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Challenges on blue food provision

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According to the objectives of Frontiers in Ocean Sustainability's Blue Food Provision section, our aim is to contribute to addressing the rising challenges created on marine resources due to global change, unsustainable practices, regulatory barriers, and other constraints. We focus on existing and emerging knowledge, technologies and tools to build capacity and maximize the contribution of marine food systems to food security (i.e., fisheries and aquaculture), nutrition and affordable healthy diets, and social equality, ensuring the achievement of the United Nations Sustainable Development Goals.

KEYWORDS

marine protein production, enhancement living marine resources, new smart technological solutions and crossovers, UN goals, global change

Introduction

The United Nations (UN) Sustainable Development Goals (SDGs) represent a universal call to enhance the wellbeing of humanity. Achieving these goals requires an increase in the capacity to feed a growing global population through the development of sustainable and equitable food production systems, ensuring a healthy future for both people and planet (UN, 2021). Blue foods—foods, derived from oceans, lakes, and rivers—hold a pivotal role in achieving the SDGs by supporting healthier, more sustainable, and more equitable food systems, particularly in climate-challenged and food-insecure communities (FAO, 2020, 2022). In 2020, the average human consumption of these aquatic foods (excluding algae) was 20.2 kg per capita, more than doubling the average of 9.9 kg per capita in the 1960s, driven by increased supplies, changing consumer preferences, technological advancements, and income growth (FAO, 2022).

Marine aquatic food production, encompassing marine aquaculture and fisheries, must increase by over 45 million metric tonnes to meet growing demand, representing a 36–74% increase compared to current yields (FAO, 2022). Seafood, being nutritionally diverse and carrying fewer environmental burdens than terrestrial and freshwater food production, uniquely contributes to both food provision and future global food and nutrition security (Costello et al., 2020). The overarching challenge lies in developing or identifying sustainable smart solutions related to aquaculture production and marine ecosystems harvesting, aligning with the UN SDGs 2, 3, 5, 9, 12, and 14, focusing on zero hunger, good health and wellbeing, gender equality, industry innovation and infrastructure, responsible consumption and production, and life below water, respectively (Costello et al., 2020).

Of the total production in 2022, 63% (112 million tonnes) was harvested in marine waters (70% from capture fisheries and 30% from aquaculture) (FAO, 2022). Therefore, this position paper concentrates on the marine realm, addressing both wild fisheries and aquaculture and their unique characteristics. In the following sections, we briefly outline seven key challenges that form the foundation for achieving and securing the future provision of blue food. However, it is essential to recognize that these challenges and their solutions often involve trade-offs, presenting a dilemma for managers in prioritizing which challenge to address.

Challenge 1: understanding the potential and limitations of marine ecosystems

Since the early 1990s, production from marine capture fisheries has plateaued at approximately 80 million tonnes per year. The increasing demand for marine products has been met by a substantial increase in aquaculture production, quadrupling from 1990 to 2020 (FAO, 2022). Total marine fisheries and aquaculture production combined amounted to approximately 112 million tonnes in 2020, with 30% corresponded to aquaculture production (FAO, 2022).

As oceans undergo global changes, both environmental and ecological factors are expected to impose greater limitations on seafood production, impacting marine economies. Addressing these future challenges will require comprehensive management approaches that consider both marine ecosystem dynamics and human dimensions concurrently (Marshak and Link, 2021). To achieve this, there is a compelling need to advance the operationalization of the ecosystem-based approach (EBA) to fisheries management within a framework of good governance. This involves moving toward more community-based management models as opposed to the traditional top-down approaches (i.e. https://www.fisheries.noaa.gov/national/laws-and-policies/policy-directive-system). Consequently, economic activities relying on the seas should adopt the concept of blue sustainability, aiming to maximize sustainable economic output (net benefits), while minimizing the current and potential impacts under an EBA. Climate change is anticipated to have profound effects on oceans, including warming, acidification, sea level rises, marine heat waves, and shifts in biodiversity (Borja et al., 2020; Borja, 2023). These changes make seafood production vulnerable to climate-driven hazards, such as shifts in the distribution of marine species, hampered shellfish production due to ocean acidification, and marine heatwaves threatening habitats and the productivity of species on which the marine ecosystem and our biosphere depend. Climate change is, generally, expected to affect some species more negatively than others, with potential benefits for the productivity of some fish stocks (Kjesbu et al., 2022).

The inclusion of adaptation measures in the fisheries and aquaculture sector is currently hampered by a widespread lack of science-based management and targeted analyses of the sector's vulnerabilities to environmental change, ecosystem dynamics, and other anthropogenic stressors. Assessing associated risks, opportunities, and available responses is crucial for sustaining and expanding marine food production despite these challenges. For instance, Free et al. (2020) conducted a comprehensive analysis that estimated a 4.1% decline in the global productivity of marine fisheries between 1930 and 2010, with some of the largest fish-producing ecoregions experiencing losses of up to 35% due to rising temperatures. Therefore, risk assessments must encompass studies on temperature-driven changes in productivity (Plagányi, 2007). While the declining global average might not be substantial, impacts vary significantly at regional scale. This regional variability in potential catch projections underscores the need for global cooperation, as conflicts between users are likely to arise within and between countries (Barange et al., 2018). Production changes are partly a result of expected shifts in the distribution of species, which are likely to cause conflicts between users (Barange et al., 2018). The interaction between ecosystem changes and management responses is crucial to minimizing threats and maximizing opportunities arising from climate change, considering the complexities between aquaculture and fisheries. Experiences from fisheries management emphasizes the benefits of implementing and enforcing science-based advice and precautionary principles, notably by improving fish stock status and fishery sustainability. This underlines the need to manage marine resources based on the best available science to minimize negative impacts on marine ecosystems, while maximizing sustainable food production (Zimmermann and Werner, 2019; Hilborn et al., 2020).

Challenge 2: enhancement of living marine resources

Human activities modify ocean environments through top-down (e.g., fisheries) and bottom-up (e.g., eutrophication induced by excess nutrient release into coastal waters and beyond) impacts; while global climate change is already transforming the climate and ecology of the global ocean exacerbating these anthropogenic impacts (Dailianis et al., 2018). Nature-based solutions (NBS) are emerging as potential strategies to address these challenges (Cohen-Shacham et al., 2016).

Several strategies can minimize impacts and enhance living marine resources, encompassing ecosystem and habitat protection and restoration, disturbance reduction, and the introduction of new individuals to improve stocks. For instance, the construction of artificial reefs increases benthic habitat heterogeneity, protecting stocks from fishing and/or enhancing the habitat for fishing species. In general, they lead to increases in macrobenthic faunal species richness and diversity in the artificial reefs in adjacent waters in the mid to long term. However, the texture and shape of artificial reefs can influence the recruitment of fauna, for instance by favoring fishes and un-favoring mollusks, and hence affecting the total biomass. Complex patterns could happen in macrobenthic faunal diversity, species richness, and evenness after reef construction (Chen et al., 2019). While artificial reefs have showed positive effects on biodiversity and the environment, a fully multidisciplinary assessment of the cost effectiveness of the proposed NBS remains challenging, with most studies focused on biodiversity and environment aspects, but usually neglecting socioeconomic aspects (Murillas-Maza et al., 2023).

