercury emissions under the mandate of the Minamata Convention, comparable to the United Nations framework for persistent organic pollutant emission sources. Ongoing global efforts aimed at minimizing carbon footprint and mercury emissions need to be enhanced in concert with a reduction in fishing intensity to maintain effective conservation measures that promote increased resilience of fisheries to climate change and other stressors.

Keywords: Europeans waters, climate change, overfishing, pollution, mercury

INTRODUCTION

Marine ecosystems and biodiversity provide important and valuable goods and services such as food, amenity benefits, tourism, and carbon sink, but a myriad of anthropogenic activities have also altered and are changing the biogeochemistry and biophysics of the oceans, affecting marine species through direct and indirect impacts (Lotze et al., 2006; McCauley et al., 2015; Halpern et al., 2019). In most parts of the world, overfishing, anthropogenic climate change and pollution are already having quantifiable effects on the marine ecosystem, and their implications for the future are of great concern. As stated by the Intergovernmental Panel on Climate Change (IPCC), human influence on the climate system is clear, and anthropogenic carbon dioxide (CO_2) emissions have impacted on the marine environment at unprecedented levels (IPCC, 2014, 2018, 2021).

Particularly, the ocean, the marine species biodiversity it holds and the fisheries they sustain are facing many threats, e.g., ocean pollution by chemical assaults [e.g., plastics, persistent organic pollutants (POPs), and mercury (methyl-mercury, MeHg)]; (e.g., Alava et al., 2017a, 2018; Schartup et al., 2019; Issifu and Sumaila, 2020; National Academies of Sciences, Engineering, and Medicine, 2021), global climate change (Noone et al., 2013; IPCC, 2018, 2021), and overfishing (Pauly et al., 1998, 2005; Rogers and Laffoley, 2011; Sumaila et al., 2011; McCauley et al., 2015). Researchers have observed that the interaction of most of these stressors in the ocean is damaging the health of marine wildlife, and reducing fisheries quality and quantity (McCauley et al., 2015; Alava et al., 2017a; Halpern et al., 2019; Schartup et al., 2019).

There have been some decades of individual studies on climate change events, pollution, and overfishing. However, it is only recently that linkages and combined impacts of these previously dispersed anthropogenic stressors are being established to holistically adapt to risk management in fisheries (Booth and Zeller, 2005; Noone et al., 2013; Schartup et al., 2019). For example, the ongoing Nippon Foundation-Nexus Program,[1] and Stockholm Resilience Center[2] aspire to address some of the challenges of ocean health (Leape et al., 2021).

This study offers conceptual framework and assess the weight of evidence of overfishing, marine pollution and climate change interactions. We argue that reducing pollution and overfishing is also climate actions. Therefore, the overarching goal of this paper includes: (1) review the combined impacts of multiple stressors on European fisheries; (2) examine the interactive impacts of multiple anthropogenic stressors (i.e., overfishing, climate change and ocean pollution) on fisheries; (3) investigate top fish species in the European waters that are vulnerable to the onslaught of climatic and non-climate stressors; (4) explore management policy options to address the impacts of climate change, overfishing and pollution on marine ecosystems.

Overfishing and Fisheries Decline

The expansion of fisheries and overfishing inflict changes in the community structure and fish size because of selective harvesting of target species and bycatch of non-target species, as well as via habitat modification, triggering changes in the biomass, species composition and size structure (Pauly et al., 1998; Bianchi et al., 2000; Jennings and Blanchard, 2004). According to FAO (2012), 87% of global fish stocks are either overexploited or fully exploited. The status of other species, such as brown shrimp is uncertain, while others are classified as underexploited (e.g., yellowfin tuna, *Tunnus albacares*). Recent estimates indicate that between 40 and 70% of fish stocks in European waters are currently at an unsustainable level—either overfished or at their lower biomass limits (Dulvy et al., 2003; Sumaila and Tai, 2020). European stock assessments report that the current size and capacity of the European Union (EU) fleet is estimated to be 2–3 times above the sustainable level in a number of fisheries (European Commission, 2008). Several offshore fisheries capture species in European waters are classified as fully exploited; e.g., herring, Norway lobster, mackerel, and horse mackerel (STECF, 2017).

Illegal fishing targeting tuna and other tuna fish species in West Africa (Sumaila, 2018; EJF, 2020) and the eastern tropical Pacific (Alava et al., 2015, 2017b; Martínez-Ortiz et al., 2015; Alava and Paladines, 2017), are exported to EU markets (Ministerio de Comercio Exterior, 2017; EJF, 2020; Monnier et al., 2020). On average, for example, the value of exports canned tuna and tuna loins from Ecuador to the EU over the 2007–2016 period accounted for 343 million USD and 124 million USD, respectively (Ministerio de Comercio Exterior, 2017). While the EU strictly regulates and supervises certified fish products and exports from fisheries overseas to mitigate and prevent illegal, unreported and unregulated (IUU) fishing, questions linger as to whether illegally harvested tuna exports are reaching the EU fish market chains.

It is important to note that this sobering statistic only considers individual stocks that are deemed commercially valuable and does not consider the amount of environmental degradation and ecosystem destruction that accompanies overfishing. The FAO also estimates that "oceans are cleared at twice the rate of forests" (FAO, 2009). Overfishing can be defined as fishing down marine food web (Pauly et al., 1998, 2005) or depleting populations due to excessive fishing mortality and defaunation (McCauley et al., 2015; Baum and Fuller, 2016). To put the deleterious impact of excessive fishing into perspective, the European hake (*Merluccius merluccius*) stocks are among the fish species under more intense overfishing, with fishing mortality rates up to 10 times higher than the optimal target (STECF, 2017). Overfishing pose one of the greatest threats to ocean health (Pauly et al., 1998, 2005; McCauley et al., 2015). Apart from depleting populations (STECF, 2017), overfishing can erode the age and size structure and spatial distribution of stocks making populations more susceptible to environmental fluctuations. This is particularly relevant for highly impacted areas and vulnerable species (e.g., elasmobranchs). Overfishing of top predators and pelagic resources has also been associated with trophic cascades and ecosystem regime shifts in the Black Sea (Daskalov et al., 2017). A combination of climate-related stresses and widespread over-exploitation of fisheries reduces the scope for adaptation and increases risks of stock collapse (Allison et al., 2009). Overfishing makes marine fisheries production more vulnerable to ocean warming by compromising the resilience of many marine species to climate change, and continued warming will hinder efforts to rebuild overfished populations (Free et al., 2019). It can also exacerbate the mercury levels in some fish species. For instance, recent studies show that Pacific salmon, squid and forage fish, as well as Atlantic bluefin tuna and Atlantic cod and other fish species are susceptible to increases in methylmercury (MeHg) due to overfishing (Schartup et al., 2019) and rising ocean temperatures (Alava et al., 2018). Overfishing

[1] https://earthlab.uw.edu/members-and-affiliates/climate-impacts-group/

[2] https://www.stockholmresilience.org/publications.html

weakens the resilience of fish stocks and marine ecosystems to climate change (Sumaila and Tai, 2020), and has even been identified as one of the greatest threats to ocean health (Pauly et al., 2005; Halpern et al., 2015; Gattuso et al., 2018). Indeed, after the collapse of northern cod stocks in Canada due to overfishing, Newfoundland and other Canadian coastal areas changed to shellfish, shrimp and crab which dominates the industry today. This transition is known as fishing down the food web and is usually the result of unsustainable fishing practices (Pauly et al., 1998).

Overfishing is linked directly to multiple destructive fishing practices such as trawling, IUU fishing, bycatch, and harmful subsidies (Sumaila et al., 2006, 2021; Agnew et al., 2009; Moomaw and Blankenship, 2014). Continued use of destructive fishing practices such as bottom trawling, which has an impact on both targeted and non-targeted species and damages ocean sea floors, may lead to overfishing. In addition to this, overfishing often correlates with large amounts of bycatch as increased effort is translated directly into unintentionally catching non-targeted species which harms marine ecosystem. Also, harmful subsidies encourage overfishing by supporting fleets that are over capacity in terms of number of ships, effort and technology (Schuhbauer et al., 2017; Sumaila et al., 2021).

Climate Change Impacts on Marine Ecosystems

In the near future, climate-driven phenomenon including deoxygenation and ocean acidification, are likely to have a growing effect on the productivity of global fisheries. Recent studies have observed fundamental changes to ocean biogeochemistry, including rising sea surface and bottom temperatures, changes in primary production, reduced pH, decreased subsurface oxygen levels (i.e., hypoxia) in coastal waters (Bindoff et al., 2019). Most of these anthropogenic disturbances are linked to fossil fuel emissions and fertilizer use, which is expected to increase in the years to come, placing further pressures on marine ecosystem (Doney, 2010).

Globally, rising sea temperature will likely shift the location, distribution and abundance of marine fisheries. In fact, Cheung et al. (2010) demonstrated that fisheries in some regions stand to gain from climate change ("winners"), while others stand to lose ("losers"). Their study estimates that the average catch potential in high-latitude regions will increase by 30–70% by 2055, benefiting countries such as Norway, Greenland, and Russia. On the other hand, average catch potential in the tropics is projected to drop by 40% by 2055, resulting in substantial losses for countries such as Indonesia, Chile, and China (Cheung et al., 2010). In effect, shifts in species distributions can create incentives for overharvest. For example, a country that is losing a fishery due to climate change may overfish the target species to compensate for the anticipated loss.

In addition to rising temperatures, rising atmospheric CO_2 levels pose a major threat to the ocean and fisheries resources. In general, alterations to ocean chemistry hinders the ability of a wide range of marine organisms such as corals, mollusks, and some plankton to grow and maintain external calcium carbonate skeletons (Orr et al., 2005). As a result, declining fisheries harvests are expected once ocean chemistry moves outside the present range of natural variability, which is expected to occur as early as 2025 in some regions of the Southern Pacific (Cooley et al., 2012). Already, high-trophic level large pelagic species such as salmon, tunas, billfish, and sharks, as well as the mid-trophic level small pelagic species such as sardines, anchovies, and squids are particularly sensitive to climate impacts (Chavez et al., 2003; Cheung et al., 2013).

In the European shelf seas, the impacts of climate change on fisheries have been noted for several important commercial species, notably nephrops, mussels, oysters, and lobster (e.g., Styf et al., 2013; Ostle et al., 2016). Fernandes et al. (2017) quantified the potential effects of ocean warming and acidification on fisheries catches, resulting revenues and employment in the United Kingdom of Great Britain and Northern Ireland under different greenhouse gas emission scenarios. Standing stock biomasses were projected to decrease significantly by 2050 and the main driver of this decrease was rising sea surface temperature (SST). The European waters account for about 14 and 15 percent of global carbon sink and fishing intensity, respectively (Cavan and Hill, 2020). In effect, losses in revenue were estimated to range between 1 and 21 percent in the short-term (2020–2050). For Europe as a whole, the annual impact was estimated to be over 1 billion USD by 2100 although subject to considerable uncertainty. **Figure 1** shows that European seas are the most fished with the highest carbon sink.

Chemical and Biological Pollutants Impact on Marine Ecosystem

The proliferation of chemical pollutants (e.g., POPs, mercury) has become a prominent environmental issue in recent years, as growing evidence draws attention to its negative impacts on marine fisheries and food webs under the impact of climate change (Booth and Zeller, 2005; Alava et al., 2017a, 2018; Schartup et al., 2019). While evidence suggests that large amounts of emerging anthropogenic pollutants such as ocean macroplastics and microplastics (Eriksen et al., 2014; Jambeck et al., 2015; Lebreton et al., 2018; Alava, 2019; Issifu and Sumaila, 2020) are accumulating in the deep sea (Rochman et al., 2014; Choy et al., 2019; Kane et al., 2020), mercury concentrations in the North Pacific Ocean are predicted to double by 2050 (Sunderland et al., 2009). Small-scale gold mining, coal and fossil fuel burning and industrial emissions are the major contributors of mercury into oceans (Mason and Sheu, 2002; European Environment Agency, 2018). The global spread of mercury and other industrial pollutants is of immediate concern, as these pollutants bioaccumulate in the tissues of marine organisms and are passed up the food chain, posing a serious threat to human health. Additionally, methylation of mercury to form MeHg has been found to increase when temperatures rise (Johnson et al., 2016). The effect of these perturbations on global fisheries is only projected to grow as industrial activity and fertilizer use increases over the next two decades (Doney, 2010).

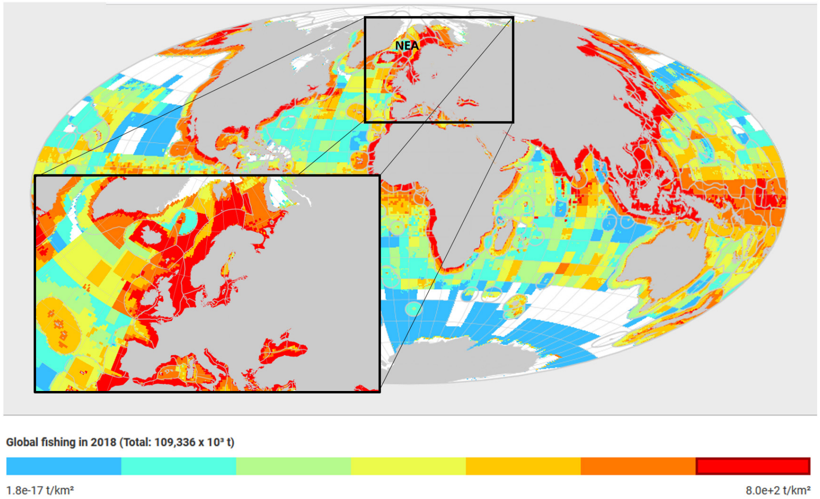

FIGURE 1 | European shelfregion (black rectangle) has one of the highest global fishing and catch areas and carbon sink intensity, especially the Northeast Atlantic (NEA). The NEA area is one of the highest-ranking areas, for both carbon sink and fishing intensity and responsible for about 14 and 15% of global carbon sink and global fishing effort, respectively (see Cavan and Hill, 2020). Map retrieved and modified from the Sea Around Us database (https://www.seaaroundus.org/data/#/spatial-catch; Pauly et al., 2020).

In the European waters, pollution is particularly important in the Black Sea, where the ecosystem has undergone different phases of eutrophication caused by increased input of nutrients, intensive farming and the use of agrochemicals and phosphate detergents. It is also noteworthy that the Black Sea and particularly the Mediterranean are hotspots for plastic and mercury pollution. Fishes absorb contaminants directly from the water and sediment and indirectly through food web transport. Higher concentration of mercury on several important commercial fish species such as anglerfish, common sole, striped mullet, swordfish, mackerel, and cod have been documented (Storelli and Marcotrigiano, 2001). Though mercury concentrations vary widely by species and ocean. There are varying health impacts associated with mercury pollution in different fish species, but the primary consequence is lower reproductive success such as decreased spawning and increased embryo mortality leading to reduced reproductive success (Sandheinrich and Wiener, 2011), increased vulnerability due to reproductive and neurological problems, which can lead to behavioral abnormalities (Dawson, 1982). In addition, elevated mercury levels have altered hormone profiles, indicating that the mercury is also affecting the health of the fish themselves (National Wildlife Federation, 2006), as well as the hatching times and the survival rates of offspring (Bridges et al., 2016) and ultimately death since fishes' inability to survive extremely high levels of mercury (Matta et al., 2001). In effect, mercury pollution should be considered a stressor that reduces the resilience of fish assemblages to climate changes.

Fish consumption is known to have beneficial effects on human health due to its nutrients—the presence of long-chain, poly-unsaturated fatty acids (LC-PUFAs). For instance, provide protection against diseases such as coronary heart diseases, high blood pressure (Oomen et al., 2000; Miles and Calder, 2012; Rangel-Huerta et al., 2012). On the other hand, fish is the main dietary source of methylmercury for all age groups in Europe, given that many of the most popular species such as the hake, swordfish, whiting and cod are among those with the highest levels of mercury (EFSA, 2015). Substantial amount of methylmercury from the consumption of fish can have an effect on the nervous system, cardiovascular, immune and reproductive systems (Carta et al., 2003; Yokoo et al., 2003; Stern, 2005; Oken et al., 2008; Houston, 2011). Sandborgh-Englund et al. (1998) found that children exposed to mercury in the prenatal period had defects in attention, language, memory, and motor function. Children born in countries with high fish consumption, such as Portugal and Spain, received most exposure to methylmercury (Science for Environment Policy, 2017). Višnjevec et al. (2013) carried out a comprehensive Europe-based review of exposure to mercury, looking at studies published since 2000 and found out that the highest exposure to mercury was in coastal populations, due to their higher consumption of fish compared to inland residents.

MATERIALS AND METHODS

Fish like all living organisms exhibits a temperature range within which they thrive. There are a number of approaches available for measuring the distribution of temperature for fish species. Here we calculated the temperature tolerance index (TTI), by using the average temperature preference range of our selected fish species. We estimated the percentage change in SST, as well as the bottom temperature in the 2050s/2100s under different climate change scenarios, using the Representative Concentrations Pathways (RCPs): RCP 2.6 (i.e., low CO_2 emission/high mitigation scenario) and RCP8.5 (high CO_2 emissions or business-as-usual). Data for SST and bottom temperature for RCP 2.6 and RCP 8.5 covers all European Exclusive Economic Zones (EEZs) and were retrieved from the NOAA's Geophysical Fluid Dynamics Laboratory Earth System Model 2M (GFDL ESM2M; Dunne et al., 2012). We included 38 EEZs of 27 European countries in the European FAO region as presented in **Supplementary Material**.

To estimate TTI, the following three equations were derived. We expressed the mean temperature preference (MTP) for each species as follow

$$MTP_i = \frac{(T_{MAX} + T_{MIN})}{2} \quad (1)$$

where T_{MAX} and T_{MIN} are maximum and minimum temperatures within the temperature preference range of each species *i*, respectively.

We estimated the change in temperature within the distribution range of each species using the following equation:

$$\triangle T = \frac{(SST_{2050} - SST_{current})}{SST_{current}} \quad (2)$$

Let $\triangle T$ denotes the change in temperature within the distribution range for each fish species, SST_{2050} represents the SST in the year 2050 under RCP 2.6 or RCP 8.5, while $SST_{currents}$ stands for the prevailing SST. We assume each species is living within its SST preference under the current status. The corresponding calculations were also done for 2100.

Finally, we calculated the *TTI* using mean temperature preference range (MTP) for species under each climate change scenario (i.e., RCP 2.6 and RCP 8.5) along with TMAX the upper limit temperature for a given fish species.

$$TTI = \frac{(MTP + MTP * \triangle T)}{T_{MAX}} \quad (3)$$

Based on Equation (3), we can check whether the projected change in temperature will exceed the highest temperature range of fish species or otherwise. The corresponding calculations were also done for 2100. We can infer whether the projected change in temperature will exceed the highest temperature range of fish species or otherwise. We assume that if the estimated (TTI) $>$ 1, then the species cannot tolerate exposure and is affected by ocean warming due to climate change; if the estimated (TTI) = 1, no exposure to thermal stress or eco-physiological health effect. On the other hand, if (TTI) $<$ 1, the projected SST is still within the temperature preference range of the species, which implies the species can still tolerate extreme SST anomalies and survive under climate change.

In an effort to capture the exposure risk to SST under climate change forcing (RCP 2.6 or RCP 8.5), a pragmatic ecotoxicological risk index to calculate the TTI_{ER} was also applied, using the mean temperature tolerance (MTT), as follows:

$$TTI_{ER} = SST_{CC}/MTT \quad (4)$$

Where, TTI_{ER} *denotes* ecotoxicological risk index to estimate the TTI, SST_{CC} is a term to express the overall average of SST to reflect the climate change forcing based on SST predictions for RCP 2.6 (i.e., $SST_{RCP2.6}$) and RCP 8.5 ($SST_{RCP8.5}$) by 2050 and 2100, respectively. A major advantage of using MTT is that it captures the distribution of the temperatures (means and variability/SD) of a given species of fish in terms of the metabolic scope (e.g., oxygen consumption influenced by ambient sea surface or bottom temperature) and affected by changes in temperatures, i.e., ocean warming (Cheung et al., 2013).

The outcomes resulting from Equation (3) were also correlated against the MTT to explore the relationship between TTI_{ER} and MTT.

Fisheries of the Europeans Waters

The EU represents the largest single market for fish and fish products in the world. **Table 1** provides the breakdown of the top 20 taxa with the highest annual catch (tons) and landed values (USD) taken from the European waters by EU countries from 2007 to 2016. In 2015, the EU fishing fleet comprised of 63,976 active vessels, of which 74% were classified as small-scale coastal vessels, 25% as large-scale and remaining 1%, distant-water vessels. These EU fleets spent 4.8 million days at sea and consumed 2.3 billion liters of fuel to land over 5 million tons of seafood with a reported value of €7 billion (STECF, 2017). The EU fishing fleet operate in major sea basin including: North Sea and Eastern Arctic, Baltic Sea, North East Atlantic, Mediterranean and Black Sea, as well as fleets operating in other fishing regions, such as the Northwest Atlantic (STECF, 2017).

In terms of volume of catches, Atlantic herring was the most important species by annual catch (233 thousand tons), followed by European pilchard (188 thousand tons), Blue whiting (134 thousand tons) and European anchovy (117 thousand tons) as shown in **Table 1**. In terms of annual landed values, landings of European hake generated the most value (358USD million), followed by Norway lobster (281USD million), European anchovy (276 USD million), and Common sole (263 USD million).

Temporal Levels of Mercury in Fisheries From European Waters

Within the group of the top 20 marine taxa (**Table 1** above) with the highest annual average landed values taken from the European waters by EU countries from 2007 to 2016, 99% of all fishes had mercury concentrations below the U.S. EPA human health criteria of 0.30 mg/kg wet weight (ww) (**Table 2**). This group of low mercury commercial fishes includes several commercially important marine species of European hake (*Merluccius merluccius*) and Great Atlantic scallop (*Pecten maximus*). Other notable low-mercury fish within this group of commercial fishes includes the Common shrimp (*Crangon crangon*), a widely distributed and commonly consumed fish across the North Sea and Eastern Arctic region (STECF, 2017). Swordfish (*Xiphias gladius*) from the Mediterranean also had elevated mercury concentrations (0.995 $\pm$ 0.539 mg/kg). In general, mercury levels are the lowest in smaller, mid-trophic or intermediate level pelagic species such as anchovies and always below (European Commission, 2002; World Health Organization and Food and Agriculture Organization of the United Nations, 2010) general guideline level of 0.5 and 1.0 mg/kg ww, respectively. Conversely, highest mercury concentrations were found in large high-trophic level pelagic species such as swordfish.

Based on Schartup et al. (2019), we estimated the increase in mercury concentration (ppm) by assuming the percent increase in concentrations predicted (i.e., mercury concentration increasing from > 30 to 50% at a temperature increase of 1°C under warming conditions) in fish species from the North Atlantic (e.g., Atlantic cod, Bluefin tuna) based on the data reported by Schartup et al. (2019), as follows:

$$[Hg\ concentration\ increase] = [Hg\ concentration] \times [\%\ Hg\ increase\ factor] \quad (1)$$

$$\left[Hg\ concentration\right] + \left[\ Hg\ concentration\ increase\right] \quad (2)$$

TABLE 1 | List of top 20 fish species by average annual catch (tons) and landed values (USD) taken from European waters by EU countries between 2007 and 2016.

Rank	Scientific name	Common name	Annual catch (tons)	Landed values (USD)
1	*Merluccius merluccius*	European hake	91,242	358,546,692
2	*Nephrops norvegicus*	Norway lobster	20,879	281,785,055
3	*Engraulis encrasicolus*	European anchovy	117,844	276,528,622
4	*Solea solea*	Common sole	15,288	263,993,935
5	*Gadus morhua*	Atlantic cod	67,938	244,583,633
6	*Dicentrarchus labrax*	European seabass	12,923	205,003,300
7	*Sardina pilchardus*	European pilchard	188,343	202,114,344
8	*Octopus vulgaris*	Common octopus	31,170	187,774,015
9	*Xiphias gladius*	Swordfish	17,540	157,200,153
10	*Crangon crangon*	Common shrimp	38,010	153,737,030
11	*Sparus aurata*	Gilthead seabream	10,414	132,940,834
12	*Scomber scombrus*	Atlantic mackerel	79,373	131,031,651
13	*Scophthalmus maximus*	Turbot	9,254	130,088,378
14	*Micromesistius poutassou*	Blue whiting	134,004	128,560,998
15	*Clupea harengus*	Atlantic herring	233,313	126,329,803
16	*Lophius*	Frogfishes	17,168	122,232,795
17	*Pecten maximus*	Great Atlantic scallop	29,994	119,150,365
18	*Mullus barbatus barbatus*	Red mullet	14,583	119,086,099
19	*Lithognathus mormyrus*	Sand steenbras	10,515	114,790,901
20	*Sepiida*	Cuttlefishes, bobtail squids	9,911	105,587,156

The annual catch of marine fisheries from 2007 to 2016 was obtained from SAU database.

Understanding average concentrations of mercury in fish and fish products by EU and WHO can help reduce mercury intake by consumers, including vulnerable populations like infants and young children as well as pregnant and breastfeeding mothers. Following fish-consumption advisories attributed to mercury (European Commission, 2002; U.S. EPA, 2002; World Health Organization and Food and Agriculture Organization of the United Nations, 2010) can help consumers make informed choices when choosing fish and fish products that are nutritious and safe to eat.

We assumed a conservative increase of 50% used for all pelagic fish (i.e., small and large pelagic fish); and for demersal or bottom fish an increase of 33% was used, based on the mercury concentration increase for Atlantic Cod reported in Schartup et al. (2019). We observed that mercury concentrations in our 20 fish species (except the predatory sword fish) were all below the established general fish consumption threshold by the EU (i.e., 0.5 mg/kg, 1.0 mg/kg predatory fish), U.S. EPA (i.e., 0.30 mg/kg, ww), and World Health Organization (WHO) (i.e., 0.50 mg/kg, ww).

Conceptual Framework

In this study, we encountered a rich knowledge base about climate change via ocean warming, overfishing and pollution and its effects on European fisheries. We constructed the conceptual framework following the approaches of Alava et al. (2017a, 2018), Bindoff et al. (2019), and Schartup et al. (2019), in order to display the coherences of the interactions of climate change and environmental stressors to assess their impacts on fisheries. **Figure 2** illustrates the interactions of climate change, overfishing and pollutants on marine fisheries and food webs.

RESULTS AND DISCUSSION

Trends reported in **Table 2** indicate that organisms with the highest mercury concentration are swordfish (1.495 mg/kg), followed by European seabass (0.25 mg/kg) and Atlantic herring (0.135 mg/kg). Comparing these trends with World Health Organization (WHO) and European Commission (EC) limits, the mercury levels are the lowest in smaller, short-lived fish and always below (European Commission, 2002; World Health Organization and Food and Agriculture Organization of the United Nations, 2010) general guideline level of 0.5 and 1.0 mg/kg ww, respectively (European Commission, 2002; World Health Organization and Food and Agriculture Organization of the United Nations, 2010). Conversely, highest mercury concentrations were found in large, long-lived species such as swordfish.

The average temperature of surface waters of European continental shelf areas such as the southern North Sea has experienced one of the greatest warming rates (Levitus et al., 2009; González-Taboada and Anadón, 2012). We explored the impacts of climate change including SST and bottom water temperature on future fisheries resilience. **Figure 3** illustrates the relationship of the estimated TTI for all fish species assessed vs. the species-specific MTT under the strong mitigation scenario

TABLE 2 | Results from the preliminary analysis of mercury levels in commercial fish and shellfish species in European waters.

Common name	Mean ± SD Mercury (mg/kg ww)	Fraction	Increase in mercury concentration (mg/kg ww)	
			[Hg concentration] × [% Hg increase factor]	[Hg concentration] + [Hg concentration increase]
European hake	0.08 ± 0.06	0.32	0.03	0.10
Norway lobster	0.11 ± 0.08	0.30	0.00	0.11
European anchovy	0.02 ± 0.02	0.30	0.01	0.02
Atlantic cod	0.11 ± 0.15	0.32	0.04	0.15
European seabass	0.15 ± 0.20	0.32	0.05	0.20
Swordfish	0.99 ± 0.54	0.50	0.50	1.49
Common shrimp	0.01 ± 0.01	0.50	0.01	0.01
Atlantic mackerel	0.05 ± 0.00	0.52	0.03	0.08
Blue whiting	0.05 ± 0.03	0.32	0.02	0.07
Atlantic herring	0.08 ± 0.13	0.50	0.04	0.13
Great Atlantic scallop	0.00 ± 0.01	0.32	0.01	0.01
Red mullet	0.05 ± 0.08	0.32	0.02	0.07
Cuttlefishes, bobtail squids	0.02 ± 0.02	0.51	0.01	0.03
Min		0.30	0.00	0.01
Max		0.50	0.50	1.49

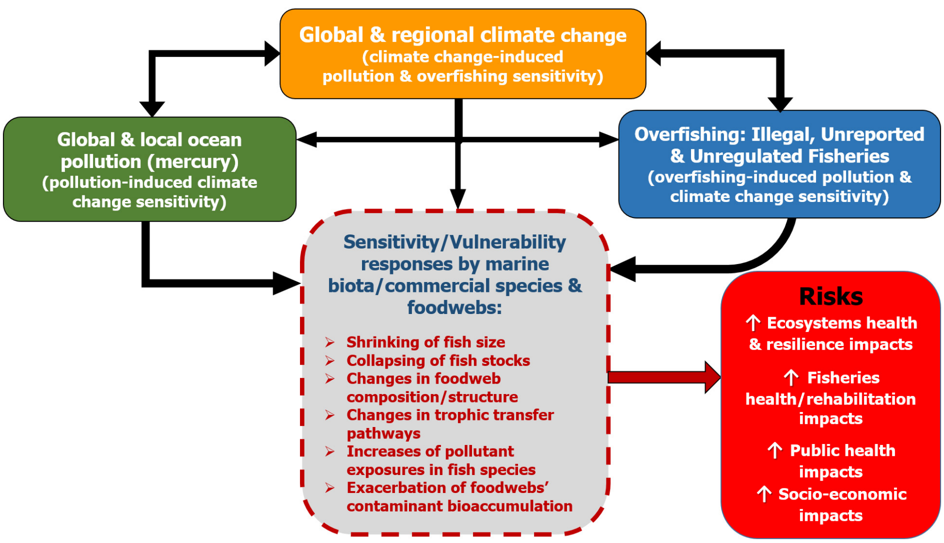

FIGURE 2 | Climate change-overfishing-pollution assessment framework. The pathways through which scenario of climatic, overfishing and pollutants hazards (orange, blue, and green boxes, respectively) and their interactions can lead to increases in exposure to hazards by the biota, ecosystems and people sensitivity (dashed gray box) and the risk of impacts to ecosystem and human health and societies (red box). Climate change is a threat multiplier that compounds overfishing and pollution. For instances, climate change induces fisheries susceptibility and vulnerability to overfishing; while overfishing and climate change influence pollution sensitivity; thus, the resilience of fish stocks and marine ecosystems can be weakened. The synthesis is based on literature review and framework presented in Alava et al. (2017a). Adapted from Alava et al. (2017a) and Bindoff et al. (2019).

(RCP 2.6), in which there is a drastic reduction in global fossil fuel emissions, and under the business-as-usual scenario (RCP 8.5).

The relationships observed in **Figure 3** shows positive correlations and significant linear regression between TTI and MTT under RCP 2.6 and RCP 8.5 by either 2050 or 2100 ($r^2 = 0.39$, $r = 0.62$, $p = 0.003$; **Figures 3A–D**), projecting that both TTI and MTT increase, as well. Some benthopelagic species (i.e., Great Atlantic scallop, red mullet, cuttlefishes, bobtail squids, frogfishes; **Figure 3D**) exhibit TTI > 1 under RCP 8.5 by 2100, as an indication of high sensitivity and exposure to increasing SST.

Conversely, when applying the ecotoxicological risk index (i.e., TTI = SST_{CC}/MTT), the relationships observed in **Figure 4** illustrate negative correlations, in which the TTI significantly decreases as the MTT increases in fish for both RCP 2.6 and RCP 8.5 scenarios by 2020 and 2100 ($r = -0.97$; $p < 0.00001$). These trends indicate that fish with higher MTT values (e.g.,

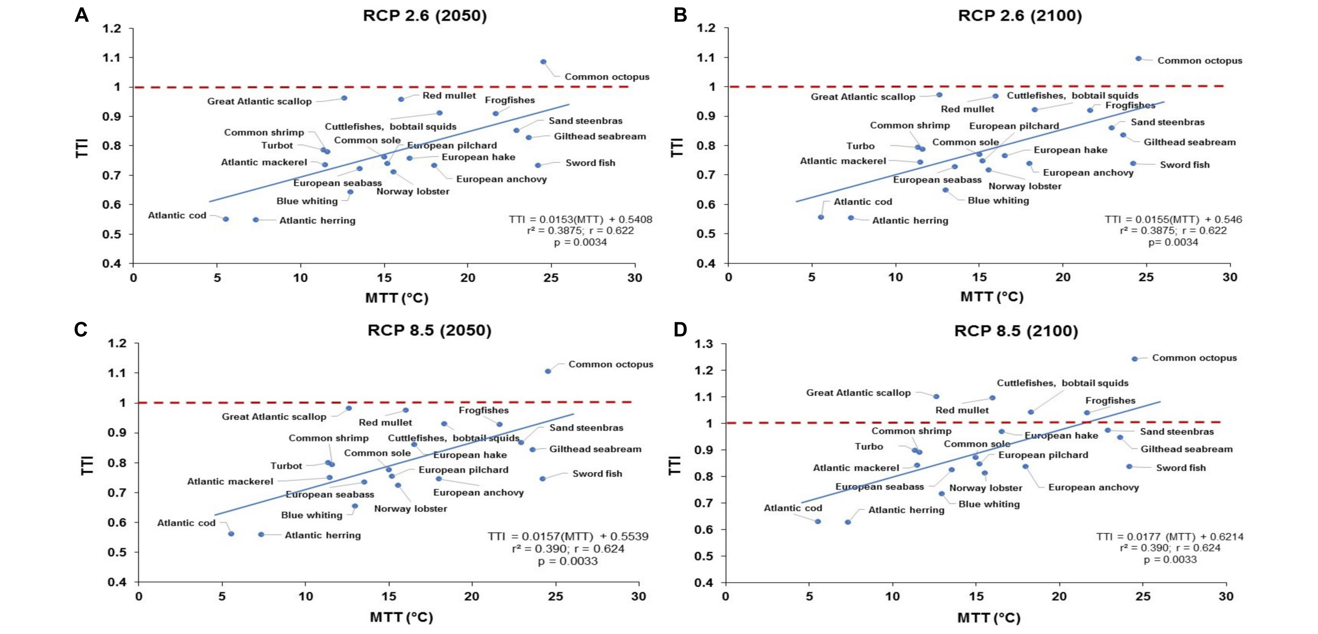

FIGURE 3 | The relationship between the estimated TTI ($TTI = \frac{(MTP + MTP * \Delta T)}{T_{MAX}}$) for all fish species assessed vs. the species-specific MTT under RCP 2.6 (i.e., low CO_2 emission/high mitigation scenario) for **(A)** 2050 and **(B)** 2100; and RCP 8.5 (high CO_2 emissions or business-as-usual) for **(C)** 2050 and **(D)** 2100. The relationship between TTI and MTT under RCP 8.5 shows that most temperate pelagic and benthopelagic species will be affected either by high SST under RCP 8.5 by 2100 **(D)**, as an indication of high sensitivity of exposure to ocean warming.

sword fish, gilthead seabream) are less impacted by and more tolerant to increasing changes of SST, while fish species (i.e., Atlantic cod; Atlantic herring) with lower MTT and higher TTI values are the most affected due to the exposure to ocean warming (i.e., RCP 8.5), appearing to be susceptible even under the mitigation or low emissions scenario (RCP 2.6), as shown in **Figures 3A–D**. The impact of SST under RCP 2.6 is relatively lower than under RCP 8.5 (**Figure 3**), with TTI increasing by an average of 5.0 and 35%, respectively, by 2050 and 2100 relative to current temperature 2001–2020. We found that bobtail squids, frogfishes, great Atlantic scallop, red mullet and common octopus will be affected by high SST under RCP 8.5 in 2050 and 2100 (i.e., potential impacts on abundance and distribution due to less resistant to changes in SST). Likewise, under the strong mitigation scenario (RCP 2.6), the impact of bottom sea temperature is lower than that under RCP 8.5, with TTI increasing by an average of 5.0 and 30%, respectively, by 2050 and 2100 relative to current temperature 2001–2020. In particular, based on the ecotoxicological risk index, these species exhibited a TTI > 1, ranging from 1.3 to 1.5 under RCP 2.6 and RCP 8.5, corroborating its lack of tolerance to ocean warming (**Figure 4**).

The combined interaction of fishing pressure impacts in tandem with climate change exacerbating mercury biomagnification has been modeled in a foodwebs of the Faroe Islands (North Atlantic), involving a depleted fish stock and cetacean species, including the Atlantic cod (*G. morhua*) and long-finned pilot whale (*Globicephala melas*), resulting in high concerns for food safety and neurotoxic effects to human health because of the high consumption of mercury-contaminated fish and marine mammal meat (Booth and Zeller, 2005). More recently, this cumulative multiple-stressor interaction was corroborated by Schartup et al. (2019), uncovering that the combination of climate change and overfishing in depleted fish populations such as Atlantic cod (*Gadus morhua)* and bluefin tuna (*Thunnus thynnus*) further contaminate fish and exacerbate bioaccumulation of the neurotoxic MeHg in foodwebs. This has obvious implications for healthy marine ecosystems, but also for the public health of coastal communities strongly relying on seafoods.

The combined onslaught of ocean warming, overfishing and pollution on fisheries in European waters may have significant implications for fish distribution, food security, and livelihoods. Pollution, overfishing, and rising SST, among other anthropogenic pressures, put at risk future prospects for food security and nutrition, and resilient livelihoods in the longer term. For instance, overfishing results in overexploitation of fish stocks, threatening the health of the ecosystem and fish stocks while generating losses in fishers' revenues, as well as a loss in socio-economic benefits such as food and nutritional security of people (Bondaroff et al., 2015; Sumaila et al., 2020). One major impact of climatic and non-climate stressors on fisheries is the changes in stock distributions, which affect where fish can be caught and who might catch them. These stressors might alter the conditions of marine ecosystems and the distributions of fish species across the oceans shift in response to climate change. This implies some traditional fisheries will move into new jurisdictions and those that cannot move fast enough perish. That means our results have significant implications to the decision makers for

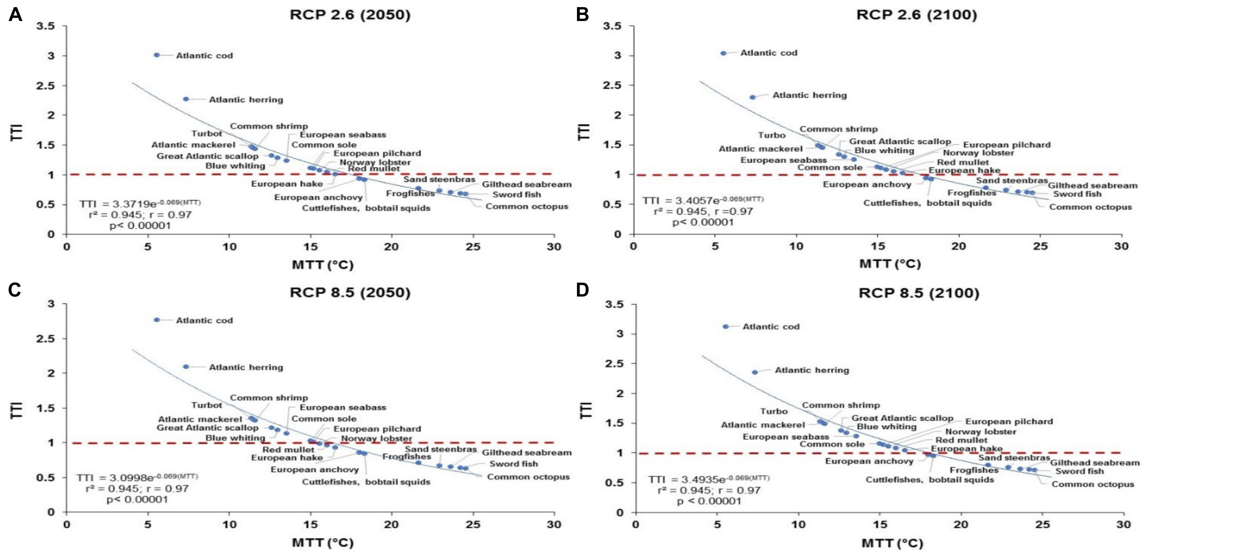

FIGURE 4 | The relationship between the estimated TTI (TTI = SST_{CC}/MTT) for all fish species assessed vs. the species-specific MTT under RCP 2.6 (i.e., low CO_2 emission/high mitigation scenario) for **(A)** 2050 and **(B)** 2100; and RCP 8.5 (high CO_2 emissions or business-as-usual) for **(C)** 2050 and **(D)** 2100. The relationship between TTI and MTT under RCP 8.5 shows that most temperate pelagic and benthopelagic species will be affected either by high SST under RCP 8.5 and even under the mitigation scenario (RCP 2.6), as an indication of high sensitivity of exposure to ocean warming.

management risks and designing policies for sustainable fisheries. It is therefore crucial for us to incorporate the outputs from this study into to risk management and policy solution framework.

This projected changes in distribution are likely to exacerbate existing conflicts between stakeholders, both within nations and when the distribution of important species changes across boundaries between neighboring economies or between country EEZs and the high seas. For instance, the rapid northwards shift of Atlantic mackerel (*Scomber scombrus*) distribution from Norwegian waters to the waters of the Faroe Islands and Iceland led to conflict over allocations between the affected countries (Jensen et al., 2015).

Another devastating impact of environmental and anthropogenic stressors on fisheries is changes in stock productivity, which affect potential yields and profits. As an example, Lam et al. (2016) modeled the impacts of climate change on fish revenues through changes in the amount and composition of catches and found that global fishers' revenues could drop by 35% due to decrease in catches by developing countries vessels operating in more severely impacted distant waters.

Our study has limitations. First, the equation TTI = (MTP+MTP*ΔT)/T_{MAX} uses maximum temperature (T_{MAX}) or the upper limit temperature tolerated by a given fish species as the denominator, in which the numerator is basically adjusted to the maximum temperature creating a maximum temperature-normalization of the fish data to produce a TTI with Equation (3). Second, while this application is fairly sound, an aspect to consider is that by using T_{MAX} in this equation, we may well overestimate or generate over-projection in terms of the thermal capacity of a fish species to tolerate larger changes in SST (i.e., not all individuals of a population are metabolically and physiologically able to exhibit a T_{MAX} and only a few or some, depending on the most temperature-tolerant individuals of the same species, which may well include outliers). Conversely, using the MTT will help to recognize and represent the species' overall mean thermal tolerance. Doing so, the basic equation TTI = SST_{CC}/MTT, where SST_{CC} is a term to express the overall average of SST to reflect the climate change forcing based on the SST predictions for RCP 2.6 and RCP 8.5 by 2050 and 2100, may well be applied to compare both methods. Again, while the use of T_{MAX} is useful, how sensitive on average a given fish species as a whole is to SST changes or scenarios under climate changes, using the MTT? Thus, future work should be conducted to test if this is the case by comparing both estimation methods.

CONCLUSION

Temperature Tolerance Index and mercury concentration patterns analysis of the European waters data series show that there is some evidence of weakening the resilience of fisheries to climatic and non-climate stressors. Our results highlight that SST could rise between 0.5 and 0.7°C by 2100 for the lowest carbon emissions scenario (RCP 2.6) and in excess of 2°C under RCP 8.5. This will ultimately weaken the resilience of fish stocks and marine ecosystem in European waters. The study has found that over 5 temperate benthopelagic species such as Norway lobster, common sole, great Atlantic scallop, red mullet, European hake and European seabass will be negatively affected (in terms of abundance and distribution) by high SST under RCP 8.5 in 2050 and 2100 because their estimated TTI > 1. Therefore, global effort that is already ongoing to minimize carbon footprint need to be intensified. It is essential for stakeholders, including governments, fishers and resource managers and citizens, should focus more attention on the monitoring of environmental parameters, such as SST, mercury pollution, to determine the resilience of fishery such as bobtail squids, frogfishes, great Atlantic scallop, red mullet, and common octopus that are more vulnerable to climate change and non-climate stressors. In addition, a prevention risk management plan based on the weight of evidence and conceptual framework proposed here (**Figure 2**) for European fisheries in tandem with national and international instruments is of paramount to proactively address and combat the multiple anthropogenic stressors, resulting from the combined interaction of warming oceans, mercury pollution, overfishing in the face of global changes. Precautionary decision-making processes and development of concerted management actions and mitigation policies for climate change, chemical pollution, and fishing activities may well follow a proactive bottom-up policy, supporting the prevention pathway and precautionary approach to mitigate and eliminate mercury pollution and neutralize carbon emissions (e.g., net-zero emissions and decarbonized economy) from anthropogenic sources (Alava et al., 2017a; Alava, 2019), as well as championing sustainable fishing activities by eradicating harmful fisheries subsidies (Sumaila et al., 2021), instead of the classic, imposed top-down policy perpetuating "business as usual" and status quo.

Also related are awareness raising, improving education, and human and institutional capacity on climate change mitigation. Anthropogenic-induced pressures such as mercury pollution from human-made sources may reduce the ability of fisheries and marine ecosystem to respond to present day climatic pressures. Enhanced resilience of fisheries and marine ecosystem by reducing stressors, including pollution and the use of habitat destructive fishing gears (e.g., dredge, bottom trawl). Also, the international community should strengthen a global ban on mercury and worldwide control of persistent organic pollutants' emission sources within the United Nations framework as well as increase fish consumption advisories for methylmercury.

The next pathway, in terms of reducing fisheries and ecosystem resilience is industrial fishing. Overfishing is the most serious threat to fisheries in the European waters, and therefore effective fisheries management measures are required in order to decrease the ecological effects of overfishing and increase the food security especially for the coastal communities in the Europe. Hence the ongoing effort in the fisheries sector as a whole on reversing overfishing on target stocks and fisheries impacts on non-commercially fished species (Garcia et al., 2018) as well as increase efforts to rebuild fisheries and promote the restoration of the fisheries (Worm et al., 2009) in European waters need to be intensified to enhance fisheries' resilience to climatic and non-climate stressors. Generally, reduction in fishing intensity including measures that promote social resilience within the fishing sector while maintaining effective conservation measures will increase resilience of the fisheries. Such strategies include enhancing transferable fishing quotas, alternative fisheries and livelihood diversification. Future research can incorporate ecosystem and foodwebs modeling experiments that explore the impact of combined environmental stressors (e.g., addressing mercury pollution, overfishing, and climate change forcing simultaneously).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval were not required for the study because we used public information.

AUTHOR CONTRIBUTIONS

II, JA, VL, and US: conceptualization, methodology, writing—original draft, and writing—reviewing and editing. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.770805/full#supplementary-material

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Reforming International Fisheries Law Can Increase Blue Carbon Sequestration

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The oceans are by far the largest carbon sink and are estimated to have absorbed roughly 40 percent of anthropogenic carbon dioxide emissions since the beginning of the industrial era. The climate services performed by the oceans can be described as an interaction between a physical and a biological carbon pump. Whereas the role of the physical carbon pump is well established, the full scale of the climate services provided by the biological carbon pump has only recently been understood. This pump is made up of services provided by different marine species, from microbes to marine mammals. Many of these species are managed under the international law of the sea and subject to the concept of Maximum Sustainable Yield (MSY). Although the MSY concept has developed since its inception, maximum generation of fish for human consumption remains the core objective according to the law of the sea. Under MSY based management, states are not required to consider the climate services represented by different marine organisms, making this regime unable to balance the interest of maximizing fish as a product against the oceans' role in carbon sequestration. In order to make optimal use of the carbon sequestering features of marine organisms, this perspective proposes five action points. Foremost, MSY should be complemented with a new management objective: maximum carbon sequestration (MCS). Although many aspects of climate-based fisheries management remain to be explored, it appears clear that this would imply allowing stocks to recover to maintain a larger amount of biomass, increasing conservation measures for species particularly efficient in providing negative emissions, differentiation of fisheries within species as well as a new approach to ecosystem management. Climate reforming international fisheries law could make an important contribution to the operationalization of the Paris Agreement on Climate Change, as well as the UN Sustainable Development Goals. As a first step, international guidelines should be developed on how to integrate the concept of maximum carbon sequestration in fisheries management.

