

REVIEW

Opportunities for Blue food in a turbulent future - what's ahead for a growing aquaculture industry?

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Keywords: Blue food, aquaculture, planetary boundaries, anthropocene, SDG, food system, climate change, nutrition, environmental performance, environmental stressors

<https://doi.org/10.48045/001c.122387>

Bulletin of the European Association of Fish Pathologists

Vol. 45, Issue 1, 2025

The scale and speed of human activities and technological developments have substantially increased since the 1950s resulting in reshaping of the biosphere and moving humanity into a new geological epoch — the "Anthropocene". This is characterized by changes in several Earth system processes and structures on which human life depends. The global food system is a major driver of changes in the biosphere – for example greenhouse gas emission and other environmental changes including global biodiversity loss. Blue foods (aquatic foods) have slowly made their way into international high-level sustainability discussions and increasingly now form part of nutritious, climate smart and low environmental impact food narratives. Today farmed and captured aquatic animals and plants play a central role in food and nutrition security for billions of people, and constitute cornerstones for many livelihoods, economies, and cultures. The blue food portfolio is highly diverse and also supported by a wide range of ecosystems, cultural practices and production modalities. This diversity poses both potential for supporting food system resilience in uncertain times, and challenges for making simple guidance on sustainable development of food production. The anticipated continuous growth of aquaculture trigger questions related to "what, how and why". Many blue foods are rich in bioavailable micronutrients and can be produced in ways that are more environmentally sustainable than some terrestrial animal-source foods. However, blue foods are diverse and planning for future expansion through i.e. aquaculture involves identification of properties for different species and systems, as well as identification of development priorities and acknowledging trade-offs and context specificity out from a broader Sustainable Development Goal framework. Environmental stressors may narrow the window for blue food production and climate change is a main driver affecting the function and productivity of aquatic and supportive terrestrial ecosystems.

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The Big Picture

Humanity depends upon the biosphere for our life-support system that enables fostering societal development and human wellbeing (Folke et al. 2016). Since the 1950s human activities and technological developments have substantially increased in scale and speed – resulting in increased material wealth, food availability, and improved wellbeing of humanity. At the same time, we find increased scarcity of critical resources, overconsumption and ecological systems being degraded to such an extent that it threatens to undermine the life-support capacity and long-term societal development (Steffen et al. 2015). This rapid development, referred to as the “Great Acceleration” (Steffen et al. 2015) (for oceans “the blue acceleration”, Jouffray et al. 2020), has reshaped the biosphere and moved humanity into a new geological epoch — the “Anthropocene” (Crutzen and Stoermer 2000; Steffen et al. 2011a, 2011b). This means that the Earth system has been set on a new trajectory moving rapidly away from the stable Holocene state of the past 12,000 years – being the “only Earth system state we know being able to support the world as we know it” (Rockström et al. 2023). A set of planetary boundaries (PB) have been conceptualised to illustrate the systemic threats of the Anthropocene, including greenhouse gas emission, land change, biodiversity loss, freshwater use, ocean acidification and nutrient pollution (Rockström et al. 2009; Steffen et al. 2015). Large focus within the planetary work has been on identification of safe operating space for humanity – i.e. the need to keep effects resulting from human development within boundaries (e.g. temperature rise) where ecosystems are at risk of being destabilised and losing functions on which humanity depends (Rockström et al. 2009). Recently new entities for planetary boundaries have been identified, e.g. chemicals, including plastics and also antimicrobial resistance (Persson et al. 2022). In addition, large scale/global tipping points also been identified (Lenton et al. 2008; Armstrong McKay et al. 2022), being of relevance to many of the planetary boundaries. The need to integrate societal wellbeing in the planetary boundary concept been increasingly stressed (Drees, Luetkemeier, and Kerber 2021) and despite this work still being in its infancy it constitutes a crucial condition for achieving global sustainability (Steffen and Smith 2013). The “Doughnut of social and planetary boundaries” (Raworth 2012, 2017) and the #SDGinPB project (Randers et al. 2019) constitute two important examples of such efforts. Figure 1 presents a conceptual illustration of how aquatic foods need to relate to different sustainability frameworks.