The culture of organisms for conservation and restoration plays a pivotal role in many management programs. Stock enhancement, including breeding in captivity programs, collecting individuals from wild populations, and using commercial or conservation hatcheries, contributes to restoring aquatic biotic resources, enhancing depleted stocks, and restoring the environment in many areas (Bell et al., 2006). Collecting individuals from wild populations with the intention to change a phenotypic trait between collection and release or introduction can be included in management programs such as genetic rescue and stock enhancement (Audzijonyte et al., 2016). While aquaculture can reduce pressure on overexploited wild stocks, stocking approaches may boost natural production and species diversity, and employment in restocking may replace more destructive resource uses (Bell et al., 2008). However, the benefits for wild populations are often hard to quantify and may be nonexistent with current stocking approaches. In some cases, it might even impair wild populations as, since stocking programs often rely on a small brood stock, releasing a large amount of their offspring actually decreases genetic diversity and effective population size. Also, aquaculture has increased the use of feeds produced from wild fish (fishmeal, fish oil) in recent years, raising concerns about its impact on wild stocks (Merino et al., 2012).

A major goal is the worldwide restoration of fish stocks (Caddy, 1999), often requiring not only reduced direct harvesting pressure but also the restoration of ecosystems and habitats. The UN has declared the 2020s to be the Decade on Ecosystem Restoration (2021–2030), recognizing the importance of reducing ecosystems and habitat degradation. Ecological restoration, when implemented effectively and sustainably, contributes to protecting native biodiversity, improving human health and wellbeing, increasing food and water security, delivering services and economic prosperity, and supporting climate change mitigation, resilience, and adaptation (Gann et al., 2019). The development of the ecological restoration of marine ecosystems requires historical baseline data as well as objectives, guidelines, and rules prior to any restoration attempt (Seaman, 2007). However, restoring marine ecosystems requires facing the logistic challenges of working in a comparatively vast and open system where many major components, including primary producers, interact and develop continuously. Also, major logistic constraints hinder marine ecosystem restoration: long timescales (sometimes several decades or centuries) are required to achieve restoration targets; substantial funding and high-technology equipment are needed, particularly in the deep sea. Moreover, it is difficult to scale up any restoration intervention to sufficient spatial scales to achieve significant impact given the complexity of the "ownership" of ocean space, with its multiple stakeholders and various jurisdictional considerations (Danovaro et al., 2021).

Challenge 3: footprint reduction

The ecological footprint, measuring resource consumption and the requirements of waste assimilation of economic activities (Wackernagel and Rees, 1996), is a critical metric for evaluating the sustainability of blue food production. In fisheries, it represents the amount of ocean productivity required to sustain commercial species' capture. Low trophic level species (e.g., small pelagic fish such as sardines and anchovies) require less ocean productivity for their own sustenance than high trophic level fish. Marine finfish aquaculture production depends on low trophic level species that are used as food or to produce aquafeed (e.g., fishmeal and fish oil).

Both aquaculture and capture fisheries have raised concerns about their sustainability and influence on the environment (Goldburg and Triplett, 1997). Blue food production is associated with substantial resource consumption and environmental impacts, such as overconsumption of energy, greenhouse gas (GHG) emission, eutrophication, and degradation of aquatic, benthic, and coastal habitats and ecosystems (Diana, 2009; Troell et al., 2009; Greer et al., 2019; Meng et al., 2019; MacLeod et al., 2020; Alonso et al., 2021). The ecological footprint for sea food production (Folke et al., 1996) is a useful tool evaluating and managing key aspects of seafood sustainability, notably the resource efficiency of seafood in the utilization of primary production. The spatial and temporal distribution of the footprint varies depending on the activity, and it is critical to examine the environmental performance across the diversity of blue foods within the rapidly emergent sector: as blue food demand increases, production shifts toward aquaculture and technological development aims toward more efficient systems (Gephart et al., 2021).

Capture fisheries have direct and indirect impacts on ecosystems, affecting abundance, age and size structure, and genetic and species composition, as well as their associated and dependent species and ecological processes at a large scale. The overall impact in aquatic systems has been described as comparable to that of agriculture on land in terms of the proportion of the system's primary productivity harvested by humans (Pauly and Christensen, 1995). As well as being political measures, ecosystem approach to fisheries (EAF) and ecosystem-based fisheries management (EBFM) are concepts meant to improve management by considering effects upon the ecosystem more holistically, in accordance with the law of the sea (Garcia et al., 2003).

Fishing and aquaculture produce protein with lower emissions per unit of output than almost all land-based animal protein sources (Hilborn et al., 2018; Bianchi et al., 2022). Still, the CO_2 emissions of the world's fishing fleet were in the range of 178–207 million tonnes in 2016 (Parker et al., 2018; Greer et al., 2019), which was around 0.5% of the world's CO_2 emissions from human activities and 4% of emissions associated with food production. Global aquaculture production used $1,765.2 \times 10^3$ TJ energy, 122.6 km^3 water, and emitted 261.3 million tonnes of CO_2-equivalent GHGs to the atmosphere, representing approximately 0.47% of total anthropogenic emissions (Greer et al., 2019). It has been demonstrated that rebuilding fish stocks not only increases output but also increases profitability and reduces emissions per unit of output as long as the fisheries management system preserves incentives for efficient fishing (Arnason et al., 2008; Kristofersson et al., 2021). Capture fisheries emissions could be reduced from 10% to 30% by increasing catch efficiency, such as with efficient engines and larger propellers, better vessel shape and hull modifications, and speed reductions. Potential measures also include the transfer to less fuel-intensive gear types and technology, notably a reduction in bottom trawling (Sala et al., 2021; Hiddink et al., 2023).

In aquaculture, new technological developments aim to reduce energy and GHGs by using green energy and combining diverse structures like wind farms and turbines with open sea mariculture cages. Further opportunities to reduce GHG emissions in aquaculture include improving technological efficiency, reducing reliance on fossil fuels, moving to low GHG-intensity feed ingredients and improving feed conversion rates. Concerns over the ecological impact and the rising cost of producing fishmeal and fish oil have driven innovations in sustainable aquaculture feeds. Today, partial or total replacement of fishmeal and fish oil in feeds has become common practice in aquaculture. These alternative feeds seek to decrease the industry's reliance on pelagic fish while maintaining both fish and human health and aquaculture productivity. Downsides of this development are increased reliance on agricultural products with associated impacts on terrestrial systems, and the inadequate nutritional value of commercial feeds. Current research focuses therefore on increased incorporation of animal protein from farmed low-trophic marine invertebrates or insects. Integrated multi-trophic aquaculture represents a possible solution, where higher-trophic species for human consumption are combined with lower-trophic species that process waste effluents or act as a food source. Other strategies have been developed to minimize impacts besides improvement in feeds, such as reducing the use of chemicals and medicines and reducing losses in food and effluents.

However, a comprehensive understanding of aquaculture sustainability at a global scale, including resource consumption and environmental threats associated with aquaculture production, is lacking. A study at such a scale is challenging yet important given the implications aquaculture has on global sustainability. Opportunities for carbon capture do exist, such as promoting the growth of macroalgae and sea grasses, or directing production to filter-feeding species like mussels. By developing integrated multi-trophic aquaculture and voluntarily designating areas for marine protection, the industry can directly contribute to carbon capture and potentially make this a source of income or net zero cost investment (Cormier et al., 2022).