Keywords: maximum climate mitigation, marine management, climate change, carbon sequestration, blue carbon, law of the sea, fisheries management, fisheries law

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INTRODUCTION

The impact of climate change and ocean warming on the productivity of fish stocks has been subject to considerable scientific discussion and analysis (Free et al., 2019; Szuwalski, 2019). However, it has become increasingly evident that fish stocks also play a crucial role in the mitigation of climate change. Climate targets thus call for consideration of climate change mitigation effects in fisheries management. In the light of this insight, this perspective discusses how marine species, and in particular fish, have a mitigating impact on climate change and how the rules for managing fish stocks should be reformed to promote these climate services.

Globally applicable principles for the management of fisheries are found in the international law of the sea, and set out primarily in the UN Convention on the Law of the Sea (UNCLOS). At the core of UNCLOS' management regime for fisheries is the concept of Maximum Sustainable Yield (MSY). Although this concept has developed since the adoption of UNCLOS in the early 1980s, not least through the negotiation and adoption of the UN Fish Stocks Agreement (UNFSA) in the mid-1990s, maximum fish stock production for human consumption remains the core objective of international fisheries regulation.

The concept of MSY[1] does not require states to consider the challenges raised by climate change and the carbon sequestration potential of fish. While recent findings indicate that fish throughout their life cycles contribute to processes which sequester considerable amounts of carbon (Mariani et al., 2020), the objective of MSY based management is limited to promote optimal food production. Managing multispecies fisheries inevitably involves weighing various objectives, including biological and economic ones (Rindorf et al., 2017). States are increasingly undertaking to also include ecosystem considerations in catch decisions. Although this can make fisheries management more sustainable, current national processes to implement ecosystem-based fishery management (EBFM) indicate that it risks becoming a missed opportunity to also include climate considerations (Holsman et al., 2020)

Combining insights from natural sciences, law and economics, this article discusses the carbon sequestration effects of fishery resources and suggests that the international principles for fisheries management should be revised so as to also consider and promote the climate services provided by marine organisms. Considering the work in progress within the UN *decade of ocean science for sustainable development*, reforming fisheries management accordingly would not only be in line with the targets under SDG 13 Climate Action (Claudet et al., 2020). Our suggestion would also have the potential to support and guide the management of sustainable small-scale and industrial fisheries while promoting the restoration of biodiversity in line with SDG 2 Zero Hunger and SDG 14 Life Below Water (Folke et al., 2016; Sumaila et al., 2019; Friedman et al., 2020).

THE OCEANS AS CARBON SINKS

Covering over 70 per cent of our planet's surface, the oceans play a crucial role in oxygen production and weather patterns, as well as in the global carbon cycle (Denman and Brasseur, 2007).

In fact, the oceans are by far the largest carbon sink in the world and are estimated to have absorbed roughly 40 per cent of carbon dioxide emissions since the beginning of the industrial era (Sabine et al., 2004; Houghton, 2007; DeVries et al., 2017). In the period 1994 to 2007, the ocean's average uptake rate was estimated to be equivalent to 31 ± 4% of the global anthropogenic CO_2 emissions with regional variations (Gruber et al., 2019). About 93 per cent of the earth's carbon dioxide is stored and cycled through the oceans (Nellemann et al., 2009).

With the adoption of (The Paris Agreement in 2015), the importance of ensuring the integrity of all ecosystems, including marine ones, and the protection of biodiversity when taking action to address climate change was recognized (Rayfuse, 2019).[2] The Paris Agreement also calls for the conservation and enhancement of sinks and reservoirs of greenhouse gases.[3] The United Nations Sustainable Development Goals adopted the same year, recognize the central role of the oceans in counterbalancing the impact of climate change. Marine climate mitigation, also referred to as Blue Carbon, has since increasingly featured in the Nationally Determined Contributions submitted by countries according to the Paris Agreement, and been included in the accounting mechanisms of the United Nations Framework Convention on Climate Change[4] (Murray et al., 2012; Hoegh-Guldberg et al., 2013; Ullman et al., 2013). These contributions have, however, predominantly focused on coastal ecosystem habitats (mangroves, seagrasses, tidal marshes) while being less concerned with the role of marine fisheries (Beaumont et al., 2014).

The climate mitigation services provided by the oceans can be described as two pumps; the physical and the biological carbon pumps. *The physical carbon pump*, also known as the solubility pump, refers to the ocean's function to absorb large amounts of carbon dioxide, an effect which is particularly articulated in cold surface waters (Houghton, 2007). The cooling of surface waters at high latitudes favors their ability to dissolve atmospheric CO_2 (mainly by increasing the solubility of the gas) as well as increasing their density. These heavy surface waters plunge down to great depths, thereby keeping the CO_2 away from further contact with the atmosphere (Houghton, 2007; Bopp et al., 2019). This process is however not without side-effects: The chemical reaction of salt water and CO_2 generates carbonic acid, pushing down the pH of the oceans. Although the exact function and potential of this cycle

[1] The maximum sustainable yield (MSY) for a given fish stock means the highest possible annual catch that can be sustained over time, by keeping the stock at the level producing maximum growth. The MSY refers to a hypothetical equilibrium state between the exploited population and the fishing activity.

[2] The role of the oceans in climate systems had however been discussed also under previous schemes, such as the Kyoto agreement.

[3] See Article 5(1) of the Paris Agreement as well as Article 4(1)(d) of the United Nations Framework Convention on Climate Change (UNFCCC).

[4] Nationally Determined Contributions are provided based on Article 4 of the Paris Agreement.

is still not fully explored (DeVries et al., 2017), its importance for the climate system is well established. What has been given less attention in discussions about the climate mitigating effect of the oceans is that the physical carbon pump is complemented by a biological carbon pump. *The biological carbon pump* plays an important role in the transfer of CO2 fixed through photosynthesis at low trophic level, *via* complex biological-driven processes to the deep ocean (Cavan et al., 2019). In this context the role played by food web dynamics and trophic-cascade in pelagic ecosystem (Casini et al., 2009) linked to anthropogenic drivers such as climate change and fishing can have a major impact on carbon sink, and the dynamics underlying these processes are often non-linear and complex.

Top-down trophic cascade effects play an important role in regulating both food web dynamics and ecosystem functioning, as for example by removing top predators and their pressure on grazers resulting in an increase in algal biomass and changes in habitat characteristics. These effects will vary from case to case, site to site, time to time and ecosystem to ecosystem. For example, an increase in the abundance of small pelagics results in an increase in CO2 cycling through the ecosystem rather than sequestered into the deep. Generally, there is a need to better understand these trends, tradeoffs and temporal variability as CO2 equilibrium in the sea is variable over space and time.

In particular, as pointed out by Cavan and Hill (2021), carbon sink is largely dependent on plankton as much as fisheries across scales. Therefore, it must be better understood how the coupling of multi-trophic dynamics (from low to high trophic level) and fisheries exploitation, particularly in the small pelagics (such as anchovies and sardines), is linked to changes in carbon sink. The connection to management measures in the fisheries should also be further explored, as the top-down/bottom-up combined effects in regulating ecosystem functioning and CO2 regulation varies across ecosystem (Mariani et al., 2020). Marine plants are also key to consider when managing interactions between wild fishery resources and other marine organisms. Marine plants that contribute to this carbon sequestration, such as mangroves and seagrass, live in rich soil. Macroalgae such as kelp forest usually grow near the shore in rocky and eroding conditions where plant materials cannot get buried. Instead, bits of macroalgae get exported to the deep sea, where the carbon can be sequestered. The importance of macroalgae in sequestering away carbon has been overlooked until recently because it is difficult to precisely measure how much carbon is sequestered and exported to the deep sea. Krause-Jensen and Duarte (2016) recently estimated that around 200 Mt tons of carbon dioxide are being sequestered by macroalgae every year, highlighting the importance of protecting valuable coastal marine ecosystems such as kelp forests from environmental degradation. However, more assessments should also be made of the interaction with kelp, seaweed and mangroves, for which the carbon sequestration effects have been extensively described (Duarte et al., 2013a; Duarte et al., 2013b, Macreadie et al., 2019).

Analysis of carbon sequestration needs to also consider interactions between wild fishery resources and aquaculture to provide more comprehensive and integrated assessments of coastal ecosystems (Jones et al., 2022). For example, the Intergovernmental Panel on Climate Change (IPCC) has recommended macroalgal production as a research field for climate change mitigation (IPCC, 2019), an ocean-based climate change mitigation also suggested by the High-Level Panel for a Sustainable Ocean Economy (Stuchtey et al., 2020). In addition, the volume of valuable, carbon-rich shell waste from bivalve aquaculture is considerable, estimated at up to 11.9 Mt per year (Tokeshi et al., 2000). Also, and although returning bivalve shells to the marine environment will eventually release the stored carbon as shells dissolve, there are considerable positive benefits of bivalve reef restoration, including indirect carbon sequestration through enhancing blue carbon habitats (McAfee et al., 2020). These types of analysis of interactions enable policy makers to provide guidance on climate-friendly aquaculture practices that can reduce emissions or enhance marine carbon storage and to identify key knowledge gaps for future research.

It appears that carbon sequestration effects could be significantly increased not only in the management of wild fishery resources but also in aquaculture, where technological approaches have been proposed to promote such effects (Ahmed et al., 2017).

Generally, in relation to food provisioning for human consumption by wild catch fisheries and aquaculture in coastal and off-shore areas, it should be considered that there is a general need to consider how operations can be moved toward zero emission targets and a focus on low trophic level species that provide, like the small pelagics, low carbon footprint.

CLIMATE MITIGATION SERVICES, FISHERIES AND ECOSYSTEM SERVICES

Recent evidence on the carbon sinks performed and represented by marine organisms indicates that these climate mitigation services may be much higher than previously thought (Lutz and Martin, 2014; Bopp et al., 2019; Boyd et al., 2019). More than 55% of carbon captured by photosynthetic activity is captured by marine and coastal ecosystems as blue carbon (Mcleod et al., 2011).

Valuing carbon sequestration is key for policy makers in order to assess monetary and socio-cultural benefits to society and human well-being. Assessments of ecosystem services have generally been subject to an increasing scientific interest and acknowledgement as they illustrate the crucial role of nature for human well-being and sustainable economic development (De Groot et al., 2012; Costanza et al., 2014). In particular, ecosystem valuation can help to disentangle trade-offs between reversing the declining state of marine ecosystems and natural capital, and possible competing economic interests (Stefanski and Villasante, 2015; Villasante et al., 2015).[5] Various international frameworks have been developed to facilitate and support such analysis e.g.

[5] Marine ecosystem valuation is a powerful tool when used to answer clear policy questions. It requires analysis of the contribution of ecosystems to human well-being, both directly and indirectly. Ecosystem valuation can help to highlight the often-unrecognized benefits to society, such as recreation or carbon sequestration and their direct and indirect human health benefits.

by the Millennium Ecosystem Assessment (MEA); The Economics of Ecosystems and Biodiversity (TEEB); and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). To an increasing extent, the ecosystem service value of carbon sequestration has gained attention (De Groot et al., 2012; Pendleton et al., 2012; Camacho-Valdez et al., 2013; Beaumont et al., 2014; Melaku Canu et al., 2015; Zarate-Barrera and Maldonado, 2015; Cole and Moksnes, 2016; Ganguly et al., 2017; Himes-Cornell et al., 2018).[6] Building on predictions made by Stern and Stiglitz on the time evolution of carbon prices consistent with the Paris Agreement, subsequent studies have assessed the economic value of blue carbon services (Stern and Stiglitz, 2017; Norton et al., 2018; Santos, 2018).[7]

It is recognized that the carbon sinking potential of the oceans can be increased by developing mitigation and adaptation measures involving the conservation and enhancement of coastal and open ocean ecosystems and processes (Duarte et al., 2013; Wylie et al., 2016; Howard et al., 2017; Bindoff et al., 2019). A recent study by Mariani et al. (2020) on the role of fisheries in preventing blue carbon sequestration, showed that the global blue carbon extraction by fisheries between 1950 and 2014 was equivalent to 318.4 million metric tons (Mt) of large fish, corresponding to 37.5 ± 7.4 Mt of carbon (MtC) released to the atmosphere. This prevented the sequestration of 21.6 ± 4.4 MtC through the mechanism of fish carcasses sinking to the deep ocean after biomass consumption by predation. They have also diversified the extraction of carbon by fisheries in terms of industrial fisheries, artisanal fisheries, subsistence and recreational fisheries. These findings show how fisheries have reduced carbon sequestration by removing large individuals, and highlighted the importance of measures to promote the rebuilding of fish stocks, thereby increasing their capacity for carbon sequestration. More recently, Villasante et al. (2021) showed that society is not pricing the negative climate effects of fishing (Dasgupta, 2021) nor considering them in global fisheries management. The authors estimated the economic value of preventing the depletion of the oceans' carbon sequestration capacity by incorporating industrial fishing activities into the existing EU Emission Trading System (EU ETS) carbon market. They found that the EU ETS could help to reduce fishing activities which are socially negative in terms of obtaining marine protein and preventing marine carbon sequestration (e.g. trawling fishing). It would help to promote sustainable small-scale fisheries and more equitable distribution of fisheries resources globally, and it would also contribute to climate resilience by protecting vulnerable habitats.

More detailed assessments of the different carbon sinking effects of fish stocks and other marine organisms should be carried out. While at present a management regime for marine living resources aiming to promote carbon sequestration has not been fully explored in terms of its objectives and outcomes, preliminary observations can be drawn based on the findings of central climate services (Davison et al., 2013) (see **Figure 1**). Most obviously, a climate-based management of fisheries would not only call for recovery of fish stocks but for maintaining them at a maximal size, so as to bind as much carbon as possible in biomass (Costello et al., 2016). This goes beyond preventing overfishing and implies a shift of objectives in fisheries management. Reference levels for what represents desirable stock sizes should be set higher across species, so as to reflect maximum carbon sequestration levels instead of maximum regeneration levels. Keeping harvesting at a minimum not only until stocks are at viable population rates, but at maximum biomass levels within boundaries set by their role in ecosystems would both support ecological and climate perspectives. Moreover, in order to facilitate an adaptation of fisheries to fluctuating biomass across stocks, fisheries management should become more flexible. Less guidance in management decisions should be sought in allowable catch in previous years. Instead, quotas should be allowed to vary spatially more widely, in line with the dynamic development of stocks, which is expected to fluctuate increasingly as the result of climate change effects (Gaines et al., 2018). Needless to say, this calls for following scientific advice considering the carbon sequestration objective rather than merely socio-economic considerations or advice focusing on regeneration levels.

Generally, the knowledge of carbon sequestration effects of marine fish species provides strong arguments not only for biologically sustainable management in general, but for maximizing fish biomass as well as biodiversity (Lutz and Martin, 2014). But more than simply calling for promoting the recovery of stocks, findings from preliminary studies of climate services provided by fish stocks indicate that certain species and categories of fish are particularly valuable for carbon sequestration purposes. It appears to be little explored how this difference in climate mitigation services manifests across species (Mariani et al., 2020). Considering the wide differences in behavior relevant for central carbon sequestration effects identified, a robust and profound assessment of climate service differences between stocks is likely to yield important learnings on what species should be prioritized in management.

Promoting climate mitigation would call for adding new approaches to established fisheries management systems. In order to maintain healthy ecosystems and balanced trophic chains which can function as efficient biologic carbon pumps, it is vital to preserve top predator species (Atwood et al., 2015). Moreover, introducing maximum size limits in fisheries regulation should be considered in order to preserve the carbon sequestration effects of large individuals (Jørgensen et al., 2007; Froese et al., 2008; Mullon et al., 2011).

[6] Most studies were performed for developing countries and focusing on mangrove ecosystems. Little research about blue carbon ecosystems valuation has been developed for Europe.

[7] Under this scenario, Santos (2018) found that the estimated value of the current blue carbon stock for Portugal mainland prices amounts to 2.349.335€, of which approximately 2.291 million € are attributed to salt marshes; while Norton et al. (2018) also estimated that carbon absorption coastal services in Ireland are valued at €819 million. Beaumont et al. (2014) also valued the ecosystem service of blue carbon sequestration and storage in coastal margin habitats in the UK. The authors found that if coastal habitats are maintained at their current extent, their sequestration capacity over the period 2000–2060 is valued to be in the region of £1 billion UK sterling. However, if current trends of marine habitat loss continue, the capacity of the coastal habitats both to sequester and store CO_2 will be substantially reduced, with a reduction in value of around £0.25 billion UK sterling.

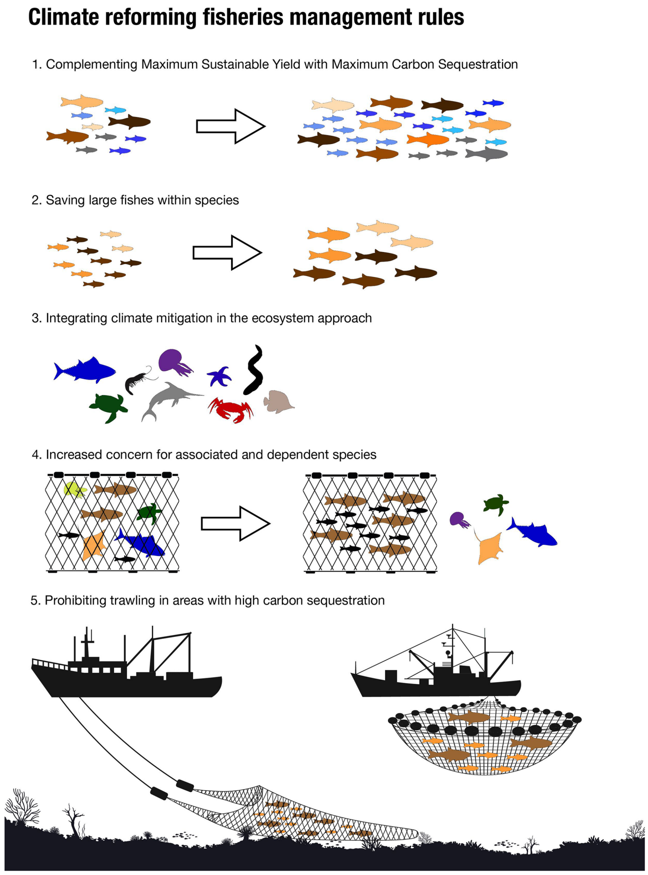

FIGURE 1 | Climate Reforming Fisheries Management Rules.

Moreover, from a climate perspective it is also critical to consider indirect effects of capture fisheries. A recent article by Sala et al. (2021) indicates that trawling has considerable climate effects by re-mineralizing sedimentary carbon to CO_2, increasing ocean acidification and reducing the buffering capacity of the ocean and increasing atmospheric CO_2. This can be effectively addressed by establishing marine protected areas where trawling is prevented. Considering the increasing exploitation of deep-sea fisheries, establishing such measures appears particularly important in deep-sea areas which have so far not been affected by trawling, where carbon has been sequestered for 100s of years (Norse et al., 2012). Declaring marine protected areas in coastal waters with high productive upwellings and carbon stocks has also been identified as key measures for climate mitigation. For example, Feijoo et al. (2021) have recently shown that marine protected areas are able to provide not only benefits in terms of increasing marine abundance of protected species but they are also more efficient in terms of energy return of marine protein. This result illustrates the importance of marine protected areas as relevant management measures for climate mitigation purposes.

To base fisheries management on climate mitigation concerns calls not only for allowing stocks to grow, but also to limit the catch of the species and individuals most valuable commercially. This represents a considerable challenge since it would go against established fisheries practices. Under the existing regime, seafood market prices promote fishing down the food chain (Pauly et al., 1998). However, climate concerns call for the opposite: Promoting the harvesting of small fish, further down the trophic chain. Moreover, it calls for decreasing trawling in general and in particular for protecting coastal waters where the carbon sequestration effects of fish stocks and sediments are particularly high.

Not only does it appear that taking these factors into consideration in fisheries management would increase the carbon sequestration effects of fish stocks. Undertaking relevant measures would also make marine ecosystems generally more resilient to the effects of climate change, thereby preventing depletion of stocks and marine ecosystem services expected under existing fisheries patterns (Karr et al., 2015; Free et al., 2019).

This emerging body of knowledge on the wasted potential of fisheries management in climate change mitigation is clearly a call for climate action. In the following sections we set out a reform agenda for international fisheries law that has the potential to transform it from an obstacle to a promoter of the integration of climate mitigation objectives in fisheries management and in the process also generate other social and ecological benefits.

THE CASE FOR LEGAL REFORM

Providing the basic framework for all uses of the seas, the 1982 UN Convention on the Law of the Sea (UNCLOS) has been heralded as one of the most remarkable achievements of international law. Not only are 168 states parties to the convention, substantial parts of it are generally considered to reflect norms of customary international law and thus binding also for non-parties like Colombia, Turkey and the USA (Tanaka, 2012). Among other things, UNCLOS sets out the fundamental rules for the management of all marine fisheries. In the exclusive economic zone (EEZ), i.e. the maritime zone normally covering the area between 12 nautical miles up to 200 nautical miles from the coast, coastal states have sovereign and exclusive rights to manage fish and other living resources.[8] This includes both conservation and utilization of such resources.[9] UNCLOS establishes a rather rigid legal framework for fisheries management, both in the EEZ of individual states and on the high seas, i.e. sea areas beyond the control of any coastal state.

This scheme comprises two countervailing objectives, which domestic regulation has to navigate between (United Nations, 1995). A primary ambition of UNCLOS is to ensure *optimum utilization* in all fisheries management. This is reflected in obligations calling for *utilizing* fish as a resource for the benefit of human purposes. This principle is formulated not only as a right but as *an obligation* of coastal states to promote the harvesting of fish stocks within their marine domains (Article 62). To the extent that a coastal state does not have the capacity or desire to harvest available fish, other states should be given access to the surplus. Accordingly, the exclusive rights of coastal states to manage organisms and ecosystems within their marine areas does not extend to letting fish stocks remain in their natural state. Instead, it in principle obliges them to promote the exploitation of such organisms although there may be ways for states to circumvent this obligation (Nordquist, 1985).

The same logic is reflected in the obligations aiming to ensure the *conservation* of fish stocks. Optimum utilization and the attendant total allowable catch should be determined according to MSY. This formula establishes that harvested species should be maintained or restored at levels which can generate the highest rate of reproduction, which (according to the logic of UNCLOS) would yield the highest future catch rates. The idea behind this concept is that regeneration of fish stocks is enhanced by harvesting up to, but not beyond, a certain level which can be scientifically assessed (Matz-Lück and Fuchs, 2015). The model has been severely criticized, in particular for oversimplifying the complexity of making stock assessments as well as for failing to take marine species interactions into account (Pauly and Froese, 2020). In particular, criticism has been voiced against the possibility of establishing the level of certainty called for in the scientific assessment provided for by the MSY concept (Finley and Oreskes, 2013). Practical difficulties in reducing fishing mortality to levels below those corresponding to MSY have also been shown in the US (Mace, 2001). Moreover, the logic of the MSY formula is also qualified by a number of environmental, economic and social factors acknowledged in UNCLOS. These provide a recourse in cases where policy makers want to avoid a strict scientific application of the MSY formula.[10] The central rule for the management of living resources under the law of the sea is thus dysfunctional, especially in the context of multispecies fisheries and ecosystem based fisheries management. It also allows states to derogate from its ecological rationale.

The focus on individual targeted fish stocks lacks a broader analysis of impact on other species. Although the effects on other species than those directly targeted in fisheries, i.e. so-called associated or dependent species, should be taken into consideration, that is only with a view to maintain such species above levels at which their reproduction may become *seriously threatened*.[11] Whereas targeted stocks should be maintained at the MSY level, non-targeted species can thus be put under considerably higher pressure (Melnychuk, 2017). This reflects a simplistic understanding of marine ecosystems and the trophic chain, as previously described. For carbon sequestration purposes, associated and dependent species may be of considerable importance.

The concept of MSY was developed to make single species stock assessments and estimation of stock status (Hilborn et al., 2021). Several studies (Larkin, 1977; Mace, 2001) have shown the difficulties of estimating MSY in a multi-species context, and set harvest strategies based on MSY that account for fish stock and predator-prey interactions, and climate driven processes. As suggested by Mariani et al. (2020), the MSY concept needs to be reformed to set biomass at a level above MSY; $>B_{msy}$, where $B_{msy,}$ is the biomass that would provide the highest long-term average catch. This would also contribute to the progress and implementation of an ecosystem approach to fisheries management (EAF) and support a move towards fisheries sustainability (Patrick and Link, 2015). Importantly, such a reform of the MSY concept would increase the blue carbon sequestration capacity of fisheries and ecosystems, thereby supporting climate mitigation.

However, it is not only the rigid management formulas that are ill-suited to promote climate mitigating effects of marine ecosystems. The rules in UNCLOS also have other shortcomings from a climate mitigation perspective. In particular, they fail to consider regional variations and lack a specific legal basis for protecting areas where stocks and sediments represent particularly high carbon sinks.

To some extent, these rules have been modified at the international level by the entry into force of the 2001 UN Fish Stocks Agreement (UNFSA), which functions as an implementing agreement, operationalizing the rules in UNCLOS for straddling and highly migratory stocks, as well as the 1995 FAO Code of Conduct for Responsible Fisheries (FAO Code of Conduct). These

[8] Articles 55-57 of UNCLOS.
[9] Articles 61-62 of UNCLOS.
[10] Article 61, paragraph 3, UNCLOS.
[11] Article 61, paragraph 4, UNCLOS.
[12] See Article 5 of the UNFSA as well as Articles 6 and 7 of the FAO Code of Conduct.

instruments introduced environmental principles such as protection of biodiversity which imply that also other interests than optimum utilization should be promoted.[12] The UNFSA also qualified the use of MSY as an objective, referring to it as a minimum standard for limit reference points.[13] It also strengthened enforcement rules, adopted a precautionary approach and considerations of ecosystem implications. The precautionary approach called for states to protect habitats of special concern and take into account uncertainties, including predicted oceanic, environmental and socio-economic conditions.[14] The adoption of the ecosystem approach in the general principles of the UNFSA[15] reflected a reform of fisheries management which had already started at domestic and regional levels, calling on all states to consider impacts on species belonging to the same ecosystems as the targeted stocks (Cadell and Molenaar, 2019). However, none of these provisions make reference to climate aspects; nor do they modify the basic principles for fisheries management. While representing important steps forward, these instruments did not alter the central status of the principles of optimum utilization and maximum sustainable yield.

Although domestic and regional fisheries management schemes exhibit considerable variation (Marchal et al., 2016), and the MSY concept of UNCLOS is not always decisive in management decisions (Mesnil, 2012), it still provides the global framework for fisheries management, and sends a strong signal to policy makers about what is currently prioritized. It also defines rights of access to fisheries based on the optimal utilization of these resources. Although with some variation, optimum utilization and maximum sustainable yield formulas remain the starting point for fisheries management in domestic settings.

Where states and regional fisheries management organizations have started to implement an ecosystem approach in fisheries management, it has the potential to enable better informed management decisions. Such advice is, however, seldom binding in the political decisions on fishing opportunities, although some countries have made scientifically defined standards binding for management (Marchal et al., 2016). For example, in the EU there has often been a considerable discrepancy between advice and ensuing management decisions (Borges, 2018). Moreover, even where management has been adapted based on ecosystem considerations, it has not implied the promotion of climate mitigating effects of fish. The success of fisheries management still tends to be judged by the conservation status of key fish stocks (Marchal et al., 2016). Evaluations of the implementation of ecosystem-based fisheries management tend to consider climate change only in terms of an external factor to which fisheries management has to adapt, not as a process that is and can be affected by fisheries management (Heenan et al., 2015; Townsend et al., 2019). Even recent scientific frameworks for comprehensive evaluation of fisheries systems mostly fail to include the sequestration of carbon as an objective (Stephenson et al., 2018; Belschner et al., 2019), thus indicating its low recognition as a factor under the current state-of-the art fisheries management.

This does not stand scrutiny when mounting scientific evidence indicates that fish stocks represent one of the most important climate mitigation services globally. Even if these effects have not been fully assessed and many unknowns remain, there is still reason not only for decreasing catch levels in many instances, but for reconsidering the basis of the framework, i.e. fisheries law. In essence, not even a successful implementation of the ecosystem approach as it is commonly understood would suffice to realize the climate mitigation potential of fish stocks. Promoting climate action in fisheries management requires rethinking the basis for existing management.

HOW TO REFORM INTERNATIONAL FISHERIES LAW

In several important regards, it appears that the obligation to harvest any surplus in fish stocks for human consumption is detrimental to the climate mitigation interest. In a revision of management rules, the perspective of fish as food needs to be balanced against the conception of fish and other living resources as blue carbon see (**Figure 2**). Such a revision should pursue potential synergies between these objectives and consider social and economic effects, in particular on small scale and subsistence fisheries.

Climate reform would involve a number of modifications to the rules in UNCLOS, or at least recognizing that UNCLOS is dated in important respects and that fisheries law needs to be supplemented with climate considerations. A climate adaptation of the optimum utilization concept would imply replacing or complementing the MSY formula with a new target, promoting climate services. This could be equally determinative as the MSY formula, and be referred to as the maximum carbon sequestration (MCS). MCS would in most cases imply increasing stock levels beyond MSY levels, to maintain the largest amount of biomass possible without risking the functioning of ecosystems. Larger stocks would not only put the carbon sequestration effects at a stable higher level. A period of dynamic stock increase would involve a dynamic sequestration of substantial amounts of carbon within a short period of time. At more specific levels, further assessments would have to be made to assess MCS of ecosystems and individual stocks and species. Where certain species are particularly valuable from a climate mitigation perspective, it follows naturally that they should be subject to special regard. Many states have diversified their fisheries management policies, and included more policy goals than optimum utilization and MSY. The increasing application of the ecosystem approach to fisheries is promising. However, fisheries management reform should not merely aim for the general recovery of fish stocks and consideration of the impact of other species of the ecosystem. In the transformation of policies, the particular climate aspects should also be considered (**Box 1**).

Taken together, a climate reform of the international fisheries regime could make a significant contribution to climate change mitigation, in line with undertakings within the Paris agreement. Moreover, it would better capture the full spectrum of the SDG agenda, including climate action and life below water in addition to food production. Not least would it send a strong signal about

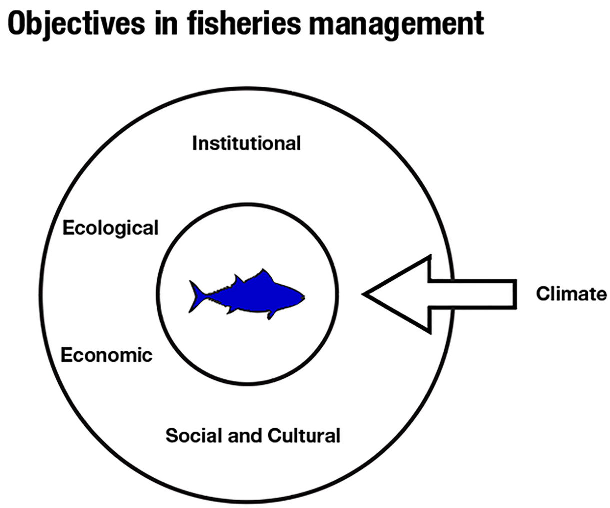

FIGURE 2 | Objectives in Fisheries Management.

Box 1 | Action Points

1. Maximum Carbon Sequestration

The mounting evidence of the climate mitigation effects of marine organisms calls for increased efforts to prepare for providing scientific advice based on the MCS concept and integrate a climate perspective through a reform of international fisheries law. Particularly at a time when the world is agreeing on the need for urgent measures to meet tight mitigation objectives, potentially significant contributions to climate change mitigation cannot be left untapped. As a first step, international guidelines should be developed on how to integrate the concept of maximum carbon sequestration in fisheries management.

2. Differentiate within species

All aspects of fisheries management, from rules in international law to allocation of quotas and development of gear ought to be differentiated not only between but within species, promoting the preservation and not catch of the older and bigger individuals (Belgrano and Fowler, 2013). This underlines the importance of limiting high-grading in fisheries. The destructive effects could be prevented by limiting quotas to specified maximum sizes, or providing incentives for limiting catch to smaller individuals in combination with developing more selective gears[16].

3. Climate integration in EAF

The Ecosystem Approach to Fisheries (EAF) should be further developed and operationalized to integrate climate aspects. Not only should the impact of fisheries on individual stocks as well as the role of keystone species in ecosystems be considered. The broader consequences of fisheries on carbon sequestration in connected ecosystems must also be taken into account (Culhane et al., 2020). In addition to fisheries management, this includes the protection of coastal and marine vegetation, such as mangroves, seagrass meadows, which promotes reproduction and binds carbon (Fourqurean et al., 2012; Alongi, 2014). It should thus be considered how fisheries can be managed so as to promote climate services not only in targeted species but throughout marine ecosystems.

4. Non-targeted species

The subordination of associated and dependent species should be replaced with equal concern for the restoration of these stocks. From a carbon sequestration perspective, indirect effects of fisheries on other species may be equally important as the impact on targeted stocks. This calls for a reform of the current total allowable catch-approach that includes more holistic perspectives, as well as renewed efforts at developing selective gears and preventing bycatch.

5. Climate relevant MPAs

Marine protected areas are able to provide not only benefits in terms of increasing marine abundance of protected species but they can also be more efficient in terms of energy return of marine protein (Feijoo et al., 2021). It is an important management measure for carbon sequestration purposes. Such areas, where sediments and fish stocks bind particularly high amounts of carbon should be closed to trawling. Currently, legal development is focused on developing high seas marine protected areas. For carbon sequestration purposes, it appears more important to compel coastal states to declare marine protected areas in coastal waters within their jurisdiction.

the potential of fisheries management to contribute positively to climate change mitigation. It would also remove legal impediments to climate focused management decisions. A new implementing agreement to UNCLOS could be one way to achieve this. However, even in the absence of such reform at the level of UNCLOS, there should still be room at regional and domestic levels for broadening the scope of ecosystems-based fisheries management to actively pursue management practices that not only benefit ecosystems and the long-term viability of stocks, but also realize the positive climate potential of fishing.

AUTHOR CONTRIBUTIONS

We are a transdisciplinary group of four researchers, representing law, marine ecology, economics, and social sciences, working on challenges associated with reconciling international fisheries and

[16]Such incentives could be financial (e.g. price signals, tax credits/allowances), behavioral (nudging through default rules for cooperation), informational (reporting requirements) or regulatory (including catch share programs such as Individual Transferable Quotas and Territorial Use Rights in Fisheries).

climate change law in line with SDG 14 (Life below water) and SDG 13 (Climate action). Although NK came up with the idea and have coordinated the work, all authors have been involved in writing and contributed with analytical perspectives, in line with their respective disciplines and areas of expertise. These include law of the sea (NK), environmental law and marine management (DL), marine ecology (AB) and economics and ecosystem services (SV).

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Exploring Changes in Fishery Emissions and Organic Carbon Impacts Associated With a Recovering Stock

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International objectives for sustainable development and biodiversity conservation require restoring fish populations to healthy levels and reducing fishing impacts on marine ecosystems. At the same time, governments, retailers, and consumers are increasingly motivated to reduce the carbon footprint of food. These concerns are reflected in measures of the EU Common Fisheries Policy (CFP) and the CFP Reform Regulation, which highlighted a need to move from traditional single-stock management toward an ecosystem approach to fisheries management (EAF). Using publicly available landings and effort data combined with estimates of adult population biomass, we develop methods to explore the potential for lowering emissions intensity and impacts on organic carbon stocks through ending overfishing and rebuilding stocks. We use the recent recovery of European hake (*Merluccius merluccius*) stocks in the Northeast Atlantic as a case study. With a focus on the hake fisheries of France, Spain, and the United Kingdom, we compare 2008 and 2016 fishing years. We make an initial estimate of the influence of changing stock status on greenhouse gas emissions during the fishery phase from fuel use and investigate the potential disturbance of organic carbon in the ecosystem, specifically via identification of bottom trawling overlap with organic-rich muddy sediments, and directly on storage in hake biomass. Our findings indicate that recovery of the hake stock was associated with reductions in overall emissions intensity from fuel and proportional impact on hake populations, however, total emissions from both fuel and landings increased, as did likely disturbance of sedimentary organic carbon in surface sediments due to benthic trawling. Ultimately, the aims of this analysis are to further explore the climate impacts of fisheries and overfishing, and to inform development of EAF in the EU.

Keywords: fisheries, carbon emissions, hake (*Merluccius merluccius*), stock recovery, sedimentary organic carbon, sustainable fisheries, ecosystem based management (EBM), ecosystem based approach for fisheries management

INTRODUCTION

Unsustainable resource extraction, biodiversity loss, and climate change threaten the health and longevity of marine ecosystems and fish populations worldwide (IPBES, 2019). Reducing greenhouse gas emissions (GHGs) is essential for reducing the ecological and social impacts of climate change and remains an international priority (United Nations General Assembly resolution [UNFCCC], 2015). Simultaneously, restoring fish populations and marine ecosystems to achieve healthy oceans are cited as international objectives for sustainable development (United Nations General Assembly resolution [UNFCCC], 2015) and conservation of biodiversity (Convention on Biological Diversity, 2021). In the European Union (EU), these objectives are reflected in measures outlined by the Common Fisheries Policy (CFP) (European Union [EU], 2013). The latter reform of the CFP proposed a new framework to manage European fisheries, and amongst several new initiatives, it highlighted a need to move from traditional single-stock management towards an ecosystem approach to fisheries management (EAF) (Prellezo and Curtin, 2015). The CFP Reform Regulation defines the EAF as "... an integrated approach to managing fisheries within ecologically meaningful boundaries which seeks to manage the use of natural resources, taking account of fishing and other human activities, while preserving both the biological wealth and the biological processes necessary to safeguard the composition, structure and functioning of the habitats of the ecosystem affected, by taking into account the knowledge and uncertainties regarding biotic, abiotic and human components of ecosystems" (European Union [EU], 2013).

Ecosystem approach to fisheries management prioritises the wellbeing of ecosystems over economic and social objectives since ecosystem wellbeing is considered a prerequisite for the latter two objectives (Murawski et al., 2008; Baudron et al., 2019). While the current CFP advocates for the implementation of some form of EAF, it remains largely unclear how to include conservation objectives within fisheries management measures in practice. The CFP aims to fish at levels consistent with achieving Maximum Sustainable Yield (MSY) for all exploited stocks (European Union [EU], 2013), an approach which does not necessarily account for impacts on the ecosystem (Ulrich et al., 2017). In Northern European waters, these fishing levels are proposed by the EU's International Council for the Exploration of the Sea (ICES) which delivers scientific advice for the management of northern European fish stocks. This advice provides biological reference points for commercial stocks, including the level of fishing mortality (F) needed to achieve MSY (F_{MSY}). According to the latest Scientific, Technical and Economic Committee for Fisheries (STECF) CFP monitoring report, stock status of the NE Atlantic (both EU and non-EU waters) has significantly improved since 2003, although many stocks remain overexploited (STECF, 2020a). Among the stocks which are fully assessed, the proportion of those that are overexploited decreased from around 75% to close to 40% over the last ten years. This trend is promising, however, in 2019, the proportion of overexploited stocks (i.e., $F > F_{MSY}$) for which there are data increased slightly (STECF, 2020a).

Regarding the climate impacts of EU fisheries, many national governments, retailers, and consumers are increasingly motivated to reduce greenhouse gas emissions (GHGs) associated with food production, including fisheries, as a form of climate change mitigation (Iribarren et al., 2010). When considering direct emissions, such as fuel use, trawl fisheries are known to produce, on average, more GHGs per kilogram of catch than virtually any other fishing gear (Tilman and Clark, 2014). The carbon footprint of seafood landed using trawl nets may be similar to, and in some cases exceeds, the footprint of terrestrial staples such as poultry or pork (Tilman and Clark, 2014; Hilborn et al., 2018). Trawl fisheries are also known to have negative effects on the marine environment via significant alterations to abiotic and biogenic structure (Chuenpagdee et al., 2003). Evidence from vessel Automatic Information Systems (AIS) data suggests that the continental shelf surrounding the EU is among the world's most trawled, although the Celtic and Greater North Seas are slightly less impacted than the waters west of Iberia and within the Mediterranean (Amoroso et al., 2018a).

In addition to direct emissions, fishing activity can affect organic carbon (OC) stocks in the marine environment, with implications for both climate and ecosystem function. One such stock is held in marine sediments, which store substantial amounts of carbon (Atwood et al., 2020; Legge et al., 2020), the active burial of which provides a climate regulation service over thousand-year timescales (Berner, 2003). Where trawling gear interacts with marine sediments, it can introduce oxygen into sub-surface sediment layers, increasing the potential loss of buried carbon through aerobic remineralisation (Aller, 1994; Hulthe et al., 1998). Sediment type is an important factor in the storage of sedimentary OC (Diesing et al., 2017; Smeaton et al., 2021), where OC is largely controlled by the proportion of clay or mud (Hedges and Keil, 1995). Trawling has a larger physical impact on muddy-sediment environments in terms of resuspension, causing significantly higher volumes of OC to be resuspended compared to sandy-bottom environments (O'Neill and Summerbell, 2011), with implications for both carbon flux and the resilience of local biodiversity (Pusceddu et al., 2014; Paradis et al., 2017). There is currently a lack of comprehensive evidence to fully demonstrate the effects of trawling on sedimentary OC stocks, but one likely outcome of regular trawling is prevention of sediment settling processes and, in turn, localised carbon sequestration (Epstein et al., 2022 PREPRINT; Oberle et al., 2016). Furthermore, using the definition outlined in Scheffold and Hense (2020), fish populations are living pools containing stocks of OC. In addition to affecting OC stocks in sediments, by removing fish biomass, fishing activity may prevent OC from sinking in the form of fish carcasses and facilitate conversion of OC in biomass to atmospheric CO_2 (Mariani et al., 2020).

In this study, we make a first attempt at combining an established approach for estimating the fuel use of a specific fishery, with novel insights into the additional perturbation of OC stocks caused by fishing. We use landings and effort data associated with the Northern and Southern stocks of European hake (*Merluccius merluccius*) from 2008 and 2016, which enables a comparison of fishing emissions and OC impacts of the fishery when the Northern stock was depleted (2008) and subsequently rebuilt (2016) (ICES, 2021a). The Northern stock of European hake (hereafter "hake") encompasses those populations living within the Greater North Sea, Celtic Seas, and the northern Bay of Biscay, while the Southern stock consists of those populations living in the southern Bay of Biscay and Iberian Coast (**Figure 1**). The combined range for Northern and Southern hake stocks is provided by ICES in terms of the following subareas and divisions: Subarea 4, 6, 7, Divisions 3.a, 8.a-d, 9.a (ICES, 2021a,b).

Hake are predatory, demersal fish, usually found at depths of 75–400 m, above muddy or sandy sediments (Lloris et al., 2005; Froese and Pauly, 2021). The Northern and Southern hake stocks may not be two distinct populations biologically but nevertheless are assessed separately for the purpose of fisheries management (Milano et al., 2014). The Northern stock is managed using the MSY approach and as such, the spawning stock biomass (SSB) is estimated during assessment of stock status by ICES. Conversely, the Southern stock is managed under the precautionary principle and SSB is not estimated. The Northern stock was overfished from at least the 1990s to the late 2000s (Murua, 2010; Villasante et al., 2011); on multiple occasions during this time, fishing mortality (F) substantially exceeded the agreed landings target (ICES, 2021a,b). However, in 2004, a recovery plan for hake was introduced which required a 70% reduction in F. Subsequently, the SSB of the Northern stock increased substantially, likely due to the reduced fishing pressure (Baudron and Fernandes, 2014). Between 2008 and 2016, SSB of the Northern stock increased by approximately six-fold, catches more than doubled, and F declined substantially (ICES, 2021a). Overall, catches of hake reported by ICES for 2016 were landed predominantly by long lines (39%), trawls (33%), and gillnets (24%) (ICES, 2017). Each gear type comes with trade-offs from varying levels of ease of use, to efficacy, to selectivity. Trawls, which trap fish as they scrape across the seafloor, are known as "active" gear types as they are continuously dragged by a moving vessel, while long lines and gillnets are considered "passive" gear types as they drift or hang idly in the current. It is worth noting that, despite modifications made to each of these gear types to increase selectivity, all three of these gear types have some issues.

In this paper we focus on the relationship between the carbon impact of the fishery, namely GHGs generated from vessel fuel use, and consider the potential perturbations to the OC stocks in the sediment and hake population, against the rebuilding of the Northern hake stock, from 2008 to 2016. We do not consider emissions from non-fuel inputs associated with fishing, for which estimates vary (for example Parker et al. (2018) assume 25% of total emissions arise from non-fuel sources). The purpose of including a preliminary ecological perturbation analysis in this paper is to introduce the impacts of fishing on OC stocks, in addition to the direct carbon footprint of boats on the water, and to advance information available for the development of ecosystem-based approaches for EU fisheries. Given the nexus between climate change, sustainable resource use, and biodiversity conservation (Sumaila and Tai, 2020), we consider whether the GHG footprint of the hake fishery overall and per tonne of catch were reduced by ending overfishing.

MATERIALS AND METHODS

We used publicly available data collected by STECF through the Fisheries Dependent Information (FDI) data call (STECF, 2017) in combination with data we requested from STECF (STECF, 2020b), which included detail on hake landings, fuel use and intensity (litres per tonne of total landings) at the level of individual fishing fleet segments (i.e., vessel size, gear type). The requested data, hereafter referred to as dataset 1, were extracted from the STECF database (STECF, 2020b) for every second year from 2008 to 2018 inclusive, according to the following selection criteria: (i) fleets operating in the North Atlantic Ocean (FAO Area 27 - NAO) and (ii) EU fishing fleet segments in which, in 2018, hake accounted for at least 1% of total landings. France, Spain, and the United Kingdom landed 91% of total hake landings in 2008 (27,416 tonnes), and 78% in 2016 (23,764 tonnes) (STECF, 2020b). Thus, fishing mortality of the hake population within the NEA was dominated by the activities of these three countries, indicating that hake was an important target species for these nations. As such, we used the landings, effort, and fuel data for these three nations to investigate the impacts of the hake fishery in terms of fuel use, sedimentary disturbance, and extraction of OC in biomass. To compare the carbon impacts of the European hake fishery eight years apart, with two vastly different estimates of SSB, we emphasised the relative fuel use and impacts on OC per kg of hake landings, as opposed to focusing on the total emissions and impacts of the fishery. Landings data from STECF (STECF, 2020b) were used in kilograms, and, unless otherwise stated, this is the basic unit of measure we refer to hereafter.

To analyse the GHG footprint associated with fishing activity we focused on the carbon generated by vessels' fuel use, which includes travel to and from fishing grounds and gear operation. These data were entirely available in dataset 1 (STECF, 2020b). We estimated fuel intensity (FI) (the amount of fuel burned while fishing hake per kilogram of hake landed), and emissions intensity (EI) (the estimated GHGs released while fishing hake per kilogram of hake landed) which is directly related to FI. Estimates for mean FI values were calculated for year and gear type. There were eight types of gear listed in dataset 1 (STECF, 2020b): (1) polyvalent passive gears (PGP), i.e. polyvalent nets, (2) drift/fixed-net gears (DFN), (3) gears with hooks (HOK), (4) demersal trawlers and seiners (DTS), (5) pots and traps (FPO), (6) vessels using active and passive gears (PMP), (7) vessels using "other" active gears (MGO), and (8) pelagic trawlers (TM). For this analysis, we grouped polyvalent passive gears (PGP) and drift/fixed-net gears (DFN) together as "DNGN". In addition to reporting the cumulative FI value for hake fished by all gear types in 2008 and 2016, we also report on FI values for the "DNGN", "HOK", and "DTS" gear types only, as these were relatively well sampled in both 2008 and 2016 ($n > 2$ for both years) and were responsible for the overwhelming majority of hake landed (>95% of total landings) in both years.

