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A roadmap to reduce the risk of overexploiting EU marine living resources in a changing ocean

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We provide a balanced overview of how risk assessment and management is being tackled in the European Union (EU) and beyond to address the challenges of overexploiting marine living resources in EU waters. We aim to guide EU fisheries and aquaculture policymakers towards key actions to foster the transition to responsible, sustainable, clean energy, and resilient fisheries and aquaculture sectors, aligning with EU environmental objectives under the European Green Deal and the Common Fisheries Policy. Despite progress in reducing fishing pressure on some stocks in recent years, most of the stated (single-stock) sustainability objectives still need to be met. The risk of overexploiting marine resources remains high, especially when combined with other pressures such as pollution and climate change. Risk is defined as the probability of an adverse event arising from natural or human activities and excessive pressures. Scientists have documented these pressures, proposing regional risk assessments to support adequate risk-based management of human activities impacting marine and coastal regions. As a next step, we recall actionable short- to long-term recommendations to reduce the risks associated with exploiting these natural resources and ensure their sustainability and resilience. This includes actions the EU can take to improve and implement fisheries policy while prioritising less harmful alternatives among current fishing methods and considering the three pillars of sustainability i.e. environmental, economic and social. Such actions include capturing in scientific advice the strong, causal links between pressures induced by human activities, natural disturbances and ecosystem states; such understanding can be used in an uncertain and changing environment, with ocean productivity possibly trending towards new levels. Finally, we restate that conserving by reducing pressures and restoring the integrity of marine ecosystems is crucial for minimising the risk of overexploitation and ensuring future fishing and farming opportunities. This is the aim of an Ecosystem Approach to fisheries and aquaculture – it should safeguard the long-term economic and social capital already invested by the public and private sectors in exploiting marine living resources to continue delivering healthy, low-carbon, low-impact seafood to EU citizens and beyond.

KEYWORDS

sustainable and climate resilient fisheries and aquaculture, environmental risk assessment and management, cumulative pressures, overexploitation, sustainability

1 Introduction

In 2021, the EU's marine wild capture fisheries and aquaculture sectors contributed 3.5 million tons and 851.6 thousand tons to global seafood production of fish, crustaceans, and molluscs (FAO, 2023; Figure 1). This production was insufficient to meet the EU's annual seafood consumption of over 11.0 million tons, leading to a dependency on imports for over 70% of its seafood demand (EC, 2021). While the global capture of wild fish, crustaceans, and molluscs has remained stable at approximately 80 million tons over the past two decades, aquaculture production has grown significantly (FAO, 2023). Yet, the EU's growth in this sector lags, with a significant portion of products in EU markets, aside from some species, such as salmon and mussels, being imported from Asia. Growth in aquaculture is deemed essential for regional food security and addressing overfished stocks within the EU, especially in the Mediterranean and Black Seas (Figure 2, STECF, 2023). However, the current capacity of EU aquaculture to help meet demand sustainably remains a concern, highlighting the need to limit consumption given that many fish stocks in EU waters remain overexploited and that the increasing demand is not driven by population growth (Sumaila et al., 2022).

Human activities at sea, including fishing and aquaculture, impact marine ecosystems, affecting marine species' development and regeneration. Ensuring a viable, long-term exploitation of marine resources that defines sustainable fisheries and aquaculture requires minimising these environmental impacts. The transition to sustainable fisheries and aquaculture should build on existing knowledge and understanding regarding each ecosystem component that fisheries affect (and the ecosystem components affecting fisheries) and support acquiring new knowledge, including solutions to minimise adverse effects. A better understanding of the impacts of fishing and aquaculture should help enhance seafood production in the EU. Sustainability also depends on external factors, such as the effect of climate change and pollution on ocean productivity (Peck et al., 2021; Bastardie et al., 2022) as well as, for example, fuel and fish prices that affect the sector's economic viability (Carvalho and Guillen, 2021). Minimizing fishing impacts and reducing dependency on fluctuating economic and environmental factors are crucial to prevent overexploitation and ensure socio-economic stability. Indeed, overfishing and unsustainable practices likely stem from a vicious circle where the impacts on marine ecosystems adversely affect fisheries' economic performance (Bastardie et al., 2021). Such a loop is mediated by side-framing factors, such as markets and regulations, which can exacerbate ecosystem degradation and reduce resilience whenever there is an economic incentive for firms trapped into unsustainable practices to increase fishing effort to offset losses or mitigate short-term risks, further entrenching this cycle of degradation and socio-economic losses. Hence, environmental and fisheries governance should be reviewed to ensure fleets convert to sustainable and responsible practices or, if not technically or financially feasible, be phased out.

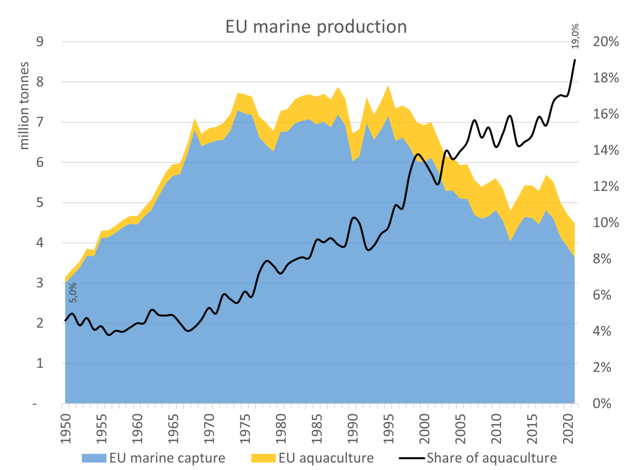

FIGURE 1
Contribution of European wild capture marine fisheries and aquaculture over time. Source FAO https://www.fao.org/3/cc0461en/online/sofia/2022/capture-fisheries-production.html (All marine areas for EU (including the EU Outermost regions) and European member states). EU Capture marine fisheries landed 3,634,168 tonnes (4.5% of global production, or 48% of EEA production), while EU Aquaculture (marine and brackishwater) yielded 852,138 tonnes (0.44% of global production or 28% of EEA production). The share of EU aquaculture was 19% of total EU aquatic production in 2021.

The EU Common Fisheries Policy (CFP), along with the other EU policies and the various national regulations governing aquaculture, are underpinned by social, environmental, and economic pillars and only a coherent, risk-averse, precautionary and balanced management effectively implemented will lead to better resource use efficiency and reduced ecological stress in the long term. However, policymakers and fisheries managers are challenged to ensure coherence when exploiting marine ecosystems due to the interaction of different sectors under various connected legislations with different interests and often conflicting objectives (Boyes and Elliott, 2014). The main objective of the EU's marine environmental management through the Marine Strategy Framework Directive (MSFD) is to reach and maintain Good Environmental Status (GES) of Europe's seas. The MSFD should serve to ensure coherence among sectors in the complex regulatory landscape governing fisheries and aquaculture in European seas as it addresses GES for both fisheries and aquaculture at the international and national levels. However, because of the likely high upfront costs in transitioning to GES, many of the measures are weakened or not implemented, preventing the necessary reduction of risks and the actions or inactions of one country, potentially compromising an entire region (Cavallo et al., 2019).

In such a context, we set out to develop a roadmap to support the transition to sustainable EU marine fisheries and aquaculture by identifying first the drivers of overexploitation and degradation, and then the mitigation measures to reverse the trend toward a virtuous cycle. This effort should lead to a unified strategy aimed at enhancing the effectiveness of fisheries and aquaculture management, thereby minimising the risk of future overexploitation of marine living resources in EU waters and beyond. The objective for such a roadmap is already clearly stated in EU law. GES is defined as: "The environmental status of marine

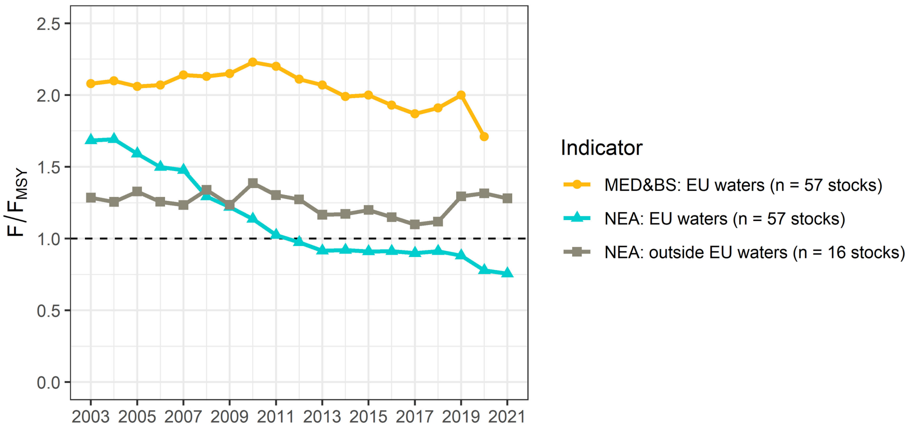

FIGURE 2
Trends in fishing pressure from 2003-2021 in EU waters: Mediterranean and Black sSas (black) and North-East Atlantic, including the Baltic Sea (red for EU waters and green outside EU waters). The vertical axis represents the fishing pressure indicator F/Fmsy, i.e. the ratio of the fishing mortality over the fishing mortality assumed to give the Maximum Sustainable Yield; a ratio of 1 or below for a given stock means the stock is harvested sustainably, shown by the dotted horizontal line. Source: STECF (2023).

waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive" (MSFD Art. 3) and operationalised in 11 Descriptors that describe what the marine environment would be when GES has been achieved (Figure 3). Both fisheries and aquaculture are captured in several descriptors, and hence, GES implies sustainable activities but also, for example, protection of the seafloor and prevention of bycatch of unwanted and/or sensitive species. Aligning fisheries and aquaculture practices with the goals and principles of the MSFD for maintaining GES and assessing the cumulative impact of the various pressures using risk-based approaches will provide a set of measures enabling a more sustainable, climate-resilient EU seafood production system for future generations.