Challenge 4: novel raw material

Exploring untapped resources is crucial for increasing the amount of raw material and enhancing the sustainability of blue food production. Given the limited supply of fishmeal and fish oil, the efficient use of fish captured from the wild is essential for the development of an efficient aquaculture industry that contributes to increasing the production of blue food. Aquafeeds can be produced by replacing fishmeal and oil with substitutes developed from alternative sources such as plants, agriculture and animal farming waste, fish processing waste, and by-products such as stick water, low-trophic marine invertebrates from wild-capture, or aquaculture such as zooplankton or mussels and tunicates, respectively, microbial ingredients, insects, and seaweed. A significant proportion of the global harvest in capture fisheries and aquaculture is estimated to be either lost or wasted every year (FAO, 2022). Reducing food loss and waste in seafood value chains represents a good potential for mitigation and offers benefits through new valorization processes and providing a relevant source of useful resources, helping to achieve the production goals for 2030 (FAO, 2022).

The annual discards from global marine capture fisheries between 2010 and 2014 were 9.1 million tonnes (95% CI: 6.7–16.1 million tonnes). About 46% (4.2 million tonnes) of total annual discards were from bottom trawls that included otter trawls, shrimp trawls, pair bottom trawls, twin otter trawls, and beam trawls (Pérez Roda et al., 2019). Mortality caused by these discarded or slipped organisms are generally thought to constitute waste or suboptimal use of fishery resources (Pérez Roda et al., 2019). Discards are a multifaceted problem encompassing the ethical problem of responsible stewardship of marine resources, designing management regimes to limit or prevent discarding while meeting multiple social, economic, and biological objectives such as the Landing Obligation established in Article 15 of the European Union's Common Fisheries Policy (CFP). A multifaceted solution is required to address the practical problems of enforcing regulations designed to prevent or minimize discards, particularly as discards occur at sea where enforcement is difficult, to solve the technical problems of gear selectivity and utilization of species with a low market demand through transformation or adding value, and the economic problems posed by efforts to reduce bycatch, increase landing of bycatch, or increase utilization of bycatch (FAO, 1996; Gilman et al., 2020). Changes in consumer attitudes to encourage the consumption of a broader range of species, including lower-trophic species, could contribute to a more balanced use of marine resources.

The valorization of side streams from fishery and aquaculture value chains is a potential solution to address one of the challenges of the circular economy: turning wastes into profit by making the best possible use. However, discards and waste from marine fisheries are generally utilized to prepare animal feed and fertilizer in Europe and accordingly with the CFP, since specimens with a size below the minimum conservation reference size cannot be used for direct human consumption (https://www.europarl.europa.eu/factsheets/en/sheet/115/eu-fisheries-management). However, nowadays the main bulk is dumped into the environment as a solid waste, usually causing pollution if it is not properly managed. In recent years, as seafood is a prime source of proteins with high biological value, side and residual streams from fishery, aquaculture, and the fish processing industry can be considered as an ideal and cheap source for the extraction of tremendously valuable ingredients. In particular, the degradation of basic proteins results in biologically active protein hydrolysates and peptides, which possess a broad spectrum of nutritional health-promoting abilities (Harnedy and FitzGerald, 2012; Shavandi et al., 2019). Holistic concepts for the valorization of residual and side streams from fishery, aquaculture, and the fish processing industry, involving all actors along the value chain in an integrated marine biorefinery, while exploiting the capabilities of industrial symbiosis, will need to be improved and increase blue food provision.

Fermentation processes from aquatic origin products can be employed for obtaining omega-3-enriched oils to obtain *on-demand* bioactive peptides and fish protein hydrolysates. These fermentation processes can easily manage large numbers of side streams (Vázquez et al., 2021). Moreover, other products such as lipase can be obtained through biocatalyst-assisted processes, pulse combustion drying, by product autolysis (via innovative silage processes), and more recently, through biofuel and biogas methods (Kavkal and Kudre, 2020). However, the big challenge lies in developing new technologies for on-board use to improve processing at sea as well as for on-land application.

Little-exploited resources such as zooplankton, invertebrates, and mesopelagic fishes hold potential for new marine products. Catches from lower-trophic invertebrates, such as mollusks and crustaceans, have increased substantially and often represent high-value fisheries, but often have a large ecological footprint (Hvingel et al., 2021; Boenish et al., 2022). Marine capture of mesopelagic fish, on the other hand, is constrained by technological limitations and high costs. Mesopelagic fish with an abundant and virtually untapped biomass (Clavel-Henry et al., 2020), coupled with a growing demand for raw feed for the aquaculture sector, emerging markets for food supplements, and changing policy for traditional fisheries, have reignited interests in their commercial exploitation. Mesopelagic fish play a critical role in transporting organic carbon to the deep sea, and the development of fisheries that exploit this area of the ocean requires a precautionary approach, noting that the effects of harvesting this biomass on marine carbon cycles are unknown, as well as the species' productivity and response to fishing (Paoletti et al., 2021).

The European fishery for the mesopelagic blue whiting (*Micromestius potassou*), one of the largest in the Northeast Atlantic in terms of landings, highlights the potential of such resources, but also the challenges to extract value from them, or make them accessible to human consumption. Thus, under an EBA it is necessary to adopt a trade-off analysis, including a valuation of all ecosystem services (benefits that societies receive from nature or nature's contributions to people, Costanza et al., 1997).

Cultivated seaweeds, a major share of global aquaculture production, have grown substantially over the past two decades, holding potential for further expansion and diversification. Seaweed cultivation can provide benefits ranging from CO_2 sequestration to enhancing livestock feed. However, potential effects of the cultivation at large scale on marine biodiversity are unknown. The limited number of species cultivated could be increased and efforts should be addressed to diversify and explore new opportunities. There is potential for seaweed culture expansion in all oceans, albeit the risks associated with climate change and ecosystem carrying capacity should be considered (UN, 2023).

Challenge 5: new smart technological solutions and crossovers

Technological solutions are a transversal aspect of all challenges in reducing environmental impacts and solving existing problems associated with blue food production. The scope of technologies involved spans engineering, food transformation, chemistry, biology, mathematics, modeling, artificial intelligence (AI), and more. Science-based knowledge holds the potential to reduce most environmental impacts associated with blue food production. In capture fisheries, interventions like improved engines using fossil-free energy and more efficient gear are key areas. Additionally, new technologies are required to reduce the environmental impacts of fishing vessels, and of gears with less impacts on the ecosystem and less risk to be lost—causing pollution and ghost fishing.