To estimate the disturbance of OC in muddy sediments caused by bottom-contacting otter-trawlers, we used swept area (SA), a measure of the seabed surface area that has been in contact with, or altered by, bottom-contacting fishing gear, such as trawls,

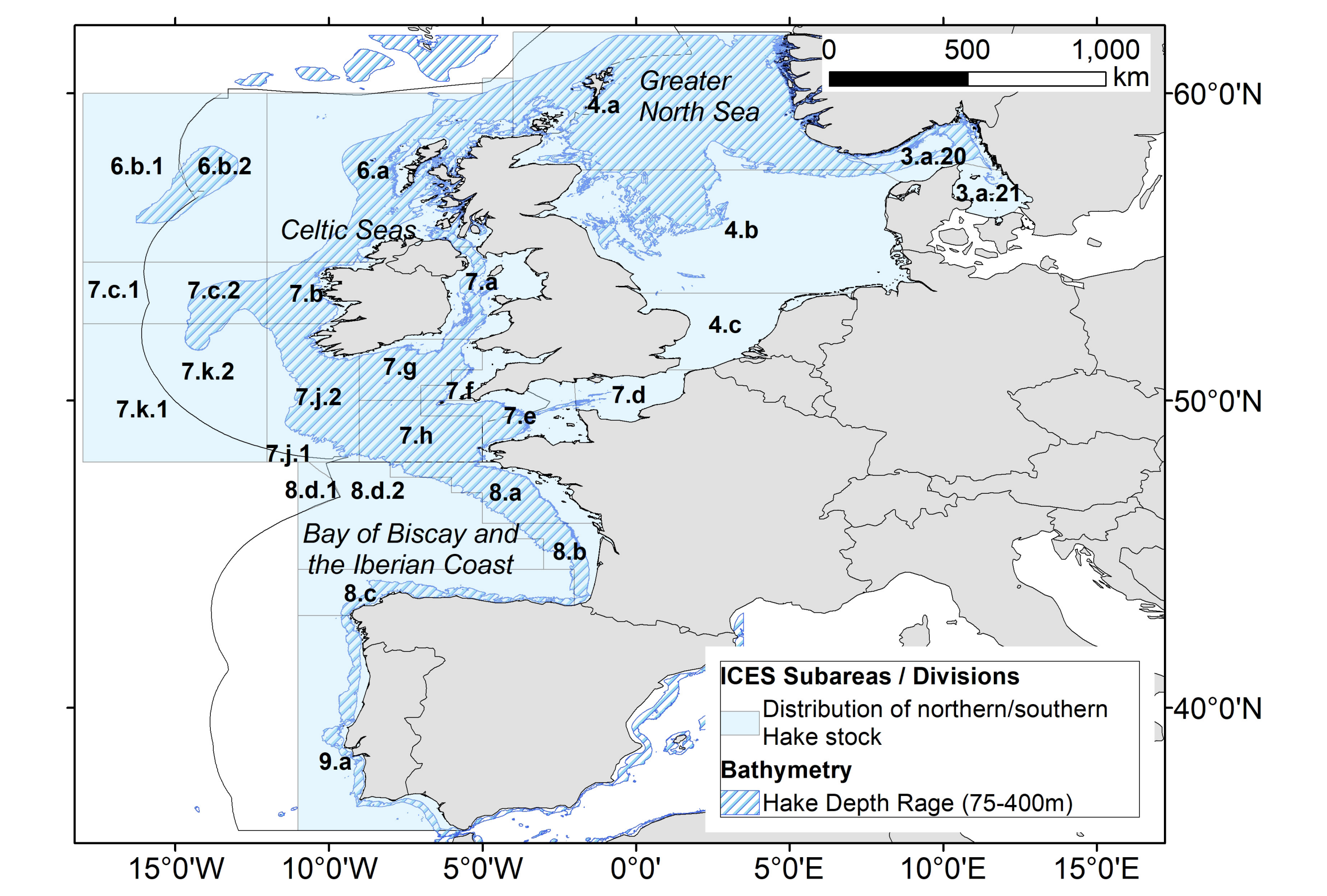

FIGURE 1 | Map showing the combined ICES Subareas and Divisions where the northern and southern hake stocks are distributed. Shaded areas indicate the approximate depth preference for hake species, 75–400 m [Bathymetry data downloaded from EMODnet Bathymetry Consortium (2020)].

and report SA per kg of hake landed. SA is determined by the width of the gear and vessel speed (Church et al., 2016). We calculated and mapped the total SA by country using publicly available FDI data (STECF, 2017), hereafter referred to as dataset 2. Although this calculation does not quantify the amount of OC lost or consider the specific mechanisms by which OC may be lost, the areal overlap provides spatial information about where the biggest impacts of the trawl fishery on surficial sedimentary OC stocks are likely to be.

We calculated SA per kg of hake landed for France, Spain and the UK using the landings data in dataset 1 (STECF, 2020b), which included hake landings, hake landings as a percentage of total landings, and effort by fishing segment (STECF, 2020b), but did not contain spatial data. Instead, dataset 2 (STECF, 2017), which included fishing effort available per ICES rectangle, was downloaded for annexes IIA, IIB, BOB, and CEL1 and years 2008 and 2016 (see **Table 1**). The data were filtered for otter trawling gears only (OT) and for the following countries: France, Spain, and the United Kingdom (data were available for England, Northern Ireland, and Scotland). Dataset 2, which provided effort, landings, and spatial data (STECF, 2017), did not contain hake landings for otter trawlers in France or Spain in 2008, or hake landings as a percentage of total landings. As such, all hake landings data for both 2008 and 2016 for France, Spain, and the United Kingdom were used from dataset 1 (STECF, 2020b). Dataset 1 were filtered by gear type "DTS", which includes demersal trawlers and demersal seiners, on the assumption that these were mostly otter trawls, since, in European waters, effort by otter trawlers is an order of magnitude greater than that of demersal seiners (Eigaard et al., 2016; **Supplementary Table 1**). To see clearer differences in SA between depleted and recovered stocks it would be best to compare fleets that landed a high percentage of hake, as detailed in dataset 1, however, we were unable to disaggregate the effort of those fleets in dataset 2, which contained the spatial data. Therefore, for the purpose of making a comparison between two years with different stock statuses, the use of OT spatial data from dataset 2 with the total landings for France, Spain and the United Kingdom from the DTS segment in dataset 1 was the best possible approach given the limitations of the data.

Finally, to estimate the fishery's impacts on the OC stock of the hake population, we first calculated the carbon removed by each country and by the different fleet segments using the landings reporting in dataset 1 for 2008 and 2016. We again grouped polyvalent passive gears (PGP) and drift/fixed-net gears (DFN) together as "DNGN," and report OC removal values

TABLE 1 | International Council for the Exploration of the Sea (ICES) Annexes and the fishing areas they encompass.

Annex	ICES area
IIA	IV; VIId
IIB	VIIIc and Ixa
BOB	VIIIa; VIIIb
CEL1	VIIb, VIIc, VIIe, VIIf, VIIg, VIIh, VIIj and VIIk

for the "DNGN," "HOK," and "DTS" fishing segments for 2008 and 2016. We also estimated the OC stock in the adult hake population for 2008 and 2016 and the proportion of OC in hake stock removed by total landings by France, Spain, and the United Kingdom cumulatively using dataset 1 and SSB estimates for the northern stock only (ICES, 2021a). This analysis was limited to using SSB estimates for the Northern stock as a proxy for the adult hake population of both stocks as SSB estimates were not available for the Southern stock, and the landings data in dataset 1 could not be disaggregated spatially to ascertain whether landings were from the Northern or Southern stocks. We reasoned that this approach was appropriate for our purpose of comparison between the two years given that total landings estimated by ICES for the Northern stock were much higher at 47,822 tonnes in 2008, and 107,530 tonnes in 2016 (ICES, 2021a), than for the Southern stock, at 16,773 tonnes for 2008 and 12,443 tonnes for 2016 (ICES, 2021b). We note that our results are therefore underestimates of the OC stock in the adult hake population of the NEA for 2008 and 2016, and overestimates of the OC removed by landings as a proportion of the adult hake population in those two years.

Hake are caught as part of a mixed-species fishery with several other target species, which makes it challenging to partition and confidently assign impacts to hake versus other species that end up in the same net. Nonetheless, we provide estimates for FI, emissions intensity (EI), and SA for hake landed by all trawlers, noting that the figures reported herein are useful for comparing the fishery impacts between a depleted and recovered stock, and do not represent precise point estimates for hake's total carbon footprint. Estimates and statistical analyses were calculated in R version 4.0.3 (R Core Team, 2020), ArcGIS version 10.1, and Microsoft Excel.

Fuel and Emission Intensity Estimates Over Time

Extrapolating Fuel Use and Calculating Fuel Intensity (FI)

To estimate the amount of fuel consumed in the pursuit of hake, we assumed that the fuel used to land hake was directly proportional to the ratio of hake landings to total landings for that fishing segment. That is, for each fishing segment reported in dataset 1 (STECF, 2020b), we assumed:

$$\frac{F_{hake}}{F_{total\ L}} \alpha \frac{L_{hake}}{L_{total}} \tag{1}$$

Where F is fuel and L is landings. Thus, we assumed that the quotient of total fuel consumption over total catch (i.e., the FI for total catch) was a reasonable proxy for the FI of hake. On this basis, we estimated FI using the following equation:

$$FI_{hake} = \frac{F_{hake}}{L_{hake}} \alpha \frac{F_{total\ landings}}{L_{total}} \tag{2}$$

Where F_{hake} is estimated as:

$$F_{hake} = L_{hake} * \frac{F_{total\ L}}{L_{total}} \tag{3}$$

Mean FI values for the three gear types were calculated by first summing the estimated values for $F_{hake,G}$ (in litres) and then the reported values for $L_{hake,G}$ (in kg), and subsequently dividing these as follows:

$$Mean\ FI_{hakeGY} = \frac{\Sigma \text{ estimated } F_{hakeGY}}{\Sigma \text{ reported } L_{hakeGY}} \tag{4}$$

Where G is gear type and Y is year.

Converting FIs to Emission Intensity Estimates

To convert FI to emission intensity (EI), we assumed that most of the fishing vessels in the EU operate using marine diesel (Borrello et al., 2013), which has a published density of 890 kg/m^3 (ExxonMobil, 2021), equivalent to 890 g/L. The fuel-to-emissions conversion factor for marine diesel (MD), as published by the International Maritime Organisation (IMO, 2015), is 3.206 g of CO_2/g of MD. After converting between units, we arrived at the conversion factor of 2.853 kg CO_2/L of fuel. Note that this number does not account for the carbon-dioxide equivalent of: (i) other GHGs released during combustion, e.g., methane and nitrous oxide; (ii) upstream emissions associated with fuel production, e.g., drilling and refining; nor (iii) downstream emissions borne from processing, e.g., freezing, packaging, and distribution. In this respect, our estimates for GHGs released by fuel consumption are likely quite conservative.

Emission intensity estimates (reported as kg CO_2 per kg hake) were derived by multiplying FI values by a factor of 2.853 kg of CO_2/L of fuel, using the following equation:

$$EI_{hake} = FI_{hake} * 2.853 \left(\frac{kg\ CO_2}{L}\right) \tag{5}$$

Sediment Disturbance

Calculating Swept Area

Swept area was calculated using standardised values for door width (km) and trawl speed (knots) for the Otter trawl class BENTHIS métier code: "OT_MIX_DMF_PEL," which is used to target hake (Eigaard et al., 2016). Following recommendations in the OSPAR CEMP guidelines (OSPAR Commission, 2017) (Agreement 2017-09) and Gerritsen et al. (2013), we used the equation:

$$Swept\ Area = Effort\ (hours) \times 0.07621 \text{ km} \times 3.4 \text{ knots} \times 1.852 \tag{6}$$

Where Effort (fishing hours) from dataset 2 (STECF, 2017) was provided with spatial data (standardised ICES rectangles), 0.07621 km is the reported average door width and 3.4 knots is average trawl speed (ICES, 2016; OSPAR Commission, 2017); and 1.852 is the conversion factor for knots to km/hr. The final SA estimates between the countries and two fishing years are compared on a relative basis. Only the average door width and vessel speed were reported by ICES (2016) and OSPAR Commission (2017), yet the width of the trawl doors is a function of the vessel size and length of the sweeps, which can vary between 25 and 250 m, and the towing speed can vary from 2 to 4 knots (Eigaard et al., 2016). Thus, there is a degree of uncertainty within the estimated SA results.

Resulting SA estimates were spatially mapped for individual countries and as combined totals for 2008 and 2016, using a Natural Breaks Classification scheme (Holt, 2008). Swept Area Ratios (SAR), i.e., the proportion of each grid cell area that is trawled, were not deemed a suitable metric for this study due to the large area of the ICES rectangles (at 0.5° × 1°, these are approximately 4,000 km^2) in combination with the low spatial resolution of dataset 2 (STECF, 2017), as it was not possible to determine where within the ICES square the reported activity occurred (Amoroso et al., 2018b). As outlined above, SA per kg of hake was calculated using total annual estimated SA (km^2) and hake landings (kg) data for each country as reported in dataset 1 (STECF, 2020b).

Combining With Sediment Type

Shapefiles for seabed substrate classified to the simplified Folk 5 classification were downloaded from EMODnet Geology (EMODnet Geology, 2016; **Supplementary Figure 1**). The total SA polygons for 2008 and 2016 were overlaid with the classified sediment layers and a spatial analysis was performed that extracted the areas of 'mud to muddy sands' (having the highest relative OC contents; e.g., Smeaton et al., 2021) directly swept by the otter trawls, and therefore considered to be impacted. We calculated the total area of the sediments considered to be impacted for both years.

Carbon Stock in Hake Populations

Using carbon measurements from six hake, 15–20 cm long and 25–35 g in wet mass, as recorded by Czamanski et al. (2011), where dry weight was 42.9 ± 6%, we calculated that OC was approximately 11.33% of hake wet weight. Dataset 1 was used to estimate the OC removed from the hake population (combined Northern and Southern stocks) in landings by country for France, Spain and the UK (STECF, 2020b), using the equation:

$$OC_{Removed} = Landings_{CY} \times 0.113256 \quad (7)$$

Where Landings are in kg, C is country, and Y is year. Using a 94% conversion rate of landed OC to CO_2 emissions described by Mariani et al. (2020), CO_2 emissions from total hake landings for gear type (DNGN, HOK, and DTS), for all three countries cumulatively, for 2008 and 2016 were calculated using the following equation:

$$Emissions_{Landings} = Landings_{GY} \times 0.113256 \times 0.94 \quad (8)$$

Where G is gear type and Y is year. To calculate the OC stock in the adult hake population for 2008 and 2016, estimates of SSB were used for Northern stock only (ICES, 2021a), since ICES does not estimate the SSB for the southern stock, using the equation:

$$OC_{SSB} = SSB_Y \times 0.113256 \quad (9)$$

Where Y is year. The range of OC in SSB was calculated using the high, mean, and low estimates of SSB reported by ICES (2021a). Finally, to make a meaningful comparison between 2008, when the stock was considered overfished, and 2016, when it was considered rebuilt, the proportion of OC removed in total hake landings for the three countries was calculated as a percentage of the total OC stock in the hake population, again using the SSB for Northern stock only and the years 2008 and 2016. For this, we used the equation:

$$\frac{OC_{Removed}}{OC_{SSB}} \quad (10)$$

Again, the range was calculated using the high, mean, and low estimates of SSB.

RESULTS

Fuel Use, FI, and EI

Between 2008 and 2016, the total fuel consumption for all fishing segments that landed hake for France, Spain, and the United Kingdom increased by 29% (from ∼49M litres to ∼63M litres), relative to hake landings more than doubling (from ∼45M kg to ∼95.5Mkg). Simultaneously, the FI (and by extension, EI) for hake landed by the gear types DNGN (polyvalent passive gears and drift/fixed-net gears), HOK (gears with hooks), and DTS (demersal trawlers and seiners) decreased by 11–54% (**Figure 2** and **Table 2**). Additional analyses on these differences are included in the **Supplementary Information**. The sample size was extremely small for those fishing segments that landed primarily hake (i.e., where hake accounted for ≥50% of the total landings), and therefore not particularly viable for statistical analyses. However, there was a declining trend in FI over time (**Supplementary Figure 2**) and, as FI is directly related to EI, the same can very likely be said for emissions per kg of hake.

The CO_2 produced in pursuit of hake (and, realistically, other species associated with the fishery) was influenced by the type of gear used to target them. For example, in 2016, hake that was landed using demersal trawlers or seiners (DTS) was approximately 37% more carbon intensive than the mean FI for the entire fishery and approximately 65% more carbon intensive than hake landed by vessels using polyvalent-, drift-, or fixed-net gears (DNGN) (**Figure 2** and **Table 2**).

Disturbance of Sediment

An increase in effort by vessels using otter trawls, and subsequently total SA, occurred for all three nations from 2008 and 2016, although the hake landings by otter trawl decreased overall (**Figure 3**). Vessels that landed hake for France, Spain, or the United Kingdom using otter trawls swept a cumulative total area of 230,103 and 520,856 km^2 in 2008 and 2016 respectively. Conversely, the total reported landings of hake by otter trawls were reduced from approximately 27,416 tonnes in 2008, to

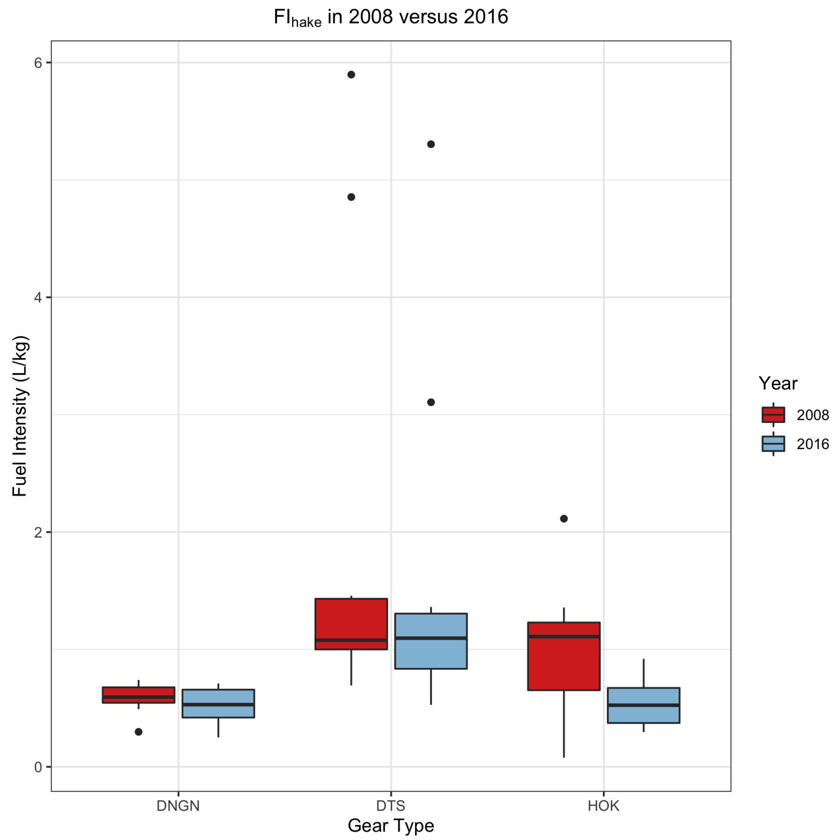

FIGURE 2 | Boxplot of individual Fuel Intensity (FI) estimates for 2008 and 2016, grouped by gear type, where each data point represents an FI estimate for a particular fishing fleet segment, calculated according to Equation (2). Sample sizes for each gear type (i.e., the total number of fishing segments using that gear), in either year, are all equal to or greater than *n* = 8, and are listed in **Table 2**. DNGN, polyvalent-, drift-, or fixed-net gear types; DTS, demersal trawlers and seiners; HOK, vessels using hooks.

TABLE 2 | The reported total landings and estimated total fuel, mean Fuel Intensity (FI), and mean Emission Intensity (EI) for hake landed by vessels equipped with particular gear types (DNGN, HOK, DTS, or all gear types) in years 2008 and 2016.

Year	Measure	DNGN	DTS	HOK	All gear types
2008	Number of Individual fishing segments	12	10	8	37
	Total $Fuel_{Gear}$ (L)	6,150,847	32,894,188	8,903,432	49,195,015
	Reported Total $Landings_{Gear}$ (kg)	10,000,827	27,416,490	6,230,559	44,973,215
	Mean FI (L of fuel/kg hake)	0.615	1.200	1.429	1.094
	Mean EI (kg CO_2/kg hake)	1.755	3.423	4.078	3.121
2016	Number of Individual fishing segments	12	10	8	37
	Total $Fuel_{Gear}$ (L)	26,726,954	21,546,642	12,364,812	63,110,975
	Reported Total $Landings_{Gear}$ (kg)	48,654,256	23,763,605	18,743,699	95,547,292
	Mean FI (L of fuel/kg hake)	0.549	0.907	0.660	0.661
	Mean EI (kg CO_2/kg hake)	1.567	2.587	1.882	1.885
Change in FI and EI estimates from 2008 to 2016 (%)		–11	–32	–54	–40

Here we use "fishing segment" to refer to the combined gear type and size of vessel. DNGN = Polyvalent-, drift-, or fixed-net gear types; DTS, demersal trawlers and seiners; HOK, vessels using hooks. Respectively, units for FI and EI estimates are: litres of fuel per kg of hake landed, and kg of CO_2 per kg of hake landed. Percent changes in mean FI and EI estimates from 2008 to 2016 are listed at the bottom of each column. Mean FI estimates were calculated according to Equation (4). Note that, mechanistically, EI estimates are directly related to FI estimates by a factor of 2.853 kg CO_2/L fuel.

23,764 tonnes in 2016. The total SA values for the two annual snapshots are presented spatially in **Supplementary Figure 3**. In terms of SA per kg of landed hake, when comparing the depleted stock of 2008 to the rebuilt stock of 2016, only the United Kingdom exhibited a lower result (33% decrease), while SA per kg of landed hake increased for France by 40% and Spain

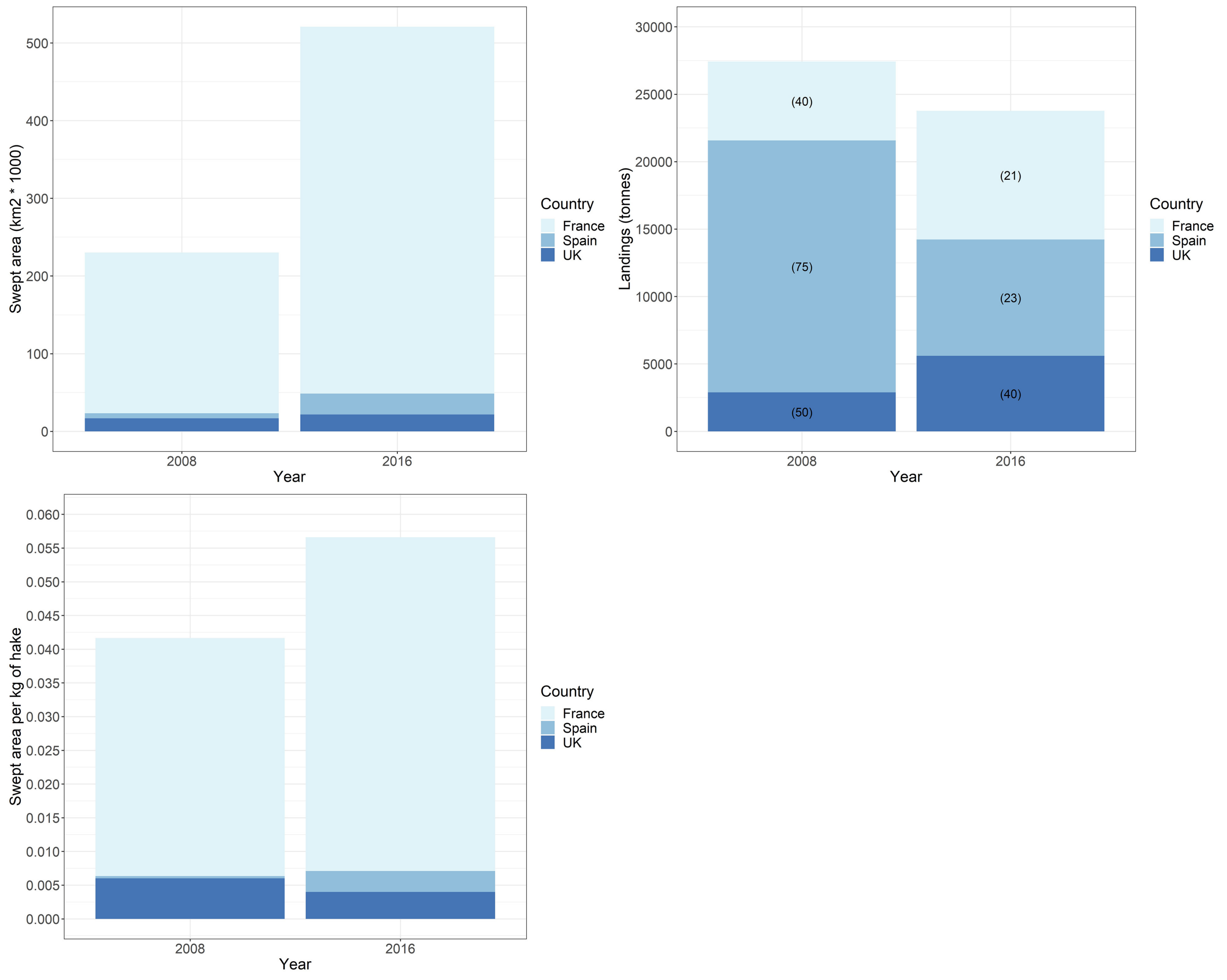

FIGURE 3 | (Top left) Swept area by otter trawls by country for 2008 and 2016 (STECF, 2017). **(Top right)** Hake landings by "DTS" by country, with percentage of total hake landings in parenthesis, for 2008 and 2016 (STECF, 2020b). **(Bottom left)** Swept area per kg of hake by country for 2008 and 2016.

by 8-fold (**Figure 3**). For France, this is a result of a combined increase in effort and landings; however, for Spain, while there is a large increase in effort in 2016, reported hake landings were greatly reduced: less than 50% of 2008's catch.

As we have emphasised throughout the text, it is important to note that this is a mixed fishery and that hake forms a percentage of the overall landings, thus the SA is not attributable to the hake fishery alone. However, irrespective of which species were caught, the area of sediment swept represents the disturbance caused in relation to the hake landed. The spatial distribution of SA per individual nation for each year is shown in **Supplementary Figure 4**. Overall, the total spatial distribution of effort is quite similar for both years. The most intense activity occurred within the Bay of Biscay, following the western coastline of France, and within the Moray Firth region of the Greater North Sea. The English Channel sees increased effort in 2016, albeit consistent in distribution. In 2008, there was activity within the southern North Sea and along the northern and western coastline of Spain which is not seen in 2016; instead, in 2016, a larger distribution of activity in the Celtic seas to the south-west of Ireland occurred. Using a somewhat crude area calculation provided by the spatial resolution of the ICES rectangles, we calculate an increase in the area of specifically muddy sediments disturbed by otter trawls from 5.72 km^2 in 2008 to 31.82 km^2 in 2016 (**Figure 4**). In 2008, disturbance of muddy sediments occurred off the west coast of France; northern coastline of Spain and west coast of Portugal; within the northern North Sea; and in the Celtic Sea to the west of Ireland. In 2016, there was less disturbance, and less activity generally, around the coasts of Spain and Portugal and the North Sea, and relatively consistent disturbance on the west coast of France. However, disturbance of a larger area of muddy sediments occurred in the Celtic Sea to the west of Ireland.

Impacts on Carbon Pool in Hake Stock

The total OC in hake landings increased between 2008 and 2016 for all three countries, with an additional 5,728 tonnes of

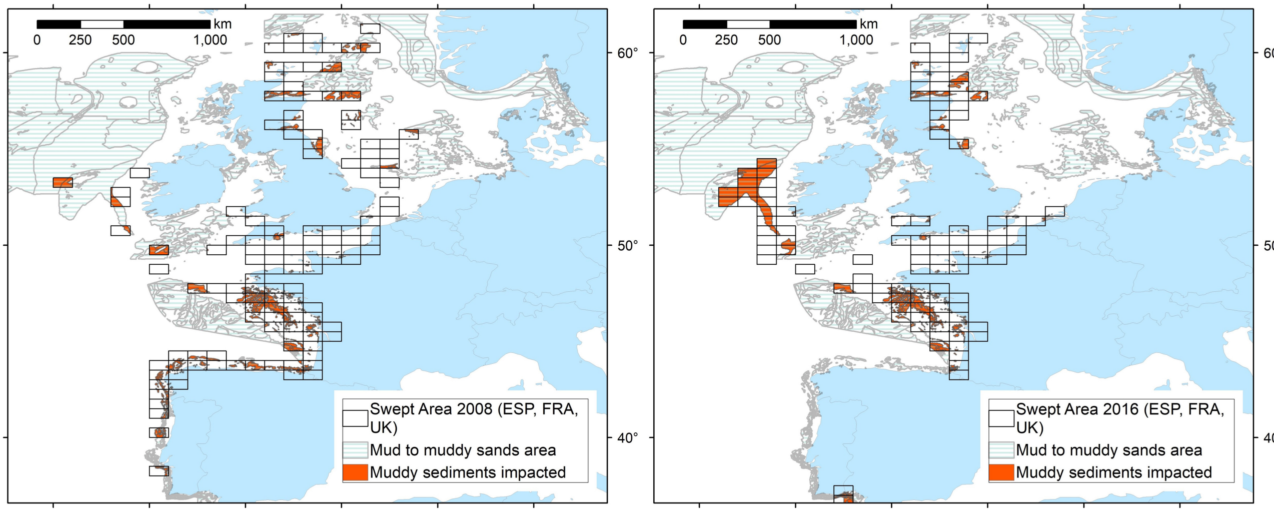

FIGURE 4 | Swept area by otter trawlers that landed hake for Spain, France, and the United Kingdom in 2008 and 2016 overlaid with muddy sediment types, with impacted muddy sediments highlighted (EMODnet Geology, 2016).

OC landed in 2016 cumulatively compared to 2008 (**Table 3**). Subsequently, total CO_2 emissions from OC in landed hake increased from 4.8M kg in 2008, to 10.2M kg in 2016, including increases in CO_2 emissions from hake landed using polyvalent passive gears, drift/fixed-net gears, and gears with hooks (**Figure 5**). However, a decrease of 0.4M kg CO_2 was observed for hake landed using demersal trawlers and seiners, as fewer hake overall were landed using that gear type in 2016. Despite total OC removal and emissions from OC in hake landings increasing between the two years, the proportion of the OC stock in the hake pool removed by landings in 2016 was much lower (31%) than that in 2008 (96%) (**Table 3**), and the OC stock in the adult hake population was approximately 6.5 times larger in 2016 than in 2008 (**Figure 5**).

DISCUSSION

Despite the limitations of the data, comparisons between the relative impacts of the fishery when the stock was overfished, as in 2008, and rebuilt, as in 2016, were possible. We have demonstrated improvements in efficiency and proportional OC storage in living stocks in 2016 compared to 2008. However, increased fishing in 2016 also resulted in increased total emissions from both fuel and landed hake, and increased ecosystem disturbance. First, we found that all gears were more fuel efficient in 2016 compared to 2008, suggesting an increase in catch per unit effort, where the unit of effort is fuel. Second, in 2016, when stocks had been rebuilt, more OC remained in the living pool of hake compared to when stocks were depleted in 2008, both in terms of total biomass and proportionally. Third, increased fishing effort in 2016 using bottom trawling resulted in higher disturbance of sedimentary OC, however, the hake catch from trawling was lower in 2016, suggesting this increase may have been due to trawls targeting other species than hake. Finally, as may be expected with increased landings, higher total fuel emissions and CO_2 release from hake landings in the Northeast Atlantic occurred once stocks were rebuilt. However, this analysis does not consider the displacement of effort and catch that may occur when a stock in one geographic location is depleted, while demand for that seafood remains constant. For instance, in 2008 frozen hake imported to Spain from outside the EU was higher than imports reported for the five subsequent years (EUMOFA, 2015), which suggests that the full emissions and OC impacts borne from the depleted stock may be higher, perhaps substantially so, from a global perspective. Likewise, we did not consider post-processing differences in our analysis, which may undergo changes when fish are imported rather than landed and marketed fresh. While our aim was to provide insights on the impacts of fisheries that will ultimately be useful for the development of EAF, such additional assessments would also improve the information available to the consumer at the point of purchase.

Overall, the increase in available hake biomass once the stock was rebuilt correlates with increased efficiency across passive gear types and proportional reduction of fishing impacts on the living pool of OC. We found that the volume of CO_2 emissions produced by vessels landing hake was influenced by the type of gear used, with the passive gillnets, hook and line, and polyvalent gears generally outperforming trawls in terms of emissions and EI. With regard to sediment disturbance, the rebuilt fishery (2016) performed better than the depleted fishery (2008) in instances where hake landings produced by trawlers were more-or-less consistent between the two years (in France and the United Kingdom for example), compared to instances where the landings from trawlers between 2008 and 2016 were substantially reduced (as in the case of Spain). These observations are likely linked to the improved stock status of hake in 2016 compared to 2008, however, the hake fishery is a mixed fishery, thus the changes in EI and impacts of the benthic trawl gear

TABLE 3 | Organic carbon (OC) impacts of hake fisheries in France, Spain, and the United Kingdom.

OC estimates	Year	Country			Total
		France	Spain	UK	
OC in landings (tonnes)	2008	1,633	2,805	656	5093
	2016	5,005	4,221	1,596	10,821
OC in stock (tonnes)	2008	5,280 (±375)			
	2016	34,780 (±2671)			
Proportion of OC stock landed (range)	2008	96% (90–100%)			
	2016	31% (29–34%)			

OC in stock refers to Northern hake stock only as SSB not estimated for Southern stock.

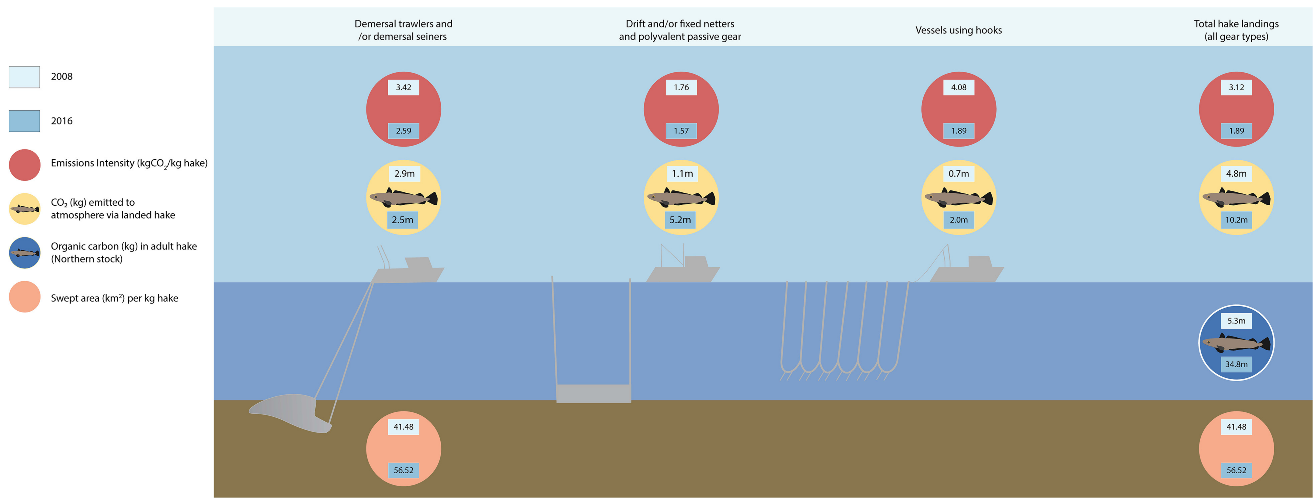

FIGURE 5 | Conceptual diagram of emissions and OC impacts by segment (demersal trawlers and/or demersal seiners; drift and fixed net gear types, including polyvalent gears; and vessels using hooks), and for total (all gear types) for 2008 and 2016.

on sediment cannot be attributed to hake stock status and hake landings alone. A greater proportion of the overall disturbance due to trawling effort in 2016 is likely to be attributable to other species, given the decline in hake landings by trawlers observed in 2016, particularly for the Spanish fleet. Unfortunately, we were unable to explore this observation further due to the limitations of the datasets. Nevertheless, the SA analysis provides useful insights into the potential disruptions to sedimentary OC posed by trawlers that land hake. Notably, hake habitat typically encompasses muddy sediments, which generally hold more OC (Diesing et al., 2017; Smeaton et al., 2021) and are resuspended for longer periods of time relative to other sediment types (O'Neill and Summerbell, 2011), implying a greater potential for OC loss via remineralisation or lateral transport offshore (Paradis et al., 2019; Epstein et al., 2022). This is not to suggest, however, that other types of seabed sediments are impervious to the impacts of trawling, both in terms of carbon and biodiversity—impacts relevant to EAF. For example, while both muddy and gravelly sediments experience relatively high benthic community depletion rates following a trawl, recovery rates for infaunal benthic communities are higher in mud than gravel due to the presence of faster-growing species (Pitcher et al., 2022).

As an early attempt to consider fishery impacts on OC in sediments and biomass using current publicly available data, there are limitations to what we could surmise. Firstly, we recognise the limitations of using two datasets which cannot be consistently filtered either by gear type or by landings with spatial data and, as such, note that the final estimates for SA per kg of hake are unreliable. Furthermore, our estimates of SA are likely to be over-estimated, not least because of the overlap of ICES rectangles with land area along coastlines (**Figure 3**). This is a function of the spatial scale of available data. We carried out a comparative analysis using a recent, much higher resolution dataset to illustrate this point (i.e., 0.05° × 0.05° as opposed to 0.5° × 1), however, we note that the SA data themselves are not comparable due to differences in the way that STECF (2017) and ICES (2021c) aggregate data. For instance, while landings data for hake are available at a country level by year from STECF (2020b), the data are aggregated into a broader gear type, for example "demersal trawls and seines" are categorised simply as "DTS." Conversely, while the ICES data are disaggregated into specific designs of otter trawl (seven spatial layers exist for otter trawls within the high-resolution ICES dataset), the data comprise all landed species and for all countries per year.

To illustrate the advantages of high-resolution spatial data, we compared our 2016 SA calculated using dataset 2 (STECF, 2017) with the ICES (2021c) dataset of the 2016 spatial layer for the BENTHIS métier code "OT_DMF," which refers to otter trawling of demersal fisheries. This BENTHIS métier code includes hake as a target species according to Eigaard et al. (2016) although hake is not specifically mentioned for this gear type by ICES (2021c). We compared the spatial distribution of SA for the area of high-intensity SA values off the west coast of France and north coast of Spain using these two datasets (**Supplementary Figure 5**). The higher resolution ICES dataset visibly reduced the estimated footprint and provided a much-improved spatial analysis of areas that are heavily impacted by trawling. An analysis of this nature might inform highly targeted management interventions, if required. The second analysis relates to estimates of the overall area of muddy sediment impacted using data of different scales/resolutions (**Supplementary Figure 6**). When we extracted the areas of muddy sediment that overlap with the SA data from dataset 2 and the ICES data (ICES, 2021c), we did not see a large difference in the disturbed area estimated by the two different resolutions. Overall, despite the data limitations described above, it is evident that the results of any spatial analysis strongly depend on the spatial scale of the dataset (Amoroso et al., 2018b) and highlights the importance of data resolution when estimating and considering fishing impacts. Therefore, with finer spatial resolution of effort data, combined with sediment maps and OC content estimates, quantification of disturbance to sediment OC are likely to improve.

Our analysis of fishing impacts on the living OC stock is focused on hake biomass only, due to the data available. Including dynamics between the target species, competitors, predators, and prey would improve the analysis and better inform management of living OC stocks under different fishing conditions. Consideration of the fishing impacts on bycatch and, when assessing a mixed fishery such as hake, other target species would be necessary, thus reporting catch composition and bycatch by segment would enable a more thorough analysis of fishing impacts on living OC stocks. Furthermore, better understanding and incorporation of a target species' natural history and trophic dynamics into the analysis could shed further light on the impact of fisheries on OC in living stocks. For instance, consideration of the age at which a species is fished may provide insights on the longevity of the OC stock in that population. The recorded maximum longevity for hake ranges from 20 to 25 years (Vitale et al., 2016); if individuals live for 20 years, they can effectively store OC for two decades. Hake occupies different trophic levels as their diet changes throughout their life stages, thus the prey controlled by juvenile and adult hake are different. Adult hake over 30cm in length, which are the target of hake fisheries, prey on demersal fishes such as blue whiting and, where adult and juvenile hake distributions overlap, they show a preference for cannibalism (Mahe et al., 2007). Removal of large hake may therefore release smaller hake from predation, increasing the chances that juveniles will reach adulthood and recruit to the fishery, while a reduction in fishing pressure on larger hake could have the opposite effect (Mahe et al., 2007). At the same time, larger hake females may facilitate faster rebuilding where stocks are depleted, as they have a higher fecundity than smaller hake females and produce more eggs (Cerviño et al., 2013). Overfishing of predators can cause widespread changes in the ecosystem as prey are released from predation, with implications extending beyond the biomass of the target population, to food webs, habitats, and ecosystem services (Östman et al., 2016; Norderhaug et al., 2021). While they are not considered a deep-sea species, hake can be found at depths down to 1000m (Morales-Muñiz et al., 2018), thus may provide a link between shallower and deep sea habitats, which play a key role in global ecological and biogeochemical processes (Danovaro et al., 2008).

The objectives of this study were to explore how ending overfishing of hake and stock recovery affected (i) the carbon emissions from fuel use during fishing activity; (ii) disturbance of OC in sediments by trawling; and (iii) impacts on the OC stocks in the population of the target species. Earlier analysis of emissions from the hake fishery in Spain considered the entire life cycle of the fishery, from extraction to processing and consumption (Vázquez-Rowe et al., 2011). However, our approach was to consider the fishery from the perspective of EAF, and thus, the only fuel emissions we considered were those caused by fishing activity directly. Our study was also limited to a snapshot view of fisheries impacts when the hake stock was depleted, in 2008, and rebuilt, in 2016. As such, we did not seek to establish the reasons for stock depletion and recovery, thus, the effects we report are not necessarily a product of ending overfishing. However, it is likely that reduced fishing pressure, required by the recovery plan introduced in 2004, contributed to the increase in hake biomass of the Northern stock (Baudron and Fernandes, 2014).

Exploration of the OC impacts of fisheries is timely given that the interaction between trawl fishing activity and sediments is increasingly recognised as an important impact for consideration in EAF (De Borger et al., 2021); recent research has highlighted the roles of fish in the carbon cycle and flux (Bianchi et al., 2021; Saba et al., 2021); and there is significant overlap between fishing grounds and areas of high productivity (Cavan and Hill, 2021). Furthermore, EU targets to end overfishing by 2020 have not been met, yet overfishing is known to affect the resilience of fish stocks to climate change and other stressors (Sumaila and Tai, 2020). During this study, we used only publicly available fisheries data and, as such, found various limitations which have resulted in unreliable estimates, particularly for SA and OC in hake stock. Improving the reliability and accuracy of estimates is necessary. Ensuring that data can be consistently disaggregated across public databases, such as by country, fishery segment, BENTHIS métier, effort, and landings, would go a long way toward improving the accuracy of estimates of the impacts of fishing on landed populations and the environment. In addition, spatial data at finer scale resolutions than ICES rectangles are especially important for generating estimates of impacts on benthic environments.

The need for EAF which can lead to better outcomes for climate, biodiversity, and people is widely recognised but not easily operationalised (Link et al., 2020). Climate-based fisheries management must go beyond a target of MSY to include climate-based objectives in EAF. This would, presumably, call for management decisions based on consideration of emissions from fuel, disturbance to OC in sediments and living pools, and the carbon functions of the ecosystem. Reference levels for what constitutes sustainable fishing and desirable stock size could then be decided across priorities, such as carbon sequestration, harvest, ecosystem health, and social and cultural facets. This analysis represents a first step towards ensuring that relevant information from emerging fields of research can be included in the development of EAF approaches and has illuminated some of the complexity involved when using publicly available data to assess fisheries impacts on ecosystems.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study and are referenced. The data provided by STECF (2020b) upon our request can be found here: https://github.com/angela-m/Hake-fishery-recovery-and-climate.

AUTHOR CONTRIBUTIONS

AM, EF, and SV contributed to the initial discussion. AM and EF led the writing of the manuscript. AM, EF, CH, and KB designed the figures and compiled the tables. All authors contributed to the literature survey, drafted and reviewed the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.788339/full#supplementary-material

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Resilience and Social Adaptation to Climate Change Impacts in Small-Scale Fisheries

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Small-cale fisheries are important for livelihoods, food security, jobs and income worldwide. However, they face major challenges, including the increasing effects of climate change that pose serious risks to coastal ecosystems and fishing communities. Although scientific research on climate change impacts has increased in recent years, few studies have explored the social impacts on small-scale fisheries. Using Galicia (Spain) as a case study, we investigated individual and household-level adaptive responses to climate change among fishers in three fishing guilds (Cambados, Campelo, and Redondela). Specifically, we estimated the economic vulnerability of shellfishers and assessed the diversity of social adaptive responses used to deal with climate change. Although fishers' income strongly depends on shellfishing in all studied areas, our findings show that less fishing experience and lower engagement in fisher associations tend to increase the economic vulnerability of the fishers. The fishers' vulnerability decreases as the size of households increases, while fishers who pay a mortgage and who live in households with fewer active members tend to be more vulnerable. The findings also show that Galician shellfishers have developed a wide range of adaptation strategies to anticipate and respond to climate change impacts, namely harvesting pricier and more abundant species, reducing household expenses and increasing social involvement in shellfishery associations. Although the adaptive strategies have helped Galician fishers to deal with climate change impacts, several threats to the sustainability of shellfisheries remain, such as a decrease in the abundance of key native shellfish species, and a high dependence on public and private aid to ensure reasonable incomes for shellfisheries. These findings are of interest and relevance to other similar small-scale fisheries around the world facing similar climate change challenges.

Keywords: artisanal fisheries, climate change, vulnerability, social adaptation, Galicia, Spain

INTRODUCTION

It has been estimated that the average temperature has increased by 0.2°C per decade over the past 30 years and that by 2017, anthropogenic activities had led to an increase in temperature of 1.0°C relative to pre-industrial levels (IPBES, 2019). Recent climate change projections predict an increase in the average atmospheric and seawater temperatures as well as increases in the intensity, duration and frequency of heat waves and extreme events (Hoegh-Guldberg et al., 2018; Oliver et al., 2018). Extreme sea level events will become more frequent and more intense, leading to more coastal flooding and a shoreline retreat throughout the 21st century along sandy coasts (IPCC, 2021).

In the case of the Atlantic coast of Europe, predictions indicate an increase in the frequency and intensity of heat-waves and extreme precipitation that will modify coastal salinity (Carvalho et al., 2021), mainly affecting estuarine areas. Although total precipitation is expected to decrease in the December-February period (IPCC 2021 Regional fact sheet - Europe), predictions suggest that it is expected to increase in the most recent IPCC report on the NW Iberian Peninsula, (IPCC WGI Interactive Atlas, https://interactive-atlas.ipcc.ch). All of these predicted changes will alter terrestrial and marine ecosystems, modifying community structure and functioning in addition to causing loss of biodiversity and livelihoods (Hawkins et al., 2009; Selden and Pinsky, 2019). This is especially true in coastal areas that are exposed to the impact of both climate change-related stressors and human activities (He and Silliman, 2019). In particular, intertidal fishing beds in estuarine areas are considered among the ecosystems expected to be most affected by the effects of increases in temperature, decreases in salinity, inorganic and organic inputs, and changes in sediment dynamics and currents, among many other stressors (Mieszkowska et al., 2013).

Research is increasingly considered key to understanding the climate change adaptation practices developed and adopted by fishing communities (Shaffrill et al., 2017). In adaptation processes there is a high degree of interdependence between the various agents involved, the institutions in which they are based, and the fishery resources on which they depend (Adger et al., 2009). Adaptation processes involve the interdependence of agents through their relationships with each other, with the institutions in which they are based, and with the fishery resources on which they depend (Adger et al., 2009). There is an urgent need to understand the social-ecological processes of adaptation strategies of the various agents of change – individuals, groups and markets – to anticipate their limitations (Adger, 2010).

While adaptation in human systems is defined as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (IPCC, 2019), adaptive capacity has been broadly defined as the conditions that underpin people's ability to anticipate and respond to change, to recover from and to minimize the consequences of change and, if possible, to take advantages of new opportunities (Smit and Wandel, 2006). Understanding the vulnerability and resilience (including social aspects) is important for the sustainability of SSFs (Folke, 2006). This could help both the scientific community and policy makers to minimize the underlying causes of social vulnerability, when dealing with social-ecological shocks and crises (Cinner et al., 2012; Villasante et al., 2021; Villasante et al., 2022).