Overexploitation in fisheries refers to overfishing, i.e. a situation where high fishing pressure leads to decreasing catches. With the MSFD, overexploitation is now broadened to include the degradation of supportive habitats and the related ocean productivity (carrying capacity). To reach GES across EU waters,

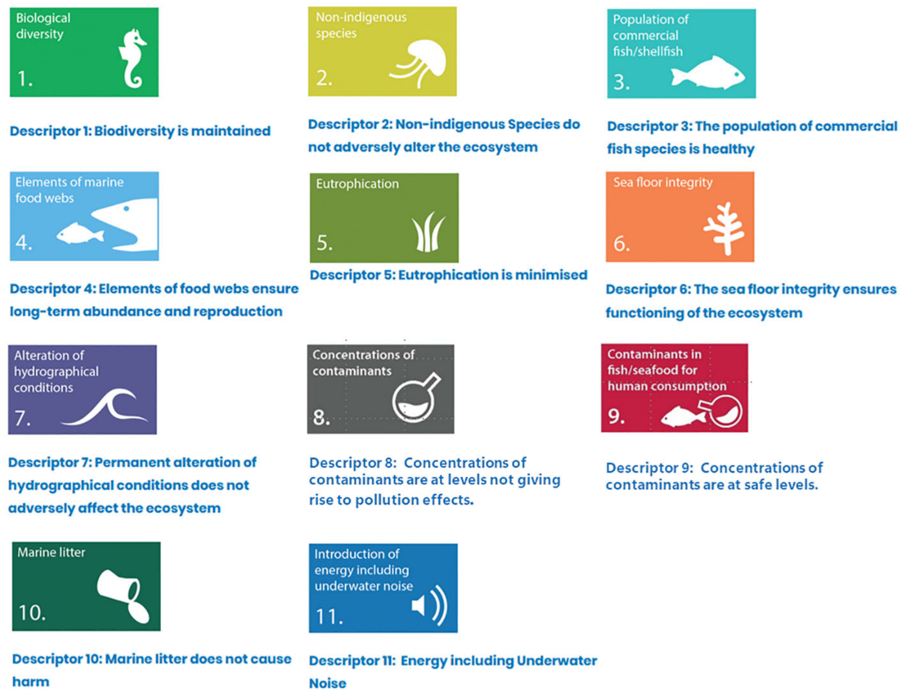

FIGURE 3
The 11 qualitative descriptors of the EU MSFD (Directive 2008/56/EC).

the greater the understanding of the combined effects of pressures affecting marine ecosystems the higher the chance of ensuring their sustainable exploitation. In this perspective, the present study aims to add value to the transformative changes needed in EU fisheries and aquaculture to support marine biodiversity and ecosystems and the changes that need to be made. The roadmap also identifies the skills and know-how needed to fill policy design, implementation, and knowledge gaps.

A lack of knowledge is certainly not the only factor making EU fisheries management less robust in achieving its targets, as the EU governance is framing the space of possibilities for a change which also explains today's situation. The current situation most likely results from a combination of factors, including inertia and path dependency, short-termism and crisis management, uncertain science and opposing lobbying efforts. When overexploitation was common before 2002, the governance framework of the CFP was revised in 2002, which changed the incentive from such a situation toward following more sustainable exploitation goals (Hegland and Raakjaer, 2020). Such governance may likely have failed whenever the past long-term assets invested in the sectors were ignored, all tending to incentivise unsuitable practices to keep going. The shift from a short-term to a long-term perspective incurs a cost that must be borne by society, including private companies. Specific to fisheries, the concentration of fishing opportunities on a few actors in recent decades has been done at the expense of small-scale fisheries and social sustainability (Hegland and Raakjaer, 2020). Policymakers trying to address such social sustainability as well as economic efficiency have led to an escalation in fishing power or the maintenance of oversized fisheries that had far-reaching consequences on both the ecosystem and the economy of the fishing sector. In this context, the limited scientific knowledge on individual pressures on marine ecosystems and their cumulative impact has likely made the scientific evidence less supportive to effectively oppose ongoing lobbying efforts for the status quo and for separating fisheries and aquaculture activities from their background impacts, failing to discontinue environmental degradation in background. We argue here that to address uncertain science, it is best to document and follow a risk-based assessment based on a precautionary approach, as a support for management actions to be taken, as permitted by the current governance framework of the CFP and related environmental regulations.

The essence of the proposed roadmap for conducting risk-based assessments toward managing risks (Figure 4) is to recognise that the existing approaches for assessing cumulative impacts need to be complemented. Current approaches (e.g., HOLAS, 2023) overlay single-pressure effects to ecosystem components while assuming those pressures affect independently and with magnitudes based on qualitative impact scores (e.g., Dailianis et al., 2018). Future approaches could improve these assessments by focusing on coherent combined pressure effects linked through causal relationships. In the case of fisheries and aquaculture, their role compared to other pressures acting on the system should be more clearly elucidated, and a systematic scenario evaluation with and without their effects investigated. With this improved approach, a risk-based assessment serves as a solid basis for running prospective scenarios exploring the effects of mitigation and adaptation measures of each pressure on reaching predefined environmental targets.

2 Fisheries and aquaculture pressuring the marine ecosystems in interaction with other pressures

While encompassed under the broader category of aquatic resource management, the EU regulates fisheries and aquaculture separately in recognition of the distinct characteristics and challenges associated with these sectors. Each has a unique regulatory framework at the EU and Member State (MS) level tailored to its specific needs and objectives. However, while fisheries

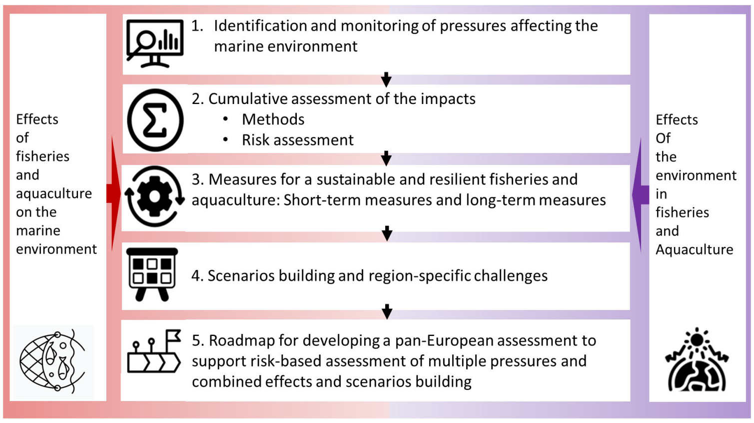

FIGURE 4
Stepwise approach towards the development of the roadmap to assess the impacts of and effects on fisheries and aquaculture and the resulting risk-assessment as a basis for actionable recommendations. Recommendations to address the actual risk management aspects are not included in the figure but discussed in section 4.

are primarily regulated by the CFP, aquaculture is regulated by a combination of directives and regulations, including the CFP[1]

This complex regulatory landscape for aquaculture challenges compliance in the sector and its development. Ultimately, both sectors share the overarching goal of responsible resource management and environmental protection, as well as the coordination of activities in shared marine spaces.

Understanding the pressures affecting the marine environment requires data to quantify and assess their impacts (see Supplementary Material; and more details in ICES Aquaculture Overviews, ICES Ecosystem Overviews, OSPAR Quality Status Report, HELCOM State of the Baltic Sea and Mediterranean Quality Status Report). Table 1 lists the main dataflows available at the EU level for assessing the impacts of pressures, and highlights some of the current coverage issues, ranging from partially to very incomplete. In data-poor conditions, a precautionary approach is recommended for managing pressures.

Under the CFP for example, data on commercial fisheries (e.g., catches and landings) may only be partially available for several reasons, one being confidentiality issues. Another reason is that vessels under 12 meters, representing over 80% of the EU fishing fleet in number, have been exempt under the EU fisheries control rules (Regulation (EC) 1224/2009) from accurately reporting on their fishing activity. This changes under the new control regulation (Regulation (EU) 2023/2842), where all vessels will be required to submit fishing logbook data electronically and be tracked through a vessel positioning data system. Additionally, for many commercial species or areas (e.g., Mediterranean and Black seas), insufficient data are available for adequate stock assessments (see STECF 23-09 for more details). Yet, the current CFP requires that all commercial fish stocks be harvested at levels compatible with the MSY by 2020. While the resource requirements for monitoring and assessing all harvested stocks may be too high, more effort is needed to cover some currently data-poor stocks, particularly those managed under catch quotas. For recreational fisheries, only a few stock assessments include recreational catches in their assessment (i.e., North Sea cod, Western Baltic cod, European seabass), and data availability and quality varies across MS, requiring standardisation effort (Grati et al., 2022). Estimates on bycatch can be obtained from MS (Regulation (EU) 2019/1241) through dedicated data calls (e.g., ICES, 2023a, GFCM, Helcom, Ascobans, Accobams).

Several studies have identified data and knowledge gaps in MSFD assessment elements to help improve and harmonize monitoring and assessment. The overall analysis of these gaps reveal low data availability, limited and heterogenous knowledge and the need for long-term time series datasets via the establishment of suitable monitoring networks (e.g., Crise et al., 2015). For example, human activities disturbing the seabed include abrasion, removal, deposition, and sealing (see also ICES 2019). Data on the spatial extent of these activities can be used to quantify the impact and provide management scenarios with trade-off analysis (ICES, 2021). Marine pollution, including chemical pollution and eutrophication, marine litter and underwater noise, is a significant problem in EU seas, as reflected by several of the qualitative descriptors of the MSFD (D5, D8, D9, D10 and D11).

Each of the single pressures listed above affects the marine environment simultaneously, and their effect accumulates in the system (Figure 4). Accounting for the interactions between multiple pressures expands the complexity of analysis (e.g., Depellegrin et al., 2021; Judd et al., 2015; Kenny et al.., 2018). Cumulative effects can be synergetic if the cumulative effect of multiple stressors is greater than the additive sum of effects of the stressors acting in isolation or antagonistic if the cumulative effect is less than the additive (Figure 5). Also, the system can compensate for the effects of certain pressures or, on the contrary, be very sensitive to disturbance.