A variety of strategies in fisheries adaptation can be used to improve sustainability, such as improved monitoring and management (Aylagas et al., 2016), increasing gear and livelihood diversification, changing fishing locations, and incorporating traditional fishing techniques (Galappaththi et al., 2022). Moreover, considering that climate change may have highly variable effects on different species (Sguotti et al., 2016), it is important to have a clear understanding of the current extent of the scientific knowledge capturing those variations. Digital revolution contributions include accurate environmental and catch registration data—not only for control purposes by European or national administrations but for scientific evaluation of stocks/populations—and improved self-monitoring of fleets and fishermen associations. In addition, digitalization will improve the verification of measures on fishing capacity applicable to vessel engine power, better traceability of fisheries products, a better knowledge of the marine environment, and improved catch certification schemes. So digitalization and advanced tools applied to fisheries, such as remote electronic monitoring (REM or EM Systems), AI, machine learning tools, sensor data, and high-resolution satellite imagery, have an enormous potential to enhance our ability to collect and analyse data toward the optimization of fishing operations and the improvement of monitoring and control capabilities for science evaluations, policymakers, and regulatory administrations.

In aquaculture, managing waste effluents and feed is critical for mitigating environmental impacts. The waste generated impacts both the water column and the bottom, causing eutrophication and disturbance of benthic habitats. Technology improvements in feed design and feeding systems can effectively reduce waste, resulting in proper management of the inputs into the culture systems. A reduction in the feed conversion ratio of 30% in a fish farm can significantly decrease the environmental impact of the fish culture system (d'Orbcastel et al., 2009). This highlights the need for proper methods to ensure the sustainable intensification of aquaculture.

Food technology advancements have led to a growing share of by-products used for food and non-food purposes. For example, in 2020 over 27% of global production of fishmeal and 48% of the total production of fish oil came from by-products (FAO, 2022). The utilization of by-products, combined with the use of new raw materials, holds promise for the future. Exploiting existing synergies among different stakeholders in the fishing value chain contribute to more sustainable and efficient practices.

Challenge 6: social aspects

Social sustainability in blue food production encompasses a wide range of aspects, including human and labor rights, living conditions, quality of life, food safety, cultural nuances, protection of vulnerable groups, and considerations for final customers. Achieving social sustainability requires the commitment of all stakeholders and robust traceability systems. The UN's SDGs serve as a starting point to involve local, national, and international government levels, in a joint effort with various actors, always considering the specificities of each region (Toussaint et al., 2022). Fishing and aquaculture are essential economic activities, providing a source of livelihood for millions of people worldwide. In 2020, an estimated 58.5 million people globally were engaged as full-time, part-time, occasional, or unspecified workers in fisheries and aquaculture (both inland and marine waters; data do not allow the differentiation of only marine activities). Geographically, the majority of all fishers and aquaculture workers were in Asia (84%), followed by Africa (10%) and Latin America and the Caribbean (4%). More than 20 million workers were engaged in aquaculture, concentrated primarily in Asia (93.5%), followed by Africa (3.1%) and Latin America and the Caribbean (nearly 3%). Europe, North America, and Oceania each had <1% of people working engaged as fishers or aquaculture workers. Although the number of people engaged as fishers or aquaculture workers is stable or declining in most areas, aquaculture farmers are increasing in Africa (FAO, 2020).

Recognizing the importance of human resource development, research, and infrastructure investment for achieving food security, FAO (1996) emphasized the need for policies to achieve that goal, including gender equality. Overall, women accounted for 2% of those engaged in the primary sector (28% in aquaculture and 18% in fisheries), but women often faced more unstable employment in aquaculture and fisheries, representing only 15% of full-time workers in 2020. In the processing sector, women accounted for over 50% of full-time employment and 71% of part-time engagement.

Just as women are not a homogenous group, the different roles of women throughout the fisheries and aquaculture sector vary widely, from harvesting shellfish and seaweed, small-scale fishing, and net-mending, to processing and marketing of fisheries and aquaculture products (Bennett, 2005). However, there is consistency in the gender dynamics that privilege men over women, and the control exercised through gender-based roles (FAO et al., 2017). It is interesting to note that these inequalities are also present in the science sector. Despite gains, women remain underrepresented in fisheries science (Arismendi et al., 2016) and face the same challenges as women in other scientific fields. It will take efforts from all to help address the issues facing women in our field, and men are important allies in this process and crucial agents of change.

Blue food systems have the potential to positively impact social justice, through offering greater food sovereignty and self-determination, particularly among ongoing global food and inflation crises. Governments play a key role in balancing wealth and welfare across the global seafood sector to ensure that the profits and proceeds of blue foods serve people and society at large. Policymakers can embed the human right to food in national fisheries policies, establishing stronger links between fishing, aquaculture, and diet-related policies. Such a step is particularly important to address gender inequalities that lead to women missing out on the full nutritional benefits of aquatic foods because they have limited access and rights to the means of production.

Addressing barriers to social sustainability involves considering the economic resources and development of the specific area, as these are not equally distributed between and within countries, and have historically limited the wealth-generating potential of their aquatic food systems, and granting preferential access to credit or exclusive fishing waters to small-scale fisheries and aquaculture workers. Social welfare safety nets can further support small-scale producers in withstanding shocks that might otherwise jeopardize their livelihoods; these strategies can extend across nations to promote a more inclusive and socially sustainable blue food sector (Failler et al., 2022).

Challenge 7: new management measures

Concerning the sustainable management of blue food provision, the UN stated in 2021 that a achieving a sustainable transformation of food and agricultural systems is imperative at all levels. This will require international cooperation, encompassing regional and North–South collaboration, and active engagement with stakeholders, including the private sector and civil society. However, there are no one-size-fits-all solutions; policies must consider local contexts, the impact of such transformations on the livelihoods of workers employed in blue food production, and the job opportunities available to them (UN, 2021). Fisheries and aquaculture are subject to regulation by several organizations at local, regional, state, and international levels, with numerous codes of good conduct and regulatory laws Code of Conduct for Responsible Fisheries | Illegal, Unreported and Unregulated (IUU) fishing | Food and Agriculture Organization of the United Nations (fao.org). Nevertheless, only about 5% of the stocks are formally assessed (Costello et al., 2020), constituting less than half of the reported global marine fish catch. Regions with less-developed fisheries management have, on average, 3-fold greater harvest rates and half the abundance compared to assessed stocks (Hilborn et al., 2021). Science-based management, utilizing fisheries monitoring, analytical assessments, and precautionary harvest rules, have been demonstrated to successfully reduce overfishing and improve stock conditions (Link and Watson, 2019; Zimmermann and Werner, 2019). However, these measures are data- and resource intensive, restricting their applicability in the Global South and for commercially less-valuable stocks in general. A lack of capacity and resources globally hinders stock assessment and management (Cope et al., 2023). Innovative approaches should be developed, considering the impacts of bycatch, recreational fisheries, artisanal fisheries, and environmental change, which can be substantial but unanticipated.