Food System challenges

Global expansion of food systems has provided for nutrition, livelihoods, and sources of income, but has also come with environmental and social costs including water scarcity, soil degradation, periodic droughts, biodiversity loss, pollution, overfishing, and greenhouse gas emissions (Gordon et al. 2017; Springmann et al. 2018; Willet et al., 2019). The food system is a major driver



Figure 1. Conceptual illustration of Blue foods put in perspective relative to key frameworks for sustainable development and safe and just space for humanity (built on Planetary Boundary, Doughnut Economy and the Sustainable Development Goals (SDGs)).

of climate change (25-30% of all greenhouse gas (GHG), land use change and biodiversity loss (occupies 50% of all ice-free land), freshwater consumption (75% of global consumptive water use), pollution of aquatic and terrestrial ecosystems through fertilizer application and runoff (Gordon et al. 2017; Poore and Nemecek 2018; Willet et al., 2019). In addition, antimicrobial use in terrestrial food producing animals substantially exceeds human use and is now increasing the risk for development of antimicrobial resistance (van Boeckel et al. 2017). A rapidly destabilizing climate is already imposing constraints and shocks to the food system – with greatest impacts on already nutritionally vulnerable populations (Choufani et al. 2017; Carducci et al. 2023). The challenge for creating a just, nutritious, and sustainable food system able to feed a growing global population will not only require a paradigm shift with respect to where, what, and how foods are produced, but it will also need to ensure equitable distribution and access (Farmery et al. 2021, 2020; Carducci et al. 2023). In 2020, the UN Committee of World Food Security High Level Panel of Experts called for a transformation of the food system, moving “from a singular focus on increasing the global food supply through specialized production and export to making fundamental changes that diversify food systems, empower vulnerable and marginalized groups, and promote sustainability across all aspects of food supply chains, from production to consumption” (HLPE 2020). In such food transformation the important role of aquatic foods (blue foods) been emphasized, e.g. at the UN Food Systems Summit 2021 and in the UN 2021 Nutrition report (FAO et al. 2020).

Blue foods

Blue foods are aquatic species produced from the ocean, lakes, rivers and from land-based systems (<http://bluefood.earth>; FAO 2022). More than 2500 species of marine and freshwater animals, plants, and algae, supported by a wide range of ecosystems, cultural practices and production modalities – from large-scale trawlers on the high-seas to small-scale fishponds integrated within agricultural systems exist (Troell et al. 2014; Short et al. 2021; Gephart et al. 2021). In 2022 the total production of aquatic animals from fisheries and aquaculture reached 223 million tonnes (185 million tonnes live weight equivalent) and 38 million tonnes (wet weight) of algae. Capture fisheries is dominated by fish harvest in marine areas meanwhile fish aquaculture mainly comes from inland waters. Asian countries dominate production representing 70% of total global aquatic animal production. Aquaculture contributes with over 57 percent of overall aquatic animal production used for direct human consumption and China is the aquaculture giant.

Consumption of aquatic foods have more than doubled the last 50 year and today provide about 17 percent of global animal protein - reaching over 50 percent in several countries in Africa and Asia. Blue foods already play an important role in achieving food security, decreasing malnutrition and building healthy, resilient food systems with lower environmental footprints (Béné et al. 2016; Golden et al. 2021; Short et al. 2021; Gephart et al. 2021; Troell et al. 2023). Arguments to derive more proteins from aquatic sources includes both restoring fish stocks and increasing sustainable aquaculture development (Costello et al. 2020; Hicks et al. 2019; Willett et al., 2019; Troell et al. 2023; Crona et al. 2023). The diverse blue food portfolio brings both opportunities and limitations and findings of e.g. the Blue Food Assessment (BFA), being the first global assessment of the benefits of and challenges facing blue food systems, assists in understanding how blue foods sustainably can be integrated into global food system decision.