3 Approaches to assessing cumulative impacts on marine ecosystems

3.1 From cumulative impact assessment to risk assessment and management

In Cumulative Impact Assessments (CIA), the spatiotemporal distributions of the ecosystem component abundance and the magnitude of the pressure are used to calculate exposure and sensitivity with a confidence assessment. This approach informs managers of areas with higher anticipated risks and about the uncertainties detected (Halpern et al., 2008; Korpinen et al., 2021; Piet et al., 2021). This has been used to produce regional impact assessments in European waters that measure the risk for overexploiting marine ecosystems, e.g., through the Water Framework Directive (WFD) along with the MSFD and the Marine Spatial Planning Directive (MSPD), collected by the European Environment Agency (EEA), EMODnet, OSPAR and HELCOM and an array of research efforts such as the VECTORS, DEVOTES, PERSEUS, CoCoNet, BENTHIS, ADRIPLAN and Med-IAMER projects, (see a review in Dailianis et al., 2018). A major limiting factor in CIA is the availability and accuracy of data and the coherence among spatial layers depending on various resolutions of the data layer. Other limitations of CIA approaches include lack of units and lack of information on the absolute magnitude of the pressure(s), methodologies sensitive to uncertainty, potential bias using expert judgment for sensitivity scoring, and not considering non-linear relationships between

1 The following EU legislation applies to aquaculture, among other activities: the Water Framework Directive (Directive 2000/60/EC); the Marine Strategy Framework Directive (Directive 2008/56/EC); the Decision on Good Environmental Status (Decision 2017/848/EC); the River Basin Management Plans; the Birds and Habitats Directives (Directive 2009/147/EC and Directive 92/43/EEC); the Industrial Emissions Directive (Directive 2010/75/EU); the Regulation concerning the use of alien and locally absent species in aquaculture (Regulation (EC) No 708/2007) and the Regulation on invasive species (Regulation (EU) 1143/2014); the Environmental Assessment Directive (Directive 2011/92/EU); and the Strategic Impact Assessment Directive (Directive 2001/42/EC). In addition to specific legislation for organic production that promotes, through certification and labelling, aquaculture complies with stricter production requirements on environmental impact and animal welfare, as well as limited and regulated use of external inputs.

TABLE 1 Data available and data gaps to monitor the effect of single pressures affecting the marine environment.

Activities	Pressures to the marine environment		Data needed to assess impact	Availability	Source
Fish and shellfish harvesting	Fish extraction	Commercial	Reported catches, landings, survey	Yes, limited	ICES, ICCAT, STECF FDI and AER
		Recreational	Reported catches	Very limited	ICES, National institutes
	Bycatch and unintended catch		Bycatch estimates	very limited	ICES, GFCM
	Physical disturbance of the seabed (abrasion)		Area swept by fishing with mobile bottom-contacting gears + map of benthic sensitivity	Yes, limited	ICES
Extraction of minerals, deposition of materials, tourism, cable work, coastal protection			Volume of gravel and sand extracted	Very limited	ICES, EMODnet, UNEP, OSPAR
			Volume of sediment deposited, dredged	Very limited	ICES, EMODnet, OSPAR
Offshore installations port anchorage, construction work	Physical loss of the seabed		Area sealed (licensed)	Very limited	ICES, STECF
			Licensed areas for gravel and sand extraction	Very limited	ICES, STECF
Transport, runoff, oil spills	Marine pollution	Chemical	Concentration of contaminants	Yes, limited	ICES, HELCOM, OSPAR, EMODnet
		Plastic/ Litter	Extent and distribution of litter in the sea	Yes, limited	OSPAR, HELCOM, EMODnet, WISE
		Underwater noise	Extent and distribution of anthropogenic sound	Yes, limited	OSPAR, EMODnet, WISE, HELCOM
		Eutrophication	Nutrient enrichment	Yes, limited	HELCOM
Aquaculture	Benthic habitat degradation		Water quality monitoring and sediment sampling and analysis at appropriate spatial-temporal scales	Yes, limited	National institutes
	Fish feeds			Very limited	National institutes
	Emerging pathogens			Yes, limited	National institutes
	Invasive species		Regular health monitoring for farmed and wild fish	Yes, limited	National institutes

pressures and state (see Stock and Micheli, 2016; Stelzenmüller et al., 2018).

An Environmental Risk Assessment (ERA) builds upon such CIAs to identify mitigation measures or control points to reduce risks such as overfishing and environmental degradation. Examples include a gap analysis in the Baltic Sea to evaluate whether existing management measures are sufficient to reach GES as required by the MSFD (Sufficiency of Measures in the HELCOM Action, 2021) or if additional measures are required. Similar approaches such as PERSEUS (perseus-net.eu) have been carried out in Southern European seas to integrate information on the hazard with the environmental exposure and vulnerability assessments to identify and rank areas at risk of not achieving GES.

In the EU's 2021 Strategic Guidelines for Aquaculture, dual needs are identified – to grow the industry while increasing its environmental performance. Tools such as ERA and CIA should allow for a better understanding of the risks and benefits posed by an aquaculture site and the cumulative impacts of aquaculture operations, helping marine aquaculture to become more environmentally sustainable (Andersen et al., 2022). For example,

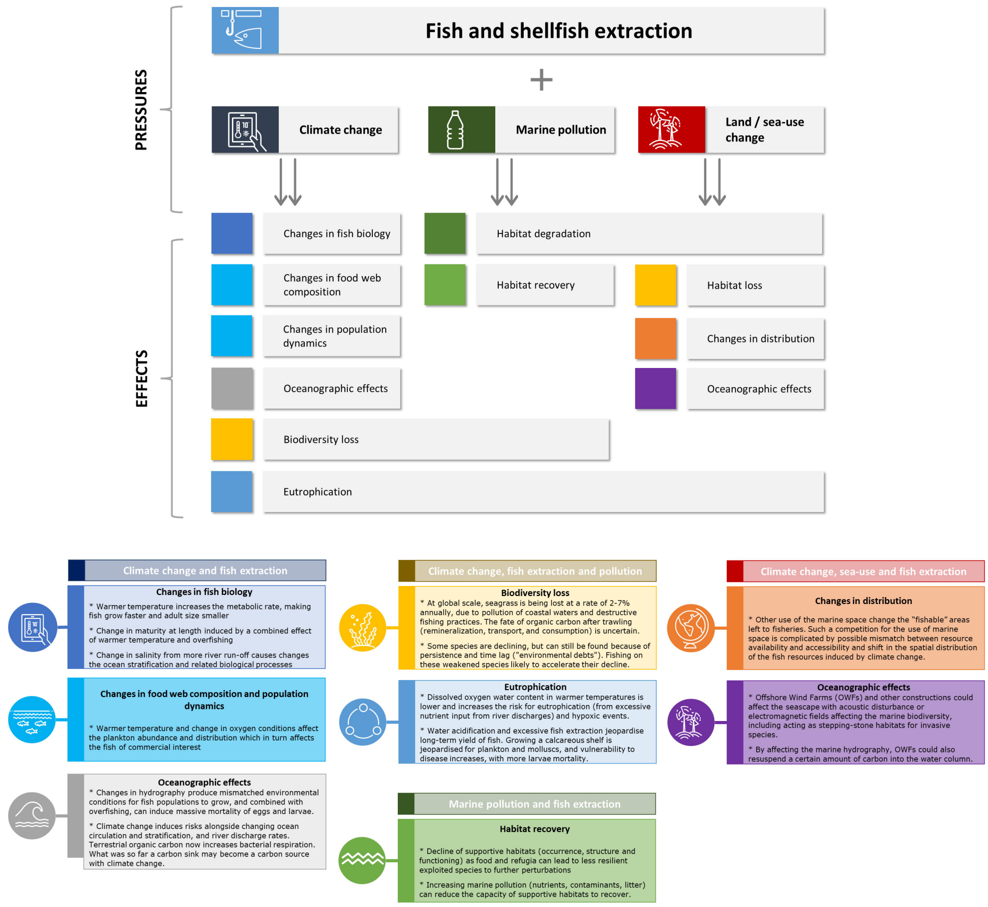

FIGURE 5
A non-exhaustive list of examples of individual pressures combined with fish extraction producing a subset of synergistic effects (double arrow) in Europe's seas (issued from a literature review as described in more details in Supplementary Material).

studies have examined the potential risks of direct impacts of shellfish farms on protected species (marine mammals and birds), indirect effects and the cumulative impacts of multiple small or large farms in a single area. Such studies are useful resources for planning and permitting in near-shore areas, where aquaculture operations may pose benefits such as carbon dioxide sequestration, sensitive habitat protection, and hazards to marine mammals. These studies also support both ERAs and CIAs as aquaculture moves offshore into the open ocean with advancing technology. Large investments in technological developments are being made that may lower the costs for more offshore farming but may potentially come to the detriment of the environment and biodiversity.

Cumulative impacts assessments have not been formulated in the EU fisheries context until recently, when the EC published in 2023 a package of fisheries-related measures that set the path for marine protection, sustainable fisheries management (COM/2023/103), and decarbonisation of the fishing industry (COM/2023/100 On the Energy Transition), aligned with the objectives of the European Green Deal (EGD). It includes an action plan to manage pressures from fisheries spatially (COM/2023/102 EU Action Plan) to restore and protect marine ecosystems and operationalise the ecosystem-based approach to fisheries management, under the EGDs Biodiversity Strategy for 2030. The plan aims to act on synergies between fisheries and environmental policies and help improve their implementation. One of the most important elements of this action plan is to regulate the activity of mobile bottom-contact fishing gears in EU waters with the aim of reducing impacts on the seafloor. How to reduce incidental bycatch with more selective fishing is also on the agenda. Such plans require innovation and research studies to analyse short-term trade-offs with the exploitation and risks affecting ocean productivity, for example, to measure the implications of displacing the existing fishing effort on surrounding habitats (Figure 6, see also STECF, 2022b).