The need to support the role of SSFs in livelihoods and food security has been recognized in various countries through adoption of the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (FAO, 2015). More recently, the United Nations launched the Decade of Ocean Science for Sustainable Development, which is expected to shed more light on the need to manage fisheries sustainably in order to support community well-being and food security (Claudet et al., 2020).

The socio-economic situation of fishers is closely related to the effects of the changing climate (Da Rocha et al., 2014), as more unpredictable or insufficient income can limit fishers' abilities to deal with impacts, such as decreasing stocks (Cinner et al., 2012; Barnes et al., 2020). Recent reviews on how marine systems and fisheries adapt to the impacts of climate change highlight the lack of examples of specific adaptation actions and measures (Miller et al., 2018). In this context, SSFs remain largely overlooked in the scientific literature (Hanich et al., 2018). Several studies have been conducted to analyze adaptation to climate change in SSFs. For example, Monirul Islam et al. (2014) examined limits and barriers in relation to restriction of fishing activities to cyclones in Bangladesh. They authors found that the limits include physical characteristics of climate and sea such as higher frequency and duration of cyclones and hidden sandbars, while barriers include, among others, inaccurate weather forecast, technologically poor boats, lack of access to credit and markets, low incomes, lack of livelihood alternatives and poor enforcement of fishing regulations. Frawley et al. (2019) also investigated the heterogeneous perceptions of social-ecological change among small-scale fishers in the central Gulf of California, and they concluded that gear ownership and target species diversification were key factors in determining the cultural models through which fishers responded to changes in the resource system. More recently, Green et al. (2021) conducted a meta-analysis to evaluate how responses to climate, environmental, and social change are influenced by domains of adaptive capacity in SSF of 20 countries, and founded that adaptive responses at the community level only occurred when the community had access to assets, in combination with other domains including diversity and flexibility, learning and knowledge, and natural capital. Galappaththi et al. (2021) also analyzed how fisheries-dependent indigenous communities respond and adapt to climate change impacts in Canada and Sri Lanka. The authors found that diversification and co-adaptive capacity were the key common main strategies adopted by artisanal fishers in indigenous communities. Finally, Gianelli et al. (2021) analyzed changes in a warming hotspot and the associated impacts on the clam fishery in Uruguay. Given the data-poor situation of most SSFs in developing countries often hinders a proper dimensioning of the extent of climate-induced changes, the study combined scientific and local ecological knowledge and found that the combination of autonomous adaptations and government-led adaptations were essential to face the challenges imposed by climate change.

Although previous studies have provided recommendations for climate change adaptation in a range of communities, few, if any, of these have focused on social adaptation in fishing groups or communities. Therefore, evidence and a better understanding of adaptation strategies for dealing with the changing climate are crucial from a policy-making perspective (Shaffrill et al., 2017).

The situation of the bivalve fisheries in Galicia (NW Spain) is representative because it is one of the most significant fishing resources in Europe in terms of landings (FAO, 2018) and, more importantly, in terms of local-scale socio-economics (Macho et al., 2013). The most important species in these fisheries are the native pullet carpet shell *Venerupis corrugata* (Gmelin 1791) and grooved carpet shell *Ruditapes decussatus* (Linnaeus 1758), the introduced Manila clam *Ruditapes philippinarum* (Adams and Reeve, 1850), and the native cockle *Cerastoderma edule* (Linnaeus 1758). These four species support the largest artisanal fishery in Spain in terms of landings and employment (~7,9 Tm of bivalves worth ~74 millions of euros and ~7,100 fishers in 2019) (www.pescadegalicia.com, accessed January 2020). However, these fisheries experience large spatial and temporal variations in catches (Juanes et al., 2012) that have been associated with strong fluctuations in environmental conditions such as temperature and salinity (Parada and Molares, 2008; Parada et al., 2012; Aranguren et al., 2014; Verdelhos et al., 2015).

Rights-based regulatory regimes, under which most of the Galician shellfishing is managed (Pita et al., 2019), seem to be relatively resilient to the consequences of climate change (Ojea et al., 2017). Nevertheless, the threats are numerous and growing. Variations in temperature and/or salinity, even within the limits of tolerance of each species, can constrain most physiological processes, such as growth and reproduction (Macho et al., 2016; Peteiro et al., 2018; Domínguez et al., 2020; Domínguez et al., 2021; Vázquez et al., 2021), and also behavior (Woodin et al., 2020). The associated constraints may lead to a recruitment failure in adult populations or delays in the time required for the species to reach commercial sizes. Future climate scenarios in Galicia predict an increase in atmospheric temperature above the world average and also an increase in the frequency and duration of extreme temperature events (Bode et al., 2009). However, no clear trends in precipitation have been observed annually (Gómez-Gesteira et al., 2011), although the average intensity of rainfall events has been projected to increase in winter and spring (Cardoso Pereira et al., 2020).

Although social and sanitary improvements can help mitigate the effects, increasingly intense heat-waves will negatively affect the health of the Galician population, especially during the summer (DeCastro et al., 2011). Summer humidity levels have also increased, and are expected to increase further, reducing outdoor comfort conditions, especially for women, who may be more sensitive to such changes (Orosa et al., 2014). Therefore, the increases in heat and humidity are expected to have strong impacts on shellfishing, which is mainly carried out by women in Galicia (Frangoudes et al., 2008; Frangoudes et al., 2013; Villasante et al., 2021). Moreover, many intertidal fishing beds are at a high risk of flooding, which will have severe effects on different bivalve populations and on the people who depend on their capture through the entire value chain (Toubes et al., 2017).

Although the Galician population perceives climate change as a major problem and shows a willingness to address it through active policies (Arcos et al., 2011), there is relatively little evidence about the social and economic consequences of climate change, or about the ecological implications of these impacts. Available evidence on the economic impacts of climate change in coastal activities of Galician coasts includes the increase of the number of large cargo ports (León-Mateos et al., 2021) and increased tourism (Toubes et al., 2017). The socioeconomic vulnerability of some fisheries, e.g. the European pilchard *Sardina pilchardus* (Walbaum, 1792) (Pérez Muñuzuri et al., 2009; Da Rocha et al., 2014), and even some SSFs like the goose barnacle *Pollicipes pollicipes* (Gmelin, 1789) (Ruiz-Díaz et al., 2020), have also been evaluated, leading to the development of adaptation strategies. However, there is a widespread lack of attention in climate change research to many components of social-ecological systems (hereinafter SES) related to Galician SSFs, especially regarding synergies and trade-offs between socio-cultural and ecological domains (Salgueiro-Otero and Ojea, 2020; Villasante et al., 2021). The historical closeness between the Galician population and fishery resources has been able to promote strong integration of the shellfishery sector into the Galician social norms and cultural traditions-, as already observed in other regions that are highly dependent on fishing activities, such as Bretagne and the Basque Country (Villasante et al., 2021).

Despite the increasing interest in the impacts of climate change in Galician SSF (including shellfisheries), economic vulnerability and social-ecological adaptation strategies are still largely unknown. This present study addresses this research gap. The specific aims of the study were twofold: (1) to estimate the economic vulnerability of shellfishers, and (2) to assess the diversity of social adaptive responses used by shellfisheries to deal with climate change. This research will contribute to providing information about the multiple strategies that enable or hinder potential solutions towards sustainable SSF.

MATERIALS AND METHODS

Study Area

The study area, Rías Baixas, is located NW in the Iberian Peninsula between 42°30 and 42°15 N and 8°45 and 8°56 W (**Figure 1**). The rias are partially mixed estuaries with a mesotidal

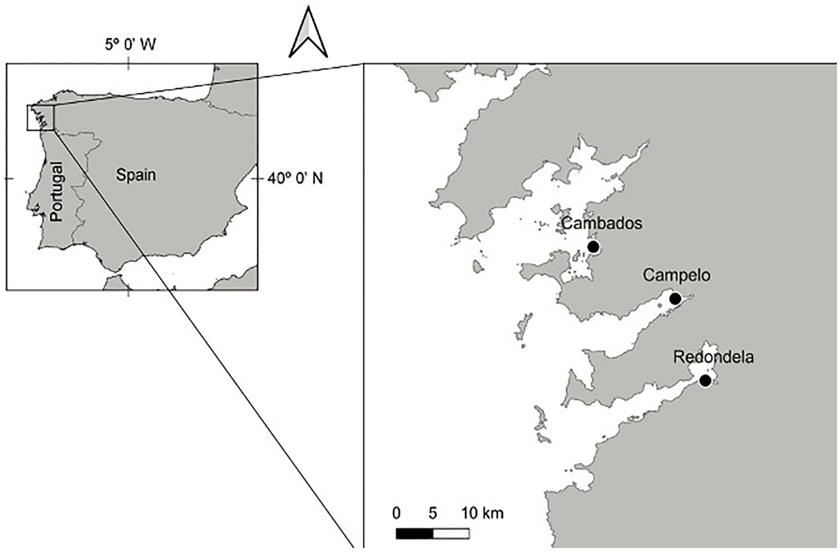

FIGURE 1 | Map of the Galician rias, highlighting the location of Cambados, Campelo and Redondela fishing guilds.

and semidiurnal regime. The hydrography in the inner part of the rías, where the fishing beds are located, is driven by two opposing processes: a continental water supply *via* the main rivers Umia and Ulla in the Ría de Arousa, Lérez in the Ría de Pontevedra and Oitavén-Verdugo in the Ría de Vigo (the mean freshwater input ranges between 20 and 26 $m^3 s^{-1}$, Costa et al., 2012), and an oceanic influence *via* upwelling of East North Atlantic Central Water in summer and the influence of the Iberian Poleward Current in winter (Prego et al., 2001). Important fluctuations in temperature and salinity occur as a result of these hydrographic conditions (Alvarez et al., 2005; Costa et al., 2012).

This region was chosen for study on the basis of socioeconomic and fishing aspects in order to compare the profile, economic vulnerability and fishers' adaptation strategies in different locations. We worked with three shellfishery associations, Cambados, Campelo and Redondela, which operate in the main shellfishing region in Spain and Europe (**Figure 1**). The shellfish beds exploited by these associations are located in areas where fishers must adapt their activities to the particular oceanographic conditions (temperature, current, salinity). Thus, the shellfish beds situated in the mouth of the cited rivers are more exposed than other areas to the effects of climate change in winter, because of heavy rains in winter, which cause acute decreases in salinity and because of exposure to the sun at low tide during heat-waves in summer. From a socioeconomic perspective, the three locations are strongly dependent on fishing activities, and the shellfish products are recognized as high quality, both nationally and internationally. However, the organization of the fishers' activities differ among shellfishery associations, due to their different business strategies, productive specialization and different market segmentation.

In order to prevent the overexploitation of the shellfish beds, the Spanish Regional Government limits the catches of fishers by implementing daily quotas. Thus, the fishers' incomes depend on their individual work (number of captures with the maximum daily quota) valued at the market price each day (Macho et al., 2013). The effectiveness of the extractions depends on each fisher's strategy, but also on the biophysical conditions of the environment and the organizational strategies developed by members of shellfishery associations (Villasante et al., 2021). In some associations, collaboration is usually generated almost spontaneously, while in others opportunistic behaviour is more frequent, conditioning the final performance of shellfishers. In this sense, collaboration between fishers belonging to shellfish associations has a multiplying effect, as these organizations have close links with suppliers, purification plants, restaurants and the canning industry. However, failure in adaptation to climate change can affect the economic productivity of the whole sector, and could also lead to the overexploitation and future depletion of resources, with potentially severe socio-economic consequences on vulnerable fishers' families.

Data Collection

We designed a semi-structured questionnaire to investigate the economic vulnerability and adaptation strategies used by fishers. The data were collected by the co-authors of this study between May- and July 2019 at the locations of the three shellfishery associations. The content of the questionnaire protocol was structured in four parts to collect information on key topics related to the impacts of climate change on shellfisheries (see the questionnaire in detail at Appendix I of the **Supplementary Material**):

-Part A (*Personal information and knowledge about shellfisheries*): Each interview began with questions to obtain information about years of experience working as shellfishers, and age, residence, education, occupation, household composition, income from shellfisheries, dependency on public and private aid, and main commercialized commercial species fished;

-Part B (*Adaptive strategies to deal with climate change*): shellfishers were also asked to indicate their perception of (a) biological changes in key attributes of species (e.g. mortality, length, abundance, presence of invasive species, etc.), on (b) which factors improved or worsened during the last decade (e.g. status of shellfisheries resources, contamination, organizational changes of associations, red tides, ex-vessel prices, etc.), and (c) the strategies developed by the shellfishers and their families;

-Part C (*Climate change impacts and future scenarios*): the interviewees were asked their opinion about predictions, suggesting that abundance of shellfisheries (except the Manila clam) will decrease in the near future (Domínguez et al., 2020; Domínguez et al., 2021; Vázquez et al., 2021), and what fishers would do if these predictions come true;

-Part E (*General opinion*): the interview concluded with an open, and general question to determine what other changes and/or measures could help to reduce the impacts of climate change on shellfisheries.

The questionnaire was designed in a multiple choice format with a five-point (Likert) response scale. We also designed a protocol that guided the data collection and the general procedures and rules of use, following Yin (2014). Researchers collected internal data from fishers through face to face meetings in the offices of the fishers´ associations. The researchers provided the interviewees with: (1) an initial explanation of the general purpose of the project and its academic and professional applications and (2) a copy of the questionnaire designed to investigate climate change impacts on shellfishing activities and social adaptive strategies developed by fishers. The researchers supported the interviewees by providing any clarifications required and controlled the researcher-bias during the data collection process. Fishers were randomly selected from a complete list of the members of each association previously identified by their leaders using the purposive sampling method (selection of a simple random sample from the sampling frame of each previously identified association) (Marshall, 1996; Agresti and Finaly, 2014). The participants have been selected ensuring a diverse representation of shellfishers of different ages (young and older), years of experience in roles (e.g. President, Secretary, etc.), and activity (e.g. shellfishing, seabed cleaning, surveillance, etc.) within the associations. Hence, our results should be interpreted as indicative of these areas, rather than of all fishers.

Researchers involved in the data collection process maintained the chain of evidence, following the sequence of selection of the sample, initial information and data collection. This allowed us to reconstruct the context in which the evidence was obtained (Villarreal, 2017). After the data collection phase, we classified the data, constructed a database and analyzed these data using the rules of validity, reliability and consistency recommended by Yin (2014).

Defining Fishers' Economic Vulnerability and Adaptive Responses to Climate Change

Small-scale fishers are considered among the most vulnerable socio-economic groups owing to their high exposure to certain natural, health-related and economic risks and shocks (Bennett, 2009; Silva et al., 2019). Consideration of this status provides a useful starting point for analyzing vulnerability in fishers' livelihoods, including economic vulnerability. Vulnerability can be assessed through a combination of exposure and sensitivity that represent the susceptibility to harm from a given environmental change, and the ability to cope with this change through learning (Bennet et al., 2016). Vulnerability is difficult to assess due to its complexity and context-specific nature, however, carrying out vulnerability assessments at the local level may help because this is the level where impacts are generally felt (Hinkel, 2011).

Fishers' economic vulnerability was calculated on the basis of four variables: 1) capture of the daily quota, 2) trends in income in the last 10 years, 3) trends in income considering future climate change scenarios, and 4) the minimum income leading to abandonment of shellfisheries. The variables used to estimate the economic vulnerability of fishers are summarized in **Table 1**, along with the qualitative approach used to score each variable. The summed value of those four variables was used to create an individual index of economic vulnerability, ranging from 0 (lower vulnerability) to four (higher vulnerability). The economic vulnerability increased with the value of the index.

Following the definition of the variables, the diversity of adaptive responses was identified on the basis of five adaptation situations regarding regime shifts in the shellfishery (e.g. capture of daily quota, social-ecological changes, decreasing income scenario, and abandonment of shellfishing activity). Thus, one point was awarded for each individual who chose at least one adaptation strategy in each of the five situations (see **Table 2**), and the average value was considered used as the diversity of adaptive responses. By contrast, if a fisher did not choose any strategy, no points were awarded.

Fishers were asked about the strategies used to adapt to the impacts of climate change, which included capture of daily quotas, social-ecological changes, decreasing income, and being forced to abandon shellfishing. The fishers were asked about what they would do if they were forced to abandon shellfisheries, with options including changing to another fishing activity or to a different occupation. Fishers could choose among adaptation strategies in each situation, and they could choose more than one option (**Table 2**).

Statistical Analyses

To analyze differences in socioeconomic and fishing aspects among the study areas, non-parametric tests were performed (Neter et al., 1996). Specifically, the Kruskal-Wallis was used with Bonferroni test and Chi-square test to check for any differences in fishers' age, fishers' experience, the household size, the number of household members employed, education level, fisher and

TABLE 1 | Description of the variables used to estimate fishers' economic vulnerability.

Variable	Description	Scores
Capture of daily quota	When fishers do not catch their daily quota their earning capacity decreases (Lucchetti et al., 2014). This limited economic benefit may be seen as making it difficult for fishers to subsiste and increases their economic vulnerability.	Capture daily quota = 0 points (not vulnerable) Do not catch daily quota = 1 point (vulnerable)
Historic income trends	Fishers are socio-economically very vulnerable due to the environmental changes in coastal areas (Bhashani et al., 2021). This leads to the degradation of the local economy and further affects the earnings of many fishers. Here, fishers' classified trends in historic income trends based on the last 10 years as decreasing, no change and increasing. Considering that decreasing trends or no change in income may be associated with economic vulnerability, a score ranging from 0 (no economic vulnerability) to 1 (economic vulnerability) was associated with this quantitative categorization.	Increasing trend = 0 points No change = 0.3 points Decreasing trend = 1 point
Income change due to regime shifts	Regime shifts may influence variation in seasonality of landings due to changes in fish stocks (Barange et al., 2018; Ma et al., 2019). Uncertainty in catch rates may lead to a decrease in the fishing income (Sumaila et al., 2011), increasing the economic vulnerability of fishers. This variable was thus classified in the same way as the previous one, with scores ranging from 0 (no economic vulnerability - increasing trend) to 1 (economic vulnerability - decreasing trend).	Increasing trend = 0 points No change = 0.3 points Decreasing trend = 1 point
Minimum income leading to abandonment of shellfisheries	The three areas were classified on the basis of the lowest income cited by fishers enabling them to remain in the shellfishery sector, and on the minimum wage in Spain for the period of 2017 (RelCAZ, 2017; www.reicaz.es). The minimum wage in 2017 was 707 € and the minimum income forcing fishers to abandon shellfisheries in Cambados, Redondela and Campelo was respectively 548 €, 438 €, and 606 €. Thus, Redondela showed the highest economic vulnerability, Cambados moderate economic vulnerability and Campelo the lowest economic vulnerability.	Redondela = 1 point (high vulnerability) Cambados = 0.6 points (moderate vulnerability) Campelo = 0.3 points (low vulnerability)

Source: own data.

household shellfisheries dependencies, income trends, and daily limit achievement between the three areas. Fisher's exact test was used for small sample sizes, including zero values, as the Chi-square test is generally used for larger counts (Larntz, 1978).

Linear Mixed-Effect Models (LMMs) were used to analyze the influence of socioeconomic aspects (independent variables) on the diversity of adaptive response of fishers (dependent variable). The independent variables used were levels of income dependency on shellfishing (<50% of income, between 50% and 75% of income, and >75% of income), fishers' age, size of household, fishers' educational level, social involvement in shellfishery associations (yes = involved; no = not involved), public and/or private financial assistance, and the economic vulnerability of the fishers. The LMM allows the inclusion of random effects, which may explain a potential source of variation on the response variable (Pinheiro and Bates, 2000). Thus, the variable area, i.e. shellfishery association, was included as a random effect to prevent remaining variation due to particular site-related factors. The collinearity between explanatory variables was evaluated using the Variance Inflation Factor (VIF), which indicated low correlation between the predictors; variables with VIF < 5 were included in the final model.

Following model selection, a model averaging approach based on a subset of competing models with a cumulated weight of 95% (Burnham and Anderson, 2002) was applied to LMMs (**Appendix 2**). This procedure was used because the differences between models in the model selection procedure were small. Model averaging analysis allows examination of the relative importance values (I) of variables, which vary from zero (less important) to one (more important). This indicates the effect size of relevant variables explaining the diversity of adaptive responses of fishers in the averaged model.

Variables were checked for homogeneity of variance (Shapiro-Wilk normality test) and explanatory variables were z-standardized to allow comparisons between effect sizes. All analyses were carried out using R software (R Core Team, 2018),

FIGURE 2 | Images of **(A)** women harvesting on foot in shellfish beds located in the Galician "rias", **(B)** the rake-like fishing gear called "raño", and **(C)** the most common shellfish species manila clam, cockle, grooved carpet shell, and pullet carpet shell.

the 'lme4' package was used to fit the LMM (Bates et al., 2015), and the 'MuMIn' package was used for model averaging (Barton, 2013).

RESULTS

Fishers' Profile

We interviewed 245 shellfishers in three areas in Galicia: Cambados (N = 65; 32% of all shellfishers), Campelo (N = 125; 54%) and Redondela (N = 55; 43%) (**Figures 2A–C**). The majority of the fishers were women, only 8% of fishers were men (which is consistent with the gender distribution in the shellfishing population). The fishers were between 26 and 65 years old (48 ± 9 years), with an average fishing experience of 13 years (± 12 years).

The age of fishers differed between areas (KW=6.274, df = 2, p= 0.04); fishers in Cambados were older than those in Campelo and Redondela. However, despite the differences in age, fishers from the three areas had the same fishing experience (μ = 13.47 years). The size of households including fishers was around 3.5 members, with the average number of active members around 1.5 members. Less than half of employed members were involved in fishing activities in the three areas: 25% in Cambados, 23% in Campelo and 31% in Redondela (**Table 3**). Educational level was similar in the three areas; fishers had an average of 14 years of education. In all three areas, most fishers did not participate in shellfishery associations. The household size (KW=0.216, df = 2, p= 0.89), the number of employed members per household (KW=3.426, df = 2, p= 0.18), and fishers' educational level (Chi-squared=7.416, p=0.29) were similar in the three study areas.

The proportion of fishers who had a mortgage was about 50% in Campelo, about 34% in Cambados and 25% in Redondela. More fishers in Redondela (52%) received at least one month of economic aid (social security benefit) from the government in the last ten years, followed by the fishers in Campelo (50%) and Cambados (41%). The most important target shellfish species were Manila clams and cockles, which represented more than half of landings in the studied areas (**Table 3**). Regarding the trend in abundance of bivalve species, the findings of the study revealed the perception of an increased abundance of all four species in the last ten years by the Cambados shellfishery association. In particular, the Manila clam (*R. philippinarum*) is more abundant than the rest of the other key commercial species (**Figure 3**).

Individual fishers' dependency on income from shellfishing was similar among areas; fishers from the three areas earned more than 75% of their income from shellfisheries (**Figure 4A**). On the other hand, households' dependency on shellfishery was

TABLE 2 | Situations and adaptation strategies cited by fishers in each study area: Cambados, Campelo and Redondela.

Situation/adaptation strategies	Area			Citations (total)
	Cambados	Campelo	Redondela	
Daily catch limit achievement				
Focus on higher value species	**3**	**23**	14	40
Focus on more abundant species	2	18	**21**	**41**
Focus on species easier to catch	2	16	11	29
Other strategies	3	1	0	4
No strategy/No answer	5	17	17	39
Social-ecological changes – Fishers				
Other formal activity	6	13	7	26
Informal activity	2	16	6	24
Greater social involvement	22	17	13	52
Lower social involvement	2	2	5	9
Reduction of household expenses	**24**	**33**	**24**	**61**
Increase household expenses	1	7	3	11
Other strategies	1	2	0	3
No strategy/No answer	6	9	1	16
Social-ecological changes – Family				
Abandonment of children's further studies	0	1	0	1
Incorporation of children in shellfisheries	2	4	1	7
Incorporation of husband/wife in shellfisheries	0	1	**2**	3
Family or public financial assistance	1	**17**	**2**	**20**
Loans	**5**	13	1	19
Migration	1	2	0	3
Other strategies	5	4	4	13
No strategy/No answer	10	11	17	38
Decreasing income scenario				
Keep working on shellfisheries	**26**	11	**11**	**48**
Change target species	15	7	10	32
Change to another fishing activity	4	3	4	11
Change to a different occupation	1	**16**	7	24
Migration	0	4	1	5
Other strategies	0	0	6	6
No strategy/No answer	2	3	1	6
Forced to abandon shellfishing activity				
Change to another fishing activity	11	11	5	27
Change to a different occupation	12	**25**	**17**	**54**
Other strategies	**14**	3	4	21
No strategy/No answer	12	3	0	15

The cited strategies were divided among the five situations of adaptation to capture of daily quota, social-ecological changes, decreasing income, and forced to abandon shellfishing. The most commonly cited strategies are highlighted in bold.

different between areas: dependency on shellfishing was highest in households in Redondela (less than 50%), followed by those in Campelo and Cambados (Chi-square=9.932, df = 4, p= 0.04, **Figure 4B**). Fishers' economic vulnerability ranged from 0.3 to 3.6 (μ = 1.96); the mean score was lowest for Cambados (1.69), followed by Campelo (2.20) and Redondela (2.07). Fishers in Campelo were more vulnerable than fishers in Cambados and Redondela (KW = 10.18, df = 2, p-value = 0.006).

Captures of the daily quota also differed between shellfisheries (Chi-square =28.8, df = 2, p= 0.00, **Figure 4C**); fishers in Redondela tended to not capture the full daily quota. The fishers in Cambados explained that their income had increased in the last 10 years, but fishers in Campelo and Redondela perceived that their income had decreased, or it had not changed (Chi-square =66.56, df = 2, p= 0.00, **Figure 4D**). This was mainly due to the increasing abundance of Manila clam and pullet carpet shell in Cambados, relative to the other shellfisheries. In addition, most fishers in the three areas anticipated that their income would decrease due to the impacts of climate change on the shellfishery system (**Figure 4E**).

The Diversity of Adaptive Responses to Climate Change

In general, fishers tended to focus on catching more abundant species when they did not capture their full daily quota. When asked about social-ecological changes, fishers tended to reduce household expenses and to ask for family or public financial aid. In a scenario of decreasing income, most fishers answered that they would keep working in shellfisheries. However, some fishers suggested other strategies to deal with the lower-income situation: to apply for government aid, to catch new species, to find a better job or to retire.

More than 50% of fishers in Campelo and Redondela declared they would abandon shellfisheries if their income decreased. Fishers would abandon shellfisheries if income decreased to average values of 548 € in Cambados (minimum 300 €/maximum 800 €),

TABLE 3 | Socioeconomic and fishery aspects of shellfisheries in three study areas in Galicia: Cambados, Campelo, and Redondela. N, number of fishers; μ, Mean; ±, standard deviation. Main species landing = percentage of landing species (on foot + on boat).

Socioeconomic and shellfishery aspects	Fishing Guilds		
	Cambados (N=65)	Campelo (N=125)	Redondela (N=55)
Age (μ years)	51 (± 8.3)	46 (± 9.2)	48 (± 8.8)
Schooling (μ years)	18 (± 2.8)	14 (± 2.6)	15 (± 2.8)
Fishing experience (μ years)	15 (± 10)	11 (± 12.7)	15 (± 14.6)
Number of people per household	3.4	3.5	3.5
Number of household members employed	1.3	1.6	2
Participation in shellfishery association (%)	20	2	17
Mortgage payment (%)	34	52	24
Social security benefits[a] (%)	41	50	52
Main species landing (%)	*Manila clam (41)*	*Cockle (36)*	*Manila clam (40)*
	Cockle (28)	*Manila clam (26)*	*Cockle (35)*
	Grooved carpet shell (18)	*Pullet carpet shell (22)*	*Pullet carpet shell (18)*
	Pullet carpet shell (12)	*Grooved carpet shell (16)*	*Grooved carpet shell (8)*

[a]*Social security benefit was calculated on the basis of the average value of the total number of months during which fishers received public assistance during the last 10 years. For the three areas, the median value was around one month. Thus, we considered one month as key assistance to the fishers for this region.*

606 € in Campelo (minimum 300 €/maximum 1000 €) and 438 € in Redondela (minimum 200 €/maximum 700 €). In addition to an unprofitable situation, fishers would abandon shellfishery activities due to illness, retirement or better job opportunities. The alternative occupations cited by the fishers if they had to abandon shellfisheries were similar between areas, with construction, teaching, politics, nursery, agriculture and tourism being the most common alternatives. In addition, fishers from the three areas cited economic issues and lack of education as important in regard to starting a new activity if they were forced to abandon the shellfisheries. Social-ecological aspects, such as the status of fishing resources, ecosystem conditions and management issues, were cited as main needs only in Campelo and Redondela.

The average LMM explained around 45% of the variation in the diversity of adaptive responses of fishers, and included area as a random effect, fishers' economic vulnerability, age and dependency on shellfishery income as the most important

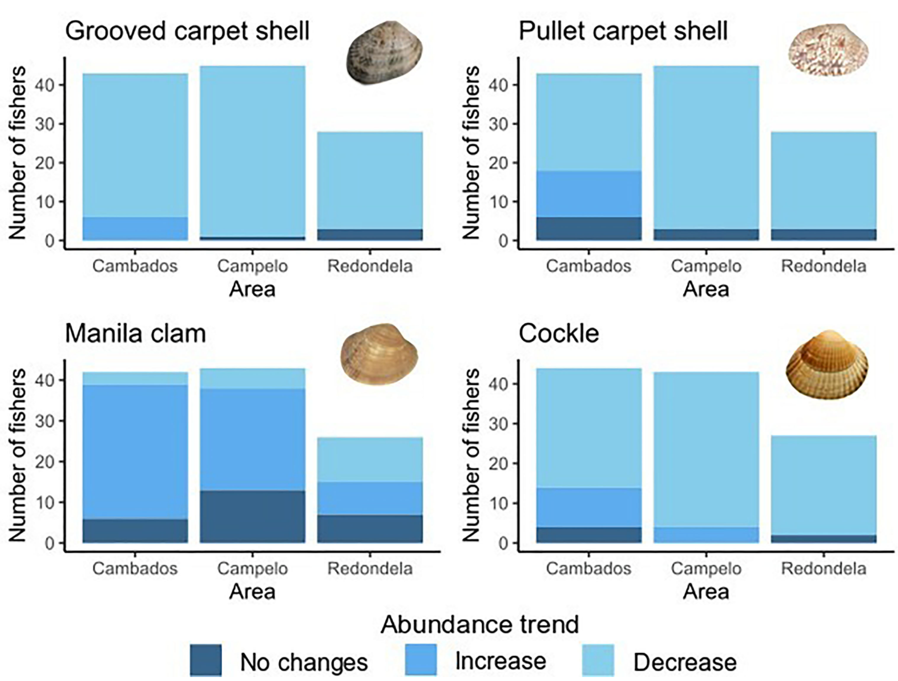

FIGURE 3 | Fishers' perceptions about the abundance of key commercial shellfish species.

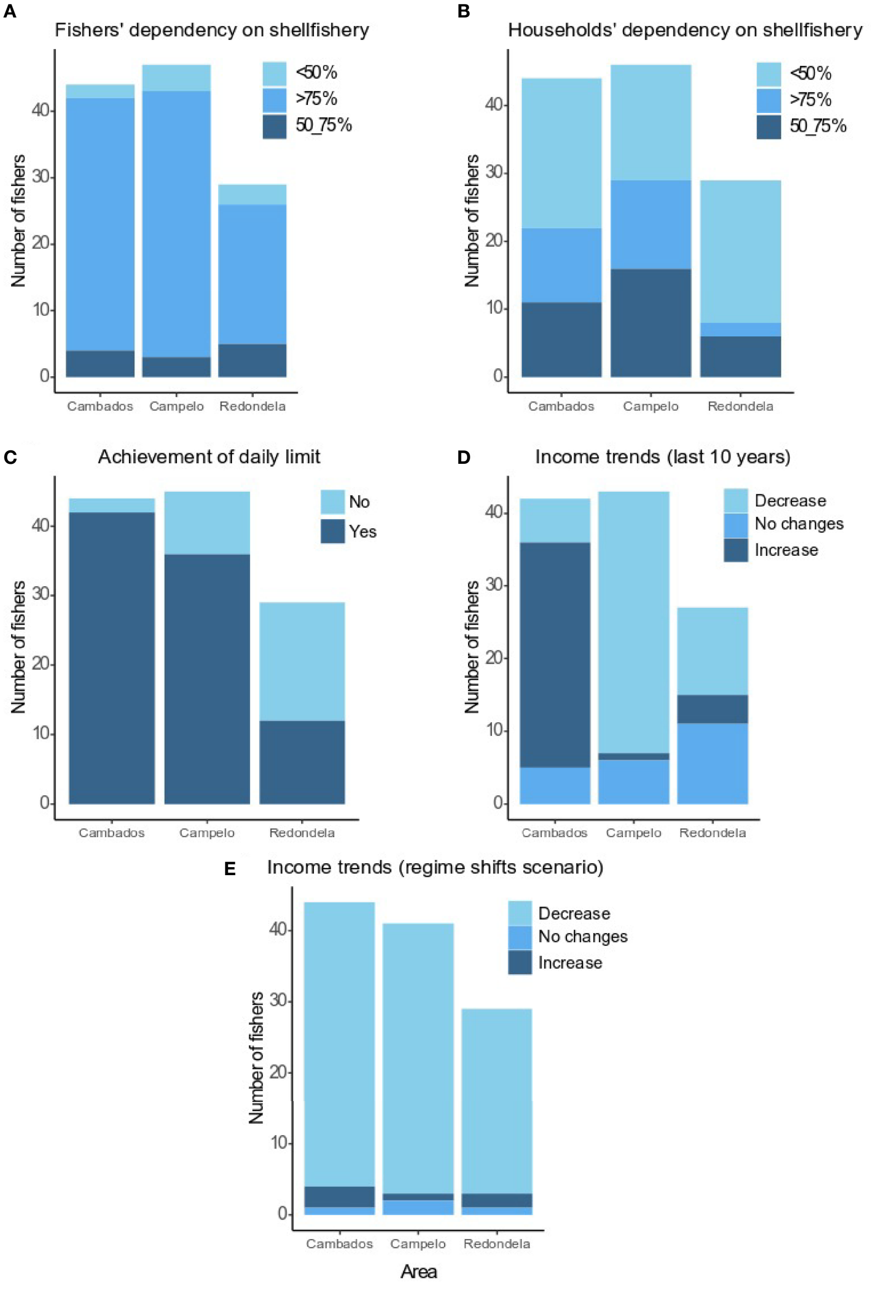

FIGURE 4 | Shellfishery dependency on **(A)** fishers and **(B)** households, and fishers' perceptions on **(C)** the capture of daily quota, **(D)** income trends (in the last 10 years), and **(E)** consideration of future climate change scenarios by area.

explanatory variables (**Figures 5A, B**). Higher economic vulnerability was associated with higher adaptation (p-value = 0.03, **Figure 6B**). The age of the fishers was inversely related to adaptation (p-value = 0.02, **Figure 6A**). Fishers who were more dependent on shellfisheries, earning more than 75% of income from shellfisheries (p-value = 0.00, **Figure 6C**) and fishers from Cambados (p-value = 0.00, **Figure 6D**), were less adaptable to changes in their social-ecological systems. Social involvement, household size, financial assistance and fishers' educational level were not significant explanatory variables in regards to the diversity of adaptive responses of fishers.

DISCUSSION

The effects on fisheries of observed and expected changes in climate are usually spatially and socially differentiated. Individuals and groups have faced risks of climatic hazards and other

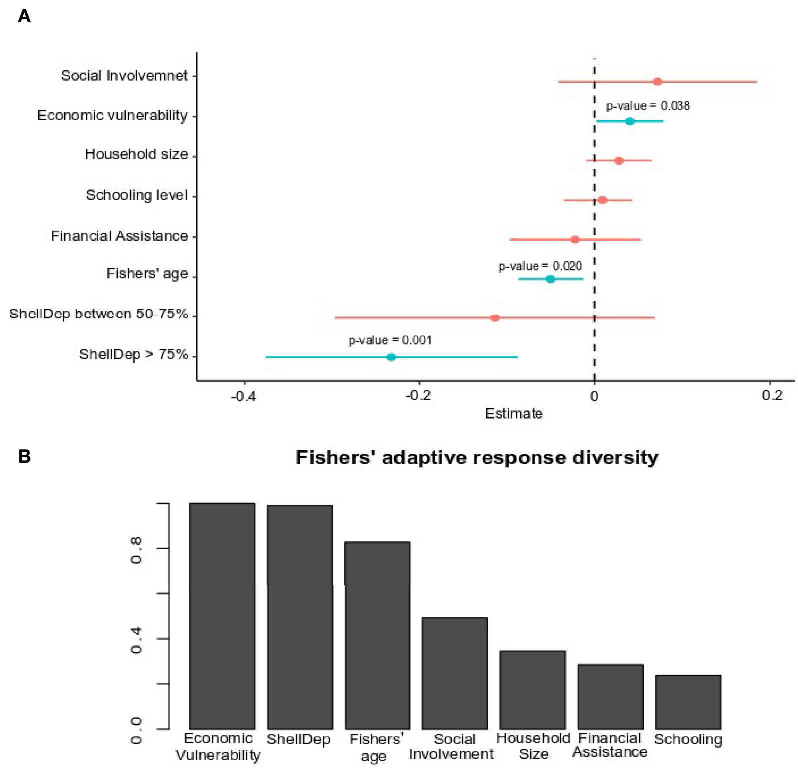

FIGURE 5 | **(A)** Coefficient estimates (± 95% CIs) showing the magnitude and direction of effects of predictors on the diversity of adaptive responses of fishers, **(B)** bar chart showing variable importance scores for the effect of each predictor. The score varies from zero (less important) to one (more important). ShellDep between 50 - 75% denotes that dependency on income from shellfisheries is between 50% and 75%, ShellDep >75% denotes that dependency on income from shellfishing is higher than 75%. Significant variables are shown in blue. Non-significant variables are indicated in red.

anthropogenic factors and they have historically been able to adapt and will continue to do so as climate is part of the wider environmental seascape of coastal development. Furthermore, human vulnerability to climate change may act as a driver for adaptive management of fishery resources (Adger, 2010).

In this section we discuss the most plausible reasons for the economic vulnerability and social adaptation strategies to further advance understanding of fishers' responses to tackle impacts of climate change.

Fishers Are Highly Dependent on Shellfishing, But Also Vulnerable Depending on Financial Assistance, Experience and Size of Households

Our first key finding was the strong dependence of the fishers on shellfishing in the three study areas (Cambados, Campelo and Redondela), as fishers earned more than 75% of their monthly income from shellfishing. However, fishers depended on obtaining private loans and public financial assistance from the regional government when income from shellfish harvesting was not sufficient for subsistence.

The study findings also demonstrated that higher economic vulnerability was closely correlated with less fishing experience and the size of households. This is consistent with the findings reported by Barnes et al. (2020), who found that past experience was positively associated with willingness to develop adaptation strategies. Fishers with a long experience in working in shellfisheries have had to deal with different situations in the past, developing a diverse portfolio of solutions in their social-ecological memory. This greater vulnerability of the harvesters with less experience could discourage young people from engaging in shellfishing. As supported by the FAO (2015) in Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, promoting government measures to economically incentivize the engagement of new people in fishing (shellfishing) activities must be highly prioritized, not only to facilitate the social-ecological memory and traditional knowledge through the current and future generations, but also to maintain the young population in coastal communities within the context of few labour opportunities.

Furthermore, lower economic vulnerability was related to a greater number of households members, because diversifying incomes from other activities (namely from small-scale and industrial fishing sectors) helped in the adaptation to climate change. Indeed, the rest of the household members generally provided complementary income from other public sources of income (e.g. public pensions for retirement, etc.). This is consistent with the findings of Green et al. (2021), who conducted a global meta-analysis to analyze impacts of climate

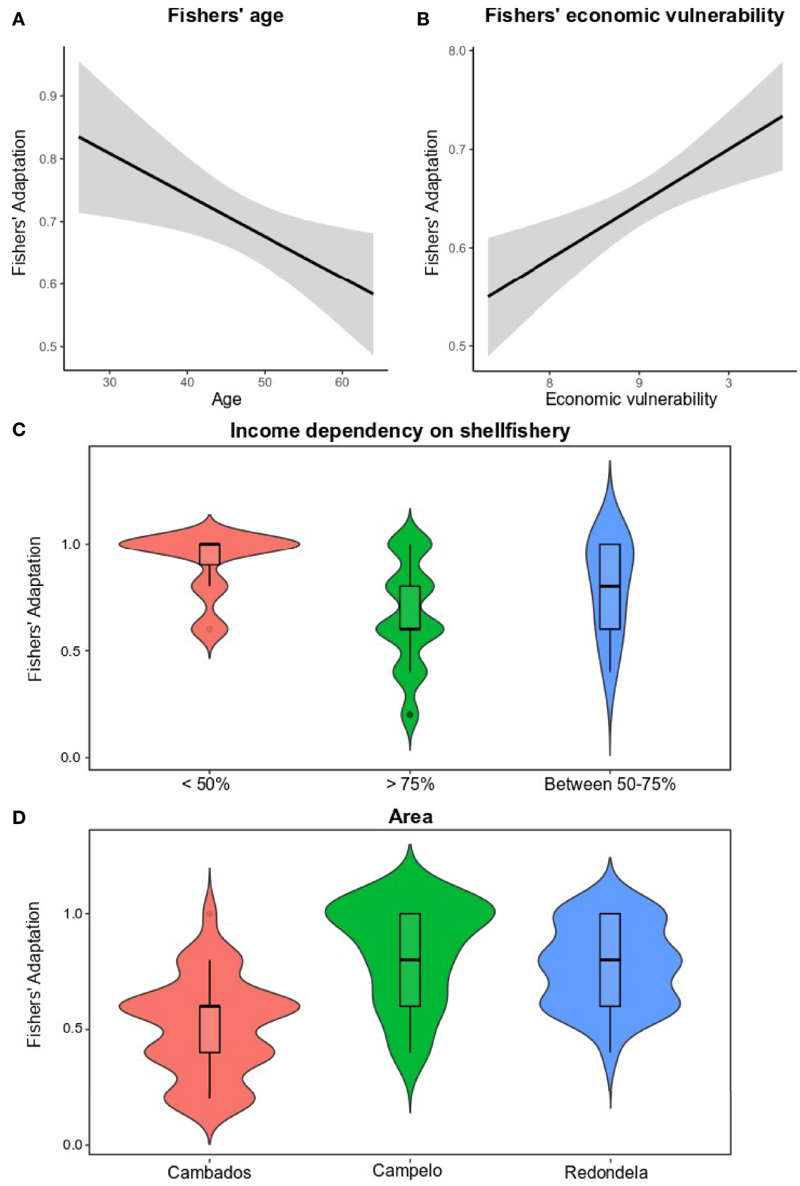

FIGURE 6 | Predictor effect of the variables from the averaged model to the fishers' adaptation to regime shifts: **(A)** fishers' age, **(B)** fishers' economic vulnerability, **(C)** dependency on income from shellfishing, and **(D)** area (area where fishing takes place).

change in SSFa and found that diversification of income was one of the key factors involved in developing diverse adaptive responses. However, in the case of Galician shellfishers, greater diversification of activities would not necessarily improve the status of fishers, given that once a certain economic threshold was reached, the fishers would be able to abandon shellfishing.

Our modelling results also predicted that economic vulnerability would be highest amongst shellfishers who were not involved in the associations. In general, our research shows that fishers perceived an improvement in the organization of their shellfishers associations. A higher involvement in the organization of shellfishers' associations allowed for a greater exchange of information on the state of the natural banks and, ultimately, led to a better socialization of the impacts of climate change. Notably, shellfishers were aware of the stronger impact of diseases and deterioration of the natural environment and worse meteorological conditions in the ecosystems.

Realizing Economic Thresholds Helps to Develop More Effective Fisheries Management

Our second key finding was the empirical demonstration, for the first time, that shellfishers' incomes must be higher than 438-606

€ per month to maintain the activity and cover fixed costs. More experienced fishers stated that they would abandon the shellfisheries earlier, which may be linked to avoid loss of income (Marshall et al., 2013).

Nevertheless, more than half of shellfishers in the three areas indicated that they would not abandon the shellfish activity, indicating the deep cultural roots of this activity. The recent increase in the minimum salary in Spain (from 707,7 € in 2017 to 965 € in 2021) (Ministry of Labour and Social Economy, 2021) could change the perception of the fishers about the minimum income needed to maintain the activity. Taking into account the trend of future increases of minimum salary, abandonment of the fishery seems to be the most likely reaction in the medium term, considering the current quotas and trends of declining catches and abundance of most of commercial shellfish species (Pita et al., 2019; Domínguez et al., 2020; Domínguez et al., 2021; Vázquez et al., 2021).

Our result is important because management strategies that explicitly include thresholds and integrating them into fisheries management policies have been shown to be more effective in achieving public policy goals than strategies that do not consider explicit thresholds (Kelly et al., 2014). Identifying economic thresholds can be extremely useful to detect early signals of regime shifts, traps or collapses, which also help to create new windows of opportunities to successfully navigate into new desirable transitions and states of shellfisheries before tipping points are reached (Biggs et al., 2009). Investigating social and economic thresholds are key to better understanding the adaptability of shellfishers to deal with climate change (Adger et al., 2009). However, it is important to highlight that limits to adaptation are endogenous in societal groups and hence also contingent on values, knowledge, attitudes to risk, ethics, and local culture, which can change over time (Adger, 2010; Villasante et al., 2021).

Fishers Adapt to Climate Change by Harvesting Available Species and Complementing Shellfisheries' Income With Other Activities

The third key finding provides evidence that adaptation strategies developed by Galician shellfishers tended to focus on harvesting the most abundant and economically valued species as the key measure to deal with climate change impacts. Our results also show that fishers adapted their individual behaviour to changes in environmental conditions by reducing household expenses and complementing shellfish with other formal or informal jobs to compensate for the economic losses. Both individual strategies would help to build resilience and adaptive capacity to deal not only climate change impacts, but also social-ecological shocks and crises such as the current COVID-19 pandemic, which has negatively impacted Galician shellfisheries by reducing their volume (-27%) and value of landings (-18%) (Villasante et al., 2021).

These results are consistent with those of Savo et al. (2017), who recently conducted a global meta-analysis of the observations of coastal subsistence-oriented fishers on climatic changes, and found that diversification is the most frequently reported adaptation strategy. At the most fundamental level, people select the available opportunities and options in relation to their personal skills and available or those that they can, afford or use.

Fishers Collectively Adapt to Climate Change by Increasing Their Involvement in Shellfishers Associations

The fourth key finding was the tendency of an increase in the social involvement of fishers in shellfishers associations. Our result is important because Galician shellfishers' associations have been experiencing a notable reduction in conflicts and mistrust between the administration and the shellfisheries sector, favouring consensus in most decisions concerning shellfishing activities (Pita et al., 2019; Villasante et al., 2021). The current co-management system in Galician shellfisheries entails the empowerment of fishers (especially women) (Pita et al., 2019), which occurs when sustainable management of the fishery resources becomes possible (Jentoft, 2005; Villasante et al., 2021)

Our result is also consistent with the fact that fishers' participation has been found to be a key pillar in a good governance system that renders social-ecological and environmental sustainability in other shellfisheries in Galicia (Aguión et al., 2022). Social trust and cooperation between agents, which are essential factors for a successful government of common resources (Ostrom, 2009), have been improved since fishers provide data and participate in monitoring programs and in designing exploitation plans.

People become empowered when they act together to form organizations and when they acquire rights and responsibilities in fisheries management (Jentoft, 2005). As Pomeroy and Viswanathan (2003) stated, successful co-management systems and meaningful partnerships can only occur when the fishing community is empowered and organized, and all participants can take advantage of short and long term benefits of cooperation. The awareness of the need for co-management leverages partner contributions, especially when the sense of urgency increases as a consequence of any crisis (Rey-García et al., 2019). Fishers who share common objectives, values, beliefs, and who trust in each other and in the group, have a better chance of realizing resilience and co-management (Grafton et al., 2019). Their adaptability to changing circumstances will be also greater because co-managers will be more willing to compromise with the group. This involvement facilitates capacity building to deal with the new challenges, reducing the cost of opportunistic behaviours (Jentoft, 2005).

Trust in specific measures adopted by the government may inhibit adaptive behaviour, which may put fishers at risk from climate-related hazards (Baan and Klijn, 2004). Given that co-management of fisheries also requires a wide range of expertise, experience and skills, Galician fishers would benefit from the social involvement in carrying out actions towards improving climate change planning and capacity building. This could translate into learning economies and provide opportunities for the members of fishing communities to put forward ideas and to adopt plans that are in line with local needs, abilities and interests (Wiseman et al., 2009).