Effective fisheries management has proven successful in rebuilding stocks and increasing catches within ecosystem boundaries. Improving global fisheries management remains crucial for restoring ecosystems to a healthy and productive state and safeguarding the long-term supply of aquatic foods (Garcia et al., 2012). Rebuilding overfished stocks could increase fisheries production by 16.5 million tonnes and enhance the contribution of marine fisheries to food security, nutrition, economic growth, and the wellbeing of coastal communities (FAO, 2022). For example, on average, 66.7% of the stocks of the ten species most landed in 2019—Peruvian anchoveta, Alaska pollock, skipjack tuna, Atlantic herring, yellowfin, blue whiting, European pilchard, Pacific chub mackerel, Atlantic cod, and largehead hairtail—were fished within biologically sustainable levels in 2019, slightly higher than in 2017. The fraction of fishery stocks within biologically sustainable levels decreased to 64.6% in 2019, 1.2% lower than in 2017. However, 82.5% of the 2019 landings were from biologically sustainable stocks, a 3.8% improvement from 2017 (Punt, 2023). This demonstrates that larger stocks are managed more effectively. Scientifically assessed and intensively managed stocks have, on average, seen increased abundance at proposed target levels. In contrast, regions with less-developed fisheries management have much greater harvest rates and lower abundance. This highlights the urgent need to replicate and re-adapt successful policies and regulations in fisheries that are not managed sustainably, and implement innovative, ecosystem-based mechanisms that promote sustainable use and conservation worldwide. Synergistic effects of fishing, environmental variation, and climate change increasingly threaten marine ecosystems and complicate management (Punt, 2023).

Blue food production depends on environmental conditions, both physical (temperature, dissolved oxygen, pH, nutrients, and water circulation) and biological, such as primary production and food web interactions. It has been shown that sustainable fisheries harvest is related to the level of primary production (i.e., basal organic production) available within a given ecosystem (Mann, 1984; Chassot et al., 2010). Environmental conditions result in geographical production variability depending on habitat and human pressures. For instance, in estuarine environments, the quantified influence of nutrient loading (which impacts primary production) on fish production might ultimately limit the magnitude of fisheries and their economy (Breitburg et al., 2009). Production limitation is a primary consideration when accounting for ecosystem overfishing (Coll et al., 2008). The reduction of fishing pressure across the board was suggested to allow the overfished stocks to recover and to sustainable fisheries to have greater resilience to pressures such as climate change, ocean pollution, and other factors (Barange et al., 2018).

Some proposals for ocean protection promote less fishing, including the call for classifying 30% of the ocean as marine protected areas where no extractive resource uses would be permitted (Langton et al., 2020). However, even if allowing for some spill-over of fish and displacement of some fishing effort from closures into surrounding areas, such proposals may stand in contrast to the goal of increasing blue food production, and particularly in small-scale fisheries, there is little scope for coastal communities to accommodate the loss of livelihoods associated with fishing. Notwithstanding the importance of the social and economic consequences, less fishing means that fisheries will produce less food. Such an outcome makes strategies of just fishing less viable, even if the other economic and social outcomes are mitigated, because fish are crucial to global food security.

New holistic management approaches are required, including to deal with the effects that climate change may have on fish stock distribution (Crona et al., 2023). Moreover, the ideal stock assessment, not applicable in poorly documented fisheries, would be able to estimate all the key parameters related to population processes within a framework that assigns appropriate weight to the data, fits the data adequately, and captures all sources of uncertainty related to estimation, including model uncertainty, process uncertainty, and observation uncertainty (Punt, 2023). An example of a holistic initiative—including fishers, scientists, managers, and consumers—is the ecolabel and the fishery certification program issued by the Marine Stewardship Council. They contribute to healthy future oceans by recognizing and rewarding sustainable fishing practices, influencing the choices people make when buying seafood, and working to transform the seafood market to a sustainable basis. This initiative includes the commercialization and the consumer knowledge to play a role in the future of marine food provision. However, the private nature of many certification schemes might create conflicts of interest and undermine public trust. Certification by public organizations or clearer regulation by state or intergovernmental agencies might therefore be needed in the future to maximize the benefits of certification.

The cumulative effect of increased human activity in the marine environment leads to competition for limited marine space, increased stress on marine ecosystems, and potential for conflicts among groups of users (Krause et al., 2015). Different management regimes exist on geographic scales, that is, national exclusive economic zone regulations, regional regulations for territorial waters, macro-regional agreements such as the Oslo–Paris Agreement (OSPAR) and Helsinki Commission (HELCOM), and objective-oriented management approaches such as marine conservation efforts and sectoral industry governance. In the last two decades, the joint "multi-use" of ocean space has been developed, thereby maximizing spatial efficiency and productivity (Schupp et al., 2019). Marine spatial planning and marine protected areas (MPAs) were developed to manage activities and protect biodiversity, respectively. However, data indicate that, for instance, dredging and trawling are negatively affecting many MPAs (Sala et al., 2021). To better manage the uses of space, it is essential to map activities using the different sources of information (i.e., VSH) available, and including small-scale vessels. In this respect, an important example can be found on the recent requirement established for artisanal vessels by the European Commission through the new Control Regulation.

MPAs limit access and some activities like fishing to help fish stocks and ecosystems recover. No-take MPAs are globally recognized management tools for reducing physical disturbance and the overexploitation of marine species, helping to restore overused fisheries (Guidetti et al., 2014) and manage the effects of climate change (Roberts et al., 2017). Despite strong evidence that marine reserves, as a protection measure, enhance overall biodiversity, it is not clear that this effect extends to all taxonomic groups (Mello et al., 2020). The specific goals of each MPA should be explicitly outlined, ideally under the SMART (Specific, Measurable, Achievable, Realistic, and Time-bound) framework (Grorud-Colvert et al., 2021). Furthermore, MPAs and conservation might be in conflict with goals to maximize food production. Such trade-offs need to be resolved, as unclear or conflicting objectives represent a major hindrance to successful resource management (Blicharska et al., 2019). Moreover, further work is required to undertake a study of cost effectiveness and cost–benefit derived from no-take marine reserves. To provide data on the success of NBS in general, appropriate indicators must be used that measure both benefits to human society and to nature. To the most traditional impacts on biodiversity and environment, others on social and economic terms should be added to reach a fully comprehensive assessment.

Conclusion

In conclusion, there is a growing awareness of the vital role aquatic food systems as drivers of food production, employment, economic growth, social development, and environmental recovery, aligning with the SDGs set out by the UN. The UN's 2030 Agenda could be realized through the transformation of aquatic food systems into more efficient, inclusive, resilient, and sustainable systems, fostering better production, nutrition, environmental stewardship, and overall quality of life.

Costello et al. (2020) noted that, considering ecological, economic, regulatory, and technological constraints, blue food provision could increase by 21–44 million tonnes by 2050, representing a 36%—74% increase compared to current yields. This increase could account for 12%—25% of the estimated increase in all meat required to feed 9.8 billion people by 2050. Additionally, recent analysis from the global non-profit Marine Stewardship Council suggests that eliminating overfishing and rebuilding fish stocks could provide nutrition for millions of additional people, and help to prevent serious and life-threatening health conditions (https://www.msc.org/). If all global fisheries were managed sustainably, it is estimated that an additional 16 million tonnes of seafood could be harvested annually, contributing to meeting nutritional demands by 2030.

FAO (2022) has introduced guidelines for a Blue Transformation process, outlining core guiding principles for action and programs. These principles encompass objectives for aquaculture, catch fisheries, and value chains, targeting achievements such as 35% growth in aquaculture production, 100% effective fisheries management, and 50% reduction in waste for 2030. Informed management through science is a pivotal aspect of this transformative process.