Both CIA and ERA are powerful tools for understanding the potential risks of cumulative effects of/on marine fisheries and aquaculture and other sectors active at sea. These tools differ in their scope and purpose: CIA examines the combined effects of multiple stressors and activities on the environment over time, whereas ERA focuses on assessing the risks associated with a single fishery, farm, species, or therapeutic use. Both approaches are essential tools for environmental management and decision-making and can complement each other when addressing complex environmental challenges associated with these industries. While the MSFD does not explicitly require a CIA, it

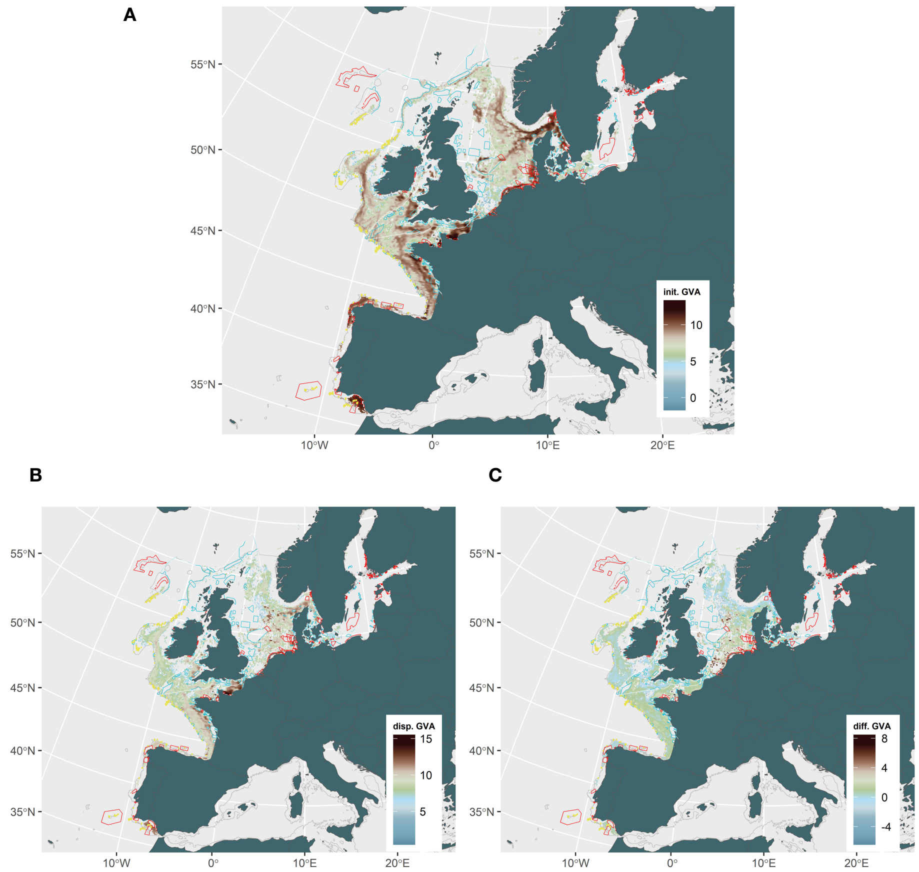

FIGURE 6
Spatialised STECF AER 2020 Gross Value Added (GVA, in log(millions euros) gridded in 0.05 degree c-squares) for North-East Atlantic MS fleets pooled (i.e. some countries are missing), **(A)** before applying the spatial restrictions in areas vulnerable to bottom fishing (in grey, polygons from Bastardie et al., 2023), **(B)** after applying the spatial restrictions and accounting for possible effort displacement, **(C)** the difference between before and after applying the restrictions expressed as a log ratio of GVA.

does emphasise the need for an ecosystem-based approach to marine management, which inherently includes cumulative impacts.

3.2 Limiting risks of overexploitation with an ecosystem approach

The Ecosystem Approach to Fisheries Management (EAFM, e.g., see Long et al., 2015) and the Ecosystem Approach to Aquaculture (EAA, e.g. see Brugère et al., 2019) involve integrating the risk-based assessment into a holistic management approach that considers multiple pressures. As ecosystem components are connected, exploitation of commercial species can lead to the degradation of marine ecosystems, loss of biodiversity, and increased vulnerability of dependent human communities. In the Ecosystem approach, a cumulative risk assessment centred on fisheries and aquaculture should be embedded to streamline the uptake of scientific outcomes into the science-policy interface for risk management (Katsanevakis et al., 2020).

The EAFM and EAA acknowledge the need to manage pressures for preserving all marine species and maintaining healthy marine ecosystems in the long run. This is because fisheries exploitation and farming practices can impact not just target species but their habitats too, accumulating various pressures in the oceans and affecting their productivity. Various environmental and human pressures are cumulatively affecting the biological, physical and geochemical conditions of marine ecosystems. These include climate change, pollution, eutrophication, and industrial sectors exploiting the seas. Additionally, developing marine infrastructure (offshore windmill farms, so-called energy islands, etc.) further exposes European seas to stressors such as habitat modification from coastal development, invasive species, pathogens and recreational fishing. Combined, these pressures can alter species' vital rates and essential life history aspects, affecting their functional diversity groups and possibly limiting future fishing opportunities. The ecosystem approach from the perspective of fisheries and aquaculture integrates several ecosystem challenges within a single construction (e.g. see a review in Bastardie et al., 2021), such as:

- the impacts of fish extraction on exploited stocks' resilience;
- the loss of biodiversity after fishing activities (bycatch and habitat degradation) or aquaculture farming (genetic erosion, effluents etc.);

- the alteration of food-web interactions due to fishing pressure;
- the anthropogenic and environmental changes, including nutrient enrichment from aquaculture, interacting with fishing opportunities, such as climate change impacts or eutrophication;
- the social and governance constraints on fishing opportunities: market demand, spatial and market competition among fisheries products, and between fisheries and fed aquaculture products;
- conflicting, inconsistent, or ill-informed policy goals across industries and stakeholders, including spatial conflicts in occupying the marine space, among fisheries and farming, or with other sectors.

Risk management through an ecosystem approach would require the policies to be flexible enough and well-equipped to address such challenges (Bastardie et al., 2022). The last reform of the Common Fisheries Policy (CFP 2013, Art. 11) introduced the possibility of making fisheries management in Europe coherent with its environmental protection objectives defined in the MSFD, EU Habitats Directive, EU Birds Directive, and other directives, that by nature are implemented at the national level. If the initiation of regulations is a competency of the EU Commission (EC), these regulations need to be adopted by the EU parliament and the EU council ("co-decision"). In matters of urgency and rapid adaptation, apart from the annual end-of-the-year meeting for setting fishing opportunities or emergency measures for the year to come, the EC can also implement delegated acts. However, most of the new legislation taken in this way is only triggered by joint recommendations from EU MS, examined and possibly adopted by the EC (Art. 12 and 13 of technical measures regulation EU Reg 2019/124). Hence, the responsibility of implementing the ecosystem approach lies ultimately with MS, which can maintain a detrimental status quo in lack of consensus or willingness to change. Examples of (the few) delegated acts include recommendations for more selective gears, or less impacting gears or closed areas to maintain the seafloor integrity and to monitor trophic guilds to ensure the functioning of the marine food webs by (EC COM (2023/520)).

The Ecosystem Approach to marine aquaculture offers a dynamic framework for considering both its environmental benefits and hazards. Implementing this approach requires using informed indicators and methodologies, guided by the best available science, for robust environmental monitoring and effective best management practices. These efforts are designed to benefit the sector, the marine environment, and stakeholder interests. This approach underscores the importance of quantifying aquaculture's full spectrum of impacts, ranging from positive aspects, such as carbon sequestration through seaweed and bivalve farming, to negative consequences, such as disease transmission to wild oysters. For instance, salmon aquaculture in the Faroe Islands is economically significant, employing 5% of the active labour force and accounting for 40-45% of the total export value. Yet, sea lice infestations represent a substantial concern, necessitating regulatory, innovative, and cost-driven responses (ICES, 2023b). Achieving sustainable growth involves adapting production methods to mitigate environmental impacts. For example, on-land production time reduces sea lice exposure in the marine environment, leading to reduced therapeutic use, yet possibly increasing point source pollution and water use.

An ecosystem approach should also include the human dimension and recognise the risk induced by pressures (dependent or independent of fisheries or aquaculture exploitation) on the social dimension and economic long-term assets in fisheries and aquaculture. However, advocating too much for incorporating socioeconomic impact assessment before any protective regulation might be counterproductive. Focusing on immediate socio-economic impacts likely sustains the long-term socio-economic losses when overfishing or habitat degradation still prevails if only poor regulation is enforced. In fisheries, if they are short-term costs, there is likely no tradeoff in the long term between exploitation and conservation, and preserving abundant fish stocks in EU waters will likely reduce, not increase, imports of fisheries and aquaculture products, therefore improving the self-sufficiency of the EU seafood market. On the contrary, in farming, more input often leads to more output, as crops on land, therefore calling for defining acceptable limits to balance environmental impact and the need for higher productivity. On the other hand, clean water is crucial for fish farming, and ecosystem degradation can negatively affect aquaculture opportunities. Hence, it is imperative to broaden our understanding of the effects of fishing on the marine environment beyond just the fishing sector and such understanding should be brought up whenever consulting stakeholders ahead of regulation implementation. The impact of marine aquaculture also demands attention. However, the ecological monitoring of its effects on the marine ecosystem is lacking within the aquaculture industry. Thus, there is a need to propose potential indicators and methodologies to assess and monitor the pressures and impacts of aquaculture (e.g., ICES Aquaculture overviews for the Faroe ecoregion in ICES 2023) and fisheries on marine biodiversity and ecosystems, identifying data availability and case studies.

3.3 Scenario building for region-specific challenges in reducing marine ecosystem overexploitation

Models and scenarios can help visualise the potential consequences of management alternatives. One approach is to build a conceptual marine-social-ecological system where key perspectives (ocean climate, governance context, ecosystem, and then fisheries management) interact with causal links that would account for multiple-perspective scenarios (Planque et al., 2019; Gammage and Jarre, 2021; Hamon et al., 2021). Such narratives can fit specific local challenges that fisheries management faces in a European context. Some examples are provided in the existing or possible case studies described below.