Considering Local Fishers Knowledge Helps to Disentangle Social Adaptation Strategies

Another key result from our study is that local fishers and associations have been proactively confronting impacts of climate change. Our study contributes to giving an explicit consideration of fishers' views, perspectives and rights of local communities, their knowledge and understanding of ecosystems, and their desired future development pathways to deal with the impacts of climate change. In particular, this study highlighted that shellfishers in Galicia have also perceived increases in mortality of species, increased amounts of seaweeds on beaches and a greater presence of parasites in the intertidal zones.

When trying to adapt to these changes, our research showed (a) an increase in the medical sick leave from the beginning of shellfishing activity, (b) greater difficulties in obtaining shellfishing permits, (c) growing pressures from external poaching and (d) in some fishing guilds, an increase in the black market for shellfish. Fishers also demonstrated strong local environmental knowledge and awareness about the impacts of climate change on their activity, which is also consistent with previous research (Shaffrill et al., 2017; Pita et al., 2020). Our findings also showed that all fishers agreed with the expert opinion (Peteiro et al., 2018; Domínguez et al., 2020; Domínguez et al., 2021; Vázquez et al., 2021) about the new scenarios of climate change for the future of shellfish, and noted that these scenarios would be negative for their activity.

These findings contributed to show the diversity of responses led by local communities and the extent to which local knowledge-based measures may be transferable and beneficial across villages, cultures and environmental conditions (Forsyth, 2013). Successful adaptation to impacts of climate change are more likely when efforts are directed at promoting knowledge generation and the maintenance of different knowledge systems, including in the sciences and local knowledge, regarding shellfishing resources and their sustainable uses (IPBES, 2019).

Does Diversity of Adaptive Strategies Help to Build Social Resilience?

Socio-economic resilience of fishing communities refers to how they are able to maintain their livelihoods and desired ways of living, after undesirable shocks (Grafton, 2010). Adaptive fisheries management allows policy makers and the fisheries sector to be more effective *ex-post* in an increasingly uncertain world, while resilience provides guidance about how to manage fish stocks, ecosystems and people to adapt to undesirable shocks and crises *ex-ante* (Grafton et al., 2019).

Substantial management efforts are usually made to reverse undesirable changes, but most of these are very costly as they are implemented after shifts, traps or collapse take place, but not before them. Strategies that could be helpful in promoting resilience in a biophysical and socio-economic sense usually include lower rates of fishing mortality, larger exploitable biomass of targeted species, and increased 'no take' areas, which may provide a buffer stock in the face of unexpected shocks (Grafton and Kompas, 2005).

In general, how individuals and communities adapt to climate change depends on a diverse range of social-ecological factors including social norms and values, local environmental conditions, socio-economic status and processes of marginalization and inequality (Savo et al., 2017). However, focusing on only a few species such as the Manila clam, which is more resistant to changes in environmental conditions (Domínguez et al., 2020; Domínguez et al., 2021; Vázquez et al., 2021), can be a high-risk adaptation strategy. Manila clam (native to the Pacific), was introduced for culture in Europe in the 1970s because of its high adaptability (Latrouite and Claude, 1976; Pérez-Camacho and Cuña, 1985; Drummond et al., 2006). The increasing market pressure due to a greater national and international demand for seafood is driving shellfishers to seed this species artificially thus increasing its abundance (Pita et al., 2019; Villasante et al., 2021).

CONCLUDING REMARKS: MOVING FORWARD

The adverse effects of climate change on SSF have been predicted to increase in the future. Although scientific research on impacts of climate change has increased in recent years, few studies have explored the social dimension of the problem, in particular in the context of SSF. Our paper contributes to this research gap, and it represents a first attempt to provide empirical evidence about social adaptation strategies developed by shellfishers in Galicia. Case studies, such as that presented here, are essential to building resilience and collective adaptation to tackle impacts of climate change.

Our finding shows that there is a strong economic dependence on shellfishing, as fishers earned more than 75% of their monthly income from the activity. We also demonstrate that higher economic vulnerability was closely correlated with less fishing experience and the size of households. Fishers with a long experience in working in shellfisheries have had to deal with different situations in the past, developing a diverse portfolio of solutions.

The results of the study show that Galician shellfishers have developed a wide range of adaptive strategies to anticipate and respond to climate change, namely harvesting commercially valued species with high ex-vessel prices and also harvesting the most abundant species. Fishers have also adapted their behaviour by reducing household expenses and complementing their income from shellfishing with other formal or informal jobs to compensate for the economic losses.

Although adaptive strategies have helped to deal with impacts of climate change, several threats to the sustainability of shellfisheries remain: the decreased abundance of key native shellfisheries species and the high level of dependence on public and private aid to ensure reasonable income for shellfishers. In addition, the sector is dealing with the lack of generational transition to work in shellfisheries to ensure not only revenues, jobs and young population in coastal communities, but also to retain the traditional knowledge and social-ecological memory of associated practices, experience and values.

Key aspects such as enhancing social relationships, increasing knowledge about climate change, improving alternative skills and involving in adaptation planning are recommended to have desirable outcomes regarding social adaptation. We believe that our findings are of wide interest and relevance to other similar SSF around the world facing similar climate change challenges. We expect that the research we have conducted in this research can guide future research and policy recommendations. Future policy directions in management of these SSF should actively involve shellfishers and include their traditional and local knowledge. Such inclusion would help in the development of more effective policies as it would incorporate understanding of locally social adaptation strategies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SV conceived the idea. SV, NC, GM, JCMB, and AS designed and performed the interviews. MROS and PFML developed the statistical analysis. All authors have equally contributed to the rest of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.802762/full#supplementary-material

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Governing Open Ocean and Fish Carbon: Perspectives and Opportunities

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Marine life plays a vital role in the ocean's biological pump by sequestering and mediating fluxes of carbon to the deep sea and sea floor. The roles that fish and other marine vertebrates play in the biological pump are increasingly attracting scientific and policy attention. In this paper, we investigated the interest in and possibilities for the international governance of open ocean and fish carbon ecosystem services. We used semi-structured interviews with representatives from environmental non-governmental organisations (ENGOs), policy makers, and policy experts, along with an exploratory review of grey and peer-reviewed literature to: 1) trace the pathway of important milestones, key actors, and their strategies to influence governance of ocean carbon, and, 2) investigate which frameworks might be used to govern open ocean and fish carbon. Strategies of key actors to direct attention to open ocean and fish carbon included collaborating with scientists, organising side events at climate and biodiversity negotiations and seminars to engage policy makers, as well as educational campaigns directed to the public and policy makers about the co-benefits of open ocean and fish carbon. While we found a strong focus of ENGO activities related to the UN Framework Convention on Climate Change, we also found strong opposition against active governance of open ocean and fish carbon by key Intergovernmental actors in this forum. Opposition stems from a lack of scientific information on how long open ocean and fish carbon is stored, difficulties in attributing carbon flows with individual countries mitigation actions, and fewer perceived co-benefits (e.g. coastal protection in the case of coastal blue carbon) for coastal communities. More viable routes for the future governance of open ocean and fish carbon may lie in international fisheries management and in current negotiations of a treaty for biodiversity conservation in the high seas.

Keywords: ocean governance, biodiversity conservation, fisheries management, sustainable fishing, climate change, blue carbon, biological pump, carbon sequestration

1 INTRODUCTION

The ocean is the largest heat and carbon sink globally, absorbing 90% of excess anthropogenic heat gained by the planet between 1971 and 2010 (Zanna et al., 2019). The ocean also absorbs CO_2 *via* a physical carbon flow and through the biological pump (Sarmiento and Gruber, 2006). The biological pump is the set of processes by which inorganic carbon (CO_2) is fixated in organic carbon by phytoplankton and exported to the deep ocean (Sarmiento and Gruber, 2006). If carbon moves from the surface layers to the deep sea (i.e. deeper than 1,000 m) it is removed from the atmosphere for at least 100 years (Passow and Carlson, 2012). There are several mechanisms through which the carbon absorbed by phytoplankton can reach the deep-sea, and marine species such as fish and a diversity of zooplankton contribute to carbon export (Sarmiento and Gruber, 2006; Wilson et al., 2009; Boyd et al., 2019). Zooplankton, fish, and whales contribute to passive carbon fixation with their biomass, this carbon is stored in food webs or can be exported through deadfall to the seafloor (Boyd et al., 2019). The vertical migrations of fish and zooplankton also actively export carbon into the deep ocean by feeding at the ocean surface and excreting carbon at depth (Davison et al., 2013; Saba et al., 2021).

There is a growing recognition that ocean biodiversity and climate are intertwined in science and policy (Rantala et al., 2019; Pörtner et al., 2021). Ocean-climate nexus and blue carbon discussions that are on-going also have led to increasing attention to carbon cycling and storage processes in the open ocean as Nature-Based Solutions to climate change (Lutz and Martin, 2014; Dobush et al., 2021). Ocean carbon refers to all biologically-driven carbon fluxes and storage in marine systems. While coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses (IOC-R, 2021), open ocean and fish carbon refers to biologically-driven carbon fluxes and storage in the open ocean (including those of marine life such as marine mammals, marine plants invertebrates including a diversity of zooplankton), particularly those mediated by fish as fish carbon.

There is a continuum of exploitation of species that contribute to carbon sequestration. Many top marine predators have declined in biomass and are at historical lows in abundance (Lotze and Worm, 2009; McCauley et al., 2015). For instance, in the past half century oceanic sharks and rays have declined by ca. 70% in abundance (Pacoureau et al., 2021). In contrast, cetaceans used to be highly exploited but are beginning to recover in abundance globally (Duarte et al., 2020; Durfort et al., 2021). Rebuilding populations to historical abundance could help sequester ca. 1.66 megatons carbon (MtC) per year for whales (Pershing et al., 2010) and ca. 1.63 MtC per year for large marine predators (Mariani et al., 2020). Mesopelagic fish also play a crucial role in active carbon sequestration (Saba et al., 2021), yet, there is increasing interest in their exploitation (Hidalgo and Browman, 2019; Alvheim et al., 2020; Grimaldo et al., 2020). Moreover, there are growing concerns about the vulnerability of these ecosystems to impacts of deep sea mining as well as oil and gas extraction (Drazen et al., 2020; Morzaria-Luna et al., 2022). In summary, rebuilding the abundance of overexploited and precautionary management of yet unexploited species provides an opportunity to enhance and maintain vital carbon sequestration services.

Climate change and ocean governance, including protection of marine biodiversity, are issues that extend beyond countries' national borders (Dellmuth and Bloodgood, 2019). In this article, ocean governance is seen as interactions among, and between, networks of state and non-state actors that share power, perceive and interpret information and steer human interactions with ocean ecosystems, guided by a combination of international and national laws such as those discussed below, as well as norms and rules of conduct (Ojo and Mellouli, 2018; Brodie Rudolph et al., 2020). To address such issues of "global commons" states have formed international organisations which have been handed power to handle these transnational issues (Merrie et al., 2014).

The UN Convention of the Law of the Sea (UNCLOS) implemented in 1982 established nation states' sovereignty at 200 nautical miles from their territorial borders into the sea, countries' exclusive economic zones (EEZ). The ongoing negotiations for an agreement on biodiversity beyond national jurisdiction (BBNJ agreement) and the UN Fish Stock Agreement (UNFSA) are legally binding instruments under UNCLOS. The BBNJ agreement will promote the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. The UNFSA mandated Regional Fisheries Management Organizations (RFMOs) to manage and conserve straddling and highly migratory fish stocks. Other key frameworks for ocean carbon include the United Nations Framework Convention for Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) which was created during the Earth Summit in Rio de Janeiro in 1992. Other conventions of relevance are the 1973 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the 1979 Convention on the Conservation of Migratory Species of Wild Animals (CMS), the 1946 International Convention for the Regulation of Whaling (ICRW), and the 1964 London Fisheries Convention (LC). The recent Sustainable Development Goals (SDG's) under the 2030 agenda and in particular SDG14 on the ocean and SDG13 on climate action are also considered an important agenda for the governance of the ocean and climate. Mechanisms through which such frameworks are implemented can be economic sanctions/rewards, local implementation into law, and creation of shared norms and ambitions (Buchanan and Keohane, 2006). Combining issues such as climate change either within a single policy framework or across, (such as climate change and marine biodiversity) could be synergistic and address governance gaps between regimes or result in lower costs to management. However, combining issues in this way could also result in issue dilution or distraction (Chan, 2021).

Non-state actors such as Environmental non-governmental organisations (ENGO), industry representatives and academic experts participate in and influence international policy fora such as those described above [alongside state representatives and intergovernmental organisations (IGOs) representatives], through formal and informal policy processes. Such processes may include supplying policy-relevant information to policy makers, informing the public about the state of the problem, coordinating across actors, or assisting in policy implementation (Orach et al., 2017; Dellmuth and Bloodgood, 2019; Dellmuth et al., 2020; Sénit, 2020). ENGOs are non-profit groups, independent from government, which are organised on a local, national, or international level to address issues of concern for civil society, and/or protect public goods (Grip, 2017). They are particularly important for the topics of climate change, ocean topics and biodiversity protection as they are thought to bring global and regional perspectives to discussions, in contrast to individual states, which would often pursue their own national interests (Grip, 2017). IGOs such as the IPCC are mandated to serve collective interests of sovereign states and are of crucial importance in global issues such as climate change and biodiversity loss and to implement international laws and conventions such as those described above (Biermann and Dingwerth, 2004).

In this paper, we investigate the evolution of the debate on ocean and open ocean and fish carbon in the context of ocean and climate governance using semi-structured interviews and a literature review. Our guiding research questions are: 1) Which milestones were important in shaping governance discussions from oceans and climate towards ocean and fish carbon? 2) Which processes and key actors were influential in shaping these milestones? and 3) Under which framework, and using which management tools, might open ocean and fish carbon be governed? We first present a timeline of milestones for the evolution of the debate on ocean and fish carbon policy. Secondly, we identify key actors and their strategies in influencing this debate. Finally, we assess which policy fora would be most suitable to govern open ocean and fish carbon.

2 METHODS

We used a mix of qualitative research methods including semi-structured interviews and literature review to answer our research questions. We conducted twenty semi-structured interviews (Bryman, 2016) with key informants (those close to the policy making sphere on the specific topics or those with expert knowledge on the specific topics) in ocean, climate, and fish carbon governance. One of the goals of the interviews was to collect data on what participants viewed as important in explaining and understanding key events (Brinkman and Kvale, 2015; Bryman, 2016). 20 of the 33 informants we reached out to, agreed on being interviewed. We investigated how the participants framed and understood the key issues, and events related to how open ocean and fish carbon appeared on the international policy agenda. Finally, we asked about the ongoing and future policy fora and instruments that could potentially regulate the open ocean and fish carbon sequestration services. We reached the saturation level with the interviews at n= 20 (Charmaz, 2014), when each new interview did not result in new information.

To find key informants we followed the lines of purposive sampling (Onwuegbuzie and Leech, 2007), we created an initial list of participants based on a preliminary literature review of reports, organisations' websites, and social media related to the topic of open ocean and fish carbon governance. We completed the list of interviewees following a snowball approach (Bryman, 2016). All interviewees were working with ocean governance but with a variety of backgrounds (**Table 1**).

We conducted the interviews *via* Zoom. They lasted between 40 – 60 minutes and were carried out between May and July 2021. All interviews but one were recorded and we took notes simultaneously.

We structured the interview questionnaire to collect relevant information for the three research questions (see SI1 for the interview guide). We organised the questionnaire subsequently into three sections. First, we asked about milestones such as events, working groups, and publications that in the interviewees' perspective advanced the ocean and climate discussion towards ocean carbon. Second, we asked questions concerning key actors in ocean climate, coastal blue carbon, and open ocean and fish carbon governance and how they were able to influence the milestones and discussions (Orach et al., 2017; Sénit, 2020). The last set of questions investigated the possible future governance for open ocean and fish carbon including under which frameworks and using which management tools open ocean and fish carbon could be governed. In the email and prior to the interview, we informed participants of the aims of the research and how we would use the information. Anonymity was granted to create an open space to discuss personal viewpoints.

We transcribed the interviews and organised the data following each of the three overarching themes covered by the interview inspired by the processes of initial and focused coding (Charmaz, 2014). We sought interviewee permission for direct quotes from the interviews. We also identified emergent sub-topics (e.g. need for measurability within the UNFCCC forum,

TABLE 1 | Number of interviewees and their backgrounds.

Sector	Number	Geographical backgrounds interviewees
Policy maker	1	EU
Intergovernmental Organisation (IGO)	3	EU (n=2), Pacific (n=1)
Environmental Non-Government Organisation (ENGO)	7	North America (n=3), EU (n=2), Europe (non-EU) (n=2)
Academia	7	North America (n=5), Carribean (n=1), Europe (non-EU) (n=1)
Private sector	2	Europe (non-EU) (n=2)

Interviewees were from US, Sweden, Norway, Canada, UK, Fiji, Trinidad and Tobago, and Australia.

and the importance of collaborating with leading countries) which are reported in the Results section as well.

We complemented the empirical data from the interviews with information collected from reports, publications, and peer-reviewed literature. This was particularly relevant for covering gaps in the process of constructing the timeline of key events in the international governance of open ocean and fish carbon (**Figure 1**).

Finally, we also investigated which international governance frameworks currently engage most with topics related to the ocean, climate and biodiversity. We identified keywords from a comprehensive policy dataset containing >3,000 policy documents from eight global, ocean-related conventions and related instruments. These were previously mentioned in the Introduction (UNCLOS, UNCLOS PART XI, BBNJ (under negotiation), CBD, CITES, CMS, ICRW, and LC). We extracted keywords for the ocean and climate interface (*ocean* and *climate*), the keyword for *blue carbon, ocean carbon* and two keywords that could indicate aspects of the biological pump (*remineralization* and *respiration*), or the biological pump itself (*biological pump and biological carbon pump, carbon pump*). The result of this analysis (see **Box 1**) gave us some first indications of the suitability of these frameworks for governing the open ocean and fish carbon sequestration services.

3 RESULTS

3.1 Key Milestones in the International Governance of Open Ocean and Fish Carbon

Through the interviews a series of milestones (events, working groups and publications) were identified for mainstreaming the ocean as an inclusive element in the climate agenda, and for enabling the emergence of the open ocean and fish carbon discussions (**Figure 1**). These events were not isolated, and many actions, initiatives, and publications (not depicted in **Figure 1**) have contributed to their development (**Table S1** for the full list of milestones and reports mentioned by interviewees). Because this article focuses on open ocean and fish carbon we selected more milestones that involved carbon sequestration in the open ocean (by marine vertebrates such as fish and whales).

As early as 1992, the UNFCCC article 4.1, mentioned the sustainable management and conservation of appropriate sinks and reservoirs of all greenhouse gases (GHGs), including the ocean, coastlines, and marine ecosystems (UNFCCC, 1992). Furthermore, the first Ocean Action Day at the UNFCCC COP15 in 2009 marked a turn into establishing research needs and policy action for coastal blue carbon in the UNFCCC process (COP15 Presidency, 2009). In 2017, during Fiji's presidency of COP23, the "*Oceans Pathways Partnership*" was launched to encourage the climate negotiations process to address the relationship between climate change and the ocean (COP23 Presidency, 2017; IGO representative, interviewee nr. 16). Chile's 2019 COP25 was themed the Blue COP for its heavy emphasis on the ocean, impacts and the role of the ocean as a carbon sink (COP25 Presidency, 2019; IGO representative, interviewee nr. 16). Blue climate discussions started around coastal ecosystems and quantification tools for these have been developed since (e.g., carbon credits under UNFCCC) (ENGO representative, interviewee nr. 1). Fish, whale, and carbon storage in the seabed emerged later in mainstream international governance discussions and were also highlighted in public reports (ENGO representative, interviewee nr. 7). The 2019 High-Level Panel report on ocean mitigation, which discussed carbon storage in the seabed as an important carbon sink (Hoegh-Guldberg et al., 2019) was highlighted by interviewees as an important milestone for ocean carbon, as well as a highly publicised scientific paper (Sala et al., 2021) on the impact of trawling on carbon stored in the seabed. The joint 2021 IPBES-IPCC report was also reported by the interviewees, this report mentioned the contributions of fish to the biological pump (e.g. Academic, interviewee nr. 18).

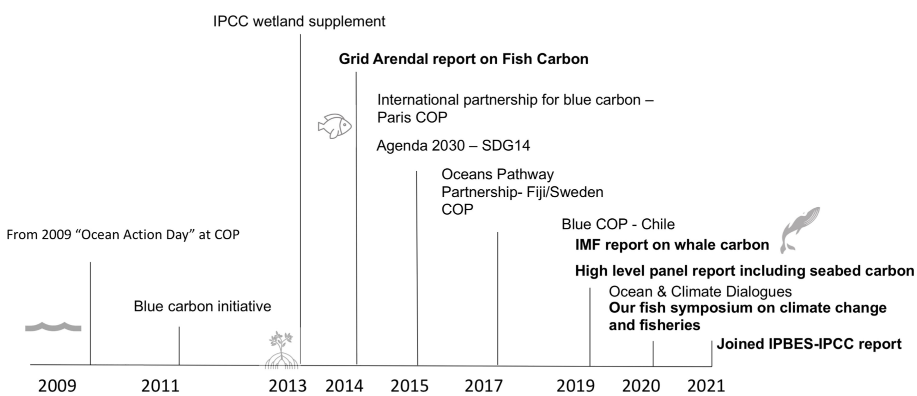

FIGURE 1 | Timeline of ocean (carbon) on the climate agenda. Events and reports printed in bold include or are about ocean and/or fish carbon. See **Table S1** for the full list of milestones and reports mentioned by interviewees.

BOX 1 | Policy documents and their focus on climate-ocean topics.

Figure 2 shows the frequency of mentions of certain topics of interest in the climate-ocean nexus, including topics that relate to the ocean as a carbon sink. We found that the CBD and UNCLOS documents have the most simultaneous mentions of climate and ocean (197 and 113 respectively). UNCLOS, CBD, UNFCCC and CMS were the only agreements that mentioned "blue carbon", and "ocean carbon" was mentioned only in the CBD. We also found that keywords indicative of the carbon pump like "respiration" and "remineralization" were mainly used in UNCLOS Part XI. This could be explained because some of these processes are discussed in the context of seabed mining which could impact carbon storage in the seabed and remineralization, which could then be respired by benthic communities (Sala et al., 2021). The CBD was the only forum that mentions "ocean carbon" and also has frequent mentions of mangroves. We found no mention of "whale carbon", "fish carbon" and "biological pump" or "carbon pump" in any of the governance documents.

Examples from some of the documents underlying the data presented in **Figure 2** are the mentioning of climate and ocean co-benefits in countries NDC's:

Example 1: "Evaluation of co-benefits the area offers in adaptation and mitigation of climate change and adjustment of management to enhance these co-benefits" (Chile NDC, 2020)

Example 2: "[...]enhancing the ocean as a carbon sink. As such, Fiji, through its National Ocean Policy, will be allocating 30% of its EEZ as Marine Protected Areas and work towards 100% management of its EEZ by 2030. (...) highlights the need to sustainably manage and protect marine and coastal ecosystems, strengthen their resilience, and restore them when they are degraded. This includes conserving ocean reservoirs as carbon sinks through supporting the restoration, enhancement and conservation of coastal ecosystems such as mangroves, sea grasses and coral reefs." (Fiji NDC, 2020)

Interviewees mostly talked about UNFCCC processes, which is to some extent in agreement with the keyword results, UNFCCC documents often mentioned ocean and climate together. However, the CBD which was hardly ever referenced by interviewees also had a high amount of joint mentioning of ocean and climate. UNCLOS was also hardly ever mentioned by interviewees but it and the CBD were the only governance frameworks that referenced elements of the biological pump in Part XI. One interviewee mentioned that fora focused on biodiversity, such as the CBD, do not often consider the climate, but this was not supported by the keyword analysis.

3.2 Key Actors and Their Role in the Evolving Awareness of the Ocean and Climate Regulation Processes

3.2.1 The Ocean as a Place of Impact and as a Place of Co-Benefits

The impact of climate change on the ocean has been highlighted in international policy making spheres such as the UNFCCC for years; it was also an important topic raised during the interviews. For instance, a number of interviewees highlighted the need for climate adaptation to help societies cope with shifts in fish stocks and the impacts of warming and acidification on marine organisms such as coral reefs. The interviewees also described a shift in attention toward the ocean as preserving ocean health for the "co-benefit" of preserving the ocean's climate regulating ecosystem services (Quote 1 & Quote 2 **Table S2**). Co-benefit, as conceptualised by the interviewees that referred to it, means that protecting ocean ecosystems is beneficial for the ecosystems and for the people that rely on them (also in light of the impacts of climate change on the ocean), but also that benefits are derived in terms of mitigating climate change. This concept of co-benefits has also been presented in the literature (Gallo et al., 2017; Chan, 2021).

3.2.2 Ocean and Climate Regulation Processes: An Evolving Awareness

Several interviewees indicated that the ocean is generally not considered a priority for those working on climate mitigation policy, whether it be at the UNFCCC, or domestically. It was reported by the interviewees that ENGOs, UN officers and policy makers from coastal countries, continuously need to push for attention towards the ocean by those working on climate change. For instance, the ENGO Ocean Conservancy used a side-event during the Climate Leaders' Summit (2021) with U.S. Special Presidential Envoy for Climate John Kerry to highlight the role of the ocean in climate change. Participants and invited policy makers "[…] *who don't normally think about oceans have a reason why they have to get smart on oceans and start to think and talk about it* […]. *I think that's been helpful.*" (ENGO representative, interviewee nr. 13). ENGO representatives and other key informants stated that this message needed to be repeated often because delegates and policy makers are frequently replaced. As mentioned in section 3.1, several COPs in which the ocean featured highly (i.e. COP23 and COP25) and the 2019 Intergovernmental Panel on Climate Change (IPCC) report on the ocean and cryosphere were mentioned several times as key milestones that convinced many actors of the important impacts of climate change on the ocean.

From the interviews it became clear that the potential to enhance and protect the sequestering services of the ocean are still predominantly associated with coastal ecosystems such as mangroves, saltmarshes, seagrasses. As reported by the interviewees, the focus on mangroves in climate agreement policy circles was thought to arise from earlier carbon offsetting methods that involved trees (REDD+), which allowed for a natural extension to mangroves in coastal areas (Quote 3, **Table S2**). Several countries such as Fiji, Chile, Costa Rica, Australia and Kenya have expressed interest in adding coastal blue carbon as a carbon mitigation strategy to their Nationally Determined Contributions (NDCs, the national level strategies to implement the Paris agreement under UNFCCC) (**Box 1**). The IPCC wetland supplement, updated in 2013, included coastal ecosystems and an approved methodology to calculate carbon stocks and changes in this system so that countries can get carbon credits for wetland restoration (IPCC, 2013). This process can only be used for coastal ecosystems where carbon is stored in the soil (ENGO representative, interviewee nr. 1).

3.2.3 Fish and Other Marine Animals as Carbon Sequesters

The interviews highlighted that awareness and knowledge about ocean and fish carbon is growing. While the fish contribution to the carbon cycle has been receiving scientific attention since at least since the 1980s, it was the ENGO Grid Arendal who coined and popularised the term "fish carbon" (Lutz and Martin, 2014).

The report (titled: Fish Carbon: Exploring Marine Vertebrate Carbon Services) was launched at the 2014 Blue Forest Meeting in Abu Dhabi, and it presented and introduced the idea of oceanic carbon sequestration in various meetings, scientific conferences, and reports in the following years.

It was pointed out by several interviewees that an increasing amount of research is emerging on the role of fishes (e.g. mesopelagic) and other marine animals such as whales and zooplankton in the ocean biological carbon pump. One interviewee pointed to the growing political attention on the topic, and that some among members of the European Union (EU) Parliament, had invited and that scientists had been invited to present on the topic at the Parliament. The contribution of fish to the biological pump was noted as a new of interest for several of the interviewees. Interviewees however also stressed that the topic (i.e. the contribution of fish to the carbon pump) is still predominantly taking place in the scientific sphere (i.e. conferences) so far only and being pushed forward by some ENGOs and scientists (Academic, interviewee nr. 18, Policy maker, interviewee nr. 8).

As mentioned in section 3.1, the 2019 IMF report (Chami et al., 2019) was considered by some of the interviewees as an important milestone. Although the IMF report is about whale carbon, it was considered to have great significance for discussions on fish carbon: '[…] *with the IMF publishing on this [whale carbon] and having it discussed at the World Economic Forum has really significantly changed this [fish carbon concept for policy making] over the past two years.*' (ENGO representative, interviewee nr. 7).

A number of interviewees referred to mesopelagic fish and their contribution to carbon cycles, (**Box 2**). The mesopelagic zone recently received increased attention in policy; exemplified by several EU funded research projects (e.g. MEESO SUMMER and MESOPP). The key motivating factor emphasised by interviewees was the high biomass estimates (Irigoien et al., 2014) highlighting mesopelagic fishes as a potentially valuable resource. In parallel to funding opportunities, a suite of reports and meetings were held featuring the mesopelagic (e.g. NAAFE, IDDRI). Interviewees emphasised the high stakes with regards to carbon flows and ecosystem processes that were supported by mesopelagic fish. They mentioned these processes as a reason for a precautionary approach regarding harvesting mesopelagic fish.

Many of the interviewees highlighted the scientific and technological uncertainties concerning fish carbon. Some of these uncertainties include, for instance, how to measure the flow of carbon, and how much of the carbon is sequestered and for how long. Interviewees mentioned that there are few concrete policy proposals that aim to integrate the carbon value of fish,

BOX 2 | Governance of mesopelagic species carbon sequestration services.

Recent scientific literature highlights the vast quantities of fish that could potentially be harvested in the mesopelagic zone (St. John et al., 2016; Alvheim et al., 2020). Mesopelagic fish are not directly consumable but could potentially be processed as nutraceuticals and fishmeal (St John et al., 2016). Experimental fisheries have thus far mainly taken place in ABNJ but in proximity to countries' EEZ (Gjerde et al., 2021). Mesopelagic fishing, if it were to be realized, would pose a trade-off between fishing and carbon sequestration. This is due to the active transport of carbon by mesopelagic species that migrate vertically (Boyd, 2019; Martin et al., 2021; Saba et al., 2021). Mesopelagic fish play a key role in food webs (Drazen and Sutton, 2017), and they and may not be very resilient to cumulative changes arising from climate change, direct harvesting, and deep-sea mining (Drazen et al., 2020).

Development of mesopelagic fisheries:

Today's mesopelagic fisheries are small and experimental (Hidalgo and Browman, 2019). Several interviewees noted that interest from the fishing industry may rise if the prospects for profitable harvesting would rise; however, highly variable catches and lack of knowledge for the causes of this variability are major barriers for fishery development. Since current fisheries are only experimental, fisheries management tools are not yet available for the mesopelagic. After catches started to be recorded under the management system in Iceland in 2010, very little mesopelagic fish were harvested (Standal and Grimaldo, 2020). A major concern for management mentioned by one interviewee was that consequences of harvesting may be experienced in a very different place where fishing occurs: "[...] *if you were try to truly assess the impact of the fishery on a species or a suite of species the scale you would look at would have to be much larger, than the footprint of the fishery itself*" (Academic Expert, interviewee nr. 12).

Governance options mentioned in the interviews for mesopelagic fish:

A number of different governance fora could proactively govern mesopelagic fish and their carbon sequestration services (Wright et al., 2020). The BBNJ agreement could be one policy instrument for governing mesopelagic fish particularly as they are not yet fished, and the number of groups potentially interested in fishing in the mesopelagic are limited (Wright et al., 2020). The agreement will use EIA, SEA, and area based management as governing mechanisms (Gjerde et al., 2021). An international, strategic environmental assessment process is conducted independent of any specific project and would aim to steer development policies (Gjerde et al., 2021). Such a process could improve understanding of the mesopelagic ecosystem before considering any exploitation. Such an assessment could, for instance, identify carbon sequestration hotspots that could be governed using area based management. Some interviewees noted that the high focus on marine genetic resources in the BBNJ could detract attention from the need to govern mesopelagic fish carbon in ABNJ. "W*e thought that it [the BBNJ agreement] would be a natural place to look because it's "Global governance of everything" but now it is really narrowing down [to marine genetic resources]"* (Academic Expert, Interviewee nr. 9). In part, this is linked to the fact that the BBNJ agreement may not undermine existing agreements and bodies (Young and Friedman, 2018). For fisheries management under UNFSA, the importance of accurate stock assessments were mentioned (Interviewee nr. 4 and nr. 12). Harvest quotas could be implemented by RFMO's and nation states based on such assessments. However, the wide-ranging distributions of mesopelagic fish and limited knowledge about their life history pose a challenge for science-based management (St. John et al., 2016) and there is some scepticism concerning the effectiveness of RFMO policies amongst interviewees (Bell et al., 2019). A collaboration between RFMOs and BBNJ agreement could be effective (Wright et al., 2020). In addition, a moratorium on mesopelagic fishing (Wright et al., 2020) has come up as a governance possibility. As a precautionary approach, the Pacific coast USA has implemented a moratorium. Motivated by the unknown consequences exploitation might have on the food web (Pacific Fishery Management Council, 2016). A moratorium on mesopelagic fishes was also mentioned by one of the interviewees, however, it is less clear which governance forum could implement such a moratorium. Finally, under the UNFCCC, one key consideration is the quantification and allocation of carbon fluxes. If carbon sequestration could be properly quantified then monetary incentives for conservation could be aligned such as putting a price on preserving mesopelagic fish for their carbon sequestration services. However, because carbon flows are not protected under UNFCCC, the limited knowledge about the magnitude of carbon stored for long-term in the seabed from those species represents one of several major barriers several interviewees explained (see Section 3.4.).

which in addition to the much-needed science information, both on the natural science side as on the legal and policy side would assist key actors to continue pushing the topic forward.

3.3 Processes Used by Key Actors to Create Attention for the Climate-Ocean Nexus

Interviewees discussed several ways in which they considered having impacted the debate around the nexus of the ocean and climate change in international policy fora. They mainly discussed events related to the UNFCCC. Potential approaches mentioned by the interviewees included the provision of technical information, the establishment of relationships with key actors including "champion" countries (countries leading on an issue in the international policy sphere), the coordination of events, and the formation of coalitions (see **Table S4** for a complete list of reported activities).

One interviewee (Policy maker, interviewee nr. 8) explained that ENGOs were instrumental in pushing the climate-ocean nexus debate. This interviewee highlighted, for example *The Ocean Pathway* which is an initiative that started during COP23 to mainstream the ocean in future COPs and is composed by a group of countries advised by (amongst others) ENGOs and IGOs. Another aim of this *Pathway* is to increase the role of the ocean in countries' NDCs. As reported by one of the interviewees, although this initiative is no longer active, it is worth mentioning it here for its pioneering work. The Marrakesh Platform and Friends of the Ocean is a new ocean pathway which is currently more active and which, similar to *The Ocean Pathway*, tries to mainstream the discussion of the ocean in climate change negotiations (IGO representative, interviewee nr. 17).

Some interviewees highlighted bridges that have been created between ENGOs, scientists and the policy sphere. For instance, as stated during the interviews, the ENGO Our Fish collaborates with scientists to present on the subject of fish carbon and mesopelagic fisheries for members of the European Parliament.

Another important collaborative strategy of ENGOs highlighted during the interviews was the establishment of good relations with representatives on government delegations. One strategy, as reported by several ENGO interviewees, is the search for "champion" countries that are leading in a certain sustainability issue. In these cases, the interviewees noted their efforts to highlight their activities while supporting countries that have a limited budget or capacity to send delegates to each negotiation. "*That's something we think about; which countries are pushing the most ambitious ocean climate action and how can we support them. How do we give them a bigger voice?*" (ENGO representative, interviewee nr. 13).

Interviewees mostly referred to impacting the policy debate around coastal blue carbon. The formation of coalitions (e.g. ENGOs and IGOs) were considered instrumental to advance the issue of coastal blue carbon. For example, the Blue Carbon Initiative, brought up by one of the interviewees, is a collaboration between the ENGO Conservation International, IOC-UNESCO and IUCN. This collaboration pushes for increased adoption of blue carbon mitigation strategies, coastal wetland preservation and carbon accounting. **Table S5** presents the list of key actors and coalitions mentioned during the interviews, as well as the policy fora with which they most frequently engage.

An event which was presented by one of the interviewees as having had an impact on policy discussions for fish carbon was "Ending overfishing as climate action". The event took place during the 2019 Blue COP co-organized among others by OurFish, and Seas At Risk. According to the interviewees, disussions have developed from this event in the UNFCCC. Moreover, an informal working group has since been established to provide the scientific basis to document the role of fish carbon in increasing climate resilience of fisheries. Moreover, a recent action plan to the European Commission from Our Fish contained the description of fish carbon sequestering services as an additional reason to conserve marine biodiversity (ENGO representative, interviewee nr. 19).

While there are some coalitions formally working together around the topic of coastal blue carbon, the interviewees did not mention any coalitions formally working on open ocean and fish carbon (Quote 4, **Table S2**).

3.4 Policy Fora for Open Ocean and Fish Carbon

Several policy fora were mentioned by the key informants interviewees that could play a role in governing open ocean and fish carbon sequestering ecosystem services. Respondents suggested six different fora. These included the BBNJ agreement, the UNFCCC, the CBD, the UNCLOS/UNFSA (including RFMO's), EU policy fora (including CFP and MSFD), and national level fisheries management (**Table 2**).

The BBNJ was the most frequently mentioned international policy forum (6 of 20 respondents), as an overarching framework that could potentially manage fish and other marine life in international waters (e.g. nascent mesopelagic fishes, **Box 2**). Management instruments under the BBNJ that were mentioned included Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), and Area Based Management (ABM). Interviewees suggested that if biodiversity is preserved, so are the carbon sequestering services of marine life, even if these ecosystem services are not quantified in detail. The BBNJ agreement at the moment does not specify carbon sequestration services of open ocean biodiversity (as specified by our search terms, see **Box 1** and **Figure 2**). However, there seems to be scope for taking these contributions under consideration with the specific policy instruments that are suggested to be implemented under the BBNJ (Gjerde et al., 2021; **Box 2**).

A concern raised by the interviewees in relation to BBNJ managing carbon sequestering services of marine life is that fisheries in international waters are already under the mandate of RFMOs. As reported by interviewees, some countries joining the BBNJ negotiations are cautious with regard to what extent the BBNJ agreement can address issues that are already supposed to be addressed elsewhere. Nevertheless, a stated aim of the BBNJ is to broadly regulate activities that may affect biodiversity in areas beyond national jurisdiction (ABNJ) (Quote 5, **Table S2**).

TABLE 2 | Interviewee reflections on potential policy fora, their possibilities for governance of open ocean and fish carbon sequestration services, possible barriers and concrete tools for management.

Policy forum	Possibilities (tools) for governance mentioned	Possible barriers mentioned
BBNJ (Biodiversity of Areas Beyond National Jurisdiction; under UNCLOS) (Currently being negotiated)	Address impacts on carbon sequestering contributions through EIA, SEA, and area based management.	May not address key pressures such as deep-sea mining and fishing (push from certain nations to exclude fishing); increasingly narrow focus on marine genetic resources.
UNFCCC (United Nations Convention Framework for Climate Change)	Carbon credits, NDC pledges towards increasing marine protected areas (**Box 1**).	Measurability and traceability concerns were mentioned, as was the fact that regulation *via* UNFCCC will only work if there is a way to account for carbon stored in the open ocean. Another concern mentioned is that biodiversity concerns could arise from interventions (i.e. geoengineering).
CBD (Convention on Biological Diversity)	Marine biodiversity conservation, more integration between biodiversity conservation and UNFCCC domain so that the benefit of biodiversity conservation for climate are addressed (and impact of climate change on)	*
UNFSA (United Nations Fish Stocks Agreement; under UNCLOS)	End overfishing of straddling stocks, governance of mesopelagic fisheries.	Concerns over RFMO effectiveness
	Management tools such as Stock assessments, fisheries regulation.	RFMO's designed only for target species, not biodiversity/ecosystem services
UNCLOS/National Level Fisheries management under UNCLOS	Fisheries management through e.g. quota, stock assessments.	Fisheries management has mainly been preoccupied with target stocks and not ecosystem services such as biodiversity and climate regulation.
CFP (Common Fisheries Policy)	EIA and area based management for fisheries, quota allocation based on good environmental (including carbon) performance.	Focused only on target species, not biodiversity/ecosystem services.
MSFD (Marine Strategy Framework Directive)	EIA and area based management for fisheries, marine biodiversity conservation.	Climate change concerns are not very well integrated in the MFSD.

**Policy fora are organized from most frequently mentioned to least frequently mentioned. Lack of enforcement and volunarity of national implementations were mentioned as a general concern for many conventions. Although no barriers to the CBD were specifically mentioned during the interviews, it does not mean there are no barriers to the CBD managing carbon sequestration services from fish.*

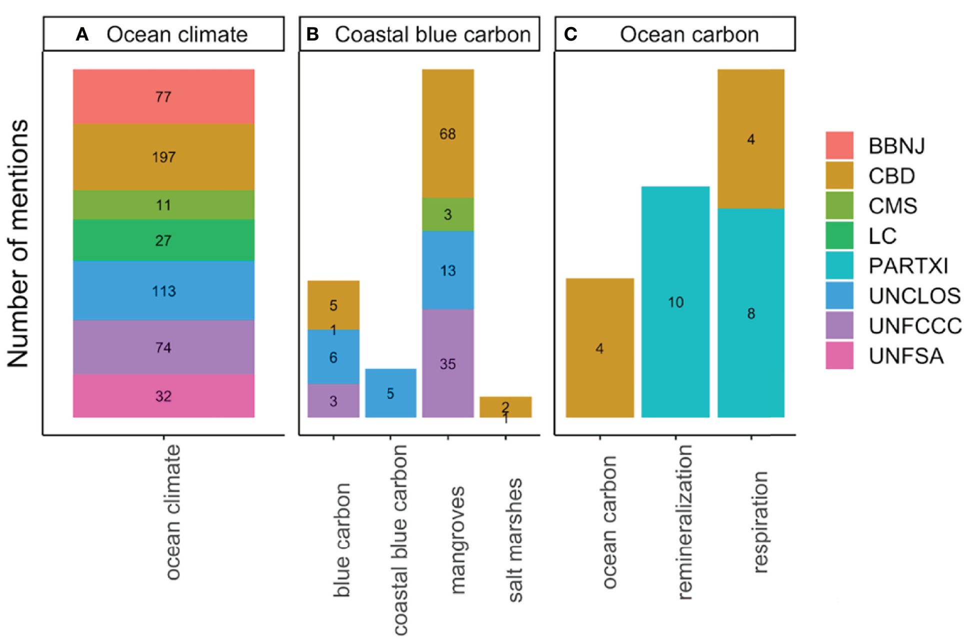

FIGURE 2 | Number of mentions per keyword in studied policy documents; BBNJ (Biodiversity of Areas Beyond National Jurisdiction); CBD (Convention on Biological Diversity); CMS (Convention on the Conservation of Migratory Species of Wild Animals); ICRW (International Convention for the Regulation of Whaling); LC (London Convention); UNCLOS (United Nations Convention of the Law of the Sea); Part XI (Part XI of UNCLOS); UNFCCC (United Nations Framework Convention on Climate Change); UNFSA (United Nations Fish Stocks Agreement). For keywords referring to **(A)** ocean and climate in the same sentence **(B)** coastal blue carbon **(C)** open ocean carbon. Note that the y-axis is log-transformed to ease interpretation.

The second most frequently mentioned forum was the UNFCCC (5 out of 20 respondents) where countries could potentially add open ocean and fish carbon sequestration to their NDC's). Policy interventions mentioned by interviewees included the 30% protection of the ocean by 2030 which is a goal that was considered feasible with our current (limited) knowledge of the ocean biological pump and the contribution of marine fauna to it (i.e. protection of large areas of ocean may protect marine habitats and animals and their carbon sequestering services) (Quote 6, **Table S2**). Fiji, for instance, aims to protect 30% of its EEZ by 2030 in its NDC to the Paris agreement, and even if the carbon contribution of that protection is not fully quantified, it is still mentioned by Fiji as a marine policy that also advances progress towards climate goals (**Box 1**). It should be noted, however, that enhancing the carbon sink contributions of the ocean was according to the interviewees, mostly directed towards coastal ecosystems, predominantly mangroves. None of the NDC's mentioned the ocean biological pump or fish carbon (**Box 1**).

Voluntary carbon markets were also mentioned as a governance strategy, however many interviewees pointed out that a much larger knowledge base would be needed for such policies. Measurability and accountability of climate mitigation actions is a big concern for NDC's as countries get carbon credits for mitigation measures. As indicated by one interviewee: "*To get blue carbon into the reporting* [of the NDC's] *we still lack robust methods for accounting of the carbon circulated in the ocean. How much is absorbed, how much is then long-term stored in the ocean floor and seabed. And how much of the carbon is stored for mid-term to centuries, in living material.*" (Policy officer, interviewee nr. 8)

Other concerns, beyond measurability, may also hamper the adoption of fish and ocean carbon mitigation into actual policy goals, especially so within the UNFCCC. First, concerns of "bluewashing" were noted in relation to the fact that if policy actions are implemented to preserve ocean carbon sinks or flows, then these actions are not fully quantifiable. Moreover, much of the marine biota that are present in the high seas are also highly mobile, which could lead to "double counting" of carbon credits in the case of e.g. implementing a voluntary carbon market for fish. This is an issue that interviewees highlighted as a major concern by those working on climate action within the UNFCCC fora (Quote 7, **Table S2**). Another type of concern that was voiced was that increasing attention to open ocean and fish carbon mitigation solutions would pull precious attention and resources away from coastal blue carbon solutions (mangroves, seagrasses, saltmarshes) for which established and measurable protocols for carbon accounting already exist.

3 of 20 interviewees also mentioned the CBD as a potential forum. One interviewee mentioned that CBD could set biodiversity targets that could be regulated under the BBNJ agreement. Interviewees also mentioned that climate contributions of biodiversity and the nexus between climate and biodiversity could be potentially better addressed in the CBD than for instance the UNFCCC. Unfortunately, the interviewees did not provide any concrete ideas or opportunities for regulatory tools that could be used to manage carbon sequestering services of marine life (see **Table 2**).

UNFSA in its capacity to regulate fishing of straddling stocks in international waters and RFMO's were also mentioned (3 of 20 respondents) as important for managing nascent mesopelagic fisheries, and fisheries in the high seas in general. However, several interviewees expressed scepticism concering their effectiveness (Quote 8, **Table S2**). The interviewees also mentioned that RFMOs may be limited in their capacity to manage open ocean and fish carbon because RFMO's are more equipped to manage target species and are not focused on biodiversity impacts of fishing (e.g. through bycatch or indirect impacts).

The EU setting was also mentioned during the interviews as potential fora for carbon sequestration services of marine life (2 out of 20); both interviewees mentioned the Common Fisheries Policy (CFP) and Marine Strategy Framework Directive (MSFD). In addition, one interviewee mentioned that within the EU regulatory framework, EIA needs to be performed for certain types of activities (Directive 2014/52/EU). This interviewee mentioned that EIA for fishing (currently not practiced), could be a future way to regulate the carbon sequestration done by fish, by quantifying the (approximate) impact the fishery has on the (potential) carbon sequestering services of marine animals during the allocation of fishing opportunities (Quote 9, **Table S2**).

Interviewees also brought up the topic that ending the overfishing of marine populations and ending destructive fishing practises (e.g. overfishing, habitat destructive practises such as trawling) that are harmful for marine biodiversity would have several climate co-benefits which align with recent research (e.g. Sumaila and Tai, 2020). For instance, restored fish populations could lead to shorter fishing trips and hence the use of less fuel.

Quota allocation with environmental and carbon sequestration concerns in mind were also mentioned as a potential tool available at the national level. Local fisheries management in national waters was mentioned (3 of 20 interviewees) as the main framework under which carbon sequestering services of marine life could be managed, mainly through the setting of fishing quota and the importance of proper stock assessments was also stressed.

A number of interviewees did not think that carbon sequestration services of marine animals such as fish and marine mammals should be actively managed, and that other ecosystem services of fish such as food provisioning should be enough to manage them. Among the mentioned reasons was that a better scientific understanding of the carbon sequestering ecosystem services was needed before deciding on suitable policy fora. Other interviewees talked about governance in general terms without mentioning specific policy fora. **Box 3** discusses different pathways for the management of fish carbon and possible knowledge requirements.

4 DISCUSSION

In this study we interviewed 20 key informants that comprised experts and policy makers on topics related to the governance of

BOX 3 | Should open ocean and fish carbon be governed?