The opportunity for Aquaculture

Diversity

Aquaculture is a unique sector that encompasses activities in all aquatic ecosystems (freshwater, brackish/estuarine, and marine), and being tightly interconnected with terrestrial ecosystems through, for example, feed resources and space, and also linked to various social-ecological systems at a broader scale. Over 400 aquatic species are farmed, and these represent a large variation in associated production and processing systems, practices, sustainability and nutritional qualities (Troell et al. 2014; Gephart et al. 2021; Golden et al. 2021; FAO 2022). Global production remains concentrated with only 22 of all species groups farmed in 2017 accounting for over 75% of global live-weight production (Naylor et al. 2021).

Aquaculture – climate and environmental performance

To keep global warming below 1.5 °C, a target adopted under the Paris Agreement at the UN Climate Change Conference (COP21), humanity needs to drastically reduce greenhouse gas emissions and also remove substantial amount of atmospheric carbon dioxide by 2050 (Almaraz et al. 2023). However, recent research indicates that even if accomplishing the reduction and removals planned, warming may still become closer to 3 °C (United Nations Environment Programme 2023). Reducing food system GHG emissions is central to meeting the global emission targets. Across the diversity of farmed blue foods, environmental pressures, including lower emissions of GHG, are lower compared to those associated with many terrestrial animal-sourced food (particularly ruminant meat) (Gephart et al. 2021). In particular, non-fed aquaculture systems, such as bivalves and seaweeds, typically result in low GHG emission and also lower (or negative) nitrogen and phosphorus emissions, and require limited freshwater and land inputs (Gephart et al. 2021). As a comparison, many fed aquaculture species/systems perform similarly to or better than chicken production, which is often considered the most efficient terrestrial animal-source food production system. For fed aquaculture, feed production is responsible for more than 70% of emissions for most groups. Emission and resource-use stressors quantified by Life-cycle analysis (LCA) dominate environmental sustainability comparisons and these are valuable for making comparison of performance across foods; but cannot fully capture final ecosystem, biodiversity and social consequences (that is, impacts). This implies that sustainability of blue foods also needs considering additional stressors and accounting for local contexts (Figure 2).

Nutritional qualities

Nutritional value of blue foods has traditionally focused on energy and protein intake, and even if these constitute important contributions, it is important to consider blue foods in large unique provision of highly bioavailable essential micronutrients and specific fatty acids (Golden et al. 2021). The top seven categories of nutrient-rich animal-source foods are aquatic foods (Figure 3), notably rich in vitamin B12 and the omega-3 long-chain polyunsaturated fatty acids DHA (docosahexaenoic acid) and EPA (eicosapentaenoic acid). In addition, they are also rich in vitamin A and calcium, and also contain iron and zinc although to a lesser extent. Fed species obtain more or less all their nutrition through feeds and the quality of this is reflected in the nutritional content of the farmed product. A lowering of aquatic ingredients in feed (in particular fish oil) has resulted in lower content of both DHA and EPA in farmed salmon (although still being a concentrated source for these fatty acids). Relevant to include in any sustainability discussion is existence of a feed-food competition in animal farming, including aquaculture (van Riel et al. 2023). This is a complex issue but if resources that can be used to feed humans are instead used in animal