3.3.1 Case study 1: open ocean to closed containment

Challenge: Traditional open net pens used for finfish aquaculture, such as salmon, incur multiple pressures on the marine environment, including escapees of non-native species and transfer of genes into wild populations, seabed impacts and benthic habitat degradation, pathogen spread, marine mammal interactions, and more. **Current solution**: Some salmon farms in Norway have transitioned from traditional open-net pens to closed-containment systems, such as land-based recirculating aquaculture systems (RAS) (Afewerki et al., 2023). **Recommendation**: Closed systems can significantly reduce the risk of escapes, interactions with wild salmon, and the discharge of waste and pathogens into the surrounding marine environment.

3.3.2 Case study 2: Aquaculture impacts through increased demand for fish feed

Challenge: Farmed salmon production is still a growing sector which requires further developments to ensure sustainable aquaculture. **Current solution**: feed producers have advanced the development and use of alternative ingredients, including plants, algae, and insects to reduce the reliance on fishmeal and fish oil (Albrektsen et al., 2022). **Recommendation**: Alternative ingredients should be used to reduce the pressure on wild fish stocks and can lower the carbon footprint of fish production using more local and lower food chain feed inputs.

3.3.3 Case study 3: Emerging pathogens and regulatory complexity

Challenge: The complexity of aquaculture regulatory systems hinders pathogen monitoring in UK aquaculture. Depending on the farm location and pathogen type, various government institutes may hold pathogen monitoring data from fish farms in the UK. **Current solution**: Several agencies regulate and monitor aquaculture activities around the UK Fish Health Inspectorate (FHI). **Recommendation**: Effective regulatory frameworks at the national level should promote regulatory simplicity and environmental protection to ensure that the aquaculture industry thrives while minimizing negative environmental impacts. This involves coordinating regulations across regions to ensure consistent rules and promote fairness among countries.

3.3.4 Case study 4: Spatial management for bottom fishing in EU seas

Challenge: Spatial management to prevent bottom mobile bottom contacting gears in vulnerable areas where the seafloor integrity is at stake may increase short-term costs due to longer travel time to reach fishing grounds. However, in the long run, spatial management can compensate for this disadvantage by protecting depleted fish stocks and ensuring a sustainable ecosystem for all. **Current solution**: The vision is to propose restricting access of detrimental fishing practices to vulnerable habitats while the anticipation of fishing effort displacement pressuring other areas is mostly ignored. **Recommendation**: Special care should be taken when implementing spatial restrictions, including anticipating the displacement of the fishing effort toward pressuring other areas, which should be incorporated into the place-by-place impact assessment of such management measures (Figure 6). Instead of restricting access, it would be more beneficial to phase out the unwished practices and switch to other techniques capable of targeting demersal species of commercial interest (passive bottom gears). One way to start phasing out bottom fishing is by redirecting harmful subsidies toward developing innovative gears or funding the transition toward alternative gears. Article 17 of the CFP expects the reallocation of catch quotas towards low-carbon fishing with less impact (STECF, 2022a). This may involve redirecting subsidies towards low-impact (including more selective practices), low-carbon fisheries, penalising inefficient techniques and benefiting the uptake of clean technologies until stocks recover and subsidies are no longer needed. No single approach can mitigate all seabed impacts; a combination of methods may prove most effective, depending on local habitat, regulations, and socio-economic factors (Sala et al., 2023).

3.3.5 Case study 5: Interaction with dolphins in the Bay of Biscay and Mediterranean Sea regions

Challenge: There is an increasing problem of dolphins damaging fishing nets or being caught in them. This causes significant damage to the nets and forces some fishers to stop fishing due to the extent of the damage (Li Veli et al., 2023), or for bycatch reduction purposes. **Current solution**: To limit this interaction, fishers and policymakers believe that the only solution is to use deterrent devices to scare away the dolphins. **Recommendation**: Fishers and dolphins often hunt the same prey, which may explain why dolphins have been observed seeking out new foraging opportunities, including stealing from fishing nets. Rather than attributing this to an increase in dolphin populations, a more viable solution would be to recognise that limiting fishing to rebuild depleted fish stocks will likely ensure a sustainable ecosystem for all dolphins and fishers. Hence, healthy and productive marine ecosystems are prerequisites for ensuring long-term fishing opportunities.

3.3.6 Case study 6. Highly selective fishing in the EU Outermost regions

Challenge: Purse-seining for tuna adversely affects other marine populations (Torres-Irineo et al., 2014). **Current solution**: Demersal hook-and-line fisheries are likely more selective and generate fewer discards (Fauconnet et al., 2018), but sucha differences are poorly documented and monitored. **Recommendation**: Lack of resources (funding observers on board, mapping habitats and connectivity, etc.), scientific capacities, and data reporting (bycatch rates, fish removals, recreational catches, etc.) hinders sound assessment and management advice, even for regulated tuna fisheries. Bridging knowledge gaps is advisable for better management and assessing potential impacts on the EU's outermost region ecosystems.

3.3.7 Case study 7. Integrated fishing opportunities in a changing North Sea

Challenge: The North Sea fisheries are now challenged by a changing climate that could lead to overfishing when fishing restrictions are not adapted accordingly. In this area, multiple moving ecosystem interactions rely on North Sea forage fish facing climate change, which are preyed on by other more valued (demersal) species. **Current solution**: In a path for integrative management, it is suggested to consider environmental considerations and socioeconomic consequences when allocating fishing opportunities among pelagic and demersal fisheries sectors. Integrative assessment would have also been beneficial in the case of the Plaice box introduced in the North Sea, which failed to achieve its objective due to a rapid mismatch between the component to protect and the area protected. Fisheries scientists were naïve not to consider the potential socioeconomic, political, and governance dimensions and would have avoided losing scientific credibility (Beare et al., 2013). **Recommendation**: Scientific advice should not be restricted to biological information, with no attention to any short-term and long-term environmental changes and socioeconomic consequences on future fishing opportunities of alternative ecological and socioeconomic (quantitative) scenarios. Otherwise, it can prove to be inefficient in implementing the rules.

3.3.8 Case study 8. Combined effects in the Baltic Sea

Challenge: Climate change affects the Baltic Sea marine ecosystem and fishing opportunities, but the extent is unknown (Saraiva et al., 2019). Changes in temperature and salinity affect the physiological processes of marine species. Increased temperature increases metabolism for animals such as fish, which require more oxygen consumed, and more detritus that trigger the microbial loop on the seafloor, creating hypoxia areas for demersal fish and invertebrates, even more, when the water column stratification is reinforced, and may favour the introduction of alien species. **Current solution**: Low oxygen events in the Baltic Sea due to warming waters and eutrophication threaten the survival and persistence of cod and other marine populations. This led to the adoption of a regional action plan intending to reduce nutrient input from river run-off. **Recommendation**: Accounting for external-to-fishing factors and taking precautionary measures such as setting fishing opportunities below the perceived MSY should be stressed to prevent the collapse of fish stocks.

3.3.9 Case study 9. Mixed fisheries inducing overexploitation in the Celtic Seas

Challenge: Demersal fishing in the Celtic Sea is a mixed fishery with different challenges (Mateo et al., 2016). Catching multiple species in a typical fishing operation can cause unwanted changes in stock structures and levels because the fishing pattern (relative catch rates of the main species) will not generally map onto the fishing opportunities in terms of TAC and quotas, and, as a result, both cod and whiting stocks in the Celtic Sea are still well below precautionary reference points. **Current solution**: Implementing single-stock MSY has been the basis for setting fishing opportunities so far. **Recommendation**: Multi-species or ecosystem MSY should be the target to avoid unsustainable compromises in fishing practices and outcomes and reduce habitat damage and bycatch of non-target species with spatial restrictions. Climate change that has already led to possible changes in distribution and fishing opportunities (e.g., Lynam et al., 2010) should be considered in the advice on fishing opportunities.

3.3.10 Case study 10. Marine productivity change in the Med. and Black Seas

Challenge: The West Mediterranean faces challenges such as changes in water temperature that reduce oxygen levels and increase ocean stratification, leading to reduced nutrient availability and growth of phytoplankton and zooplankton (Hidalgo et al., 2022). These changes could affect commercially important fish species like hake and red mullet. Invasive species are also a concern in the Mediterranean region. Moreover, fishing vessels face technical interactions while catching multiple species in a single trip. **Current solution**: The recent expansion of the number of assessed stocks in the Mediterranean provides better information on stock status, while various ecological studies inform on ongoing threats to the marine ecosystem as a whole. **Recommendation**: Precautionary measures must be taken to prevent collapsing fish stocks, which would likely include fishing less than the single-stock MSYs, and enforcing catch limits besides the current effort reduction multiannual plan in place. In such an endeavour, managers should prioritize filling in knowledge gaps for the region as soon as possible. Most Med. stocks are not stocks with quantitative assessments; therefore, they have insufficient available knowledge to apply the MSY approach properly. They are not managed by TACs and F-ranges, as is the case in NEA multiannual plans.

3.3.11 Case study 11. New opportunities and threats in the Barents Sea

Challenges: Human activities, including fishing, hunting, transportation of goods, oil and gas, tourism and aquaculture, have strongly impacted the Barents Sea ecosystem. Retreating ice edges are opening new grounds for trawling and transport routes. Activities in some of these newly-opened grounds may affect benthic communities that were previously protected by ice cover (ICES, 2022b). **Current solution**: It is recognized that the largest commercially exploited fish stocks (capelin, cod, and haddock) are now harvested at fishing mortalities close to those in the management plan and have full reproductive capacity. **Recommendation**: Account for bycaught and vulnerable species into setting the fishing opportunities and balance the fishing capacity as some of the smaller stocks (golden redfish *Sebastes marinus* and coastal cod in Norway) are already overfished.