Extending the concept of sustainable blue production throughout the entire whole value chain requires a co-responsibility, as often practiced and expected within the fishing sector and related organizations (administrations, non-governmental bodies, scientists, etc.). Value chain responsibility is particularly relevant for fulfilling UN Strategic Goal 12, emphasizing sustainable and responsible consumption and production patterns. Tracing fish and seafood products along the value chain is essential to ensure accurate identification of species, origin, and production methods, enabling consumers to make informed decisions and producers of sustainably produced fish to reap the benefits of their investments.

To contribute to blue food provision, scientists must focus on three steps: (i) translate scientific findings into a narrative that inspires collective effort; (ii) acknowledge and navigate setbacks and trade-offs without derailing the transformation toward a more efficient blue food production system; and (iii) retain a steadfast focus on the end goal, viewing challenges not as problems but as opportunities for solutions (Borja, 2023). However, achieving improved blue food production requires commitment from governments, the private sector, and civil society to maximize the opportunities in fisheries and aquaculture. This includes expanding and intensifying sustainable aquaculture, effectively managing all fisheries, and upgrading aquatic value chains. Proactive public and private partnerships are crucial for enhancing production, reducing food loss and waste, and ensuring equitable access to lucrative markets. Additionally, the inclusion of aquatic foods in national food security and nutrition strategies, coupled with initiatives to raise consumer awareness on their benefits, is essential for increasing availability and improving access.

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

BM-N: Conceptualization, Writing – original draft. FZ: Writing – original draft. GM: Writing – original draft. LA: Writing – original draft. AM-M: Writing – original draft. EM: Conceptualization, Writing – original draft.

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Conflict of interest

EM was employed by Blue Growth and Marine Services.

The remaining 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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References

Alonso, A. A., Álvarez-Salgado, X. A., and Antelo, L. T. (2021). Assessing the impact of bivalve aquaculture on the carbon circular economy. *J. Cleaner Prod.* 279:123873. doi: 10.1016/j.jclepro.2020.123873

Arismendi, I., Brooke, I., and Penaluna, E. (2016). Examining diversity inequities in fisheries science: a call to action. *Bio. Sci.* 66, 584–591. doi: 10.1093/biosci/biw041

Arnason, R., Kelleher, K., and Willmann, R. (2008). *The Sunken Billions: The Economic Justification for Fisheries Reform. Agriculture and Rural Development.* © World Bank. Available online at: http://hdl.handle.net/10986/2596~https://api.semanticscholar.org/CorpusID:129016214

Audzijonyte, A., Fulton, E., Haddon, M., Helidoniotis, F., Hobday, A. J., Kuparinen, A., et al. (2016). Trends and management implications of human influenced life-history changes in marine ectotherms. *Fish Fish.* 17, 1005–1028. doi: 10.1111/faf.12156

Aylagas, E., Borja, A., Irigoien, X., and Rodriguez-Ezpeleta, N. (2016). Benchmarking DNA metabarcoding for biodiversity-based monitoring and assessment. *Fron. Mar. Sci.* 3:96. doi: 10.3389/fmars.2016.00096

Barange, M., Bahri, T., Beveridge, M.C.M., Cochrane, K.L., Funge-Smith, S., and Poulain, F. (2018). *Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options.* FAO Fisheries and Aquaculture Technical Paper No. 627. Rome: FAO, p. 628.

Bell, J. D., Bartley, D. M., Lorenzen, K., and Loneragan, N. R. (2006). Restocking and stock enhancement of coastal fisheries: Potential, problems and progress. *Fish. Res.* 80, 1–8. doi: 10.1016/j.fishres.2006.03.008

Bell, J. D., Leber, K. M., Blankenship, H., Lee- Loneragan, N. R., and Masuda, R. (2008). A new era for restocking, stock enhancement and sea ranching of coastal fisheries resources. *Rev. Fish. Sci.* 16, 1–9. doi: 10.1080/10641260701776951

Bennett, E. (2005). Gender, fisheries and development. *Mar. Policy* 29:4514459. doi: 10.1016/j.marpol.2004.07.003

Bianchi, M., Hallström, E., Parker, R. W., Mifflin, K., Tyedmers, P., and Ziegler, F. (2022). Assessing seafood nutritional diversity together with climate impacts informs more comprehensive dietary advice. *Commun. Earth Environ.* 3:188. doi: 10.1038/s43247-022-00516-4

Blicharska, M., Smithers, R. J., Mikusiński, G., et al. (2019). Biodiversity's contributions to sustainable development. *Nat. Sustain.* 2, 1083–1093. doi: 10.1038/s41893-019-0417-9

Boenish, R., Kritzer, J. P., Kleisner, K., Steneck, R. S., Werner, K. M., Zhu, W., et al. (2022). The global rise of crustacean fisheries. *Front. Ecol. Env.* 20, 102–110. doi: 10.1002/fee.2431

Borja, A. (2023). Grand challenges in ocean sustainability. *Front. Ocean Sustain.* 1:1050165. doi: 10.3389/focsu.2023.1050165

Borja, A., Andersen, J. H., Arvanitidis, C. D., Basset, A., Buhl-Mortensen, L., Carvalho, S., et al. (2020). Past and future grand challenges in marine ecosystem ecology. *Front. Mar. Sci.* 7:362. doi: 10.3389/fmars.2020.00362

Breitburg, D. L. J. K., Craig, R. S., Fulford, K. A., Rose, W. R., Boynton, D. C., Brady, B. J., et al. (2009). Nutrient enrichment and fisheries exploitation: interactive effects on estuarine living resources and their management. *Hydrobiologia* 629, 31–47. doi: 10.1007/s10750-009-9762-4

Caddy, J. F. (1999). Fisheries management in the twenty-first century: will new paradigms apply? *Rev. Fish Biol. Fish.* 9, 1–43. doi: 10.1023/A:1008829909601

Chassot, E., Bonhommeau, S., Dulvy, N. K., Mélin, F., Watson, R., Gascuel, D., et al. (2010). Global marine primary production constrains fisheries catches. *Ecol. Lett.* 13, 495–505. doi: 10.1111/j.1461-0248.2010.01443.x

Chen, Q., Yuan, P., and Chen, P. (2019). Integrated response in taxonomic diversity and eco-exergy of microbenthic faunal community to artificial reef construction in Daya Bay, China. *Ecol. Indic.* 101, 512–521. doi: 10.1016/j.ecolind.2019.01.049

Clavel-Henry, M., Piroddi, C., Quattrocchi, F., Macias, D., and Christensen, V. (2020). Spatial Distribution and Abundance of Mesopelagic Fish Biomass in the Mediterranean Sea. *Fron. Mar. Sci.* 7:573986. doi: 10.3389/fmars.2020.573986

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S. (2016). *Nature-Based Solutions to Address Global Societal Challenges.* Gland, Switzerland: IUCN. doi: 10.2305/IUCN.CH.2016.13.en

Coll, M., Libralato, S., Tudela, S., Palomera, I., and Pranovi, F. (2008). Ecosystem overfishing in the ocean. *PLoS ONE* 3:e3881. doi: 10.1371/journal.pone.0003881

Cope, J. M., Dowling, N. A., Hesp, S. A., Omori, K. L., Bessell-Browne, P., Castello, L., et al. (2023). The stock assessment theory of relativity: deconstructing the term "data-limited" fisheries into components and guiding principles to support the science of fisheries management. *Rev. Fish Biol. Fish.* 33, 241–263. doi: 10.1007/s11160-022-09748-1