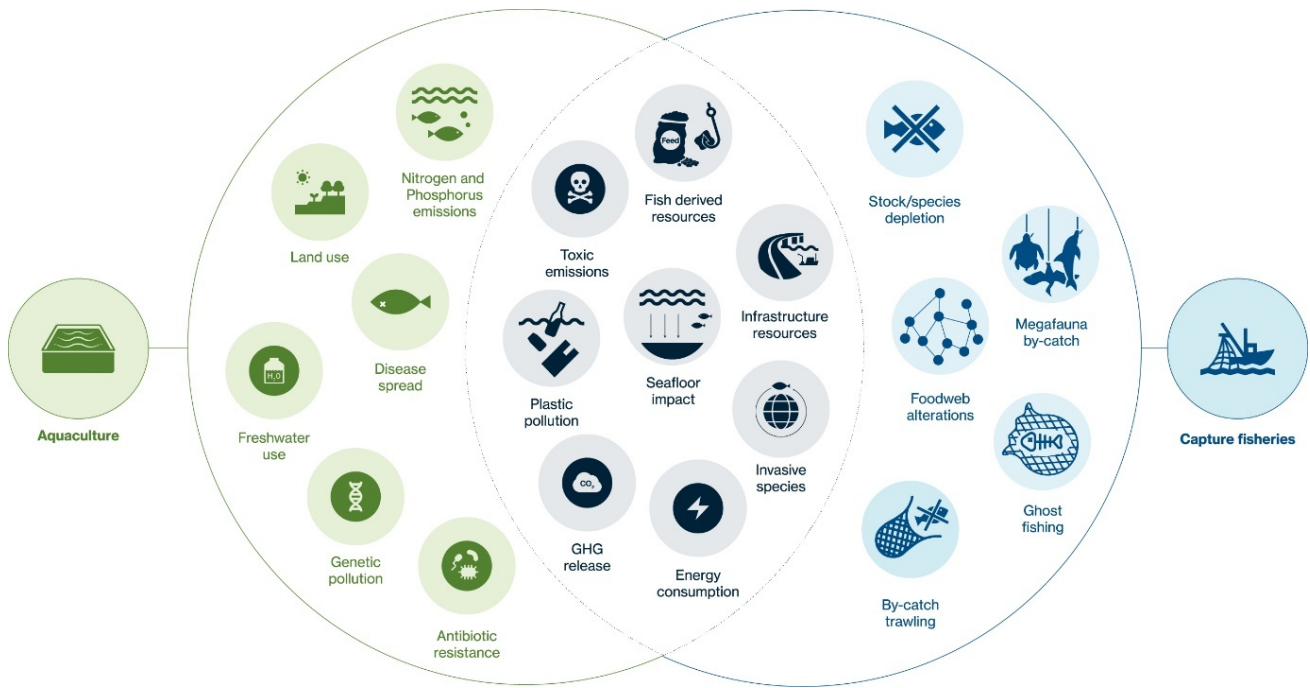


Figure 2. Major stressors generated from aquaculture and capture fisheries - including both LCA impact categories usually being quantified and others less studied stressors that can be critical drivers of ecosystem (and social) impacts.

feeds this need to be considered out from both an efficiency and equity perspective (Luthman et al. 2022). The use of high-quality food-competing ingredients (e.g. fishmeal and soya beans) should be minimized and utilization of waste and for humans non-edible co-products in aquaculture feed should increase (Sandström et al. 2022). Aquaculture's role in circular food systems for improving efficiencies should also be further explored (Chary et al. 2024).

Blue foods and the Sustainable Development Goals

The 2030 Agenda with its 17 Sustainable Development Goals (SDGs) (UN General Assembly, 2015) presents humanity with a pathway to a more prosperous, equitable, and sustainable future. It aims not only to eradicate poverty and hunger and improve health and nutrition, but also to reduce inequalities and build peaceful, just, and inclusive societies while remaining within planetary boundaries. The food system connects to the SDGs in multiple ways through resources, environments, economics, and people's well-being. The diverse aquaculture sector makes important contributions toward achieving the Sustainable Development Goals (SDGs)/Agenda 2030 (Troell et al. 2023). Aquaculture is an important sector contributing to human well-being and plays an increasingly important role in efforts to meet the SDGs (Hambrey 2017). Aquaculture may contribute to all 17 SDGs but the most obvious are those related to (A) eliminating hunger and improving health (SDGs 2, 3); (B) increasing environmental sustainability of oceans, water, climate, and land through responsible production/consumption (SDGs 6, 12, 13, 14, and 15), and (C) reducing poverty, achieving gender equality, improving livelihoods, and reducing inequalities (SDGs 1, 5, 8, and