3.3.12 Case study 12: Deep-sea habitats

Challenge: Fragile, unique, and slow-to-recover cold water coral communities (as well as low productivity fish species associated to them) need protection from irreversible degradation, especially in vulnerable areas like seamounts, canyons, and ridges (Bennecke and Metaxas, 2017). **Current solution**: Remotely Operated underwater observation Vehicles (ROVs) can explore isolated deep seamounts and canyons and obtain information about their characteristics. **Recommendation**: Freezing the footprint of bottom trawl fisheries can prevent their expansion into deeper waters until potentially vulnerable habitats are identified. The EU Deep-sea access regulation continues designating closed areas of interest when some Vulnerable Marine

TABLE 2 Recommendations for short-term actions to take for effective risk management of EU fisheries and aquaculture challenges, indicators, and knowledge gaps on individual pressures affecting marine ecosystems and their possible interactions with the fishing and aquaculture sector (see Supplementary Material) to monitor and limit further degradation of the yield potential of marine wild capture fisheries (FI) and aquaculture (AQ).

	Short term action	Objective	Rationale
FI	Fishing at the highest long-term yield (A1)	Treat the CFP MSY target as a limit and not a reference point that may be exceeded, even during short-term economic crises or fishing sector challenges	EU multi-annual plans allow MSY to correspond to an F-range in intended fishing mortalities. The upper range can be used in cases of perceived risk of underexploitation to avoid economic losses. However, it causes structural risks for overexploitation as the lower limits correspond to single-species MSY values. The upper limits of the F target range are uncertain and depend on growth and predation assumptions, while the risk of overexploitation using it is increased.
		Increase selectivity of fishing gears by increasing mesh size to obtain the highest long-term yield on target species and avoid unwanted catches of other species	To achieve the CFP objectives, more precautionary fishing is necessary. Increasing gear´s mesh size and fish size limits can change the size composition of harvested stocks and increase productivity. This results in higher yield and preservation of marine ecosystems and sensitive species ("Ecosystem MSY").
AQ	Develop and implement best-practices for environmental monitoring (A2)	Increase the environmental performance and health of aquaculture operations	Through the use and development of best practices for water quality monitoring, sediment monitoring, benthic health assessments
AQ	Coordinated spatial planning (A3)	Make space for (sustainable, responsible, low trophic, low impact) aquaculture production systems across European seas today and for the future of the industry.	EU Member States have made some progress in integrating aquaculture activities in their maritime spatial plans, in line with the MSP Directive, however, further progress is needed to plan for future developments in the industry (e.g., the move to offshore and RAS).
FI	Phasing out the least efficient fishing techniques and promoting low-impact low-carbon fisheries (A4)	Document the seabed habitat and associated benthic communities to identify areas vulnerable to bottom fishing	A threshold should be established and agreed upon by society, which would be based on the maximum amount of fishing pressure that could still maintain the system within the range of natural disturbance effects (For more information on how to determine the threshold on seafloor integrity, refer to Hiddink et al., 2023).
		Designate vulnerable areas and disproportionally important marine habitats and prevent bottom fishing to conserve fish populations and seafloor integrity.	Likely only co-benefits at phasing out bottom-contacting fishing and seeing the fishing sector shifting toward other practices, including reducing the damage that will come with increased ocean productivity, leading to more food, jobs and income than the current suboptimal exploitation damaging the long-term natural capital of seafloor.
		Implement fishing closures to protect vulnerable species or life stages with spatial selectivity.	It's crucial to support fisheries that minimize their impact on marine ecosystems. Passive gears alone won't solve the bycatch issue. Technical solutions are needed to reduce bycatches, with an increase in gear selectivity and spatial selectivity (CFP Art. 11). Factors such as economic viability, social acceptance, and technical safety should be assessed to improve conservation goals (Suuronen, 2022).
		Prohibit subsidies contributing to IUU fishing and supporting fleets fishing upon overfished stocks. Revise subsidies for fuel and increase funding on research towards innovative low-impact fishing techniques	Overexploitation of marine resources leads to a need for more energy input to maintain the same yield. The EU fishing fleet is estimated to have lost €1.14 billion in 2018 due to exempted fuel taxes (Carvalho and Guillen, 2021) The ongoing energy taxation revision aims to align taxation with EU energy and climate policies, promote clean technologies, and remove outdated exemptions. Phasing out fuel subsidies in fisheries can support small-scale or low-impact fisheries and implement EU CFP article 17 of 2013. Identifying "Best Available Practices" based on a scoring of fishing practices regarding several sustainability dimensions.
FI+AQ	Fully implementing area-based management and in an MSP context (A5)	Evaluate possible benefits or unwished effects of displacing the fishing effort on the surrounding, still-open areas	Conservation efforts should balance biodiversity and human needs to avoid spreading degradation from fishing effort displacement in non-protected areas.

(Continued)

TABLE 2 Continued

	Short term action	Objective	Rationale
			Displacing activities to surrounding areas should be avoided, and creating isolated areas of protection is not ideal. The debate is between prioritizing specific areas or integrating conservation into human landscapes.
		Attach a robust management plan to each designated area.	EU Member States have established many marine protected areas, including the Natura 2000 sites. However, enforcement of management plans is crucial. Global commitment to protect 30% of the ocean by 2030 has not been followed with action (Grorud-Colvert et al., 2021). The EU has set a target of protecting 30% of the surface area of its waters, including 10% that are strictly protected.
FI+AQ	Follow up on commitments and value knowledge (A6)	Set clear reduction targets or mitigation objectives with incentives, receive guidance on operational changes, and communicate improvements up the supply chain	For fisheries to reduce their impact on the marine environment (including physical abrasion, bycatch, and emissions), regulators must monitor their impact, set clear reduction targets with incentives, receive guidance on operational changes, and communicate improvements up the supply chain. Policymakers should undertake science products.
		Conduct proper Environmental Impact Assessment	Conducting impact assessments and risk-based approaches are necessary for full commitment. Environmental Risk Assessments should be conducted to anticipate the risks posed by fishing pressure and other pressures. Prerequisites for risk assessments include capacity-building, knowledge acquisition and dissemination, and documentation tracking the CFP's performance towards its objectives
FI+AQ	Promoting incentive-based management (A7)	Promote results-based management and joint accountability between the policymakers and the fishing and aquaculture sectors.	Co-management and results-based management systems prioritize local fishers' involvement in developing gear modifications and bycatch mitigation measures to avoid unwanted catches (for CFP Art. 15). Participatory approaches could increase mutual trust and promote the involvement of small-scale fishers (Ramirez-Monsalve et al., 2016). Develop more flexible governance so that successful solutions can be translated into law quickly. Promoting awareness and ocean literacy is also essential to incentivize the sector to change mindsets.
		Develop market instruments for incentive-based management of fisheries and aquaculture.	Creating an eco-labelling certification can help maintain market access and receive a price premium on low-impact fishing catches. Member vessels must comply with criteria for sustainable use of exploited seas and wholesalers could demand only certified fish. Eco-labelling certification should consider availability, accessibility, price signals, marketing, tradition, cultural habits, convenience, and accessibility (Santos et al., 2022).
FI+AQ	Modernise the EU fleet and ensure generational renewal (A8)	Set the stage for educating a new generation of fishers and seafarers as soon as possible	The aging population in the EU fleet sector ("graying of the fleet") has led to a decrease in the availability of workers. This generational renewal challenge must be addressed as aging fishers and operators tend to be less likely to adopt new technologies. To minimize their impact, current and future skippers should learn how to use low-impact technologies, alternative fuels, and gears, which requires upskilling and re-skilling.
		Advocate for the education of a new generation of marine engineers.	This includes developing ocean literacy/awareness raising with training for sustainable practices/ support developing naval construction, instructors for new education and needs for new habilitation. In addition to this, there is also likely a shortage of qualified marine engineers and naval construction

(Continued)

TABLE 2 Continued

	Short term action	Objective	Rationale
			facilities that also prevent the uptake and downscale of the appetite for new technologies.
FI+AQ	A climate-aware fisheries management in EU (A9)	Review all EU fisheries and stock assessments to accurately assess the potential impact of climate change on them	Under the CFP, it is crucial to manage EU fisheries sustainably in the face of climate change impacts on marine ecosystems. A scenario-based framework can help assess the effects of environmental changes caused by climate change on ecological and economic factors. Regular re-evaluation of stock boundaries and data collection systems is necessary to account for changes in stock distribution, timing of biological processes, natural mortality rates, and invasive species (Trenkel et al., 2023).
		Manage EU fisheries in a climate change future with a governance system that can quickly react to changing conditions	Regular meetings between scientists, managers, and the fishing industry are crucial to address the threats of climate change on marine ecosystems and fishing opportunities. Changing reference points, such as FMSY, based on biological considerations should be streamlined. Tracking allocation keys between countries as species distribution gradually shifts and offers scenarios for changing EU fishing opportunities allocation keys to adapt to it.

Such actions should be taken in parallel to ensure an effective policy. “A” stands for “Action”.

Ecosystems (VMEs) are detected (EC, 2019, 2022), given the disproportionate costs that restoring such hotspots of biodiversity would require.

3.3.13 Case study 13: Coastal and shallow waters

Challenge: An array of pressures in coastal and shallow waters affects fish populations and their habitats (Kraufvelin et al., 2018). **Current solution**: Fisheries managers consider the broader ecosystem and environmental context driving changes in individual stocks. **Recommendation**: Policymakers should continue focusing on restoring the EU seas and coastal waters using nature-based solutions and well-informed fisheries management and through an integrated approach to managing fisheries, aquaculture, and the marine environment for long-term food security. Connecting environmental management (also including land-based activities) to fisheries management and restoring EU waters will benefit the fisheries and aquaculture sectors, increase the availability of resources harvested or grown locally, and increase the self-sufficiency of the EU in producing fisheries and aquaculture products.