Currently there is a lack of knowledge on ecosystem trade-offs arising from fishing for nutrition and species' contribution to carbon fluxes (Saba et al., 2021; Martin et al., 2021). Estimates of the contributions of fish to the sequestration of carbon to the deep sea vary widely. A recent synthesis reports that fish contribute 16.1% (±13%) to total carbon flux out of the euphotic zone, which could equate to an annual flux of 1.5 ± 1.2 PgC per year, an estimated 8% of which gets extracted by marine fisheries (Saba et al., 2021). Quantification of these carbon flows is still ongoing as mentioned by several interviewed experts in this study. Saba et al. (2021) and Martin et al. (2021) list several recommendations for science on the role of the fish-based contribution to the ocean carbon flux, including a better integration of field, lab and modeling studies and more experiments on representative species for functional taxa. Once more data becomes available on fish-based contributions to carbon flux, and these contributions become more specific for the different taxa and regions, more clarity can arise around the carbon trade-offs associated with exploiting marine populations, or other impactful activities such as deep-sea mining (Drazen et al., 2020). For instance, the estimated carbon footprint of fishing of 0.73 GtC, between 1950-2014 (Mariani et al., 2020) is still much lower than the carbon footprint of livestock production (Hilborn et al., 2018). Next to the natural science knowledge needs, studies are needed on how governance of open ocean and fish carbon can be materialized, legally and practically. For instance, if instruments such as EIA and SEA were to consider open ocean and fish carbon, more knowledge would be needed on how to implement the assessment and evaluate trade-offs between carbon flux and the social cost of carbon (Nordhaus, 2017).

There are four potential management options that we identified through our interviews: Option 1) exploiting fish stocks to a lesser degree while considering their carbon sequestration value in fisheries management systems. Maximum sustainable yield (MSY), a common fisheries management target could include a carbon sequestration target. Interviewee nr. 7 referred to this simple heuristic as MSY+C, which in some fisheries may lead to lower rates of extraction than those for MSY as found by Jennings and Wilson (2009) for carbonate production by fish. Incentives for this approach could come from voluntary carbon markets. Option 2) investing more in efforts to halt illegal and unreported fishing as well as overfishing. Option 3) taking a precautionary approach for new fisheries, i.e. a moratorium on exploitation of certain fish populations that play an especially important role in the global carbon cycle, e.g. mesopelagic fish Martin et al., 2021). Option 4) When considering human activities, account for carbon emissions lost carbon sequestration services, and possibly cascading ecosystem effects on carbon sequestration in EIA and SEA (Martin et al., 2021). Knowledge needs will differ for all those options, with most needed to consider the value of carbon in fisheries management (option 1) EIA or SEA (option 4), than for the precautionary approach and the knowledge on the damaging effects of overfishing (option 2 and 3, respectively).

ocean and fish carbon. Based on the interview results, we mapped out a timeline of milestones in the governance of coastal and open ocean and fish carbon (**Figure 1**) and we asked interviewees about opportunities for policy action with regards to ocean carbon (see results in **Table 2**). Key findings were that while much of the attention ENGOs directed toward fish carbon was focussed on the UNFCCC, many interviewees found this forum an unlikely arena for the management of open ocean and fish carbon. These doubts were raised due to key uncertainties with regards to the tracking of open ocean and fish carbon and the mobility of marine fauna. Several interviewees mentioned the BBNJ as a promising avenue for governance of open ocean and fish carbon, however important barriers of this governance forum were also highlighted (**Table 2**).

4.1 The Evolving Science and Debate on the Oceans and Climate Change

The international debate on ocean and climate has evolved over the years. Earliest discussions focussed primarily on climate impacts on the ocean. This grew to also include Nature-Based Solutions (Roberts et al., 2017; Seddon et al., 2019) such as carbon sequestration ecosystem services of the ocean, with an emphasis on coastal ecosystems (Chan, 2021). This has further progressed to discussions of open ocean and fish carbon sequestration (Mariani et al., 2020; Pörtner et al., 2021). Scientific attention at the nexus of oceans and climate has mainly focused on climate change impacts on marine ecosystems and societies that depend on them (e.g. Cheung et al., 2010; Pinsky et al., 2013; Olsen et al., 2018; Rogers et al., 2019). Work on adaptation to those impacts were a natural extension to this research and policy focus (Fulton et al., 2011; Ojea et al., 2017; Young et al., 2019; Woods et al., 2022). Related governance challenges on this climate and ocean space include fisheries conflict, and static, non-adaptive management arrangements (Spijkers and Boonstra, 2017; Pinsky et al., 2018; Spijkers et al., 2018). Fisheries have grown to be a major issue for coastal nations in their NDCs, primarily in the adaptation sections (Gallo et al., 2017), and RFMOs are increasingly under pressure to consider climate adaptive management approaches (Pentz et al., 2018). In the BBNJ agreement, impacts from climate change may be considered in the assessment of cumulative impacts (Gjerde et al., 2021).

4.2 Climate Co-Benefits of a Healthy Ocean and the Emergence of the Topic "Fish and Open Ocean Carbon"

Healthy marine and coastal ecosystems sequester more carbon than ocean ecosystems that are heavily affected by anthropogenic degradation (Chmura et al., 2003; Saba et al., 2021). The presentation of policy making for the ocean-climate nexus has now resulted in a lively discourse on the carbon sequestering capabilities of marine ecosystems at important policy fora such as the UNFCCC (Chan, 2021) but to a lesser extent at policy fora aimed at biodiversity protection such as the BBNJ agreement or the CBD. Coastal blue carbon is carbon that is absorbed and stored by marine plants, and has received substantial attention both as a climate mitigation and adaptation strategy in policy fora such as UNFCCC, attention which has be supported and pushed for by IUCN and ENGOs (Howard et al., 2017; Lovelock and Duarte, 2019). To date, this push for, and increase in blue carbon measuring and offsetting has concentrated on coastal blue carbon, including rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses, where the carbon is stored in the soil (Howard et al., 2017). Such ecosystems both store more carbon per m^2 than terrestrial forests (Chmura et al., 2003; Sapkota and White, 2020) and assist with coastal protection, which is especially needed with sea level rise (Marois and Mitsch, 2015). The interest in open ocean and fish carbon associated with marine organisms' carbon sequestration and cycling has emerged recently, with increasing publications in the contributions of different species to carbon cycling in the open ocean (Mariani et al., 2020; Bianchi et al., 2021; Martin et al., 2021; Saba et al., 2021). However, the body of scientific literature on the carbon sequestering services of coastal blue carbon is much larger (Kelleway et al., 2017), but even for these ecosystems actual implemented policies are still sparse (Cooley et al., 2019). There will thus be several important hurdles that need to be cleared before open ocean and fish carbon could be governed explicitly. However, the increasing awareness of this ecosystem service of fish and the developing science around it may create increased awareness of the trade-offs associated with actions that have negative consequences for fish populations (e.g. direct exploitation, or habitat damage) (Saba et al., 2021).

4.3 ENGOs and Intergovernmental Organisations' Role in the International Policy Fora on the Topic of Open Ocean Carbon

ENGOs and intergovernmental organisations such as IUCN or IOC-UNESCO have highlighted the co-benefits derived from a healthy ocean for the climate. This message is now embedded in the international policy space, especially within the UNFCCC (Chan, 2021). In the case of ENGOs this is an interesting result because it highlights their role in international policy fora. ENGOs bring a global and regional perspective to the policy-making fora, a perspective which contrasts to the protection of national interests brought by individual states (Grip, 2017). Some individual states for which the ocean is particularly important (i.e. small island developing states, or states with long coastlines) have particularly pushed for ocean action in the climate realm (as opposed to e.g. landlocked countries). We learned from our interviews that ENGOs have formed alliances with some of these countries, and in this way have helped to increase attention to the ocean in the climate regime as after all "*the making of international agreements remain the domain of states*" (Sénit, 2020).

ENGOs representatives talked about a mix of strategies, with a heavy emphasis on insider tactics in the case of ocean carbon (inside negotiating hubs, i.e. information, expertise and opinions provided in oral or written interventions during formal and informal settings (Blasiak et al., 2017; Sénit, 2020). While ENGOs engaged in outreach to create awareness on the ocean, and some of the co-benefits that can be derived from a healthy ocean, the topic of climate-ocean nexus seemed to be a story that is being told within ENGOs. At the same time, while interviewed actors noted a growing interest by policy makers on the topic of ocean and fish carbon, it is too early to say that the interest is merely in the research itself, or to develop actual policies.

4.4 Possible Policy Fora for Open Ocean and Fish Carbon

Interviewees were asked the question *how can carbon sequestration in the ocean be effectively managed*? Six different fora were suggested: BBNJ, UNFCCC, CBD, UNCLOS, UNFSA (RFMOs), EU policy fora (CFP and MSFD), and national fisheries management. The BBNJ, UNFCCC, and UNFSA are current fora which discuss open ocean and fish carbon to varying degrees (**Box 1**). Preserving biodiversity for climate regulation is beneficial, both for addressing rapidly declining biodiversity, and for its sequestration capacities. However, a number of interviewees concluded that the time is not ripe to actively manage carbon sequestering capabilities of marine life such as fish and whales under the UNFCCC framework. Some of the concerns that were raised by the interviewees related to the measurability and traceability issues in connection to the open ocean fish carbon. The science is still at very early stages which may mean that avenues for "bluewashing" (unquantifiable actions related to ocean mitigation solutions) are opened and that countries may use the carbon sequestering capabilities of the ocean to avoid other difficult transitions. This concern is more widely applicable to carbon offsets using biodiversity targets (Rantala et al., 2019).

Although many uncertainties remain, the science on carbon sequestering capabilities of fish and marine life is growing rapidly (Martin et al., 2021; Saba et al., 2021). It is not unimaginable that in a further future also flows of carbon could be protected within UNFCCC. It should however be noted that most carbon sequestered by the ocean is released back into the atmosphere on longer timescales (Passow and Carlson, 2012), and this sequestration is thus not a permanent solution to the amount of carbon released into the atmosphere by anthropogenic activity.

Results of this paper regarding policy fora largely confirmed their role in protecting ecosystems and biodiversity described in previous literature. RFMO's for instance were mentioned by the interviewees for their importance in the management of high seas fisheries (and for their relevance to the future management of e.g. mesopelagic fishes). However, interviewees also indicated that RFMO's were not very effective in enforcing ecosystem based management, something that is also reflected in the literature (Koubrak and VanderZwaag, 2020). In a similar vein national level fisheries management was also mentioned as a possible solution for managing ecosystem services of fish, amongst which would be their carbon sequestering capabilities. Interviewees mentioned the focus on single species as a possible barrier, an issue which is also reflected in previous literature (Link, 2002). The BBNJ agreement was mentioned as a possible forum using its tools such as EIA and area based management, which has been emphasised before (Gjerde et al., 2021). Nevertheless, a number of interviewees were concerned that negotiations for the BBNJ agreement were currently dominated by the issues of Marine Genetic resources, as has been noted elsewhere (Blasiak et al., 2017; De Santo et al., 2020).

4.5 Integration Between Policy Fora

Interviewees suggested that agreements could benefit from increased cooperation and integration with each other. For instance, it was mentioned that in biodiversity agreements such as the CBD and BBNJ, the consideration of carbon sinks is lacking and within the UNFCCC the role of biodiversity is currently not considered. It was stressed that those agreements could benefit from increased cooperation and integration with each other between themselves and the UNFCCC. "Within the *UNFCCC few think about the impacts of climate on biodiversity or whether biodiversity might have an impact on climate; they don't really talk to each other. It is worth thinking about whether* *we can bridge the silos between those working on biodiversity and those working on climate."* (ENGO representative, interviewee nr. 13).

A number of interviewees also mentioned the creation of a working group between several policy fora (UNFCCC, UNCLOS, CBD) as an option to find synergies between biodiversity and climate change targets, as well as impacts that go both ways (climate change impacting biodiversity, biodiversity impacting climate change). The synergy (and possible trade-offs) between biodiversity protection and climate regulation, and the role that existing UN frameworks could play in this cross-cutting issue has been addressed previously (Azizi et al., 2019; Rantala et al., 2019; Pörtner et al., 2021). Rantala et al. (2019) focused mostly on terrestrial ecosystems and found that concrete measures towards sustainable agriculture that addresses both carbon and other greenhouse gas emissions and biodiversity protection are mostly missing from the CBD and UNFCCC. Azizi et al. (2019) found some level of overlap between ocean and biodiversity international agreements, but concluded that clusters of agreements were largely self-referential and operated in silos.

Surprisingly, there was not a single mention of UNCLOS Part XI by interviewees as a potential forum for the management of open ocean and fish carbon. This was surprising as deep sea mining would be regulated under this convention in areas beyond national jurisdiction (Thompson et al., 2018) and could have a large impact on carbon sequestration in the deep sea (Nagender Nath et al., 2012; Stratmann et al., 2018).

4.6 Trade-Offs and Synergies Between Carbon Sequestering, Biodiversity and Food Provisioning of Marine Fishes

Possible trade-offs between climate action and biodiversity enhancement deserve further attention. Climate regulation action could also negatively affect biodiversity and ecosystem functioning (Rantala et al., 2019). In the case of fish carbon leaving more fish biomass in the sea, people could switch to other foods. This switch could result in more greenhouse gas emissions in the case of animal-based products (Hilborn et al., 2018). Halting overfishing however, will likely only be synergistic, both for food security (Srinivasan et al., 2010; Cabral et al., 2019), greenhouse gas emissions from fuel used for fishing (Hornborg and Smith, 2020; Byrne et al., 2021), but also for preserving the carbon sequestering services of fish populations (Mariani et al., 2020; Cavan and Hill, 2022).

Our study has several important caveats that need to be considered when interpreting the results. We have focused on ENGOs, IGOs, policy experts, and policy makers but we did not consider the industry perspective. During the interviews it was mentioned that industry could become engaged with the topic of open ocean and fish carbon if there are concrete policy proposals, policy action, or regulations put into place. It would be of interest to examine what would motivate industry groups to allocate time and effort to the topic of fish and ocean carbon. Moreover, using the snowball approach for sampling we may have missed voices in the debate (Parker et al., 2019). The approach also gives us a biased sample of interviewees that may share a similar message (Parker et al., 2019) Moreover, the approach for selecting key informants, both the web-based search and the snow-ball approach has probably been the cause for the fact that most of our interviewees work for North American or European institutions, despite actively trying to include a more diverse perspective. The article should therefore not be read as representative of the fields of coastal blue carbon and open ocean and fish carbon. The snowball approach was however a very useful tactic for us to find voices in the debate that were not as prominent in the public sphere.

An example of voices that we missed were indigenous communities. Small island developing states (SIDS) and indigenous communities often rely heavily on natural resources for their livelihoods, and for some indigenous and SIDS communities, seafood and fisheries are important for livelihoods, food security and cultural heritage (Bess, 2001; Cisneros-Montemayor et al., 2016; Blanchard et al., 2017). Governance for open ocean and fish carbon could have implications for these communities, by for instance restricting fishing access (Mascia et al., 2010; Ban and Frid, 2018). Therefore, it is crucial that indigenous voices are represented when policy solutions are designed, to pursue sustainable and equitable pathways for ocean and fish carbon governance (Klain et al., 2014). The governance of open ocean ecosystems can potentially affect the lives of indigenous communities through food-web effects on top predators e.g. many tuna and sea turtles feed in the open ocean and also provide ecosystem services (e.g. fishing, tourism, respectively) to indigenous communities. Moreover, since these communities, including SIDS, are more at risk from climate change the inclusion of these voices is also needed for these debates and governance designs (such as the BBNJ). In addition, our interview results showed, for instance, that SIDS such as Fiji have been key in raising awareness for the oceans in particular (Chan, 2021) and creating leverage for climate interventions (Benwell, 2011).

5 CONCLUSION

We found that many of the key events that were mentioned by the interviewees were UNFCCC initiatives. However, given the strict requirements within UNFCCC for measurability and traceability, other governance fora (e.g. CBD or BBNJ agreement) seem a more likely venue for the governance of open ocean and fish carbon sequestration services. Increased attention to open ocean and fish carbon in these fora (CBD or BBNJ) may facilitate the establishment of feasible policy proposals. Moreover, based on the interviews it seems that opposition to the "fish carbon" concept from specialists working with coastal blue carbon may slow down policy adoption in intergovernmental fora such as UNFCCC. The results of our interviews highlighted that the area based management and EIA tools facilitated through the BBNJ agreement are the most promising candidates to govern mesopelagic fish and their important carbon sequestering ecosystem services (which is in line with Gjerde et al., 2021), especially if combined with other governance fora (i.e. RFMO's or UNFSA). This is an important finding to keep in mind for the ongoing negotiations regarding biodiversity in ABNJ.

DATA AVAILABILITY STATEMENT

The data sets presented in this article are not readily available because the information provided in the confidential interviews was used for research purposes. The results from these interviews are included in this article which is published online and made available to the public. Personal information and interview transcripts are anonymous.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by WMU Research Ethics Committee, REC DECISION # REC-21-05(R). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, MSW, MO and LE. Analysis, MO, LE, and PR-M. Visualization, MO and LE. Writing, MO, LE, PR-M, and MSW. Editing, all authors. Supervision, MSW. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.764609/full#supplementary-material

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Overfishing Increases the Carbon Footprint of Seafood Production From Small-Scale Fisheries

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Small-scale fisheries (SSFs) and the foods they produce are extremely important, contributing 25–50% of global seafood landed for direct consumption. In some cases, SSFs provide seafoods with an exceptionally low carbon footprint, but like all food, it is important to understand the factors that regulate that footprint in the face of increasing demand and a worsening climate-ecological crisis. We utilize long-term fisheries monitoring data from Northwest Mexico to generate novel stock assessments and, subsequently, test the relationship between underlying fishery biomass and fuel intensity observed among several motorized SSFs. Using fuel data from over 4,000 individual fishing trips, in combination with estimated biomass data for 19 regional stocks, we show that the fuel footprint per kilogram of seafood increases sharply as the stock's underlying annual biomass (B) falls below its estimated biomass at Maximum Sustainable Yield (B_{MSY}). We find an inverse relationship between B/B_{MSY} and fuel intensity using a test for simple correlation between the two (r= -0.44), a linear regression analysis ($R^2_{adj.}$ = 0.17), and a mixed-effects model with gear type, year, and genus modelled as random effects. These results indicate that efforts to end overfishing, rebuild fishery stocks, and/or minimize intensive fishing practices will help to decrease the carbon emissions generated by motorized wild-catch fishing. We anticipate that this study will contribute an important "missing link" to discussions on how best to secure climate-resilient fisheries and, ideally, help SSF stakeholders garner recognition and support for SSFs in this context.

Keywords: artisanal fisheries, carbon footprint, fuel intensity, management, maximum sustainable yield, Mexico, overfishing, small-scale fisheries

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INTRODUCTION

Fisheries are an integral source of animal protein to nearly 1-in-5 of the world's roughly 7.2 billion people (FAO, 2017; FAO SOFIA, 2018), making them a key element in all considerations related to global food security. While the production of wild-caught seafood has reached something of a plateau in terms of annual landed biomass (Pauly and Zeller, 2016), demand for seafood (and other animal products) has been steadily increasing over the last several decades and is projected to grow for the foreseeable future (Kearny, 2010; FAO SOFIA, 2018; Costello et al., 2020). Because seafood, like all food, bears some environmental footprint, it is important to understand the factors that maintain, diminish, or grow that footprint in the face of increasing demand and a worsening climate-ecological crisis (IPBES, 2019; IPCC, 2022).

Fishing is inextricably linked to nearly all marine landscapes, flora, and fauna — and the act of *overfishing* has been shown to have deleterious effects on abiotic and biogenic habitat, dramatically altering species abundance and the preservation of biodiversity, with often negative impacts on coastal communities of people (e.g., Turner et al., 1999; Worm et al., 2006; Sumaila and Tai, 2020; Sumaila et al., 2021). In the 1990's, scientists began to document the serial depletion of fisheries stocks worldwide (e.g., Pauly et al., 1998), namely at the hands of industrial/large-scale fisheries, and several high-profile papers drew public attention to the fact that a large proportion of the world's fish populations were experiencing overfishing or were already overfished (Pauly et al., 1998; Worm et al., 2006). Since then, numerous governmental and non-governmental policy agendas have been dedicated to ending overfishing and rebuilding stocks (FAO SOFIA, 2018). While these efforts have been met with some success (Duarte et al., 2020; Hilborn et al., 2020), overfishing remains a serious problem (FAO SOFIA, 2018), particularly for stocks which lack formal assessments (Costello et al., 2012; Hilborn et al., 2020).

SSFs produce anywhere from 25–50% of all seafood landed for direct consumption (Pauly and Zeller, 2016; FAO, 2017; FAO SOFIA, 2018; Greer et al., 2019) and, in some cases, serve as a source of food with an exceptionally low carbon footprint (Nijdam et al., 2012; Hilborn et al., 2018; Ferrer et al., 2021). SSFs can be motorized or non-motorized, targeting thousands of taxa and supporting millions of jobs in both the fishing and post-production sectors (FAO, 2017; FAO SOFIA, 2018). At the same time, SSFs tend to be "data-poor," and often lack formal fishery stock assessments (Costello et al., 2012; FAO SOFIA, 2018; Hilborn et al., 2020). This makes them often difficult to manage (Costello et al., 2012; FAO SOFIA, 2018; Hilborn et al., 2020) and notoriously underrepresented in socio-political discussions surrounding (sustainable) global food production (e.g., Cohen et al., 2019). Given their diversity, there does not exist a universal definition for SSFs (Hidden Harvest Report, 2012; Smith and Basurto, 2019), but for the purposes of this article, we define SSFs to be those fisheries targeted by vessels < 12m in length (FAO, 2022).

Key considerations vis-à-vis "sustainable" seafood are the existence or non-existence of overfishing within that fishery/particular region, as well as gear type, and extent of fishing effort. Ending overfishing is a valuable endeavor in its own right, with several co-benefits, such as increased ecosystem biomass and avoided damages to aquatic habitat (Sumaila and Tai, 2020). A decrease in the total carbon footprint and/or fuel intensity of fisheries are two *additional* co-benefits that have been theorized by fisheries scientists; the logic behind this idea being that an end to overfishing would require a decrease in overcapacity of the world's fishing fleets, shrinking the total fuel footprint of fisheries while growing available biomass across a number of stocks, and effectively increasing the Catch per Unit Effort (CPUE) (The World Bank, 2017; Sumaila and Tai, 2020). This idea is compelling and largely intuitive, yet the relationship between overfishing and emissions is supported by a limited number of empirical studies and relevant inquiries focused on SSFs are noticeably scant (see Parker and Tyedmers, 2015; Rousseau et al., 2019; Bloor et al., 2021).

Here, we utilized long-term fisheries monitoring data from Northwest Mexico to generate novel stock assessments and to, subsequently, test the relationship between underlying stock status and fuel intensity among several SSFs in the region [note that we use fishery biomass as a proxy for stock status]. Like others have alluded to (e.g., The World Bank, 2017; Sumaila and Tai, 2020), we hypothesize that there exists an inverse relationship between fishery biomass (B/B_{MSY}) and fuel intensity — that is to say, as fishery biomass decreases, the fuel required to land one unit of seafood increases. To substantiate this hypothesis, we utilized two independent fishery databases, in combination with methods for "data-poor" stock assessment (developed by Froese et al., 2017), to explore the relationship between estimated B/B_{MSY} and fuel intensity across 19 Stocks, and 39 "Stock-Years of Interest" (defined in Section 2.3). We end with a discussion on the theoretical climate-fishing feedbacks that have been proposed in the literature to date, and discuss the importance of our results in the context of overlapping social, climate, and biodiversity objectives.

METHODS

To test the relationship between fishery biomass (B/B_{MSY}) and fuel intensity, we draw from the following independent data sources: (i) fuel and catch data from the Gulf of California Marine Program (GCMP) Fisheries Monitoring Network, hereafter referred to as "the GCMP database" (Mascareñas-Osorio et al., 2017); and (ii) fisheries landings data supplied by the Mexican governmental agency known as *Comisión Nacional de Acuacultura y Pesca* (CONAPESCA), hereafter referred to as "the CONAPESCA database" (Mascareñas-Osorio et al., 2018). Both of these databases are updated periodically, and the data used herein reflect observations from the GCMP database recorded through March, 2018, and from the CONAPESCA database recorded through December, 2019. See **Figure 1** for a stylized representation of our methodology, and consult the **Supplementary Material** section to access relevant dataframes. All analyses were performed using Microsoft Excel in combination with R version 4.0.3 (R Core Team, 2020).

Collecting High-Resolution Catch and Fuel Data From SSFs in Northwest Mexico (Utilizing "the GCMP Database")

Northwest Mexico is home to two of the country's most productive fishery zones: the southern extension of the California Current Ecosystem, and the Gulf of California (GoC) (Cisneros-Mata, 2010, FAO, 2022). Indeed, from our own interrogation of the CONAPESCA database, we found that from 2006 to 2014, SSFs in Northwest Mexico contributed

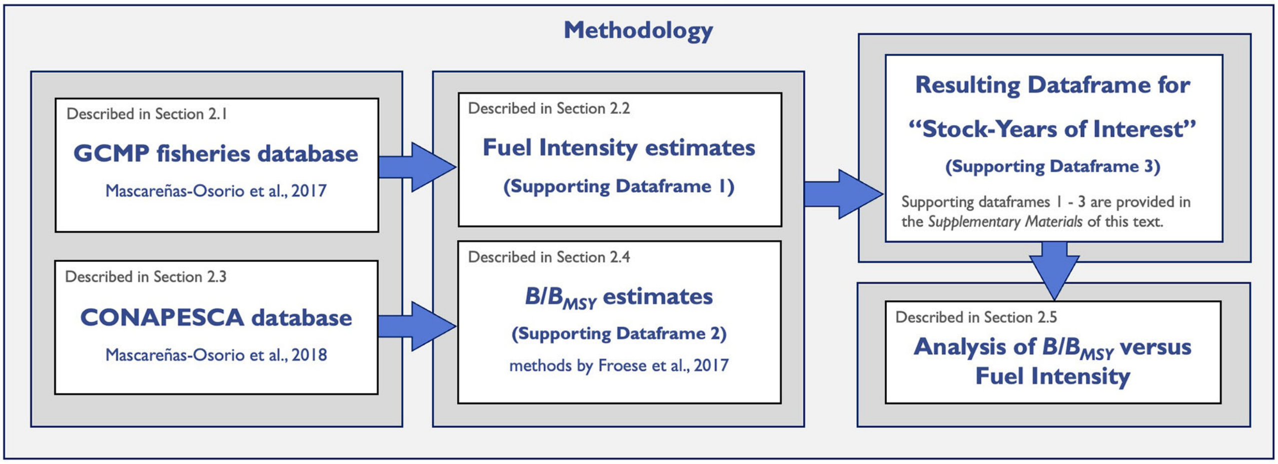

FIGURE 1 | Infographic showing our methodological flow from Section 2.1 to 2.5. Here, "GCMP" stands for the Gulf of California Marine Program, and "CONAPESCA" stands for the *Comisión Nacional de Acuacultura y Pesca*.

52% of the total biomass generated by the nation's marine SSFs (Ferrer et al., 2021).

Understanding the critical importance of SSFs in and around the GoC, colleagues with the GCMP and local small-scale fishers have worked collaboratively for over a decade to collect high-resolution fisheries monitoring data from in and around the Baja California Peninsula (see http://gulfprogram.ucsd.edu/slider-home/projects/). This monitoring program employs portable GPS tracking devices to populate a database with thousands of fishing tracks (> 25,000), about 5,000 of which are further appended with information related to catch and fuel consumption. These records within the GCMP database comprise the universe of data we used to generate the fuel intensity estimates described below.

Fuel Intensity Estimates From the GCMP Database

A fuel intensity estimate (FIE) is a measure of fuel efficiency, telling us the fuel consumption per unit of X, where in this case X is one kilogram of wet weight[1,2] seafood. To generate FIEs, we divided the gasoline consumption (in liters) by the wet weight of catch reported for each single-species fishing trip identified/located in the GCMP database. To avoid the numerous uncertainties associated with partitioning fuel consumption among trips targeting multiple species (Vázquez-Rowe et al., 2012), we constrained our analysis to records for single-species trips. We also excluded any records that were obviously duplicated, incomplete, split, or erroneous (e.g., average boat speed > 80 km/hr). The resulting dataframe ($n_{records}$= 4,795) is included in the **Supplementary Material** section of this text, entitled "**Supporting Dataframe 1**". The raw data for this analysis (Mascareñas-Osorio et al., 2017) are available upon consultation at dataMares.ucsd.edu.

Extracting Time Series Data From the CONAPESCA Database Based on Two "Criteria for Inclusion"

To generate stock assessment profiles (described in Section 2.4), we first needed to extract catch time series from the CONAPESCA database (Mascareñas-Osorio et al., 2018). The particular version of the CONAPESCA database that we used is a repository consisting of tens of thousands of records for small-scale and industrial fishing activities, targeting over 500 taxa, reported in all of Mexico's Pacific states. Thus, to extract the relevant time series from this rather large database, we needed to identify the "Stocks of Interest" for which we would eventually require estimates of B/B_{MSY} (Section 2.4); we did so based on the definition of a "Stock," and the two "Criteria for Inclusion," we describe below.

We define a "Stock" (S) as any genus (G) living in fishing zone (Z), such that $S = G_Z$. Subsequently, we define a "Stock-Year" (S_Y) as a stock (S) in a specific year (Y), such that one $S_Y = G_{Z,Y}$. So, for example, we consider *Callinectes-Lower Pacific-2015* and *Callinectes-Lower Pacific-2016* as two separate "Stock-Years" borne from the same "Stock" of swimming crab (*Callinectes* sp.). We defined fishing zones (Z) *a priori*, based on expert knowledge of the area and a large geographic separation of recorded ports (**Figure 2**). The fishing zones relevant to our analyses are as follows: (1) the "Central Pacific" (CP), which includes ports circa

[1] Key assumption: About half of the fishing records we analyzed reported total landings in terms of wet weight (kilograms), while the other half were marked as having been been butchered or prepared in some way. We assumed that, in most cases, prepared weight accounted for 40% of total wet weight (Nijdam et al., 2012), such that *wet weight = prepared weight* • $(0.40)^{-1}$, with two notable exceptions to this rule: beheaded shrimps, where we assumed that the rest of the shrimp's body accounted for 65% of total wet weight (https://louisianadirectseafood.com/seafood-handbook/), and shark / ray fins ("aleta"), which we assumed accounted for just 5% of total wet weight (Cortes & Neer, 2006). For fishing trips where the style of preparation was not explicitly noted, we assumed that the catch was reported in terms of wet weight. Note that the statistical significance and interpretation of our results appears robust to alternative conversion factors of prepared-to-wet weight, where some conversion factors actually increased the statistical-significance and effect size of our results.

[2] See: https://www.epa.gov/nutrientpollution/sources-and-solutions-fossil-fuels

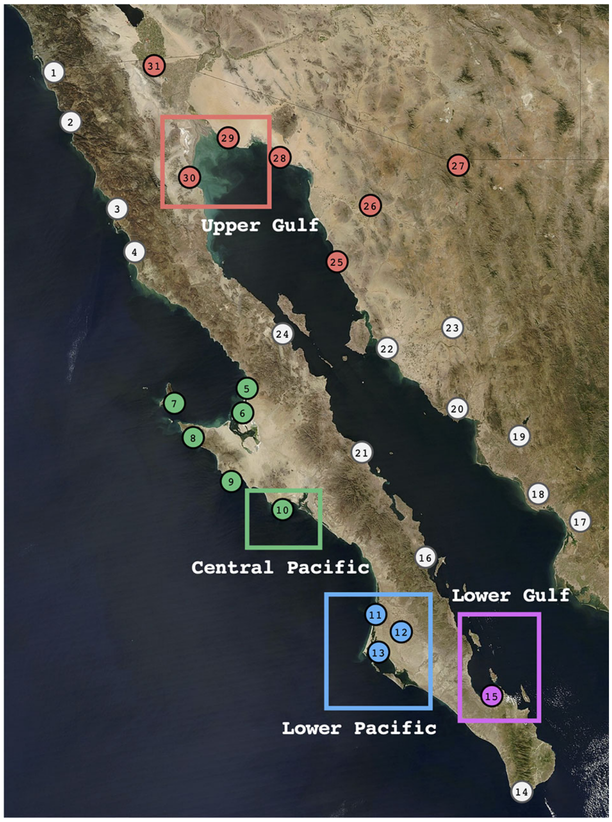

FIGURE 2 | Map of Baja California, where each circle represents a fishery office recorded in the CONAPESCA database, and each square demarcates the approximate spatial footprint of fishing trips for which there exist records of fuel consumption in the GCMP (Gulf of California Marine Program) database. For a complete roster of CONAPESCA office names, see **Table S1**. Respectively, the offices shown in green (#5 - #10), blue (#11 - #13), purple (#15), and red (#25 - #31), represent those with fishery reports that we used to generate stock assessment profiles for "Stocks of Interest" in the "Central Pacific", "Lower Pacific", "Lower Gulf", and "Upper Gulf" (as described in Section 2.4). Conversely, we did not utilize CONAPESCA landings data reported by those offices shown in grey. (Underlying map of Baja California is courtesy of the MODIS Rapid Response Team and NASA, and is available for download at: https://commons.wikimedia.org/wiki/File:Baja_peninsula_(mexico)_250m.jpg).

Punta Eugenia; (2) the "Lower Pacific" (LP), which includes major ports on the Pacific side of Baja California Sur, near Bahía Magdalena; (3) the "Lower Gulf" (LG), which we've defined as the ports in and around La Paz, south of Loreto; and finally, (4) the "Upper Gulf" (UG), which spans the region from the Colorado River Delta to the Midriff Islands in the GoC. Note that, on average, small-scale fishers in the region only travel about 63 kilometers in a given fishing trip (see "**Supporting Dataframe 1**"), and it is unlikely — though not impossible — that fishers in, for example, the LP would land and register their catch in the LG.

With these definitions in mind, we decided upon two "Criteria for Inclusion," that is, two criteria used to determine whether or not a stock would be included in our final statistical analyses and therefore in need of assessment. First, we stipulated that a stock (*S*) can be found in the CONAPESCA database with ≥ 10-years' worth of landings data; and second, that that stock has at least one Stock-Year (S_Y) represented in the GCMP database with ≥ 10 paired observations of fuel consumption and catch. Ultimately, these "Criteria for Inclusion" produced a list of 19 "Stocks of Interest" for which we were able to extract landings time series from the CONAPESCA database, and which are associated with the 39 "Stock-Years of Interest" listed in **Table S2**.

The reason for our first "Criteria of Inclusion," in which we have stipulated that *n years of CONAPESCA catch data must be ≥ 10*, has to do with the number of years required to generate a reliable stock assessment. According to Froese et al. (2017), it is sometimes possible to generate an stock assessment profile with as little as five-year's worth of catch data, however, the fewer the number of years, the larger the uncertainty. Moreover, for species with low or very-low intrinsic population growth (e.g., ocean whitefish *Caulolatilus princeps*), about 10 years' worth of landings data are required to generate an informed prior about the fishery's catchability and, in turn, its Maximum Sustainable Yield (Froese et al., 2017). The second criteria we have defined, that *n paired observations of fuel use & catch in the GCMP database must be ≥ 10*, has to do with the methods we used to test the relationship between B/B_{MSY} and fuel intensity among "Stock-Years of Interest" (described in Section 2.5); summarily, we wanted to include only those Stock-Years for which it would be possible to generate a reliable estimate of *mean* fuel intensity.

Methods for Stock Assessment: Synthesizing B/B_{MSY} Values for "Stock-Years of Interest"

B/B_{MSY} is often used as a measure for stock status and a proxy for "overfishing," where B is the current (available) stock biomass, and B_{MSY} is the estimated stock biomass at "Maximum Sustainable Yield" (MSY). MSY is the theoretical level of extraction equal to the rate of added population growth over an indefinite period of time — the highest level at which it is possible to extract fish from a population while still maintaining that stock's standing biomass. By fishing a stock at MSY, the biological stability, economic value, and contribution to fishers' livelihoods (derived from that stock) are more likely to be preserved in the long-term (Giron-Nava et al., 2021). Meanwhile, fishing a stock at levels *above* MSY is considered "overfishing," which, if allowed to persist, will eventually diminish or crash that population (e.g., New England Cod; Pershing et al., 2015).

Herein lies a key distinction between "overfishing" and "overfished". Overfishing, estimated as the current fishing mortality versus fishing mortality at MSY (F/F_{MSY}), is the actual *act* of fishing beyond MSY at any given point in time. In contrast, B/B_{MSY} tells us if a stock is currently overfished, which, if it is, is usually the direct result of habitual or chronic overfishing. We contend that, in this respect, B/B_{MSY} carries some amount of "memory" vis-à-vis fisher behavior in response to stock status over time. We have therefore elected to use B/B_{MSY} as our proxy for overfishing, where biomass (B) exists on a gradient from "pristine" ($B/B_{MSY} = 2$) to "overfished" ($B/B_{MSY} \leq 0.5$), such that when B is precisely equal to biomass at MSY, the ratio of B/B_{MSY} is equal to 1.

To generate B/B_{MSY} estimates for the 39 "Stock-Years of Interest" described above (in Section 2.3), we applied a data-poor method for fishery stock assessment developed by Froese et al. (2017) to the catch time series we extracted from the CONAPESCA database. Summarily, this method, which Froese et al. (2017) dub the "Simple CMSY," applies a Bayesian model to fisheries-dependent time series to generate most-likely values for B/B_{MSY} over time. It does so based on the landings data combined with informed priors about the stock's intrinsic population growth (r) and starting biomass (B_0). To better understand the theoretical and mathematical underpinnings of the Simple CMSY method, we recommend reviewing the original research by Froese et al. (2017) as well as a subsequent application of their methods to SSFs in Mexico executed by Giron-Nava et al. (2019). The resulting stock assessment profiles we generated using this method are included in *Supplementary Materials* - "**Supporting Dataframe 2**".

Examining the Relationship(s) Between B/B_{MSY} and Fuel Intensity

To test for a relationship between B/B_{MSY} and fuel intensity across the 39 "Stock-Years of Interest," we employed three complementary statistical analyses. We reasoned that if there exists a strong (linear) relationship between B/B_{MSY} and fuel intensity across SSFs, it would be apparent *via* a simple correlation test and, likely, a simple linear model. Thus, we began with (i) a Pearson's correlation test between estimated values for B/B_{MSY} and *mean* values for fuel intensity ($Fuel\ Intensity_{means}$). We then constructed (ii) a simple linear regression, where $Fuel\ Intensity_{mean}$ values are predicted by B/B_{MSY}. Each $Fuel\ Intensity_{mean}$ value is calculated as the arithmetic mean of all FIEs associated with that particular Stock-Year. Here, we compared B/B_{MSY} values to $Fuel\ Intensity_{mean}$ values in an effort to control against the influence of uneven sample sizes across Stock-Years (sample sizes for each are listed in **Table S2**).

The third and final analysis we conducted was (iii) a mixed effects model where any individual estimate for fuel intensity is predicted by its corresponding value for B/B_{MSY} as a fixed effect, along with three random effects: gear type, genus, and year. One might reasonably expect that the fuel-use per kilogram of landed seafood on any given trip is borne from a number of factors beyond the fishery's underlying stock biomass which could cause or covary with B/B_{MSY}. We know, for instance, that fishing patterns, fleet (over)capacity, management schemes, underlying ecosystem dynamics, weather patterns, and changes in climate are all important factors that can determine fishery outcomes (e.g., Worm et al., 2006; Pershing et al., 2015; Schuhbauer et al., 2017; Hilborn et al., 2020; Giron-Nava et al., 2021). For the most part, these dynamics lie beyond the scope of this paper, or the data are not available at this time. We can, however, begin control for *some* of this complexity — both observed and unobserved — by incorporating the additional information we have access to *via* the GCMP database about gear type, genus, and year (at the trip-level).

We controlled for gear type as a random effect based on findings from previous studies, which indicate that gear type plays an important role in the overall emissions borne from fishing activities (Parker and Tyedmers, 2015; Parker et al. 2018; Ferrer et al., 2021) . Likewise, we included genus and year as random effects since target taxa and unobserved changes over time likely play important roles in predicting fuel expenditures. We chose to model these three factors as random effects because, while we anticipate that they do matter, we are not explicitly interested in the *fixed* effects of gear type, genus, nor temporal factors on the observed discrepancies among individual estimates for fuel intensity. Rather, our primary interest lies in understanding the generalized relationship between B/B_{MSY} (a fixed effect) and fuel intensity (a continuous output) *across* gear types, target genera, and years.

We generated the mixed effects model using the "lme4" package in R (Bates et al., 2015), and utilized the R "lmerTest" package to generate associated *p* values (Kuznetsova et al., 2017). Notably, the "lmerTest" package applies "Satterthwaite's method" (Fai and Cornelius, 1996) to estimate degrees of freedom, covariance, and significance values for unbalanced samples in mixed effects models. Thus, in contrast to our first and second analyses, it was not necessary to test B/B_{MSY} against $Fuel\ Intensity_{mean}$ values here, due to the very nature of the mixed effects model itself. Instead, we compared estimates for B/B_{MSY} against *individual* estimates for fuel intensity, generated over 4,491 single-species fishing trips. (Data associated with each of these trips can be accessed in *Supplementary Materials* - "**Supporting Dataframe 3**.")

RESULTS

Stock Assessment Profiles

We have included the results from our stock assessments in "**Supporting Dataframe 2**". Specifically, we report estimated values and confidence intervals for B/B_{MSY} and F/F_{MSY} for all 19 "Stocks of Interest" over time (2001–2019), as generated by the Simple CMSY method.

Stocks that are both overfished and experiencing overfishing are those with a $B/B_{MSY} < 1$ and a $F/F_{MSY} > 1$ (e.g., Giron-Nava et al., 2019; see also UW - Sustainable Fishing 101: https://sustainablefisheries-uw.org/seafood-101/overfished-overfishing-rebuilding-stocks/). Conversely, stocks that are fished "sustainably" are those that are neither overfished ($B/B_{MSY} > 1$) nor experiencing overfishing ($F/F_{MSY} < 1$). There are many cases in between, where stocks can be overfished but recovering ($B/B_{MSY} < 1$, $F/F_{MSY} < 1$), or not yet overfished but experiencing overfishing ($B/B_{MSY} > 1$, $F/F_{MSY} > 1$). With these definitions in mind, we found evidence of at least some overfishing in every year for which we were able to generate assessment data. We also found evidence that many of these stocks are currently overfished.

In 2019, the most recent year for which we were able to generate assessment data, we found that out of the 19 stocks, nine (47%) were overfished and experiencing overfishing ($B/B_{MSY} < 1$, $F/F_{MSY} > 1$); zero (0%) were overfished and recovering ($B/B_{MSY} < 1$, $F/F_{MSY} < 1$); two (11%) were not overfished but were experiencing overfishing ($B/B_{MSY} > 1$, $F/F_{MSY} > 1$); and eight stocks (42%) were being fished sustainably ($B/B_{MSY} > 1$, $F/F_{MSY} < 1$). Of the eight stocks that were fished sustainably that year, six of them were located in the LP, one in the LG, and one in the UG.

Our results for B/B_{MSY}, on which we've based our assessment of overfishing, are largely consistent with anecdotal evidence, ecological research (e.g., Lluch-Cota et al., 2007), and local ecological knowledge about the region's fish populations (e.g., Sáenz-Arroyo et al., 2005). For example, as of 2016, Giron-Nava et al. (2019) found that in the GoC, 69% of the stocks analyzed (n = 121) were overfished and still being fished at unsustainable levels; 13% were overfished but recovering; 11% were not overfished but were being fished at unsustainable levels; and just 7% were fished "sustainably," neither overfished nor experiencing overfishing.

Relationship Between B/B_{MSY} and Fuel Intensity

A visual assessment of the data (**Figures 3A, B**) suggests that, the relationship between B/B_{MSY} and fuel intensity is inverse and exponential of some type, and we therefore report our results for B/B_{MSY} against $\log_{10}$(Fuel Intensity) or $\log_{10}$(*Fuel Intensity$_{mean}$*) values where appropriate. We've elected to report the results of our first two analyses in terms of B/B_{MSY} versus *Fuel Intensity$_{mean}$* for reasons explained above (in Section 2.5), however, the interpretation of our results does not change if we compare values of B/B_{MSY} to demeaned values for fuel intensity (**Figure S1**).

We found a statistically-significant negative correlation between B/B_{MSY} and $\log_{10}$(*Fuel Intensity$_{mean}$*) using a Pearson's test for correlation, where $r(df = 37) = -0.44$ (p value < 0.01). Subsequently, we conducted a simple linear regression, where $\log_{10}$(*Fuel Intensity$_{mean}$*) was predicted by B/B_{MSY} with an $R^2_{adj.} = 0.17$ (df = 37, p value < 0.01) (**Figure 3C**). Finally, the existence of an inverse relationship between B/B_{MSY} and fuel intensity was further corroborated by the results of our mixed effects model (**Figure 3D**), where B/B_{MSY} is a statistically-significant predictor of $\log_{10}$(Fuel Intensity) (p value < 0.01), when accounting for gear type, genus, and year as random effects. According to this model parameterization, the association between B/B_{MSY} and $\log_{10}$(Fuel Intensity) has a negative correlation of $r = -0.36$. Notably, B/B_{MSY} remained a significant predictor of both fuel intensity and *Fuel Intensity$_{mean}$* under a variety of controls and robustness checks (**Figure S1**).

DISCUSSION

Projections indicate that as the effects of climate change continue to manifest, many fisheries (though not all) will be negatively impacted (Allison et al., 2009; Free et al., 2019). As fisheries change or degrade, fishing effort may increase while, on net, CPUE declines. As net CPUE declines, fishers working in both small-scale and large-scale fishery settings may burn more fuel in an effort to land the same amount of fish, contributing more CO_2 to the atmosphere along with other fossil fuel-derived pollutants. Burning more fuel is likely to increase the costs of production, while depleting regional air and water quality[2], and potentially contributing to other social and environmental consequences (Aburto-Oropeza et al., 2018). To sustain their livelihoods, fishers may expend more effort fishing — be it in the form of more time spent on the water, gear deployed, *etc.* — increasing the expense/labor associated with fishing as well as the likelihood that stocks will become overfished. Thus, one can hypothesize a "positive" feedback loop (albeit small and asymmetrical) where, as overfishing increases, the fuel intensity of seafood grows and climate change continues, resulting in increasingly negative fishery outcomes (Sumaila and Tai, 2020).

Our results indicate that at least one aspect of this theoretical feedback loop very likely exists, in that the fuel intensity per kilogram of seafood appears inversely related to underlying stock biomass among several SSFs in Northwest Mexico. One cannot necessarily infer causation from our results, however, the relationship between B/B_{MSY} and fuel intensity proves suggestive *and* predictive under a variety of controls. Given the inverse and log-linear nature of this relationship, fuel intensity increases sharply for those seafood products generated by fisheries with a $B/B_{MSY} < 1$. This lends credence to the theories we described earlier (The World Bank, 2017; Sumaila and Tai, 2020), which posit that the act of habitual overfishing contributes to the carbon footprint associated with fishing.