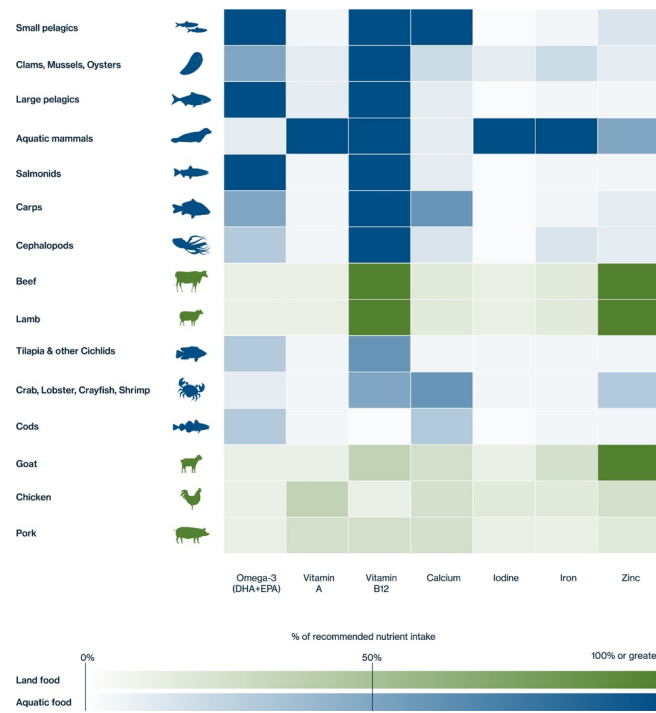


Figure 3. Nutrient diversity of aquatic animal-source foods in relation to terrestrial animal-source foods. From Blue Food Assessment – redrawn from Golden et al. 2021.

10). Not so obvious, but also relevant, relates to aquaculture's potential for energy production (e.g., algal biomass), adding food production in cities (e.g., vertical farming, aquaponics, community farming), contribution to technology development and development of various partnership (local to global) (SDGs 7, 9, 11, and 17). How well aquaculture can be positioned to be part of the solutions progressing toward achieving the SDGs will depend on good governance at all levels (local, national, regional and international) of decision-making (Hambrey 2017; Stead 2019; Farmery et al. 2021). There are many factors influencing what the outcomes for SDGs will be from different types of aquaculture systems in different situations. Some aquaculture systems (e.g., of naturally low trophic species, including extractive species) have relatively low environmental footprints compared with many terrestrial animal production systems and can even provide environmental restorative functions, but as with all food systems different trade-offs will result, for example, environmental performance versus societal benefits. Thus, increasing understanding about environmental, social, and economic characteristics of the multifaceted nature of aquaculture will provide for more context-specific policies and solutions. Unpacking aquaculture's diverse functions and generation of diverse values at multiple spatio-temporal scales enables improving aquaculture's present and future contribution to human well-being and planetary health.