4 Actionable recommendations to ensure sustainable and resilient fisheries and aquaculture

Fishing or farming pressure is often deemed acceptable if it ensures income from landings, provision of seafood, and delivers social benefits. However, viewing fishing or farming regulations as a tradeoff between economic gains and environmental sustainability is generally misguided. In the long run, there is no such tradeoff. The CFP is more of a balance between economic benefits, chasing for immediate return, and social benefits, as degraded, less productive fishing stocks and exploited marine habitats cannot handle increased pressure, affecting the fishing and aquaculture industries and the long-term economy. Degrading marine ecosystems leads to missed opportunities and displacement of human pressure to land-based animal protein production systems (Hilborn et al., 2018). This affects the fishing industry’s sustainability, economic viability, and social benefits. Reducing pressures (production) must also be counterbalanced by measures reducing demand (consumption) to prevent further overreliance on seafood imports in the short term.

The inflexibility of the CFP legislation and the EU Treaty may restrict action due to stringent decision-making processes, suggesting the need to revise the CFP Regulation 1380/2013 (Penas-Lado, 2020). Nonetheless, marine scientists are in consensus on specific actions that can help achieve the CFP objectives within the existing legislation framework. Such actions base their principles on:

- Minimizing the impact of individual pressures
- Understanding interactions and mitigating combined pressures, especially where these are known to interact negatively
- Defining clear criteria, research needs and other mitigation measures
- Developing new indicators and strengthening monitoring programs to track progress towards management targets
- Ensuring a concerted implementation to maximise success in achieving environmental targets with the involvement of all affected stakeholders
- Addressing the cost of transitioning to responsible, sustainable fishing and farming practices as a barrier to overcome

One immediate action includes accounting for the outcomes of multispecies assessments when setting fishing opportunities. The

TABLE 3 Identified long-term actions to avoid overexploitation of marine living resources in EU waters.

Long-term Actions	Objective	Rationale
Continuation in scientific instrumentation, data processing and software development for knowledge acquisition, monitoring and performance indicators	Monitored indicators should cover information on stock assessments and fish population dynamics	Gather reliable empirical data to support any research used to close knowledge gaps and give guidance. Experts caution against relying solely on models based on simulated data. To obtain useful data, various instruments and protocols are needed at different scales.
	Monitored indicators should cover information on marine ecosystem assessments and dynamics.	Support any research and modelling that will be used to close knowledge gaps and give guidance on environmental factors affecting fisheries and aquaculture. A risk-based approach is necessary to enable actions facing complex phenomena, interactions, and uncertainty.
	Study the socio-ecosystem dynamics	Support any research and modelling that will be used to close knowledge gaps and give guidance on the effect of, and the impact on, socioeconomic drivers of sustainable fisheries and aquaculture
Continuation in supporting oceanographic research and monitoring, and mapping seabed habitats to understand pressure-impact relationships.	Funding of the global ocean observing system	Data acquisition and integration should help develop digital marine ecosystem platforms for including the environmental drivers, marine biodiversity with harvested stocks, wild capture fleets, aquaculture and seafood market dynamics, also with other sectors active at sea
	Mapping the seabed, biogenic habitats and carbon-rich habitats	Determine carbon storage, sequestration and export by depths and hydrographic conditions, given measurement challenges, and to identify hotspots for high fishing and carbon export, likely located in the carbon sink around the coasts. Carbon-rich habitats are often productive nurseries for commercial species and marine life.
Continuation in knowledge integration of spatial marine data and fishing effort spatial allocation	Acquiring a basic understanding of the physical and biological drivers in marine ecosystems	It is imperative to accurately describe the expected changes in physical drivers and ecological responses, including detecting possible resilience thresholds for which marine ecosystems are at risk, if exceeded, of crossing a tipping point toward lower ocean productivity.
	Integrate and share collected data into large data warehouse	Regular collection of fisheries and environmental information and crossing data from different fields (physics, ecology, economics) with various applications, such as marine spatial planning for aquaculture and wind energy, rapid response analyses for oil spills, marine dead zones, high-resolution stock assessments, and spatially explicit socioeconomic analyses.
Continuation in supporting Cumulative Impact Assessment with up-to-date fisheries information along with adopting a regional-based approach.	Update Cumulative Impact Assessment with new fisheries layers	In most CIA, the catches are used with the assumption that large catches correspond to high pressure. However, stocks providing high catches may be large and sustainably exploited, whereas stocks providing low catches may be at a low level
	Run regional Cumulative Impact Assessment (CIA) regularly	EU fisheries management is applied with general CFP principles but tailored to local circumstances and external factors and challenges the local fisheries and aquaculture face (see Annexes)
	Assess the sufficiency of existing management measures to reach the environmental goals	The CIA should also address the sufficiency of measures in reaching the overall environmental regional goals (such as GES) and how measures need to be upscaled (implementation, enforcement, incentives) or complemented with new measures to achieve objectives.
	Develop of risk-based assessment including detailed knowledge on causes of impacts	The CIA should adopt a risk-based approach that considers the interaction between external-to-fishing pressures and fisheries, as mitigating risks independently may not ensure the functioning of marine ecosystems.

use of scenario testing in setting quotas for mixed fisheries, which is compatible with standard stock assessments and annual, single-stock advice frameworks, helps to bridge the gap between the traditional single-species approach and a more comprehensive ecosystem approach in fisheries management accounting for ecological and economic externalities among overlapping fisheries, as detailed in ICES multispecies assessments (ICES, 2023b), and mixed fisheries (ICES, 2022a).

Another immediate action would be using stock-specific indicators to set an ecosystem-based fishing mortality reference point (e.g., F_{ECO} in Bentley et al., 2021) when setting fishing opportunities. This can help scale fishing mortality based on the ecosystem conditions for the stock while retaining the integrity of current assessment models and the CFP MSY objective. However, the F_{ECO} target is still defined on single-species precautionary limits (Thorpe et al., 2021) and is further confined to the F_{MSY} ranges defined in the multi-annual plans' legislation (Howell et al., 2021), which for some stocks such as 'under Blim' stocks may not be enough as a standalone solution to take environmental factors into account, and in specific cases could potentially promote an incremental risk management approach, where more drastic responses may be needed.

Environmental and fisheries management aims to ensure seafood production stays within planetary boundaries, renews the exploited resources, and protects and conserves supportive habitats. To effectively adapt to changes and tackle fishing and farming pressures and related risks, it is crucial for fisheries and aquaculture managers to implement the legislative tools at their disposal fully. EU policymakers need to take action to curb the degradation of marine aquaculture and fisheries' yield potential in the short-to-medium term (Table 2). Moreover, the focus should extend beyond immediate mitigation measures to embrace long-term strategies. Hence, EU policymakers and practitioners should manage risks by implementing long-term actions now to avoid overexploitation situations in the future (Table 3).

5 Discussion

5.1 Risk management for EU fisheries and aquaculture: reduce the risk by using "best available techniques"

Efforts are underway to develop a pan-European assessment of the impacts of fisheries and aquaculture to provide a comprehensive understanding of the risks and effects in a risk assessment framework. This initiative aims to support evidence-based decision-making for risk management and contribute to the sustainable management of European seas. Developing a risk-based assessment involves compiling various data to create decision-support systems for policymakers and stakeholders. Aquaculture is currently developing a standardized assessment framework and establishing national and international data collection and sharing mechanisms, which could be evaluated through pilot studies.

Risk assessment serves as the initial step, with risk management being the ultimate target. Our contribution aimed to outline a roadmap towards this goal. We have seen that risk assessments analyse the probability of undesirable events stemming from overlaying multiple pressures impacting marine ecosystems and exploitation opportunities. Risk management involves enhancing resilience and developing adaptive strategies to mitigate these pressures before they escalate and increase the risks of overfishing and environmental degradation. For fisheries, this roadmap is designed to help adjust the rules within a flexible CFP, equipping fishing resources, dependent fishing communities and markets with greater resilience to natural disasters and economic downturns. Hence, a strengthened CFP should prioritize environmental objectives (Table 2 A1) when policymakers face tradeoffs between fishing returns and acceptable environmental impacts. Policies that fail to prioritize conservation will lead to further degradation of ecosystem components, including those without commercial fishing interest, through the bycatch of vulnerable species or habitat degradation.

Fisheries are not the only factor affecting marine ecosystem dynamics. For example, pollution and climate change also threaten future fishing opportunities (Supplementary Material). In parallel, as the aquaculture sector develops, it is essential to identify appropriate areas for farming. This involves carefully managing risks to avoid impacting existing activities (Table 2 A2) and selecting locations that fulfil aquaculture requirements while minimizing any adverse environmental impacts in a space-competitive environment (Table 2 A3). Short-term tradeoffs are inevitable whenever more stringent environmental policies, though costly in the short-term for fisheries or society, can yield long-term benefits. The risk assessment must be thorough, providing robust supporting evidence and favouring less harmful alternatives (Table 2 A4), all while balancing economic, environmental and social sustainability. Furthermore, advancing the implementation of risk management requires the effective dissemination of risk management science within policy and management decisions (e.g., Juda, 1999).

In this perspective, some in the fishing industry argue that adverse environmental impacts are an inevitable consequence of seafood consumption and economic benefits. This stance essentially absolves itself of the responsibility to reduce pressure on harvested stocks impacted by adverse environmental conditions and advocates for disconnecting fisheries management from environmental management (FishFocus, 2023). However, fisheries differ significantly in sustainability and economic viability. We argue that unsustainable practices should either shift to better alternatives as they arise or be phased out altogether to prevent the long-term degradation of EU marine productivity and natural capital. As adverse effects will affect future fishing opportunities, spatially adjusting fishing pressure will also be inevitable (Table 2 A5). Consequently, fisheries management should not assure business as usual or promote unlimited aquaculture developments, overlooking changes in ocean productivity. Delay in action only magnifies economic and social consequences, including diminishing self-sufficiency in supplying the EU seafood market. This underscores the importance of alleviating pressure on marine ecosystems to restore EU seas while ensuring that efforts to meet market demand, for example, do not simply shift negative impacts elsewhere.