Cormier, R., Elliott, M., and Borja, A. (2022). Managing marine resources sustainably – the 'management response-footprint pyramid' covering policy, plans and technical measures. *Front. Mar. Sci.* 9:869992. doi: 10.3389/fmars.2022.869992

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi: 10.1038/387253a0

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. Á., Free, C. M., Froehlich, H. E., et al. (2020). The future of food from the sea. *Nature* 588, 95–100. doi: 10.1038/s41586-020-2616-y

Crona, B. I., Wassénius, E., Jonell, M., Koehn, J. Z., Short, R., et al. (2023). Four ways blue foods can help achieve food system ambitions across nations. *Nature* 616, 104–112. doi: 10.1038/s41586-023-05737-x

Dailianis, T., Smith, C. J., Papadopoulou, N., Gerovasileiou, V., Sevastou, K., et al. (2018). Human activities and resultant pressures on key European marine habitats: an analysis of mapped resources. *Mar. Policy* 98, 1–10. doi: 10.1016/j.marpol.2018.08.038

Danovaro, R., Aronson, J., Cimino, R., Gambi, C., Snelgrove, P. V. R., et al. (2021). Marine ecosystem restoration in a changing ocean. *Restor. Ecol.* 29:e13432. doi: 10.1111/rec.13432

Diana, J. S. (2009). Aquaculture production and biodiversity conservation. *BioScience* 59, 27–23. doi: 10.1525/bio.2009.59.1.7

d'Orbcastel, E. R., Blancheton, J. P., and Aubin, J. (2009). Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment. *Aquac. Eng.* 40, 113–119. doi: 10.1016/j.aquaeng.2008.12.002

Failler, P., Pan, H., and Akbari, N. (2022). Integrated social-economic-ecological modeling for fisheries: the ECOST model. *Front. Mar. Sci.* 8:704371. doi: 10.3389/fmars.2021.704371

FAO (1996). *Rome Declaration on World Food Security.* World Food Summit, 13-17 of November 1996, Rome Italy. Available online at: http://www.fao.org/wfs/index_en.htm

FAO (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in Action.* Rome: FAO.

FAO (2022). *The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation.* Rome: FAO.

FAO, IFAD, UNICEF, WFP, and WHO (2017). *The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security.* Rome: FAO. The State of Food Security and Nutrition in the World 2017 (fao.org).

Folke, C., Kautsky, N., Berg, H., Jansson, A., and Troel, M. (1996). Footprint concept for sustainable seafood production: a review. *Ecol. Applic.* 81, 563–571.

Free, C. M., Jensen, O. P., Anderson, S. C., Gutierrez, N. L., Kelisner, K. M., Long, C., et al. (2020). Blood from a stone: Performance of catch-only methods in estimating stock biomass status. *Fish. Res.* 223:105452. doi: 10.1016/j.fishres.2019.105452

Galappaththi, E. K., Susarla, V. B., Loutet, S. J., Ichienm, S. T., Hyman, A. A., and Ford, J. D. (2022). Climate change adaptation in fisheries. *Fish Fish.* 23, 4–21. doi: 10.1111/faf.12595

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., et al. (2019). International principles and standards for the practice of ecological restoration. Second edition. *Restor. Ecol.* 27, S1–S46. doi: 10.1111/rec.13035

Garcia, S. M., Kolding, J., Rice, J., Rochet, M.-J., Zhou, S., Arimoto, T., et al. (2012). Reconsidering the consequences of selective fisheries. *Science* 335, 1045–1047. doi: 10.1126/science.1214594

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., and Lasserre, G. (2003). *The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook.* FAO Fisheries Technical Paper. No. 443. Rome: FAO.

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., et al. (2021). Environmental performance of blue foods. *Nature* 597, 360–365. doi: 10.1038/s41586-021-03889-2

Gilman, E., Perez Roda, A., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., et al. (2020). Benchmarking global fisheries discards. *Sci. Rep.* 10:14017. doi: 10.1038/s41598-020-71021-x

Goldburg, R., and Triplett, T. (1997). *Murky Waters: Environmental Effects of Aquaculture in the United States.* New York, NY: Environmental Defense Funds 197.

Greer, K., Zeller, D., Woroniak, J., Coulter, A., Winchester, M., Palomares, M. D., et al. (2019). Global trends in carbon dioxide (CO_2) emissions from fuel combustion in marine fisheries from 1950 to 2016. *Mar. Policy* 107, 1–9. doi: 10.1016/j.marpol.2018.12.001

Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Horta e Costa, B., Pike, E. B., et al. (2021). The MPA Guide: A framework to achieve global goals for the ocean. *Science* 373:eabf0861. doi: 10.1126/science.abf0861

Guidetti, P., Baiata, P., Ballesteros, E., Di Franco, A., Hereu, B., Macpherson, E., et al. (2014). Large-scale assessment of mediterranean marine protected areas effects on fish assemblages. *PLoS ONE* 9:e91841. doi: 10.1371/journal.pone.0091841

Harnedy, P. A., and FitzGerald, R. J. (2012). Bioactive peptides from marine processing waste and shellfish: A review. *J. Funct. Foods* 4, 6–24. doi: 10.1016/j.jff.2011.09.001

Hiddink, J. G., van de Velde, S. J., McConnaughey, R. A., De Borger, E., Tiano, J., Kaiser, M. J., et al. (2023). Quantifying the carbon benefits of ending bottom trawling. *Nature* 617, E1–E2. doi: 10.1038/s41586-023-06014-7

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., et al. (2020). Effective fisheries management instrumental in improving fish stock status. *Proc. Natl Acad. Sci. USA* 117, 2218–2224. doi: 10.1073/pnas.1909726116

Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., and Walsworth, T. E. (2018). The environmental cost of animal source foods. *Front. Ecol. Environ.* 16, 329–335. doi: 10.1002/fee.1822

Hilborn, R., Hively, D. J., Loke, N. B., de Moor, C. L., Kurota, H., Kathena, J. N., et al. (2021). Global status of groundfish stocks. *Fish Fish.* 22, 911–928. doi: 10.1111/faf.12560

Hvingel, C., Sainte-Marie, B., and Kruse, G. H. (2021). Cold-water shellfish as harvestable resources and important ecosystem players. *ICES J. Mar. Sci.* 78, 479–490. doi: 10.1093/icesjms/fsab005

Kavkal, S. S., and Kudre, T. G. (2020). Optimization of biodiesel production from marine fish waste oil using calcined chicken eggshell as a cost-effective catalyst by response surface methodology. Available online at: https://ssrn.com/abstract=3904620

Kjesbu, O. S., Sundby, S., Sand,ø, A. B., Alix, M., Hjøllo, S. S., Tiedemann, M., et al. (2022). Highly mixed impacts of near-future climate change on stock productivity proxies in the North East Atlantic. *Fish Fisher.* 23, 601–615. doi: 10.1111/faf.12635

Krause, G., Brugere, C., Diedrich, A., Ebeling, M. W., Ferse, S. C., Mikkelsen, E., et al. (2015). A revolution without people? Closing the people–policy gap in aquaculture development. *Aquaculture* 447, 44–55. doi: 10.1016/j.aquaculture.2015.02.009