Our results give us some idea of the carbon emissions that could be avoided with even slight improvements to stock biomass. Given that the majority of carbon emissions

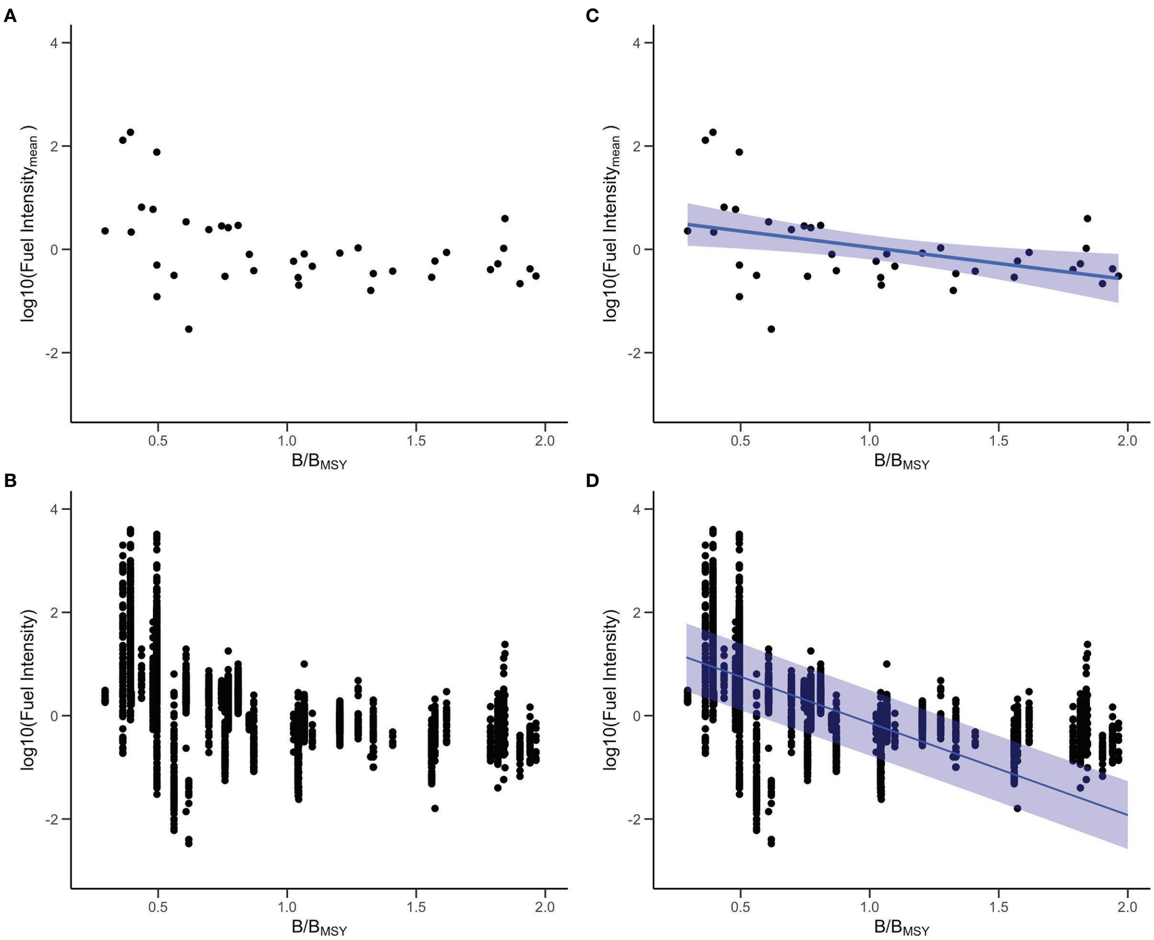

FIGURE 3 | A plot of the raw data showing **(A)** mean and **(B)** demeaned values for estimates of fuel intensity. On the x-axis, B/B_{MSY} is plotted from 0.25 to 2.0, and on the y-axis, the appropriate measure of fuel intensity is plotted in log10 scale. In panels **(B)** and **(D)**, each point represents a unique B/B_{MSY}-fuel intensity combination derived from an individual fishing trip, and in panels **(A)** and **(C)**, each point represents a unique B/B_{MSY}-$Fuel\ Intensity_{mean}$ combination associated with a particular Stock-Year. Panel **(C)** shows the linear regression of B/B_{MSY} versus fuel intensity, where the blue line represents the predicted relationship, and the band around the line depicts 95% confidence intervals; note that the $R^2_{adj.}$ for this simplified linear relationship is 0.17 (p value < 0.01). Finally, panel **(D)** shows the results of our mixed effects model, where fuel intensity is predicted by B/B_{msy} (statistically-significant fixed effect), as well as "gear type", "genus", and "year" modelled as random effects; the blue line represents the relationship predicted by our mixed effects model, and the band around the line depicts 95% confidence intervals predicted by the "effects" package in R (Fox et al., 2020).

associated with wild-caught seafood are generated by burning fossil fuels while fishing (Vázquez-Rowe et al., 2012; Parker and Tyedmers, 2015), we can devise a short back-of-the-envelope calculation as follows: the average $Fuel\ Intensity_{mean}$ of seafood landed among Stock-Years with a $B/B_{MSY} \geq 1$ is 0.66 L fuel/kg catch, and for those with a $B/B_{MSY} < 1$ is 22.31 L fuel/kg catch. Thus, if we assume a fuel-to-emissions conversion factor of 2.3 kg CO_2-equivalent per liter of gasoline (Natural Resources Canada, 2014)[3], the carbon footprint generated by Stock-Years examined herein with a $B/B_{MSY} < 1$ contributes (on average) an additional 50 kilograms of CO_2-equivalent per kilogram of wet-weight seafood, compared to those with a $B/B_{MSY} \geq 1$.

Evidence of this nature might motivate climate-oriented policies designed to restore fisheries and alleviate fishing pressure, or perhaps generate novel possibilities for those countries that seek to better incorporate the ocean and blue carbon into their Nationally Determined Contributions under the Paris Agreement ("NDCs") (see Gallo et al., 2017). Indeed, our results expand our understanding of, and appreciation for, the ways in which the protection of biodiversity and a stable climate are inextricably linked: abating climate change will help to conserve healthy fish populations, and, vice versa, the conservation of healthy fish populations may help to mitigate climate change (IPBES, 2019; IPCC, 2022). The conservation of marine ecosystem services (IPBES, 2019) and fish populations as

[3] This conversion factor only accounts for the quantity of greenhouse gases emitted directly by the burning of gasoline. It does not, for example, account for the upstream emissions associated with the production of fossil fuels, nor the downstream emissions associated with seafood production and transport.

"blue carbon" sinks (e.g., Mariani et al., 2020) are two popular examples of how ending overfishing might be considered a form of climate action. Now, we have evidence to suggest that, in addition to conserving ecosystem services and blue carbon sinks, ending overfishing is likely to make it more carbon-efficient to supply seafood security going forward.

To be clear, SSFs, in all their importance, diversity, and abundance, likely account for a relatively small portion of greenhouse gas emissions borne from total seafood production. While the carbon footprints of SSFs are heterogenous and can be high (see Purcell et al., 2018; Ferrer et al., 2021), Greer et al. (2019) estimate that SSFs land about a quarter of the world's wild catch for a little less than a quarter of all fishery emissions. At the same time, we know that the carbon emissions borne from the fishing sector in general are non-negligible (accounting for ~1% of *all* global CO_2 emissions; Sumaila and Tai, 2020), and it's possible that the relationship we've identified here is generalizable to the fishing sector more broadly. While this remains a largely open question, we posit that, independent of the answer, investing time and resources towards ending overfishing presents a prime opportunity for stakeholders with varied interests (e.g., fisheries management, fisheries livelihood, blue carbon) to collaborate in protecting and rebuilding healthy fish populations.

To this end, we argue that it is important to continue designing and investing in culturally-relevant and participatory management schemes that support fishers in fishing sustainably (e.g., Bloor et al., 2021; Gómez and Maynou, 2021; see also FAO SOFIA, 2018). For fisheries in Northwest Mexico, successful community-based efforts to ensure sustainable fishing among SSFs are already underway, and have been for some time. The Community Catch Monitoring Program in the Upper GoC (see Juárez, 2021), and the SCPPPA cooperative that governs fishing in the town of Punta Abreojos (Cota-Nieto et al., 2018), are just a two notable examples. For the former, Juárez (2021) describes how local rights-based management efforts have helped to stabilize the Gulf Corvina fishery over the last decade — and for the later, Cota-Nieto et al. (2018) describe how a number of strategic, participatory management actions taken by fishers and other community members have ensured the town's fishing success over multiple generations.

Strategies for ending overfishing more broadly include: eliminating harmful fishing subsidies while supporting those that are beneficial, particularly among SSFs (Schuhbauer et al., 2017; Sumaila et al., 2021); protecting SSFs from exclusionary or exploitative fishing and management practices, including those conducted by industrial fisheries and other large-scale industry interests (see Schuhbauer et al., 2017; Cohen et al., 2019); improving our fishery assessments among historically "data-poor" stocks (Costello et al., 2012; Hilborn et al., 2020) and prioritizing SSF data needs (e.g., Smith and Basurto, 2019); working to alleviate illegal, unreported, and unregulated fishing (IUU) (World Bank, 2017); closing tax loopholes and shuttering tax havens that undermine biodiversity objectives and have, in some cases, been shown to contribute to IUU (Dempsey et al., 2021); and finally, investing in the restoration of ecosystems upon with healthy fisheries depend (Sumaila et al., 2012; Duarte et al., 2020).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

EF conceived of the initial idea for this article and implemented its execution. AG-N helped established the methods underlying this article, contributed to analysis, and edited the manuscript. OA-O helped contribute to the vision, methods, and execution of this research, including production of the results and manuscript. All authors contributed to the article and approved the submitted version.

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Ecosystem-based fisheries management increases catch and carbon sequestration through recovery of exploited stocks: The western Baltic Sea case study

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Legal requirement in Europe asks for Ecosystem-Based Fisheries Management (EBFM) in European seas, including consideration of trophic interactions and minimization of negative impacts of fishing on food webs and ecosystem functioning. This study presents the first mass-balanced ecosystem model focused on the western Baltic Sea (WBS). Results show that heavy fishing pressure exerted on the WBS has forced top predators such as harbour porpoise and cod to cover their dietary needs by shifting from forage fish to other prey or find food outside of the model area. The model was then developed to explore the dynamics of four future fishery scenarios: (1) business as usual (BAU), (2) maximum sustainable fishing ($F = F_{MSY}$), (3) half of F_{MSY}, and (4) EBFM with $F = 0.5\ F_{MSY}$ for forage fish and $F = 0.8\ F_{MSY}$ for other fish. Simulations show that BAU would perpetuate low catches from depleted stocks with a high risk of extinction for harbour porpoise. In contrast, the EBFM scenario would allow the recovery of harbour porpoise, forage fish and cod with increases in catch of herring and cod. EBFM promotes ecosystem resilience to eutrophication and ocean warming, and through the rebuilding of commercial stocks increases by more than three times carbon sequestration compared to BAU. The model provides an interrelated assessment of trophic guilds in the WBS, as required by European law to assess whether European seas are in good environmental status.

KEYWORDS

eutrophication, fishery scenarios, food web resilience, ocean warming, sustainable fishing, top predators, trophic interactions

1 Introduction

Overfishing belongs to the strongest negative anthropogenic interventions on marine ecosystems (Jones, 1992; Hall et al., 2000; Kaiser et al., 2006). In northern Europe, this is particularly true for the Baltic Sea, where all major species such as cod and herring have been heavily overfished for decades. Beyond depleting target species, overfishing exerts significant negative impacts on the marine ecosystem and its components (Gilles et al., 2005; Frederiksen et al., 2006; Herr, 2009; Thiel et al., 2013; Andreasen et al., 2017) and the erosion of fish stocks alters ocean biogeochemistry: by the 1990s, the global reduction of fish biomass caused by fisheries almost halved biomass cycling rates (Bianchi et al., 2021). Impacts of fisheries diffuse through the whole food web thus modifying carbon, nutrient and oxygen cycles (Getzlaff and Oschlies, 2017). The Common Fisheries Policy (CFP, 2013) of the European Union (EU) demands an end of overfishing. The Marine Strategy Framework Directive (MSFD, 2008; MSFD, 2017a; MSFD, 2017b) of the EU calls for an ensemble of criteria requiring: (1) the preservation of biological diversity with species abundance or demographic characteristics not altered by anthropogenic pressures, (2) a healthy size and age structure of exploited stocks, and (3) marine food webs with species composition, diversity, balance and productivity not affected by stress factors of anthropogenic origin. This study determines the current state of the western Baltic Sea (WBS) ecosystem and explores potential future developments under different exploitation scenarios (study area in Figure 1).

Ecosystem-Based Fisheries Management (EBFM) represents a new direction for fisheries management, reversing the order of priorities so that management starts with ecosystem considerations rather than the maximum exploitation of several target species (Pikitch et al., 2004). EBFM aims to sustain healthy marine ecosystems and the fisheries they support. Specifically, it aims to rebuild and sustain populations of non-target and protected species. Network modelling has been evoked as a suitable tool to implement ecosystem-based management because its focus on connections among components is functional to understanding the dynamics of socio-ecological systems and helps designing effective management strategies (Long et al., 2015). For instance, an ecosystem model of the North Sea (Mackinson et al., 2009) was applied to assess multi-annual management plans formulated by the EU Commission (STECF, 2015). Moreover, in silico experiments showed that biodiversity confers resilience to fish extraction in the Baja California food web (Rocchi et al., 2017). The positive relationship linking biodiversity to resilience confirms previous findings based on field data analysis (Lindegren et al., 2016) and mesocosms experiments (Moustaka-Gouni et al., 2016).

The purpose of this study is the creation of the first mass-balanced ecosystem model for the WBS by using the best available, recent data and focusing on the interaction between fisheries and ecosystem components. This work focuses on three main aspects. First, quantifying the impacts of long-term overfishing of western Baltic cod (*Gadus morhua*, Gadidae) and western Baltic spring-spawning herring (*Clupea harengus*, Clupeidae) on the whole system. Second, studying the role of herring and sprat (*Sprattus sprattus*, Clupeidae) as low-trophic level key species in the food web. Third, assessing the competition between marine mammals and fishers as well as the consumption of fish by seabirds.

Fishing pressure dramatically reduced stock size and catches of the western Baltic spring-spawning herring and western Baltic cod

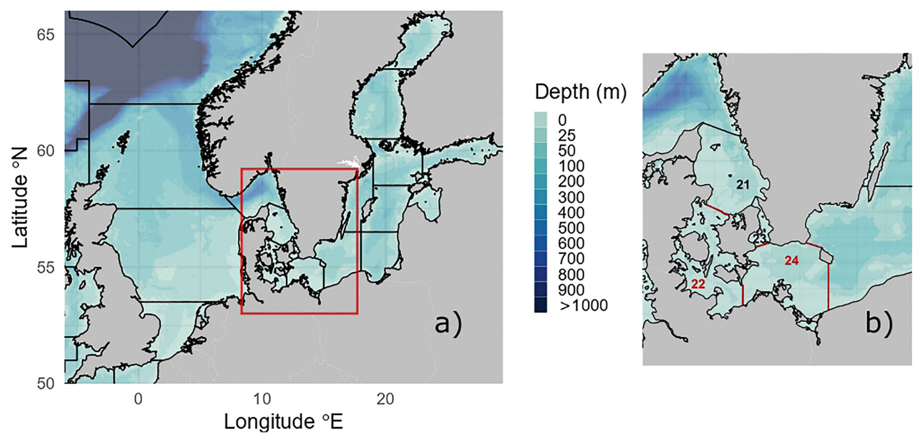

FIGURE 1
Western Baltic Sea (WBS) position in the context of the northeast Atlantic shelf region including the entire Baltic Sea region **(A)**. The WBS ecosystem **(B)** is bounded by ICES subdivisions 22 and 24 (red line). Maps were produced using R package *marmap* (v. 1.0.6) (Pante and Simon-Bouhet, 2013).

over the last 25 years (ICES, 2019a). Comparing data for 2019 against 1994 shows a decline of spawning stock biomass (SSB) of herring and cod by approximately 75% and 38%, respectively (ICES, 2020a; ICES, 2020b). These changes had a strong negative impact on catches of herring (-85%) and cod (-56%). Moreover, cod experienced repeated recruitment failures resulting in a population now dominated by a single year class (ICES, 2019a; ICES, 2019b; Froese et al., 2022). Herring and sprat are planktivorous fish that occupy strategic positions in the WBS food web (Casini et al., 2004; Andreasen et al., 2017). They represent bottlenecks for energy delivery from lower trophic levels of the planktonic food web to larger-size predators such as cod, seabirds and marine mammals (see the wasp-waist structure of marine food webs in e.g. Cury et al., 2000; Scotti and Jordán, 2015). Overfishing has severely compromised the size of reproducing adult populations of western Baltic spring-spawning herring and western Baltic cod, making them vulnerable to threats caused by climate change and eutrophication. Changes in atmospheric circulation resulted in lower frequency and intensity of North Sea water inflows into the Baltic Sea (Mohrholz et al., 2015; Mohrholz, 2018). These events, together with eutrophication, increased the extent of low-oxygen zones in cod-spawning habitats (Möllmann, 2019). Declining water inflows from the North Sea also lowered the salinity in areas relevant for cod reproduction. These conditions increased the sinking of cod eggs, which experienced higher mortality rates because of the exposure to unfavourable anoxic zones (Hüssy et al., 2012). Overfishing of western Baltic spring spawning herring eroded its stock and exposed the population to the negative impacts of raising temperatures, with a later onset of winter negatively correlated to reproductive success (Polte et al., 2021).

To explore the consequences of alternative fishing regimes at the ecosystem level, an Ecopath with Ecosim (EwE) model (Polovina, 1984; Christensen and Pauly, 1992; Christensen et al., 2000; Pauly et al., 2000) of the WBS was constructed based on an earlier version by Opitz and Froese (2019). Referring to the legal framework outlined by the CFP and MSFD, the WBS model was used to compare different fishery management options for the recovery of depleted stocks and sustainable future catches. Additionally, it was analysed how the different fisheries scenarios impacted endangered species such as the harbour porpoise, and assessed whether fishing pressure may induce a shift in the WBS community composition. Finally, impacts that BAU and EBFM have on the WBS food web resiliency to eutrophication and warming, and on carbon sequestration rates attributed to commercially exploited fish stocks were quantified.

2 Materials and methods

The Ecopath base model represents the WBS ecosystem in 1994. This is the first year for which complete ICES catch and stock size data sets were available for the majority of fish groups included in the model and particularly for cod, herring and sprat — the economically most important species in the WBS. The Ecopath model is a static snapshot and provides a description of the average annual carbon circulation in the ecosystem. Time series from 1994 to 2019 for catch and stock biomass were used to produce a reference model with Ecosim as a prerequisite to explore the ecosystem-level impacts of alternative fishery management solutions. Predictions were made assuming different fishing mortality rates along a medium-term scenario (i.e. 2020-2050) and for the period 2020-2100 (i.e. to ensure all trends attaining a novel steady state).

The area represented by the WBS model covers ICES subdivisions (SDs) 22 and 24 (Figure 1B). Fitting the model to these management areas was practical to match ICES fishery data structure and ecologically, the WBS is also a conveniently uniform area that clearly differs from the surrounding regions. To the north, limited exchange of ocean water through the Danish straits creates persistent salinity gradients resulting in brackish water conditions in the WBS. To the east in the Arkona Basin (SD 24), low salinity causes eastern Baltic cod eggs to sink and exposes them to bottom contact, threatening eggs survival due to lethal temperatures (<1.5°C) or oxygen depleted conditions (<2 ml l^{-1}); thus limiting eastern Baltic cod recruitment in the western Baltic management area (Hüssy et al., 2016). The Öresund – separating Sweden from Denmark (SD 23) – has mostly rocky floor and exhibits ecological properties different from the sandy-muddy areas in the WBS (SDs 22 and 24). The chain of lagoons in the southern WBS contributes to the sedimentation and chemical, physical and biological transformation of freshwater discharges from rivers, being particularly effective in the removal of inorganic nitrogen compounds (Kuss et al., 2020). Taken together, the WBS ensures data availability, ecological homogeneity and correspondence with active management units.

The Ecopath with Ecosim software tool[1] was used for model preparation. Ecopath creates mass-balanced snapshots of ecosystem resources and their interactions, represented by biomass pools connected through trophic links. The biomass pools may consist of a single or groups of species representing ecological guilds. Pools may be further split into ontogenetically linked groups such as done here for adult (>35 cm) and juvenile (<=35 cm) cod. Biomass was expressed as grams of carbon per square meter (gC m^{-2}) to account for differences between the carbon contents per wet weight (WW) in the trophic groups (see Supplementary Materials). Ecopath bases the parameterization on the assumption of mass balance over an arbitrary period, usually a year. In accordance with this basic feature, the WBS model used annual means as inputs for parameters. The parameterization of an Ecopath model requires satisfying two

1 www.ecopath.org

master equations. The first describes the production of biomass for each group:

$$Production = catch + predation + net\ \ migration + biomass\ \ accumulation + other\ \ mortality - import \quad (1)$$

The second is derived from the principle of matter conservation within a group:

$$Consumption = production + respiration + unassimilated\ \ food \quad (2)$$

A detritus compartment (D) receives flows originating from other mortality (M) (disease, starvation) and non-assimilated food (NA), so that:

$$D = M + NA \quad (3)$$

Input of at least three of the following four elements is required for every group: (a) biomass, (b) production/biomass ratio (P/B or total mortality, Z), (c) consumption/biomass ratio (Q/B) and (d) ecotrophic efficiency (EE). Here, EE expresses the proportion of the production of a group that is extracted by other system components, i.e. the proportion of total mortality due to predation/grazing and fisheries (Heymans et al., 2016). If all four elements are available for a group, the program can estimate the degree of either biomass accumulation or net migration. For further details, see Christensen et al. (2000).

The Ecosim component of EwE provides a dynamic simulation capability at the ecosystem level, with key initial parameters inherited from the base Ecopath model. The basics of Ecosim consist of biomass dynamics expressed through a series of coupled differential equations. The equations are derived from the Ecopath master equation and take the form:

$$\frac{dB_i}{dt} = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - (MO_i + F_i + e_i)B_i \quad (4)$$

where dB_i/dt represents the growth rate of group i in terms of its biomass B_i during the time interval dt. The term g_i indicates the net growth efficiency (production/consumption ratio), and $\Sigma_j Q_{ji}$ stands for the total consumption by trophic group i over all resources j. The element $\Sigma_j Q_{ij}$ defines the total predation by all predators j on trophic group i. The last part of the equation includes the non-predation (i.e. other) natural mortality rate (MO_i); the fishing mortality rate (F_i); the emigration rate (e_i); and the immigration rate (I_i) (Walters et al., 1997; Walters et al., 2000).

Ecosim allows for time dynamic simulations of biomass changes and for the assessment of predicted biomass with respect to independent time series data. Sum of squares (SS) quantifies the goodness of fit between observed values and model predictions. Time-varying fishing mortality was deduced using empirical ICES data on catch (C) and biomass (B); it was calculated for each year i as $F_i = -\log_e(1-C_i/B_i)$ (Table 2 in Hu and Wroblewski, 2009). Ecosim was applied to perform simulations with F as driver and to compare model predictions to time series of biomass and catch. Moreover, Ecosim allows the dynamic forward projection of future biomass and catch of trophic groups based on assumed F exerted on commercial groups. This feature enabled evaluating the impact of different fisheries scenarios on future biomass and catch in the WBS.

2.1 Trophic groups represented in the model of the WBS ecosystem

Altogether, the WBS ecosystem model comprised 18 trophic groups. Groups are briefly summarized here, and input sources are listed in Table 1; a more detailed description and input quality ranking are found in the Supplementary Materials (Table S6).

Top predators are represented by harbour porpoises (*Phocoena phocoena*, Phocoenidae) and a seal compartment lumping together harbour seal (*Phoca vitulina*, Phocidae) and grey seal (*Halichoerus grypus*, Phocidae). Theoretically, the river otter (*Lutra lutra*, Mustelidae) should be included as predator but no information on species abundance was available and its biomass is negligible. Approximately 50 seabird species are included which occur in the WBS ecosystem as listed by HELCOM[2]. They are composed of a mixture of proper seabirds and some aquatic bird species that are not primarily connected to the sea.

Demersal fish groups included western Baltic cod (*Gadus morhua*, Gadidae) divided into adult (>35 cm) and juveniles (< = 35 cm) compartments adhering to the official EU minimum landing size of cod in the Baltic Sea after 2014[3]. An alternative model including the fraction of eastern Baltic cod in SD 24, estimated from otoliths (ICES, 2019c), is presented in the Supplementary Materials (metabolic parameters from Tomczak et al., 2012); this eastern Baltic cod compartment refers only to the biomass of mature adults because no recruitment occurs for this stock in the WBS (ICES, 2013a). Flatfish incorporated five commercially important species: brill (*Scophthalmus rhombus*, Scophthalmidae), dab (*Limanda limanda*, Pleuronectidae), flounder (*Platichthys flesus*, Pleuronectidae), plaice (*Pleuronectes platessa*, Pleuronectidae) and turbot (*Scophthalmus maximus*, Scophthalmidae). A final demersal fish compartment represented over 130 species

2 www.helcom.fi

3 www.ices.dk/sites/pub/Publication%20Reports/Stock%20Annexes/2019/cod.27.22-24_SA.pdf

TABLE 1 Sources consulted to retrieve variables and parameters used to build the EwE model.

Group name	Biomass	P/B	Q/B	Diet	Catch
Harbour porpoises	A. Gilles (pers. comm.); Viquerat et al. (2014)	Araújo and Bundy (2011)	Andreasen et al. (2017)		Scheidat et al. (2008); van Beest et al. (2017)
Seals	Harvey et al. (2003)	Harvey et al. (2003); Mackinson and Daskalov (2007)	Deutsches Meeresmuseum[5]	Gilles et al. (2008)	The Finnish Game and Fisheries Research Institute (2013); Vanhatalo et al. (2014)
Seabirds	ECOLAB, FTZ, Büsum[6]	Tomczak et al. (2009)		Mendel et al. (2008)	Zydelis et al. (2009, 2013); Bellebaum et al. (2012)
Adult cod	ICES (2020a, 2020c)	ICES (2020c)	Mackinson and Daskalov (2007)	Funk (2017)	ICES (2020c)
Juvenile cod	ICES (2020a, 2020c)	ICES (2020c)	EwE multi-stanza routine; Mackinson and Daskalov (2007)	Zalachowski (1985)	ICES (2020c)
Flatfish	DATRAS BITS CPUE[7]	Mackinson and Daskalov (2007)			Rossing et al. (2010); ICES (2019a, 2019d, 2019e, 2019f, 2019g, 2020d)
Other demersal fish	DATRAS BITS CPUE[7]; Balancing procedure	Elmgren (1984); Wulff and Ulanowicz (1989); Jarre-Teichmann (1995); Sandberg et al. (2000); Sandberg (2007); Mackinson and Daskalov (2007)			Rossing et al. (2010)
Herring	ICES (2020b, 2020e)	Mackinson and Daskalov (2007)		Elmgren (1984); Rudstam et al. (1994); Jarre-Teichmann (1995); Harvey et al. (2003); Sandberg (2007)	Rossing et al. (2010); ICES (2018, 2020b, 2020e)
Sprat	ICES (2019a, 2019h, 2020f)	Mackinson and Daskalov (2007)	Elmgren (1984)	Elmgren (1984); Rudstam et al. (1994); Jarre-Teichmann (1995); Harvey et al. (2003); Sandberg (2007)	Rossing et al. (2010); ICES (2018, 2019a, 2019h, 2020f)
Other pelagic fish	DATRAS BITS CPUE[7]; Balancing procedure	Elmgren (1984); Wulff and Ulanowicz (1989); Jarre-Teichmann (1995); Sandberg et al. (2000); Sandberg (2007)			Rossing et al. (2010)
Pelagic macrofauna	Jarre-Teichmann (1995); Harvey et al. (2003)				
Benthic macrofauna	M. Zettler (pers. comm.)	Jarre-Teichmann (1995); Sandberg et al. (2000); Harvey et al. (2003); Sandberg (2007)			
Benthic meiofauna	M. Zettler (pers. comm.)	Jarre-Teichmann (1995); Sandberg et al. (2000); Harvey et al. (2003); Sandberg (2007)			
Zooplankton	Elmgren (1984); Wulff and Ulanowicz (1989); Rudstam et al. (1994); Jarre-Teichmann (1995); Sandberg et al. (2000); Harvey et al. (2003); Sandberg et al. (2004); Hansson et al. (2007); Sandberg (2007); Tomczak et al. (2009); Casini et al. (2012)			Jarre-Teichmann (1995); Sandberg et al. (2000); Harvey et al. (2003); Sandberg (2007)	
Bacteria/ microorganisms	Elmgren (1984); Wulff and Ulanowicz (1989); Rudstam et al. (1994); Jarre-Teichmann (1995); Sandberg et al. (2000); Harvey et al. (2003); Sandberg et al. (2004); Hansson et al. (2007); Sandberg (2007); Tomczak et al. (2009); Casini et al. (2012)				
Phytoplankton	Wulff and Ulanowicz (1989); Elmgren (1984); Jarre-Teichmann (1995); Sandberg et al. (2000)	Jarre-Teichmann (1995); Harvey et al. (2003)			

(Continued)

TABLE 1 Continued

Group name	Biomass	P/B	Q/B	Diet	Catch
Benthic producers	Wulff and Ulanowicz (1989); Elmgren (1984); Jarre-Teichmann (1995); Sandberg et al. (2000); Bergström (2012)	Wulff and Ulanowicz (1989); Jarre-Teichmann (1995)			
Detritus/DOM	Wulff and Ulanowicz (1989); Sandberg et al. (2000)				

Details for each compartment are summarized. In the same row, cells are merged when values for different input data were obtained from the same source.

populating the lower parts of the water column[4]. Initial estimates rely on 52 species caught during DATRAS BITS surveys (listed in Table S1); the group also included nine flatfish species not fully assessed by ICES and not represented in the flatfish compartment.

Pelagic fishes are represented by compartments for western Baltic spring-spawning herring (*Clupea harengus*, Clupeidae) stock, the western part of the Baltic Sea sprat (*Sprattus sprattus*, Clupeidae) stock, and 35 other pelagic fish species populating upper and midwater depths (data were available for 10 species only, which were recorded in the DATRAS BITS surveys; see Table S1).

Other faunal compartments were defined by pelagic macrofauna comprising all animals >2 cm inhabiting the water column. These are mainly jellyfish such as moon jellyfish (*Aurelia aurita*) and lion's mane jellyfish (*Cyanea capillata*), other cnidarians such as hydrozoans, and several species of polychaetes. A vast benthic macrofauna trophic group represented >500 invertebrate species (i.e. Annelida, Arthropoda, Bryozoa, Chordata, Cnidaria, Echinodermata, Mollusca, Nemertea, Phoronida, Platyhelminthes, Porifera, Priapulida, and Sipunculida) >1 mm in size and associated with benthic habitat. A benthic meiofauna group represented all animals < 1 mm in size, not identified to the species level, which are associated with bottom substrates.

Planktonic groups were defined by zooplankton, phytoplankton, and a broad bacteria/microorganisms compartment. Zooplankton merged micro-, meso-, and macrozooplankton. Microzooplankton comprises planktonic animals from 0.02 to 0.2 mm in size (e.g. phagotrophic protists such as flagellates, dinoflagellates, ciliates, radiolarians, foraminiferans and metazoans such as copepods nauplii, rotiferans and meroplanktonic larvae), mesozooplankton comprises planktonic animals from 0.2 to 2 mm in size (mainly adult copepods and cladocerans), and macrozooplankton includes all planktonic animals >2 mm in size (mainly mysids and amphipods). Phytoplankton included pelagic microalgae (>0.02-0.2 mm) and at smaller size scales, bacteria and other microorganisms<0.02-0.03 mm are included as pelagic and benthic-associated forms. Mixotrophic flagellates are also included in this broad microorganisms' compartment.

At the bottom of the trophic chain there are also benthic producers represented by benthic (macro- and micro-) algae and seaweeds composed of Angiospermophyta, Charophyta, Chlorophyta, Ochrophyta, Phaeophyta, Rhodophyta and Xanthophyta. Finally, the detrital compartment is defined as dead organic matter — particulate and dissolved.

2.2 Dynamic modelling of different fishery management scenarios

The first step to explore ecosystem responses to changes in fisheries management was the development of a static model

4 www.fishbase.org

5 www.deutsches-meeresmuseum.de/wissenschaft/infothek/artensteckbriefe

6 www.ftz.uni-kiel.de/de/forschungsabteilungen/ecolab-oekologie-mariner-tiere

7 www.ices.dk/data/data-portals/Pages/DATRAS.aspx

10.3389/fmars.2022.879998

with Ecopath for 1994 and the fitting of the related dynamic model to time series of stock and catch from external sources. Simulations served to test whether the biomass, consumption and productivity levels estimated for the various groups in 1994 could reasonably predict biomass and catch observed in the following 25 years.

In order to evaluate how well the model resembles the real world WBS ecosystem, Ecosim provides a tool to compare time series of predicted with observed biomass and catch for selected groups: juvenile cod, adult cod, herring, sprat and flatfish. Ecosim uses time series of fishing mortality F as the main driver to produce predictions of time series of biomass and catch. Time series of F made available in ICES stock assessments typically refer only to certain age groups and biomass often concerns adult individuals only, whereas catches always comprise juveniles and may include discards. In addition, ICES reports the biomass available at the beginning of the year whereas EwE works with the average of monthly biomass estimates, which typically is higher because of within-year recruitment and somatic growth of the individuals. All of these factors lead to situations where catches may exceed the reported biomass, which is highly unlikely given the productivity of the considered species. Therefore, total stock biomass was used when available rather than biomass from select classes of mature individuals as reported by ICES. Furthermore, catches were corrected compared to values in ICES advice documents because: (1) they were solely estimated for SDs 22 and 24 while in some cases, e.g. herring, ICES reported catches refer broadly to SDs 20-24; and (2) total catch is the sum of commercial landings, recreational fishery and bycatch/IUU fishery.

Pattern and magnitude of predicted biomass and catch were then compared with real data trends and the goodness of fit was evaluated by the sum of squares (SS). Further validation was achieved through pattern-oriented assessment of predictions, which indicates the capacity of the model to reproduce biological phenomena observed in reality (Heymans et al., 2016). First, the stock-recruitment relationship obtained modelling the cod ontogenetic development was evaluated to verify whether it yields the expected hockey-stick shape. Second, a scenario without fisheries was simulated to check if the model attains a steady state dominated by either herring or cod (Köster and Möllmann, 2000). Third, outcomes of the present model were contrasted with those of other EwE models developed for the Baltic Sea.

In a second step, the calibrated model was used to explore the impact of different fisheries scenarios in the period 2020-2050 (medium-term scenario) and during the years 2020-2100 (i.e. to allow the model reaching steady-state conditions). In the latter, responses were assessed during the last 20 years of each simulation to avoid biases due to the transition phase. Biomass and catch of all trophic groups attained in fact a new equilibrium in the period 2081-2100. Five distinct scenarios were tested, where F_{MSY} is the fishing mortality corresponding to the maximum sustainable yield (MSY):

1. Scenario *no fishing*: F = 0
2. Scenario *business as usual (BAU)*: F of all exploited stocks corresponding to the average of fishing mortalities during last five years (2015-2019)
3. Scenario F_{MSY}: F = F_{MSY}
4. Scenario *half* F_{MSY}: F = 0.5 F_{MSY}
5. Scenario *EBFM:* F = 0 for juvenile cod while fishing mortalities of herring and sprat were set to 0.5 F_{MSY} and those of adult cod and flatfish to 0.8 F_{MSY}

To project forward ecosystem dynamics, constant F values were employed. The scenarios are exploratory and describe the food web at equilibrium state under different combinations of fishing pressure. The objective was to assess alternative solutions to achieve sustainable fisheries (1) by referring to ICES advice where F_{MSY} is used as a target and (2) by taking into account the ecological role of species (e.g. lower exploitation of forage fishes since they represent a bottleneck to energy transport from the planktonic food web to the upper trophic levels). Table 2 shows the species/trophic groups and the respective F values used for the simulation of fisheries management scenarios into the future; F_{MSY} indicated in Table 2 are official reference values from ICES (2020a, 2020b, 2020c, 2020d, 2020e, 2020f). The choice of applying F_{MSY} from single-species stock assessments rather than estimating them with EwE avoids the risk of overly optimistic predictions. Ecosim may in fact overestimate the amount of biomass that can be sustained by mature fishes,

TABLE 2 Fishing mortality (F) values employed to simulate management scenarios.

Species/trophic group	F = business as usual	F = F_{MSY}	F = 0.8 F_{MSY}	F = 0.5 F_{MSY}
Adult cod	1.112	0.260	0.208	0.130
Juvenile cod	0.522	0.122	–	0.061
Herring	0.696	0.310	–	0.155
Sprat	0.390	0.260	–	0.130
Flatfish	0.106	0.310	0.248	0.155

The values of F for the business-as-usual scenario were calculated as the average of fishing mortalities in the last five years (i.e. 2015-2019). The relative proportion found between F_{MSY} and business as usual F for adult cod was used to estimate F_{MSY} of juvenile cod. The absence of values in the column F = 0.8 F_{MSY} for juvenile cod, herring, and sprat is because under EBFM the limit to extract forage fishes was set to F = 0.5 F_{MSY} and no fishing of juvenile cod was allowed (i.e. F = 0).

especially when projecting onto exploited ecosystems with a high prevalence of younger individuals (Aydin, 2004), which is exactly the status of the western Baltic Sea in the period used for model validation.

2.3 Uncertainty analysis

Trends of biomass and catch obtained with Ecosim starting from the 1994 Ecopath model do not account for the consequences that the uncertainty of inputs has on predictions. This aspect may be relevant because data used to build the 1994 Ecopath model show different levels of reliability as they include local variables (e.g. stock biomass of the adult cod) and parameters borrowed from EwE models of similar ecosystems (e.g. Q/B and P/B ratios of zooplankton); see Table S6. Moreover, evaluating the performance of alternative fisheries management strategies requires quantifying the sensitivity of predictions with respect to the uncertainty of inputs (Heymans et al., 2016). To this end, multiple simulations were run in Ecosim using a Monte Carlo approach creating a series of plausible biomass and catch trends generated through random samplings of symmetrical intervals centred on the 1994 Ecopath model. Prediction uncertainties in trophic group biomass, P/B and Q/B ratios were represented as coefficients of variations (CV) for interval ranges produced in Monte Carlo simulations that reflect the specificity of input data to the WBS (Corrales et al., 2017; Supplementary Materials section *Uncertainty analysis* and Table S10 for correspondence between pedigree classification and CV). Different sets of random draws were used where fishing mortality was the sole forcing factor while a single set of random draws was applied to perform pairwise comparisons between BAU and EBFM under multiple stressors. This last choice ensured that differences in outcomes across scenarios were due to the interplay of stressors and fisheries management rather than diverse combinations of parameters.

2.4 Multi stressors' scenarios

Exploration of future scenarios considered fish extraction as the main driver altering fish stock biomass, an assumption corroborated by previous studies on the WBS (Möllmann et al., 2021; Froese et al., 2022). However, when food web resilience is eroded by excessive fishing the importance of other stress factors cannot be neglected (Möllmann et al., 2021). Additional scenarios were then simulated applying a fully factorial design that combines changes in the biomass of phytoplankton and consequences of warming on the recruitment of key species including western Baltic cod, herring and sprat. For this purpose, variations in stock biomass and catch of all commercial targets were modelled considering two fishery strategies, business as usual and EBFM. Simulations were run over the period 2020-2100 with Monte Carlo estimates of uncertainty. Simulation results were expressed as biomass or catch ratios. Stock biomasses obtained with either BAU or EBFM scenarios were divided by estimates under no fishing without any stressor; when the ratios fall below 0.5 then the biomass is lower than B_{MSY}. Catches under either BAU or EBFM were normalized using catch estimates under the MSY scenario (C_{MSY}) without any other stressor as a reference; where C_{MSY} represents a reference threshold for fisheries management.

Phytoplankton biomass was varied ±25% compared to reference runs considering fishery as the only driver. Such changes lie within the limits observed for phytoplankton in the WBS during the 2000s (Henriksen, 2009) and reflect relative diatoms variations predicted by the model ERGOM for the WBS in response to meteorological forcing and varying levels of nutrients input (Friedland et al., 2012). In general, phytoplankton biomass may increase from nutrients enrichment while the decline of nutrients concentration and elevated temperatures cause the biomass to decrease (Wasmund et al., 2019).

To relate prospected ocean warming impacts on western Baltic cod, herring and sprat recruitment, forcing factors for future projections include (1) the total mortality of cod and herring (both progressively increased in the period 2020-2100) and (2) sprat SSB, evenly increased through the time series. These conditions reflect detrimental impacts exerted by ocean warming on cod and herring recruitment (Voss et al., 2012; Polte et al., 2021) and account for the empirical positive relationships between higher temperatures and sprat recruitment (Voss et al., 2012; Supplementary Materials section *Multi-stressors' scenarios*). Ecosim simulations served (1) to explore whether fishing according to a business-as-usual model increases the fragility of depleted stocks in the face of warming (Möllmann et al., 2021), and (2) to quantify the buffer potential EBFM holds for the decline of cod and herring recruitment caused by warming. This modelling scheme both implicates the impact of ocean warming on main commercial stocks and potential effects propagated at an ecosystem-level triggered by warming over the heavily depleted stocks of western Baltic cod and herring.

2.5 Fisheries management and carbon sequestration

A last aspect investigated here concerns the carbon sequestration achieved through the contribution of main commercial targets, depending on fisheries management type. Net flows to detritus were determined in four trophic groups (i.e. sprat, herring, western Baltic cod, and flatfish) under either EBFM or BAU. For each fish group, the net flow was quantified as the difference between flows to detritus (i.e. non-assimilated food and natural mortality) and flows from detritus (e.g. in the case of herring, sprat and juvenile cod, it represents part of the diet). Net flows were calculated by extracting an Ecopath snapshot of static carbon flows in the ecosystem during 2095. Such year was chosen as barycentre of the last decade, to ensure the model attained a new equilibrium in response to fisheries. Test runs showed that values found for the 2095 network were representative of averages computed over last 10 years. First, carbon sequestration caused by the four fish groups was determined for the reference model (i.e. with input parameters as defined in the model construction phase) under either EBFM or BAU. Net carbon flows to detritus were calculated by summing the contribution of all four fish groups. Second, a unique set of 99 Monte Carlo simulations randomly varied input parameters according to the pedigree classification, which allowed the extraction of 99 static networks used for both fisheries management scenarios in correspondence with 2095. Third, a distribution of net carbon flows to detritus was obtained for EBFM and BAU, with net flow quantification made following the same approach used for reference models. Our hypothesis was that larger stock sizes found with EBFM indirectly support larger carbon flows towards detritus.

3 Results

3.1 The 1994 Ecopath model

Carbon flows between trophic compartments in the WBS ecosystem reveal a relatively simple system (Figure 2). Top predators harbour porpoises and seals (trophic level > 4) have a small biomass and consequently small consumption compared to the fisheries operating at comparable trophic levels. Cod, flatfish and other demersal fish are the main fish predators of herring, sprat and benthic macrofauna. The role of herring as key species is marked by strong carbon flow exchanges. Herring feeds mainly on zooplankton and makes energy available to higher trophic levels that cannot consume plankton directly (e.g. predatory fishes, birds, seals and harbour porpoises) and to fisheries.

Some cannibalism occurred within the cod population, with 4.3% of the adult cod diet consisting of juvenile cod, and 0.3% of the juvenile cod diet including other juvenile cod. These low percentages have only a marginal effect on the population. Harbour porpoises consumed two times more juvenile cod than adult cod, however the high mobility of harbour porpoises and low abundance of juvenile cod in SDs 22 and 24 drove a shift in harbour porpoise diet towards imported food obtained by roaming in neighboring ecosystems outside the model area. Thus, adult cod became the main predator of juvenile cod in the baseline model by consuming up to 7.2% of its production, which corresponds to 7.2% of the total juvenile cod mortality (i.e. including predator and fishing mortality).

In some cases, consumption of fish by predators exceeded the annual production. For instance, modelling mobile predators such as harbour porpoises required considering the consumption of juvenile cod outside of the study area to satisfy their energy demand. Competition for fish as food (mainly herring and sprat) occurs between fisheries and other top predators, with the fisheries extracting about 8.5 times more than harbour porpoises, birds, and seals combined. Figure S4 illustrates the relative impact of all trophic groups on the ecosystem based on a comparison between keystone indices (Libralato et al., 2006). Herring shows the highest keystone index value as a single fish species with a relatively large stock size feeding low in the food web and thus transporting matter from lower trophic levels to predators high in the food web (low-trophic level species with high impact on the food web). Although sprat occupies a strategic position by transporting energy from zooplankton to higher trophic levels, its impact on the food web is lower due to its smaller stock size in SDs 22 and 24 during the recent decades. More details on inputs, balancing procedure and final values of the Ecopath model for 1994 are given in the Supplementary Materials.

3.2 Dynamic modelling of different management scenarios with EwE

EwE allows for the dynamic forward projection of biomass (B) and catch (C) of trophic groups based on fishing mortality (F) exerted on the commercially exploited groups. Prediction curves of the overall model reasonably reproduce biomass and catch values against reported values (SS = 67.17), with SS of functional groups ranging from 1.190 for herring catch to 19.080 for juvenile cod catch (Figure 3). Average SS (6.72) lies within the range of reported values for other EwE models (5.39 in Wang et al., 2012 to 37.06 in Chagaris et al., 2020). The WBS model also attains better fit and higher SS scores than single trophic groups in other models (Adebola and de Mutsert, 2019). Finally, 1000 Monte Carlo simulations improved by less than 10% the predictions compared to the reference model (best SS = 62.83). Although no indication exists in the literature about thresholds to rank SS, comparisons with other EwE models and relatively stable uncertainty values suggest a good model fit onto the WBS.

The Monte Carlo simulations enabled non-parametric confidence intervals showing 2% and 98% of the distributions based on varying levels of input data uncertainty (see shaded areas delimiting fitted trends in Figure 3). After 2010, observed biomass and catch lie mostly within the confidence interval of the predictions, with more deviations found for adult cod biomass and juvenile cod catch. In general, model predictions display a better match with observed catch than biomass.

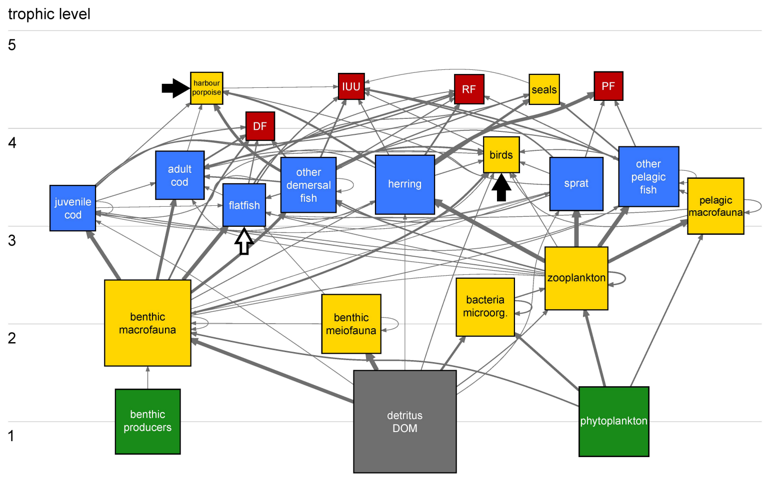

FIGURE 2
Carbon flow network of the WBS ecosystem in 1994. Trophic groups and fisheries are represented by 22 squares/compartments (17 living, one non-living and four fisheries) and interconnected by 99 links/flows. Color codes for the compartments: primary producers, green; fish, blue; non-fish, yellow; non-living, grey; and fisheries, red. Compartments are ordered vertically according to the effective trophic level (Scotti et al., 2006) and their size is proportional to the biomass on a log_{10} scale, except for fisheries. Grey, arrowheaded links indicate carbon flows from donor compartments (e.g. prey and resources) to receiving compartments (e.g. predators and consumers). Strength of flows is proportional to feeding preferences of consumers. Black and white arrows indicate import of food (harbour porpoises, birds) and immigration (flatfish) from adjacent ecosystems, respectively. Note that their size here is not proportional to their intensity. Table S9 provides size of all flows in the network in absolute numbers. Herring occupies a crucial position for transferring carbon from zooplankton to higher trophic levels and to fisheries, with the latter extracting about 89% of carbon flows leaving the herring compartment.

3.2.1 Exploring ecosystem development under different fisheries scenarios

Predictions of biomass and catch were extended up to 2050 (Figures 4, 5, medium-term scenario) and 2100 (Figures S5, S6, long-term simulations), respectively, for the four fisheries regimes described above (i.e. BAU, EBFM, F_{MSY}, and half F_{MSY}) and the no-fishing scenario. If not indicated otherwise, values reported in the manuscript for comparison with present stock and catch status are those of the medium-term scenario (i.e. up to 2050).

The no-fishing scenario was included to test model robustness, because the removal of top predators with highest consumption (i.e. combined fisheries in the WBS model) may lead to chaotic development and unrealistic predictions. However, in the absence of fishing none of the trophic groups collapsed or overshot realistic limits of carrying capacity (Figure 4). The main species in the system, cod and herring, are predicted to interact in a way that herring biomass rebuilds first and faster, leading to a herring-dominated regime (Köster and Möllmann, 2000), followed by cod recovery such that herring is increasingly controlled and finally balanced by predation pressure. The model predicts sprat restoration above the 1990s levels, but the role of this species remains of secondary importance compared to herring. Flatfish biomass peaks after 2021, when the group is the largest of the system, but its biomass declines thereafter and flatfish become less important than herring.