Fisheries scientists often use trade-offs to inform managers but should increasingly focus on demonstrating the consequences of management decisions and fostering trust with managers and stakeholders (Table 2 A6) as, again, protecting marine habitats also safeguards the fisheries that depend on them, narrowing the debate on potential trade-offs when habitats can no longer sustain the levels of exploitation. Increases in fish biomass are compatible with increases in yields. This contrasts with other economic sectors where economic growth implies trade-offs with the environment (Hilborn and Costello, 2017). While trade-offs might exist between different segments of the fleet - such as pelagic versus demersal fisheries, or small versus large-scale operations, and between passive and active gears - economic benefits and biodiversity levels do not inherently conflict, provided that a healthy marine ecosystem underpins exploitation efforts. Diverse systems are also more stable and productive in the long term i.e. resilient, for example, to climate change or invasive species etc. (see Cleland, 2011; Wang and Loreau 2016; Boudouresque et al., 2017; Sundstrom et al., 2018; also including more "cornerstone species", Bracken and Low, 2012; Coulon et al., 2023 and the "overyielding" ecological hypothesis). This is because a healthy environment can support future fishing opportunities by maintaining ecological complexity, including nursery areas, feeding and spawning grounds, shelters, etc., benefiting both the environment and the fishing industry.

The trade-off lies between economic benefits (profit, labour productivity) and social benefits (gross value added, income redistribution among fleet segments and crew). Long-term sustainability is generally overshadowed by short-term economic gains, enabled by poor management and governance shortfalls, like failing to capture and redistribute resource rents during challenging transition periods for a more balanced approach. Instead of trading off long-term societal benefits for immediate profits, all stakeholders should prioritize the use of "Best Available Techniques" that reduce environmental impacts while also ensuring fair wages and economic viability for business (Table 2 A7). On the contrary, focusing solely on capital productivity (i.e. profits) can lead to short-termism, deterring operators from adopting new eco-friendly innovations and techniques (Table 2 A8). Another example is the continued use of damaging fishing practices that cause habitat degradation and pollution, inherently detrimental to society. Hence, various management options should be triggered to help mitigate the effect of fishing pressure on ecosystem components (see the Technical Measures Regulation (EU) 2019/1241). One important management measure is the implementation of Marine Protected Areas (MPAs), as illustrated in Figure 6. MPAs can benefit low-impact fishing by excluding harmful bottom-contacting gears and switching from mobile to static fishing gear, improving target and non-target species populations inside the protected area (Table 2 A5). Fisheries management must ensure that only fishing activities with minimal impact, proven to impact species and habitats in a manner that does not exceed the biological reference points or impact thresholds, are still permitted among the activities. Minimal impact must be defined as the unavoidable impact caused by utilizing the "best available technique" for fishing at the current level of technology while continuously striving to improve those technologies.

Contrary to this endeavour, it is sometimes argued that without mobile bottom-contacting gears, it is unfeasible to supply every fish type, leading to market exclusions or substitutions with economic repercussions for the EU food market. Yet, it is critical to explore whether there are or were economically viable alternatives for some of these species in the past (e.g., bottom nets for demersal species) when stock populations were larger and healthier. This would also consider consumer preferences, their shifts as well as incentives for new, abundant species or those detached from unsustainable extraction (Table 2 A7). The depletion of fish populations is likely to have occurred alongside damaging fishing techniques, such as bottom trawling. Hence, it makes sense to base fisheries regulation on what productivity they could have, not on current features in heavily impacted conditions (e.g., Davies et al., 2021; Adriatic Jabuka Pit's recent successful example in Martinelli et al., 2023). Shifting from fuel-intensive, active gear fisheries to those that use passive gears with less energy-demanding fishing vessels also comes with co-benefits in the current effort for decarbonising the EU fleet, aiming for a climate-neutral sector by 2050 (Byrne et al., 2021; Bastardie et al., 2022).

In the face of overfishing and other impacting factors, fisheries and aquaculture management must not compromise on sustainability. Instead, they should collaborate with other industries to address and lessen the pressures and risks to the marine environment. It is crucial to conduct risk assessments on an ecoregion basis and address specific regional challenges and data needs for closing knowledge gaps as identified, allowing fisheries managers and regional sea planners to identify co-benefits tailored to local circumstances for reducing the drivers of overfishing and overexploitation alongside other impacting sectors (see Table 3). Implementing stricter measures may lead to higher short-term costs for the sectors. Without addressing these costs, resistance to regulations will persist, hindering the transition to sustainable practices. While some costs are inevitable, ultimately the aim is to avoid the long-term economic losses associated with continued unsustainable exploitation.

5.2 A transition toward responsible, sustainable, and resilient fisheries and aquaculture: From high to low risk of degradation in EU by accounting for causal links

There may be a disconnect between our scientific tools and the interpretation of the prevailing governance system. For instance, the CFP focuses on MSY, while they may be various interpretations of the MSY target in the CFP. To continue working toward limiting the risk of overexploiting marine resources in EU, we should identify and learn from governance models that offer the flexibility to adapt and meet the demands of policymakers. In EU waters, and notably in the Mediterranean Sea, achieving the ecosystem MSY is critical, given that fishing pressure remains above (single-stock) sustainable levels for many stocks and is currently, on average, double the target in the Mediterranean region (Figure 2). However, this must be done while also considering the potential harm to the fisheries sector. To help with the transition, regulators should identify co-benefits and compensate for short-term trade-offs and upfront costs. Stakeholders need to consider beyond immediate needs and avoid discounting the long-term benefits that a healthy ecosystem can bring. Therefore, scientists should define reference levels that would achieve levels close to MSY (aligned with the second objective of CFP Art. 2.2 to restore and maintain above biomass levels capable of producing the MSY) and further define an "ecosystem MSY" and an acceptable level of combined pressures to account for both the need for immediate yield and the preservation of the ecosystem for future yields. Without such ecosystem-based knowledge, a precautionary approach should be adopted to ensure that the lack of data or assessments does not prevent actions to conserve the resources supporting viable exploitation.

With climate change firmly impacting marine ecosystems alongside other pressures, managing EU fisheries and aquaculture for a future shaped by climate change becomes imperative (Holsman et al., 2019; Howell et al., 2021; Woods et al., 2022; Hidalgo et al., 2022). To mitigate the risks in fisheries, it is essential to integrate climate impact knowledge into stock assessment and forecasts, to re-evaluate stock boundaries and data collection systems when mismatches arise due to a changing climate affecting stock distribution, timing of biological processes, natural mortality rates, invasive species, etc., with a dynamic monitoring and management approach (Table 2 A9). Accounting for climate change-induced effects on past trajectories of stock development is also vital for accurately incorporating these impacts in the possible explanatory variables (Trenkel et al., 2023). Additionally, offering fishing companies more flexibility regarding fishing opportunities could help safeguard against drastic changes in species availability and accessibility. However, such flexibility should not come against equity and concentrating the fishing quotas into a few hands that can afford to continue to use non-sustainable fishing techniques.

The EU aquaculture sector is held to some of the highest standards worldwide in terms of quality, health, and environmental regulations (EC, 2021). Unlike capture fisheries, which are largely managed through the CFP, aquaculture falls under a wide range of diverse EU policies and directives. There is a clear need to (1) resolve regulatory complexities to enable growth and environmental compliance by the industry and (2) to foster a common vision among European countries to develop the sector in a way that contributes to the EU directives that balance the use and economic benefit of marine resources and the protection of biodiversity and ecosystems services (ICES, 2020). By sharing best practices, aquaculture is poised to develop in a manner that is both economically and environmentally beneficial to European marine waters and coastal communities (EC, 2021).

The transition from high risk to low risk of overexploiting marine ecosystems requires adopting a clear risk approach mapping out the causal links between ecological processes and productivity. A causal chain can be visualised in graphic models, depicting the causes of risks leading to undesired states. An integrated approach recognises that multiple risks can lead to an overall risk and that pressures can interact in complex ways with cumulative effects. However, knowledge regarding the outcomes of such interactions and the effects of human activities is still lacking, and further research is needed (Table 3). In the absence of complete knowledge and understanding of the issues in detail, best practices for a risk-based approach aim to:

- Identify and evaluate the effects of unwished marine ecosystem states. A holistic approach is necessary. Management bodies can achieve this by integrating various drivers and examining the interactions among individual risks. Current knowledge should also be described.
- Clarify priorities and decide where to focus given limited resources. There are so many possible interactions in a fishery ecosystem that one analysis or tool cannot effectively address them all (Gaichas et al., 2016).
- Develop scenarios that explore different risk status based on the combination of future drivers. Stakeholders should be involved in co-constructing these scenarios to ensure they are relevant and meaningful. The scenarios should take into account foreseen mitigation and adaptation measures.
- Assess cumulative effects of management alternatives, best with models, especially when drivers are uncertain. Different prediction paths, like IPCC Regional Concentration Pathways and Socio-Political Pathways, can be used to project bio-economic impacts on wild-capture fisheries and aquaculture growth in different European regions. These scenarios describe different pathways of marine use and fisheries' social and economic returns. Risk levels should be projected to short (5y), medium (2035) and mid-century (2050) horizons contrasted against the path identifying responsible, sustainable, and resilient fisheries at the lowest or acceptable level of risk.

Risk-based approaches should be streamlined in scientific advisory bodies. The International Council for the Exploration of the Sea (ICES) provides an example advising the EU on the sustainable exploitation of marine commercial fisheries. ICES brings together independent scientific experts to evaluate best practices and provide the best available science to decision-makers under the CFP and the MSFD (ICES, 2023a) with ongoing efforts to deliver integrated ecosystem advice. Such an approach should also benefit aquaculture through independent scientific cooperation and advice to bring the best available science to decision-makers on the environmental impacts and best practices for aquaculture policy and management throughout Europe.

While bringing the best available science to the table is required, it alone is not enough. The regulatory framework must also ensure that any proposed action, which could be costly for the fishing and aquaculture sectors, does not lead to severe social or economic consequences. Rather than resisting these measures, lobbying efforts should focus on identifying alternative ways to achieve sustainability within fisheries and aquaculture.

Author contributions

FB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LS: Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Conceptualization, Data curation, Formal analysis, Investigation, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. NC: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Visualization, Writing – review & editing.

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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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Publisher's note

Supplementary material

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