Kristofersson, D., Gunnlaugsson, S., and Valtysson, H. (2021). Factors affecting greenhouse gas emissions in fisheries: evidence from Iceland's demersal fisheries. *ICES J. Mar. Sci.* 78, 2385–2394. doi: 10.1093/icesjms/fsab109

Langton, R., Stirling, D., Boulott, P., and Wright, P. J. (2020). Are MPAs effective in removing fishing pressure from benthic species and habitats? *Biol. Conser.* 247:108511. doi: 10.1016/j.biocon.2020.108511

Link, J. S., and Watson, R. A. (2019). Global ecosystem overfishing: Clear delineation within real limits to production. *Sci. Adv.* 5:eaav0474. doi: 10.1126/sciadv.aav0474

MacLeod, M. J., Hasan, M. R., Robb, D. H. F., et al. (2020). Quantifying greenhouse gas emissions from global aquaculture. *Sci. Rep.* 10, 11679. doi: 10.1038/s41598-020-68231-8

Mann, K. H. (1984). "Fish production in open ocean ecosystems," in *Flows of Energy and Materials in Marine Ecosystems: Theory and Practice*, ed. M. J. R. Fasham (New York, NY: Plenum Press) 435–458. doi: 10.1007/978-1-4757-0387-0_17

Marshak, A. R., and Link, J. S. (2021). Primary production ultimately limits fisheries economic performance. *Sci. Rep.* 11, 12154. doi: 10.1038/s41598-021-91599-0

Mello, M. H. L., Smith, A. M., Wood, A. C. L., and Tidey, E. J. (2020). Enhanced biodiversity and abundance of benthic invertebrate macrofauna in a New Zealand marine reserve. *Aquatic Conserv. Mar. Freshw. Ecosyst.* 30, 1854–1867. doi: 10.1002/aqc.3333

Meng, W., Feagin, R. A., Hu, B., He, M., and Li, H. (2019). The spatial distribution of blue carbon in the coastal wetlands of China. *Estuar. Coastal Shelf Sci.* 222, 13–20. doi: 10.1016/j.ecss.2019.03.010

Merino, G., Barange, M., Blanchard, J. L., Harle, J., Holmes, R., Allen, I., et al. (2012). Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Global Environ. Change* 22, 795–806. doi: 10.1016/j.gloenvcha.2012.03.003

Murillas-Maza, A., Broszeit, S., Pouso, S., Bueno-Pardo, J., Ruiz-Frau, A., Terrados, J., et al. (2023). Ecosystem indicators to measure the effectiveness of marine nature-based solutions on society and biodiversity under climate change. *Nat. Based Solut.* 4:100085. doi: 10.1016/j.nbsj.2023.100085

Paoletti, S., Nielsen, J. R., Sparrevohn, C. R., Bastardie, F., and Vastenhoud, B. M. J. (2021). Potential for mesopelagic fishery compared to economy and fisheries dynamics in current large scale danish pelagic fishery. *Front. Mar. Sci.* 8:720897. doi: 10.3389/fmars.2021.720897

Parker, R. W. R., Blanchard, J. L., Gardner, C., Green, B. S., Hartmann, K., Tyedmers, P. H., et al. (2018). Fuel use and greenhouse gas emissions of world fisheries. *Nat. Clim. Change* 8, 333–337. doi: 10.1038/s41558-018-0117-x

Pauly, D., and Christensen, V. (1995). Primary production required to sustain global fisheries. *Nature* 374, 255–257. doi: 10.1038/374255a0

Pérez Roda, M. A., Gilman, E., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., et al. (2019). *A third assessment of global marine fisheries discards.* FAO Fisheries and Aquaculture Technical Paper No. 633. Rome: FAO. p. 78.

Plagányi, E. E. (2007). *Models for an ecosystem approach to fisheries.* FAO Technical Report 477. p. 108.

Punt, A. E. (2023). Those who fail to learn from history are condemned to repeat it: a perspective on current stock assessment good practices and the consequences of not following them. *Fish. Res.* 261:106642. doi: 10.1016/j.fishres.2023.106642

Roberts, C. M., O'Leary, B. C., McCauley, D. J., Cury, P. M., Duarte, C. M., Lubchenco, J., et al. (2017). Marine reserves can mitigate and promote adaptation to climate change. *PNAS* 114, 6167–6175. doi: 10.1073/pnas.1701262114

Sala, E., Mayorga, J., Bradley, D., Cabral, R. B., Atwood, T. B., Auber, A., et al. (2021). Protecting the global ocean for biodiversity, food and climate. *Nature* 592, 397–402. doi: 10.1038/s41586-021-03371-z

Schupp, M. F., Bocci, M., Depellegrin, D., Kafas, A., Kyriazi, Z., et al. (2019). Toward a common understanding of ocean multi-use. *Front. Mar. Sci.* 6:165. doi: 10.3389/fmars.2019.00165

Seaman, W. (2007). Artificial habitats and the restoration of degraded marine ecosystems and fisheries. *Hydrobiologia* 580, 143–155. doi: 10.1007/s10750-006-0457-9

Sguotti, C., Lynam, C. P., García-Carreras, B., Ellis, J. R., and Engelhard, G. H. (2016). Distribution of skates and sharks in the North Sea: 112 years of change. *Global Change Biol.* 22, 2729–2743. doi: 10.1111/gcb.13316

Shavandi, A., Hou, Y., Carne, A., McConnell, M., and Bekhit, A. E. A. (2019). Marine waste utilization as a source of functional and health compounds. *Adv. Food Nutr. Res.* 287, 187–254. doi: 10.1016/bs.afnr.2018.08.001

Toussaint, M., Cabanelas, P., and Muñoz-Dueñas, P. (2022). Social sustainability in the food value chain: what is and how to adopt an integrative approach? *Qual.Quant.* 56, 2477–2500. doi: 10.1007/s11135-021-01236-1

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H., and Fang, J. G. (2009). Ecological engineering in aquaculture - Potential for integrated multitrophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297, 1–9. doi: 10.1016/j.aquaculture.2009.09.010

UN (2021). *Department of economic and social affairs, policy brief: Population, food security, nutrition and sustainable development*. Available online at: https://www.un.org/development/desa/dpad/publication/un-desa-policy-brief-102-population-food-security-nutrition-and-sustainable-development/

UN (2023). *Sustainable Development Goals*. Home – United Nations Sustainable Development. Available online at: https://www.un.org/sustainabledevelopment/

Vázquez, J. A., Fraguas, J., Mirón, J., Valcárcel, J., Pérez-Martín, R. I., and Antelo, L. T. (2021). Valorisation of fish discards assisted by enzymatic hydrolysis and microbial bioconversion: lab and pilot plant studies and preliminary sustainability evaluation. *J. Cleaner Prod.* 246:119027. doi: 10.1016/j.jclepro.2019.119027

Wackernagel, M., and Rees, W. (1996). *Our Ecological Footprint: Reducing Human Impact on the Earth.* Philadelphia: New Society Publishers.

Zimmermann, F., and Werner, K. M. (2019). Improved management is the main driver behind recovery of Northeast Atlantic fish stocks. *Front. Ecol. Environ.* 17:2002. doi: 10.1002/fee.2002