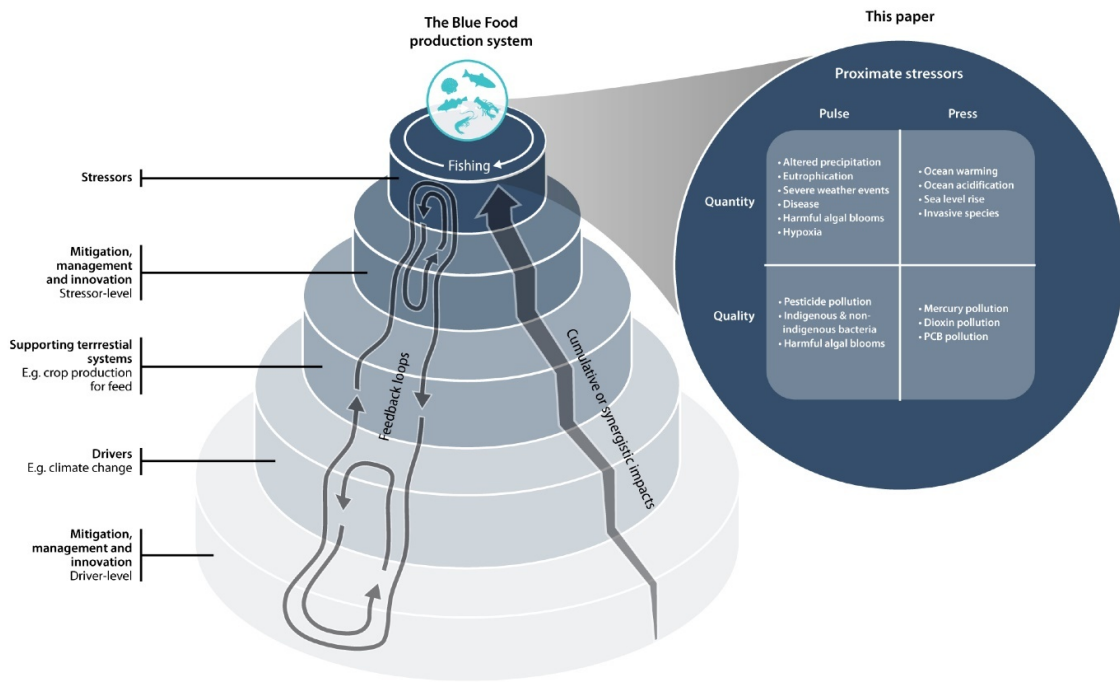


Figure 4. A conceptual framework for analysis of the broader context of stressors on blue food production systems (from Cao et al. 2023). The layers of the “cake” indicate the hierarchy and scale of impacts on aquatic food production systems and also human mitigation efforts, from the first level of underlying drivers (e.g., climate change), to the influence of linked terrestrial systems (e.g., nutrient inputs) and the resulting direct stressors. Feedback loops indicate the potential ameliorative effect of human mitigation efforts at the driver and stressor levels. Gray arrows indicate the potential for cumulative and/or synergistic impacts on production systems as consecutive layers are considered. The fishing feedback loop indicates the unique self-impacting nature of wild capture fisheries as both a production system and a stressor. The zoomed-in matrix indicates the nature of key stressors including effects on both quantity and quality (food safety) and the distinction between pulse and press type of stress.

A closing window for Aquaculture

Except for climate change limited attention has been paid to how different types of aquaculture systems will be influenced by anthropogenic environmental changes (Cao et al. 2023). Emergent and increasing stressors affecting both the production quantity and quality need to be considered. Quantity is impacted by climatic stressors, including warming, acidification, sea level rise, severe weather events and altered precipitation, impact on production, and also by non-climatic stressors like hypoxia, eutrophication, diseases, invasion and parasites (Cao et al. 2023). In addition, stressors being concern for food safety (quality) includes harmful algal bloom toxins, non-indigenous and indigenous bacteria, heavy metals, pesticides, and antibiotics. These stressors can either be persistent and long-term, as with sea level rise (SLR) or pulses (brief and short-term although potentially frequent, as with severe weather events) (Cao et al. 2023). Harmful algal bloom (HAB) toxins are unique among this set in having a dual effect on both the quantity and quality of blue foods. An additional emerging stressor could be plastic contamination (Persson et al. 2022). Figure 4 presents a conceptual framework for analysis in the broader context of stressors on blue food production systems including also capture fisheries.

Short Conclusion

The expectations of a growing seafood industry are high, especially for an increased growth of the aquaculture sector. Development of sustainable feeds will be a major challenge as we approach a turbulent future characterized by increased scarcity. Innovations will have to look at feed resources not competing with human foods - thus out from a broader equity perspective. Ongoing and future direct and indirect effects from climate change will pose different challenges for both fed and extractive aquaculture species. Climate smart aquaculture should consider both climate impacts resulting from production, but maybe more important the ability of the production system to adapt to emerging climate driven changes.

Submitted: December 05, 2023 CET. Accepted: August 09, 2024 CET. Published: August 09, 2024 CET.



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