The business-as-usual (BAU) scenario continues average fishing mortality (F) of 2015-2019 until the end of the simulation. Under this scenario (Figure 4), cod biomass declines even below the 2019 level (-8%), herring stock biomass decreases towards the end of the time series by about 40% compared to 2019 while the biomass of sprat and flatfish slightly increases. These results suggest a shift compared to the 1990s from a cod and herring dominated system to a food web where sprat and flatfish are prevalent. Catches of cod in the decade 2041-2050 stabilize around the values recorded in 2016. Catches of herring are lowest compared to all other management scenarios and decline towards the end of the time series by 44% compared to the level of 2015-2019 (Figure 5). Catches of sprat and flatfish slightly increase compared to 2019 (i.e. in 2041-2050, sprat and flatfish catches are 1% and 12% higher, respectively); sprat catches are highest compared to all other scenarios suggesting that it benefits from the depletion of cod and herring.

The F_{MSY} scenario (Figure 4) leads to an improvement of the ecosystem because it ends the high fishing rates applied in the BAU scenario. In comparison to 2019, during the period 2041-2050 the biomass of all stocks increases except flatfish (-55%), with stock sizes growing about six-fold for both cod and herring. During the same decade, the F_{MSY} scenario predicts that catches of cod double compared to 2019 while herring catches are five times more than in 2019 (Figure 5). Comparing predicted cod catches for 2050 against 2020 they amount to almost five times the initial value.

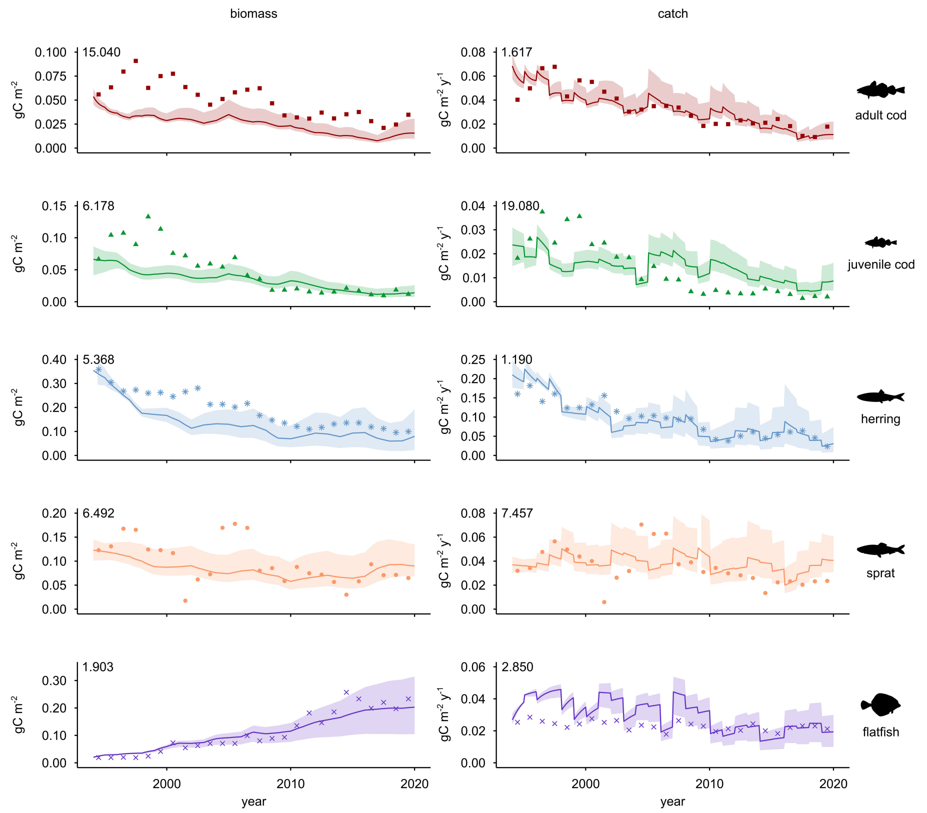

FIGURE 3
Comparison between observed data and Ecosim predictions for trends of biomass (left) and catch (right). Results refer to commercially most relevant fish stocks, from 1994 until 2019. Fishing mortality (F) is the forcing factor used to perform simulations. Plots show changes for adult cod, juvenile cod, herring, sprat, and flatfish. The match between model predictions (continuous line) and observed time series (dots) is visualized. Shaded areas illustrate non-parametric confidence intervals (2% and 98%). Numbers in the upper left corner of plots represent the sum of squares (SS) of residuals between predictions and observations, as a measure of goodness of fit.

The more precautionary half F_{MSY} scenario (Figure 4) applies F values that are 50% of those adopted under the previously described F_{MSY} scenario and except for flatfish (-41%), this scenario results in a strong recovery of all stocks; compared to 2019, during 2041-2050 the biomass of cod and herring increases seven-fold. In the same period, catches of cod, herring, sprat and flatfish are not as high as under the F_{MSY} scenario (Figure 5). Of the fisheries scenarios, this one leads to the lowest catches in 2020 for all fish groups but flatfish.

The Ecosystem-Based Fisheries Management (EBFM) scenario (Figure 4) implements rules as keeping fishing pressure below the maximum level (here: 0.8 F_{MSY}), applying especially low F values (here: 0.5 F_{MSY}) to key species such as herring and sprat, and setting catches of juvenile cod to zero (Pikitch et al., 2004). As a result, when comparing average stock sizes in 2041-2050 to those in 2019, biomass of all groups except flatfish increases under EBFM. In the period 2041-2050, cod and sprat attain slightly lower stock sizes (-4% and -0.2%, respectively) while herring biomass equals its total under the half F_{MSY} scenario. In all cases, stocks under EBFM are larger than in the F_{MSY} scenario. Level of catches for cod, herring and flatfish are intermediate when compared to the F_{MSY} and half F_{MSY} scenarios; sprat catches equal their total under the half F_{MSY} scenario while they decline compared to the F_{MSY} scenario. In the EBFM scenario, 2050 catches of cod increase by 30% while herring catches exceed those under BAU threefold. Catches of sprat decrease 53% and flatfish catches increase 14% when comparing EBFM and BAU scenarios in 2050 (Figure 5).

A comparison between outcomes of all simulations shows that harbour porpoise biomass is expected to achieve the best recovery under the EBFM and half F_{MSY} scenarios, attaining in the period 2041-2050 an average size of about 80% of the scenario without fishing. The F_{MSY} scenario ensures the recovery of the population without reaching the levels of previous scenarios. With BAU, harbour porpoise continues to decline towards a probable local extinction (Figure 4). Under BAU conditions the diet of harbour porpoise consists mostly of other demersal fish, whereas under the EBFM scenario the diet consists mainly of herring, and is very similar to the one found in the absence of fishing (Figure S7). Fishers often complain that

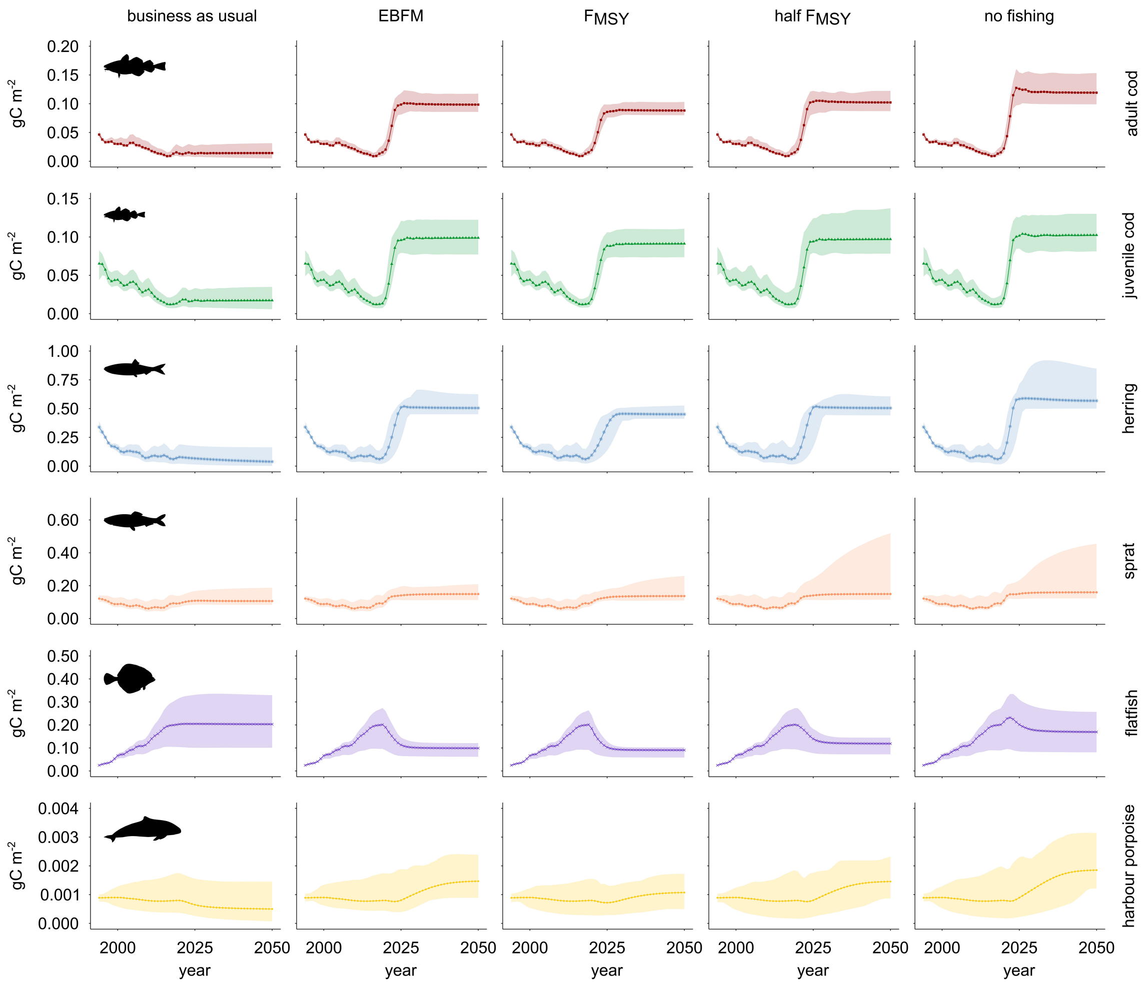

FIGURE 4
Biomass of commercially most relevant fish stocks and harbour porpoise in the WBS under five alternative fisheries management scenarios. Columns refer to fishing regimes: business as usual (BAU), Ecosystem-Based Fisheries Management (EBFM), maximum sustainable yield (F_{MSY}), half of maximum sustainable yield (F_{MSY}), and no fishing. Rows show trends for the trophic groups. Solid lines depict the predictions generated using the reference model while shaded areas indicate approximate 95% confidence limits. Under BAU, flatfish and sprat dominate the ecosystem thus confirming the regime shift triggered by overfishing during the last decades. All other scenarios lead to the recovery of the cod and herring stocks. BAU is incompatible with the preservation of a healthy harbour porpoise population.

birds, seals and harbour porpoises are competitors responsible for the poor state of cod, herring and sprat stocks. However, medium-term predictions for cod, herring, and sprat under BAU conditions show that these groups taken together consume only a fraction of the amount taken by the fishers (Figure S8).

In summary, predictions for major fish groups in the WBS suggest a continuation of low biomass and catch, and a decline with potential loss of harbour porpoises under the BAU scenario. Fishing at F_{MSY} rebuilds all stocks except flatfish, albeit with lower biomass levels compared to the subsequent two scenarios. Fishing at half F_{MSY} shows the best rebuilding of biomass for all commercial species but herring, which exhibits the largest stock size with EBFM (Table S12). This may be attributed to an increase in biomass of predators such as harbour porpoise and cod, or derive from the competition between sprat and herring. The EBFM scenario accounts for the need to reduce fishery impact on key species such as herring and sprat. Herring, in particular, shows the highest keystone index value as a single fish species transporting matter from the low trophic levels to predators feeding towards the top of the trophic chain (Figure S4). Under the EBFM scenario, there is good development of biomass both for cod and herring, and to a lesser extent for sprat. Moreover, cod and herring catches increase significantly in 2050 compared to average values of the period 2015-2019 (68% and 50% more, respectively). Catches of flatfish slightly increase (+18%) compared to the average value in the period 2015-2019, but with largely reduced fishing effort and thus lower cost of fishing. Flatfish exhibit a decrease of stock size while sprat

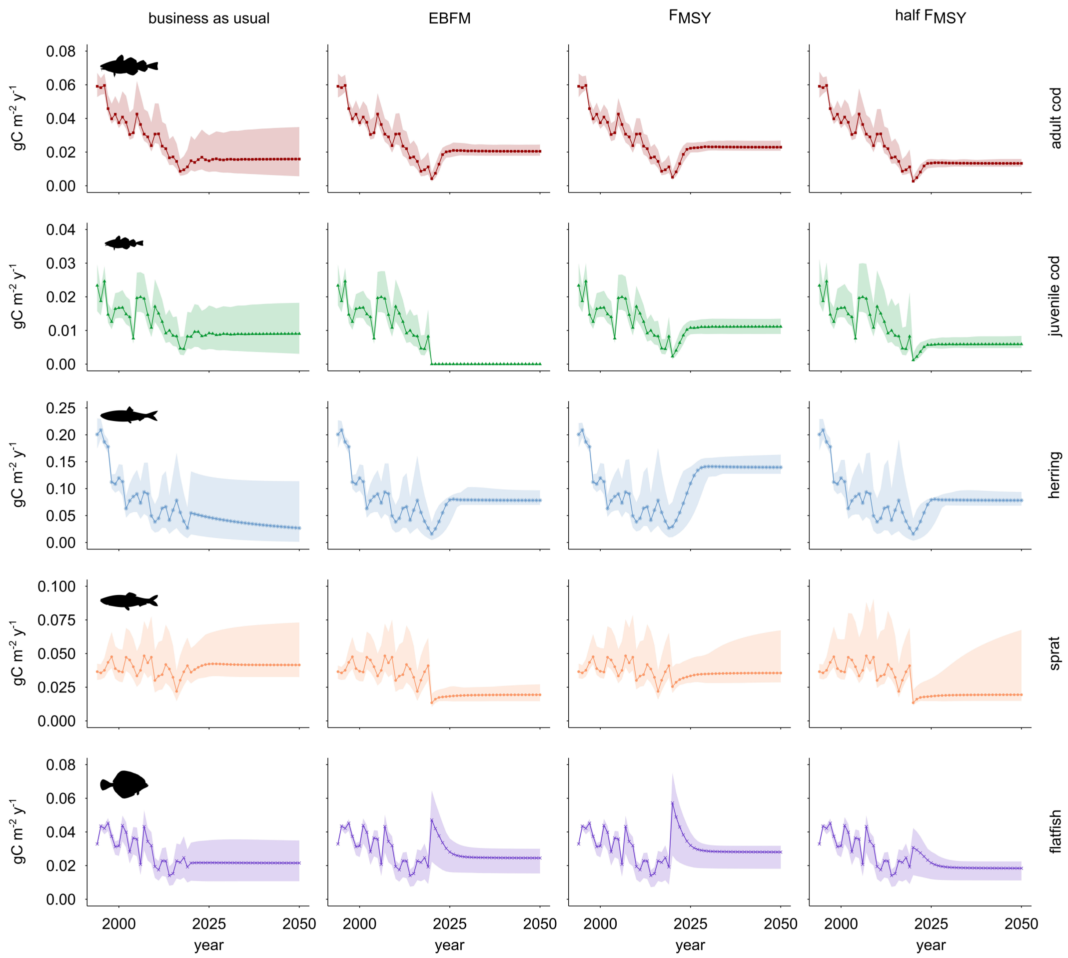

FIGURE 5
Catch of commercially most relevant fish stocks in the WBS ecosystem under four alternative fisheries management scenarios. Columns refer to fishing regimes: business as usual (BAU), Ecosystem-Based Fisheries Management (EBFM), maximum sustainable yield (F_{MSY}), and half of the maximum sustainable yield (F_{MSY}). Rows show trends for the various trophic groups. Solid lines depict the predictions generated using the reference model while shaded areas indicate approximate 95% confidence limits.

is the only group experiencing a decline in catches. Values of biomass recorded for EBFM are all higher than in the F_{MSY} scenario while all catches found with F_{MSY} outscore those of EBFM. Stock size and catch of all fish groups are similar when comparing EBFM to the half F_{MSY} scenario and only herring shows higher values for both biomass and catch in the EBFM scenario.

3.2.2 Exploring ecosystem development under multiple stressors

The predictions obtained using fisheries management scenarios were driven by alternative fishing mortality combinations. Under the assumption that future environmental conditions will change compared to average values in years 1994-2019, new simulations considering variations in phytoplankton biomass and impact of ocean warming on western Baltic cod, herring and sprat recruitment were performed. Responses to these stressors in isolation and combined across BAU and EBFM scenarios were quantified by averaging the values during last 20 years of long-term (2081-2100) scenarios.

In all stressor scenarios, the biomass of herring and western Baltic cod returned by the reference model was larger under EBFM (Figure 6). However, considerable uncertainty surrounded many estimates except for flatfish and, in some cases, adult and juvenile cod. Biomass changes triggered by warming are comparable in magnitude with those predicted when decreasing the phytoplankton biomass (-25%) although flatfish do not seem to be particularly responsive. Flatfish are not sensitive to changes in phytoplankton biomass because they feed mostly on benthic macrofauna and do not depend on the pelagic grazing chain (Figure 2). Moreover, ocean warming may

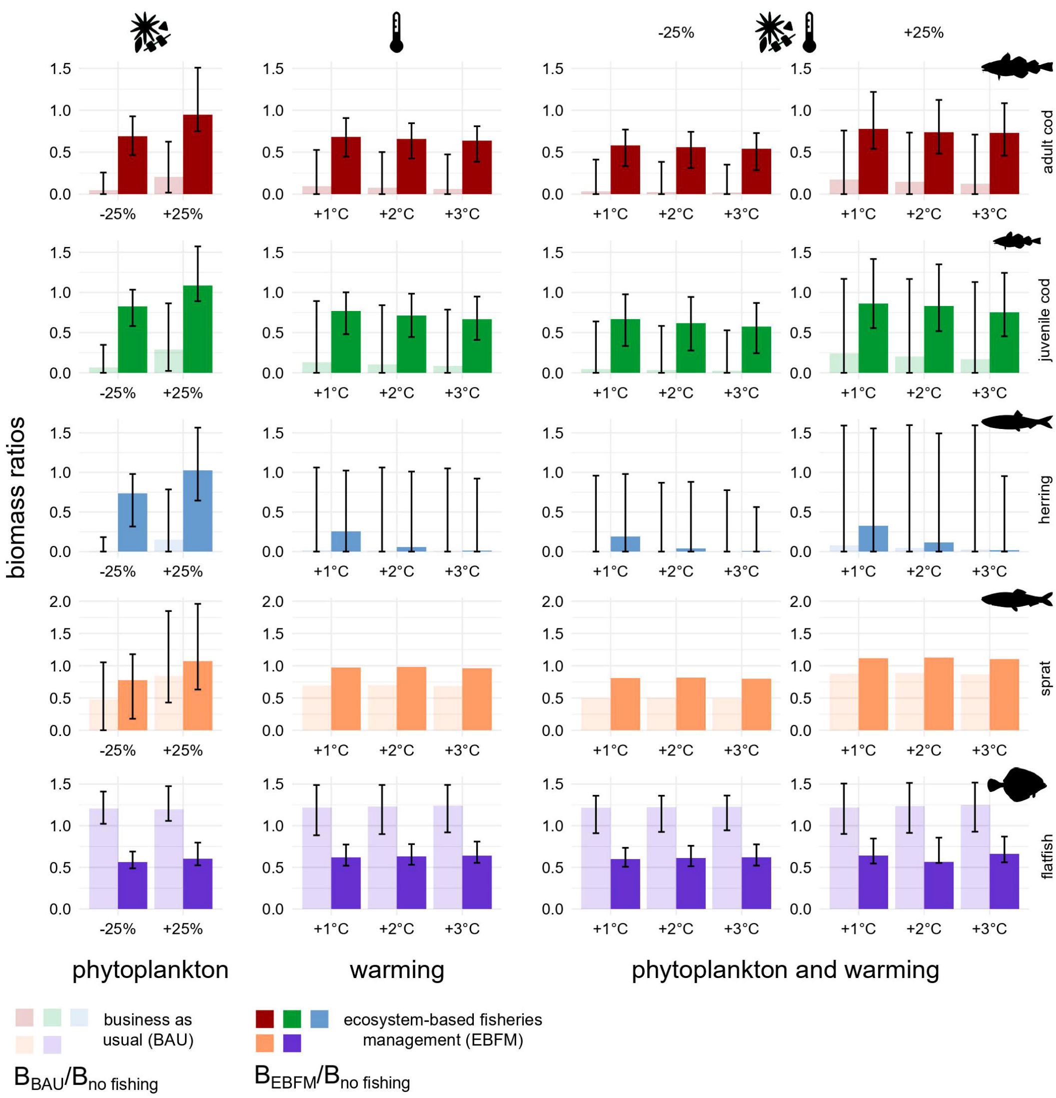

FIGURE 6
Biomass ratios under fishing pressure plus phytoplankton biomass change, ocean warming, or all factors in combination. Each bar illustrates the ratio between the biomass under BAU (transparent) or EBFM (opaque) and the no-fishing scenario biomass, all quantified using reference runs. Ratios equal to 0.5 indicate B_{MSY}. Biomasses were computed as the average of values estimated for the last 20 years of each simulation (2081-2100). Error bars were built using the corresponding Monte Carlo randomizations and show 2% and 98% percentiles as lower and upper bounds, respectively. Under all warming scenarios, sprat bar plots do not have error bars because its stock biomass was used as forcing factor.

influence flatfish only indirectly as no impact on their recruitment was modelled. The uncertainty of predictions is always larger under BAU and attains extreme levels for herring. In the case of herring, marginal impacts caused by increasing temperatures, which also depend on the direct negative effect on recruitment modelled according to Polte et al. (2021), are more evident than for other fishes and partially buffered by EBFM. All findings persist with simulations that include the presence of eastern Baltic cod in SD 24 (Figures S9 and S11).

In most stressors scenarios, catches of herring and flatfish under EBFM exceed those found with BAU (Figure 7). The same pattern holds true for adults of western Baltic cod, except when phytoplankton biomass was assumed to increase by 25%. The scenario based on changes in phytoplankton biomass is the only one considered for sprat. Its biomass was in fact the forcing factor used for all other simulations as it reflects increases of recruitment triggered by warmer waters. For sprat, fish extraction is always higher under BAU, irrespective of the direction of phytoplankton biomass change (Figure 7, first column), due to the concurrent decline of its main food web competitor (i.e. herring). Yields predicted for herring in presence of all three stress factors (Figure 7, last two columns) were the

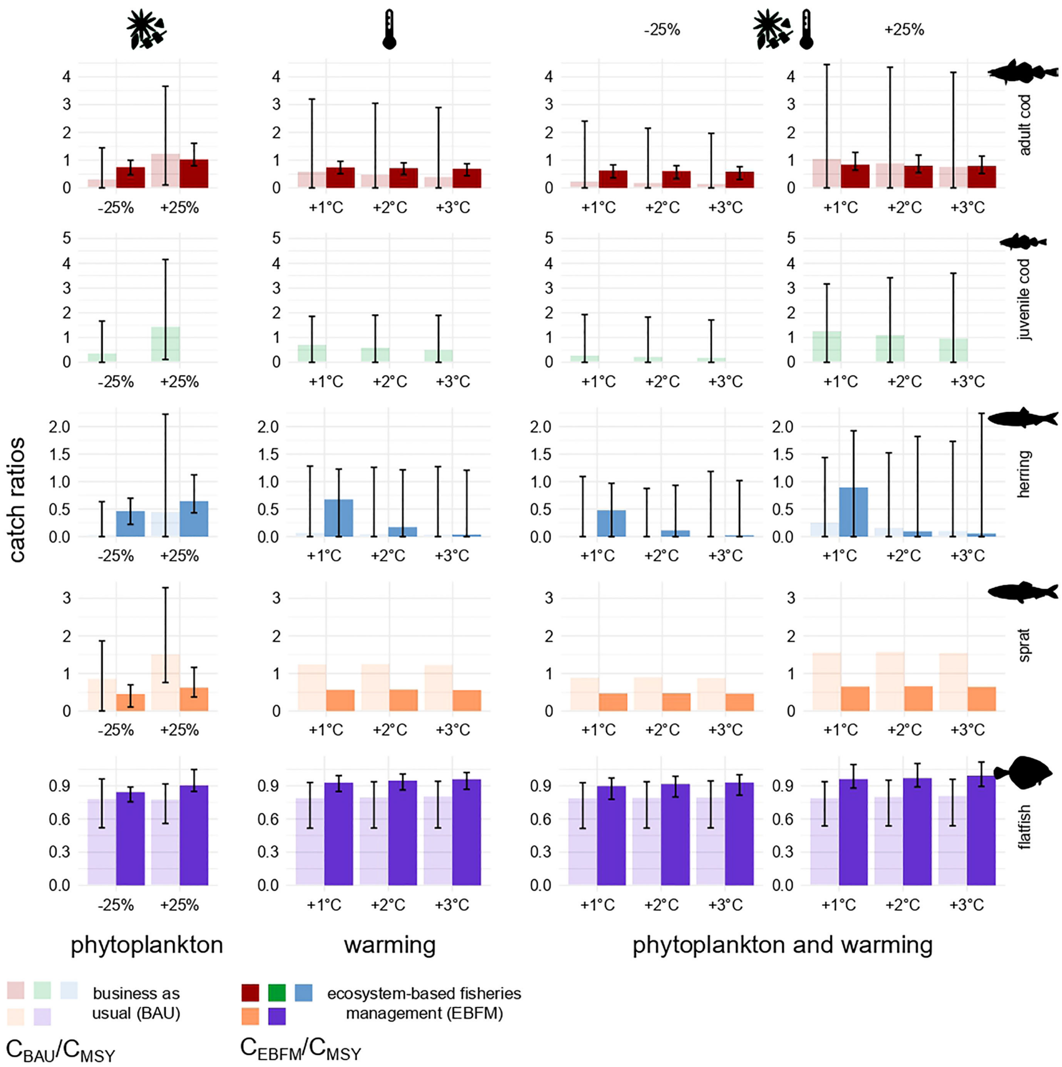

FIGURE 7
Catch ratios under the impact of fish extraction plus phytoplankton biomass change, ocean warming, or all factors in combination. Each bar illustrates the ratio between the catch under BAU (transparent) or EBFM (opaque) and F_{MSY} catch, all quantified using reference runs. Ratios equal to 1 indicate the C_{MSY} level. Catches were computed as the average of values estimated for the last 20 years of each simulation (2081-2100). Error bars were built using the corresponding Monte Carlo randomizations and show 2% and 98% percentiles as lower and upper bounds, respectively. Under all warming scenarios, sprat bar plots do not have error bars because its stock biomass was used as forcing factor.

sole responses sometimes exhibiting higher uncertainty under EBFM than under BAU. Robustness and consistency of the findings are confirmed by other simulations executed considering the presence of eastern Baltic cod in SD 24 (see Figures S10, S11).

3.2.3 Exploring carbon sequestration under BAU and EBFM

Comparative analysis shows carbon sequestration caused by the four commercial targets occurs at a rate that under EBFM is 3.4 times faster than with BAU. Uncertainty analysis indicates that EBFM results in carbon sequestration rates 2.5 to 4.6-fold greater than BAU (2% and 98% percentiles, respectively).

4 Discussion

4.1 Quality of the 1994 WBS model

The Ecopath model for 1994 combines all living components of the WBS ecosystem and quantitatively connects them *via* their diet. The WBS food web in 1994 was a system already under stress as indicated by the high ecotrophic efficiency for all fish species and trophic groups. Such values reflect heavy exploitation of fish where annual consumption — largely driven by fisheries and to a lesser extent by natural predators — approaches annual production. Therefore, when the EE of a trophic group is close to 1 there is no scope for its biomass increase while low EE stands for the fact that only a small fraction of production is utilized within the ecosystem.

The WBS is not a closed system: water mass inflows and outflows transport organisms actively swimming and drifting therein, meanwhile harbour porpoises, birds, and other predators actively search for food in nearby ecosystems. In the Ecopath base model for 1994, this was accounted for by assuming import or immigration of scarce food items. An important Ecopath rule is that such exchange with neighboring systems may not exceed the production of matter within the model system. Summary statistics for the model area showed a total system production of 632.1 gC m^{-2} y^{-1}. Such production largely exceeds exports out of system boundaries (0.2 gC m^{-2} y^{-1}) and carbon flows entering the system as imported food through mobile organisms (i.e. birds and harbour porpoises) or flatfish immigration, which altogether amount to 0.04 gC m^{-2} y^{-1}.

Herring is a key species in the WBS (Essington and Plagányi, 2013) and, in terms of energy transfer to higher trophic levels, far exceeds similarly planktivorous sprat; the Ecopath modelling showed consumption of zooplankton by herring was 63% greater than sprat (1.5 gC m^{-2} y^{-1} vs. 0.92 gC m^{-2} y^{-1}). Herring relevance may be attributed to its biomass, as its stock size is more than twice that of sprat, and may be due to higher trophic flows predicted by the model as herring is consumed in larger amounts than sprat.

There is a strong need for higher quality input data — especially surrounding catch and bycatch values — for top predators (Table S6) such as harbour porpoises, seals, and birds. For the 1994 Ecopath base model, the seal biomass was very low and the two species composing the compartment, *P. vitulina* and *H. grypus*, might have been grouped with harbour porpoise into a single marine mammals' cohort. However, harbour porpoises was treated separately because they are threatened by extinction and thus of special concern in the WBS. The different dietary needs between harbour porpoises, which are particularly dependent on energy-rich food and must eat constantly to meet high metabolic energy demand (Read and Hohn, 1995; Wisniewska et al., 2018), and seals also justify their separation. Birds are a unique case spanning several trophic levels composed of benthic macrofauna eaters such as ducks, and fish eaters such as seagulls and cormorants while also comprising migratory and non-migratory species (ICES, 2016). For these reasons, the discussion focuses mainly on fish and harbour porpoise.

4.2 Quality of the EwE predictions

Catch and biomass predictions for the years 1994-2019 obtained with fishing mortality as a driver match values of stock size and catch remarkably well. This finding directly supports the hypothesis that the depletion of cod and herring in the WBS and the retraction of sprat towards the northern central Baltic were not primarily caused by changes in carrying capacity but were driven by overfishing (ICES, 2020f; Möllmann et al., 2021; Froese et al., 2022).

The foraging arena concept, expressed in EwE through a vulnerability parameter of prey towards their predators, has the effect of "*dampening the unrealistically large population fluctuations usually predicted by the Lotka-Volterra formulation*" (see Plagányi and Butterworth, 2004). Vulnerability parameters are usually difficult to estimate and default values of 2 were therefore adopted. Another EwE routine allows performing uncertainty analysis by exploring effects of random changes in input parameters through Monte Carlo simulations (see Heymans et al., 2016). Running 1000 such Monte Carlo simulations resulted in only a negligible change in the SS, which decreased from 67.17 to 62.83, suggesting that model outcomes are robust to single changes in inputs.

The following aspects and trends underpin the trustworthiness of model predictions. (1) Juvenile and adult cod are being treated as interdependent development stanza (i.e. life history stages) and the resulting modelled relationship between juvenile and adult cod biomass (Figure 8) resembles the expected hockey-stick stock-recruitment relationship (Froese et al., 2016a; see Figure S1 and related text in the Supplementary Materials). (2) Most ecosystem models enter states where some stock sizes crash or explode when left unchecked for an extended period, but no such behaviour was displayed in the WBS model. Under the no-fishing scenario, no group collapses or increases indefinitely, and without fishing all groups attained equilibrium levels that seem to be reasonable representations of their carrying capacity when compared with historic values or typical stock sizes (see Figures 4 and S5). The stability of the no-fishing scenario adds to the results of pre-balancing (PREBAL) diagnostics (Figure S2) and suggests the parameterization of the model is meaningful and robust. Thus, in the WBS model for the year 2019 stock sizes of cod and herring reached 13% and 12%, respectively, of their carrying capacity. (3) Köster and Möllmann (2000) suggested the existence of two stable states for the Baltic Sea ecosystem, one dominated by herring and the other one by cod. Model predictions without fishing (Figure 4) showed that a herring-dominated state would establish first since herring biomass increases faster (2020-2030). After peaking at 0.59 gC m^{-2} in 2027, the herring stock slightly declines and then levels off at density values of around 0.57 gC m^{-2} (2081-2100) under the top-

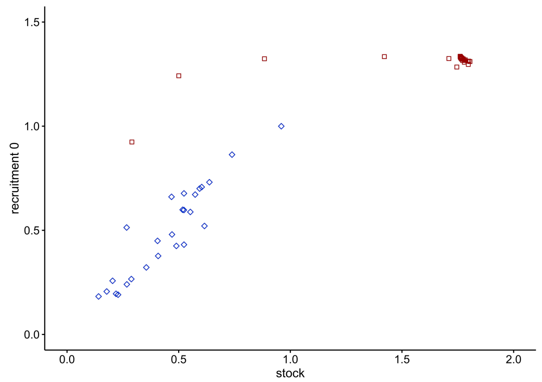

FIGURE 8
Stock-recruitment relationship of cod in the WBS ecosystem. Blue squares depict the trend from 1994 to 2019 after fitting of the model; red squares illustrate the time series from 2020 to 2100, with predictions obtained under the EBFM scenario.

down control of predators. (4) Finally, the present findings are supported by previous research: based on an ecosystem model for the central and eastern Baltic Sea by Harvey et al. (2003); Hansson et al. (2007) predicted a continued and ultimately drastic decrease of the herring and cod populations under a status quo scenario similar to the BAU scenario in the WBS model.

4.3 Correction of misconceptions

A number of misconceptions exist about the trophic relations in the WBS. One of these predicts that an increase in adult cod biomass would intensify the rate of cannibalism on juvenile cod (ICES, 2013b). However, our model shows that if fishing pressure is reduced herring biomass increases and so does its relative importance in adult cod diet. Because of such dietary shift, the cannibalism on juvenile cod plays a minor role in meeting the energy demand of adult cod. This is evident in the stock-recruitment relationship, which emerged from the model (Figure 8): after an early peak, the number of juveniles should continuously decline with increase in biomass of cannibalistic adults but this does not happen.

Another misconception is that birds (especially cormorants) consume a large fraction of cod and herring. The model illustrates that under the BAU scenario the joint consumption by birds, seals and harbour porpoises on cod, herring, and sprat, under medium-term time scale (2041-2050), is less than the extraction by fisheries. Similarly, Hansson et al. (2018) found that in the Baltic Sea the competition between marine mammal and seabird predators and fishers for the consumption of herring, sprat and cod is negligible.

A third misconception is that the lack of nutrients may limit primary production in the WBS. Our model suggests that about 1.2% of the primary productivity is required for the current regime of catches of the commercially most relevant fish stocks (Table S11). This number is very low compared to the usual 24-35% of other coastal systems (Pauly and Christensen, 1995). It suggests that the biomass of herring and sprat is presently too low to transport large amounts of energy from zooplankton to upper trophic levels and fisheries. Instead, much of the production goes to detritus and increases the extension of oxygen-deficient zones[8] (Hammarlund et al., 2018).

4.4 EBFM for the WBS

One reason for implementing EBFM is to balance good fishing yields with stock sizes that enable both prey and predators to fulfil their natural roles in the ecosystem. Although no generally accepted framework exists to make such judgement, stock sizes larger than two-thirds of the unfished stock offer safe assumptions. Comparing the predicted stock sizes for cod and herring under the EBFM scenario with the respective stock sizes during the herring-dominated regime in the no-fishing scenario indicates a relative stock size of about 80% for both cod and herring (Figure 4). Another reason for implementing EBFM is the restoration of species threatened by extinction or otherwise sensitive to fishing, such as harbour porpoises, seals and birds. Future model developments should devote increased attention to the role of top predators. The current grouping of birds is in fact insufficient to explore the impact of different fisheries scenarios because it combines species with diverse traits and feeding habits.

The CFP (2013) and the MSFD (2008, 2017a, 2017b) of the EU call for the implementation of Ecosystem-Based Fisheries Management in European seas, now a legally binding principle for managing the entire marine environment of the EU (MSFD, 2008; EU COM, 2020), with the objective to minimize negative impacts of fishing and to safeguard biological wealth and natural functioning of ecosystems. To abide with these objectives, multiannual management plans shall take into account knowledge about the interactions between the fish stocks, fisheries and marine ecosystems. While enabling a sustainable use of marine goods and services, priority should be given to achieving and maintaining good environmental status. This requires that pressures of human activities do not exceed levels that compromise the capacity of ecosystems to remain healthy, clean and productive. With these obligations from the MSFD, the entire spectrum of species (including non-commercial fishes)

8 https://www.eea.europa.eu/data-and-maps/indicators/oxygen-concentrations-in-coastal-and/assessment

and habitats in European seas must be included in management decisions (Kreutle et al., 2016). For the assessment of the good environmental status, the EU Commission (MSFD, 2017a; MSFD, 2017b) laid down criteria and methodological standards for ecosystems, including food webs, and yet in the Baltic Sea, several EU member states have not assessed many aspects for Descriptor 4 in their MSFD reports to the EU Commission (HELCOM, 2018b; EU MSFD Art. 8 report[9]). The WBS model addresses most of these legal requirements and allows, for the first time, a comprehensive assessment of the MSFD criterion D4C2, referring to not adversely affecting diversity, abundance and balance of trophic guilds.

While common sense implementations of EBFM have been proposed (Pikitch et al., 2004; Froese et al., 2016b), such as fishing all stocks below F_{MSY} and reducing fishing pressure even further for forage fish like herring and sprat (Pikitch et al., 2012), few studies have explored a range of alternative fishing scenarios. This study shows for the first time for the WBS that, without changes to the present fishing regime, low biomass and catch will continue. This was certainly the case for the post-hindcasting years 2020 and 2021, when cod and herring biomass reached all-time lows (ICES, 2021a; ICES, 2021b). The business-as-usual scenario also predicts that without a rescue effect from the Belt Sea where harbour porpoises occur at high abundance, the decline of these mammals in the WBS persists. The average density of harbour porpoises under BAU conditions is expected to attain 0.106 individuals per km^2 (Table 3), which is in the range of values found in the WBS during the 1990s (Table 1 in Scheidat et al., 2008); such densities might improve with increasing attention dedicated to the reduction of bycatches (Chladek et al., 2020). Under all scenarios, most trophic groups respond quickly when levels of fishing mortality are altered, and fish stocks and catches attain novel equilibrium levels within five years from the implementation of new management strategies (Figures 4 and S5). Instead, the harbour porpoise biomass reaches new equilibrium states after 2050 in every scenario, indicating that the recovery of the population is a long-term process. The delayed response of the harbour porpoise confirms that top predators occupy as consumers very fragile food web positions, which make them particularly vulnerable (see Scotti and Jordán, 2015).

Although the WBS model was developed for an ecosystem with unique features, it demonstrates a procedure that could be applied more generally. Ecosystem-based fisheries management, proposed for the sustainable use of resources and biodiversity conservation, was built according to some fundamental principles of fisheries and ecology that can be extended across ecosystems. This study shows that fishing mortality must always lie below F_{MSY} for sustainable extraction of fish biomass and that food web position is integral to describe ecosystem-level effects including indirect effects, such as the threatening of top predators by the decline of energy supplied by forage fishes (i.e. when fished > F_{MSY}) in case of their excessive exploitation.

9 https://water.europa.eu/marine/data-maps-and-tools/msfd-reporting-information-products/ges-assessment-dashboards/country-thematic-dashboards

TABLE 3 Impact of alternative fishery scenarios on harbour porpoise density in the WBS.

Scenario	ind. km^{-2}
BAU	0.106
EBFM	0.307
F_{MSY}	0.225
half F_{MSY}	0.305
no fishing	0.388

Values were estimated from the average gC m^{-2}, obtained using model predictions for the years 2041-2050. Carbon content was assumed to be 10% of wet weight and an average weight of 47 kg per individual was used for calculations (see Table 2 in Andreasen et al., 2017). Density of individuals predicted by the model is comparable with what reported by Scheidat et al. (2008) for the WBS in the period 2002-2006.

4.5 EBFM enhances resilience to ocean warming and phytoplankton changes

The Baltic Sea ecosystem is affected by multiple stress factors including nutrient pollution, deoxygenation, ocean warming and acidification (Reusch et al., 2018); these stressors act concurrently and their effect may be exacerbated in the presence of heavily depleted stocks (Möllmann et al., 2021; Polte et al., 2021). Although excessive fish extraction represents the primary and most pervasive cause behind the collapse of iconic stocks like western Baltic cod and western Baltic spring-spawning herring (Froese et al., 2022), this study also developed a wider view of future scenarios that account for changes in phytoplankton biomass and ocean warming. Nutrient enrichment enhances phytoplankton productivity leading to increased density. Phytoplankton degradation stimulates oxygen consumption and results in hypoxic or anoxic conditions, which threaten suitable habitats for fish spawning (e.g. seagrass ecosystems) and impair the recruitment of herring and cod (Hüssy et al., 2016; Kanstinger et al., 2018). Ocean warming has been shown to have overall detrimental effect on herring and cod recruitment as it shortens the temperature window for successful hatching and increases the hypoxia (Dodson et al., 2019; Voss et al., 2019). These aspects were simulated with extra runs of the EwE model with main findings that (1) under all stressors scenarios, EBFM always ensures the best stock recovery compared to BAU, except for flatfish (Figure 6); (2) warming always affects negatively catches of adult cod and its impact may exceed benefits of bottom-up forcing caused by 25% raise of phytoplankton biomass (Figure 7); and (3) the uncertainty associated to predictions that take into account multistressors is generally larger under BAU than under EBFM (Figures 6, 7) — presumably because of the reduced resilience of stocks at low biomass. Results illustrate that EBFM is compatible with the long-term, sustainable use of resources. It preserves the resilience of the WBS food web, making suitable safeguards that balance between trophic groups and to maintain the productivity of the main commercial fishes in response to warming and varying phytoplankton concentrations. Under ocean warming and with the decrease of phytoplankton biomass, EBFM allows the stock size of adult cod to exceed levels attained in the early 1990s while total catches remain below the values reported for that decade. Fish extraction shows a leading role in determining stock status in the WBS, which agrees with findings of another ecosystem model built for the central Baltic Sea (Niiranen et al., 2013).

Recently, Bianchi et al. (2021) showed that fisheries play a relevant role for ocean biogeochemistry. Biomass decline caused by fisheries accompanied drastic changes at global scale, reducing biomass cycling roughly 40% compared to levels attained during the preindustrial period. In the WBS, clear-cut differences emerge when quantifying carbon sequestration under BAU and EBFM scenarios: larger stock sizes found with EBFM support larger carbon flows (i.e. natural mortality, urine and faeces) towards detritus compared to BAU, suggesting about three times higher carbon sequestration under EBFM.

4.6 Limitations and caveats

EwE is suitable to assess how altering biomass of specific trophic groups spreads effects throughout the food web given explicit interaction terms from primary producers to top predators. The whole-ecosystem approach implemented in EwE (and allowed by other software tools such as Atlantis; see Forrest et al., 2015) is ideal for investigating the impact that primary production has on higher trophic level consumers. Differently, MICE and OSMOSE are less suitable for modelling such a bottom-up forcing on all compartments, due to their focus on a selected set of trophic groups (Plagányi et al., 2011). Conclusions drawn from ecosystem models should always be assessed within the limited capabilities of the software program used and assumptions made during model building. A summary of the main caveats and limitations in the EwE model of the WBS include: First, fishing efforts are constant and do not vary in response to changing biomass, indicating the absence of any feedback to management following stocks recover or decline (Chagaris et al., 2015). Second, the importance of marine protected areas for reconstituting stocks and conserving endangered species cannot be evaluated since the model does not consider spatial dynamics. However, an Ecospace version could be developed from this EwE model, thus allowing to replicate Ecosim over a 2D grid (Christensen and Walters, 2004). Spatial dynamics are especially relevant for high trophic level groups which are typically patchy and highly mobile. In the case of the WBS, the integration of EwE with Ecospace could provide clearer mapping of marine mammal feeding grounds for juvenile cod and herring. Third, feeding preferences are an input to Ecopath, stored in the diet composition matrix with the static architecture of trophic interactions. Together, they influence predator consumption rates, which linearly increase as a function of prey biomass (Plagányi and Butterworth, 2004). These features differ from those of two other popular end-to-end ecosystem models such as Atlantis and OSMOSE (Table 1 in Smith et al., 2015). For instance, the spatio-temporal co-occurrence and size-based constraints regulate the likelihood of trophic interactions in the individual-based framework of OSMOSE, making it more suitable to model an opportunistic feeding behaviour while specialized diets are better described in EwE (Travers et al., 2010). Fourth, metabolic parameters used for the 1994 Ecopath model define the starting conditions for Ecosim. These parameters do not vary under simulation, a feature that prevents the modelling of any evolutionary response to changing environmental conditions. Finally, the WBS model considers ontogeny with the multi-stanza routine (i.e. juvenile and adult cod) but a higher number of age classes and, consequently, of feeding interactions might have emerged from Atlantis and OSMOSE (Table 1 in Smith et al., 2015).

5 Conclusions

The trophic model presented here shows for the first time the “big picture” of the WBS food web by quantifying structure and flows between major trophic groups. The model is a preliminary but thermodynamically sound hypothesis of the WBS food web, especially useful for the assessment of broad trophic guilds as required by European law. Results show that the fishing pressure presently exerted on organisms within the WBS forces top predators such as harbour porpoises and seals, but also cod and other demersal fish, to compete heavily for fish as food. A common strategy adopted to cover their dietary needs is to shift consumption towards organisms lower in the trophic web, mainly benthic macrofauna. Highly mobile organisms like the harbour porpoise may search for suitable prey in adjacent ecosystems such as the Kattegat, Skagerrak, central Baltic Sea and North Sea. Simulations show that the business-as-usual scenario would perpetuate low catches from depleted stocks in an unstable ecosystem where endangered species may be lost. In contrast, the EBFM scenario allows rebuilding of the harbour porpoise population and the recovery of all stocks except flatfish, with strongly increased catches well above the present levels for cod and herring. EBFM confers resilience to the WBS food web, making it less susceptible to changes exerted by increased phytoplankton biomass and ocean warming. It results in lower levels of uncertainty for future predictions on catches, a desirable condition to plan management actions (see modern portfolio theory; Runting et al., 2018). At larger scales, EBFM improves carbon sequestration as required for slowing climate change, only furthering the urgent reasons to abandon business as usual and adopting the legally required ecosystem-based fisheries management.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

MS, SO, and RF conceived the study. SO built the reference model. MS assembled the alternative models, and performed new simulations and uncertainty analysis. All authors contributed to manuscript preparation and approved the final version. None of the authors has any conflicts of interest to declare. This manuscript has not been published nor is under consideration for publication elsewhere.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.879998/full#supplementary-material

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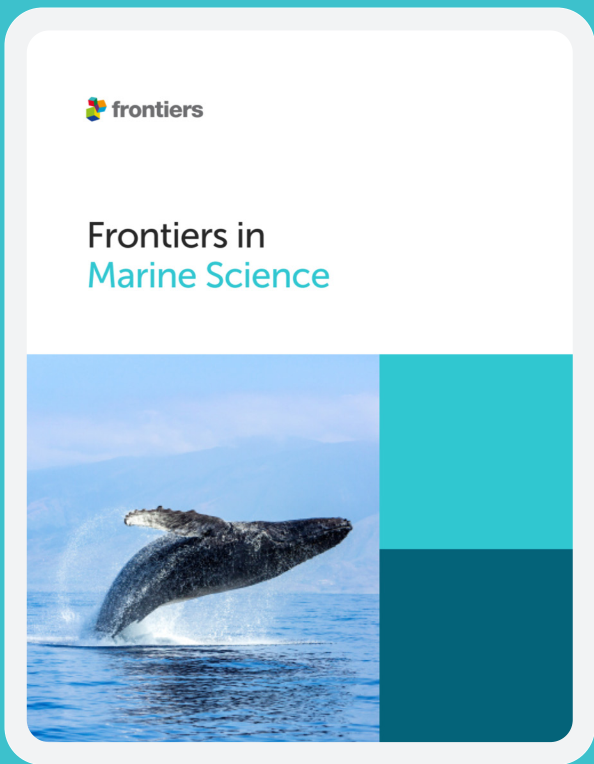

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