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Alternative seafood:
Assessing food, nutrition and livelihood futures of plant-based and cell-based seafood

WorldFish

In partnership with

INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE
IFPRI

Alternative seafood: Assessing food, nutrition and livelihood futures of plant-based and cell-based seafood

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Terminology

Aquaculture	Fish farming, shellfish farming	Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding or protection from predators. Farming also implies individual or corporate ownership of the stock being cultivated. For statistical purposes, aquatic organisms harvested by an individual or corporate body that has owned them throughout their rearing period contribute to aquaculture, while aquatic organisms that are exploitable by the public as a common property resource, with or without appropriate licenses, are the harvest of fisheries (Edwards and Demaine 1998).
Capture fisheries	Fisheries, wild fisheries	The harvesting of naturally occurring living resources in both marine and freshwater environments. The term can be further classified as industrial, small-scale/artisanal and recreational.
Fish		Fish, crustaceans, molluscs and other aquatic animals, excluding aquatic mammals, reptiles, seaweeds and other aquatic plants.
Food fish		Fish, crustaceans, molluscs and other aquatic animals, excluding aquatic mammals, reptiles, seaweeds and other aquatic plants, produced for human consumption.
Seafood	Aquatic foods	Fresh, brackish and marine aquatic plants, animals, especially fish, crustaceans and molluscs but excluding aquatic mammals, and other organisms, especially seaweed and microalgae, that are regarded as food.
Seafood, alternative		All plant-based, fermentation-derived and cell-based seafood alternatives that mimic the taste, texture, appearance and/or nutritional properties of conventional seafood.
Seafood, cell-based	Cultivated seafood, clean seafood, lab-grown seafood	Genuine animal seafood that can replicate the sensory and nutritional profile of conventionally produced animal seafood because it is comprised of the same cell types and arranged in the same three-dimensional structures as animal seafood muscle tissue.
Seafood, conventional		Seafood produced by capture fisheries and/or aquaculture.
Seafood, plant-based		Products that are structured plant-, algae- or fungus-derived foods designed to replace conventionally produced seafood either as standalone products or within recipes. For clarity, fermentation-derived products are grouped within this category.

List of abbreviations

BAU	business as usual
CCRF	Code of Conduct for Responsible Fisheries
CGIAR	Consultative Group on International Agricultural Research
DFID	Department for International Development
FAO	Food and Agriculture Organization of the United Nations
IFPRI	International Food Policy Research Institute
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IUU	illegal, unreported and unregulated
OECD	Organisation for Economic Cooperation and Development
SDGs	Sustainable Development Goals of the United Nations
SFS	sustainable food systems
TOC	theory of change

Executive summary

Aquatic foods, or "seafood," are plants, animals and other organisms produced in a diverse range of aquatic environments. They are an integral part of the global food system and contribute significantly to food and nutrition security and livelihoods globally. They are particularly important to low- and middle-income economies, where they provide nutrition, employment and income for many. The demand for aquatic foods continues to grow rapidly. But at a time of significant and unprecedented aquatic ecosystem stress, questions arise about the sustainability and resilience of present supplies and their ability to meet future demand.

Collectively termed "alternative seafood," plant-based seafood and cell-based seafood are emerging as a new source of food with potential to augment future seafood supplies. Rapid technological development in this field could complement existing initiatives for sustainable fisheries and aquaculture. However, it could also disrupt the seafood industry globally, with implications for the many people who depend on seafood for their nutrition and livelihoods.

This report sets out to explain and explore the emerging alternative seafood sector. It focuses on identifying research questions regarding the implications of alternative seafood for food and nutrition security, livelihoods and the environment in low- and middle-income nations.

The report presents an overview of both the "conventional seafood" sector, comprised of fisheries and aquaculture, as well as the alternative seafood sector. A sustainable food systems framework has been adopted to elaborate the implications, opportunities and challenges of the alternative seafood sector for food and nutrition security, livelihoods and the environment, now and over the next decade.

The research involved a review of literature and mass media as well as interactions with diverse stakeholder groups, including development specialists and stakeholder groups involved in production, investment, research, retail and advocacy of conventional and alternative seafood. Together with the International Food Policy Research Institute (IFPRI), we developed preliminary future growth scenarios for the plant- and cell-based seafood subsectors over the next decade. These were used to explore how their projected growth might impact global seafood supply and demand and to examine the utility of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) in informing decision-making and prioritizing research.

A theory of change approach was used to assess preliminary conclusions, underlying assumptions and key research questions. Following reviews by stakeholders during two virtual workshops (Asia-Europe and Africa-North America), six priority questions were identified for future research:

1. How are markets for plant- and cell-based seafood likely to develop in different regions?
2. How can plant- and cell-based seafood best contribute to food and nutrition security?
3. How much and what types of employment are likely to be created and/or lost in low- and middle-income countries by the plant- and cell-based seafood subsectors?
4. How can the development of the subsectors be guided to generate well-governed value chains that maximize societal benefits?
5. How do the environmental impacts of plant- and cell-based seafood compare with those of conventional seafood?
6. How can changes in conventional and alternative seafood production and/or consumption generate observable improvements in aquatic ecosystem health?

1. Introduction

Aquatic foods, hereafter called seafood, are an integral part of the global food system that contribute significantly to food and nutrition security and livelihoods (Subasinghe et al. 2019). Seafood is increasingly acknowledged as a key part of a diverse, healthy diet and is an especially important source of essential micronutrients for the poor (Willett et al. 2019). More than 1 billion people depend on fish as their main animal protein source (FAO 2020c). Currently, more than 4.5 billion people get at least 15% of their average per capita animal protein intake from fish (Subasinghe et al. 2019). Global population growth coupled with rising incomes is fueling an increase in seafood demand at a time of significant and unprecedented stress on oceans, lakes and rivers. The global supply of seafood comes from both aquaculture and capture fisheries, which an estimated 820 million people depend on for their livelihoods (FAO n.d.; OECD n.d.-a). While initiatives to enhance the sustainability of fisheries and aquaculture are gaining traction (Brugère et al. 2019; FAO 2020c), seafood production, especially in capture fisheries, is also shifting toward regions where laws and regulations are more difficult to enforce (The Good Food Institute 2019). To address the considerable concern about the sustainability of present supplies and the industry's ability to meet future demands (Barange et al. 2018; The Good Food Institute 2019), equitable, innovative, scalable approaches are required.

Consumer awareness of public health issues (e.g. contaminants, zoonotic diseases, antimicrobial resistance), human rights violations, environmental degradation and ecosystem disruption are also becoming drivers of changes in both consumption and production. Development and commercialization of alternative seafood (plant-based and cell-based seafood) is an underexplored path that could potentially alleviate some of the pressure on aquatic ecosystems (Rubio et al. 2019; The Good Food Institute 2019). Recent literature on plant-based seafood (made from plants, marine or otherwise) and cell-based seafood (manufactured through cell culture) (The Good Food Institute 2019) and growing investment interest necessitates an exploration of how alternative seafood might contribute to sustainable production of seafood. This report focuses on understanding the development of alternative seafood markets and the implications, opportunities and challenges for the food and nutrition security and livelihoods of the millions of people in low- and middle-income countries that depend on fisheries and aquaculture.

Cell-based seafood: poke bowl and fish maw.

2. Objectives

This study is primarily a scoping exercise. It aims to develop an overview of both the conventional and emerging alternative seafood sectors and the potential impacts of the latter, positive and otherwise, on food and nutrition security, livelihoods and the environment. In particular, it is concerned with how a growing alternative seafood sector might impinge on these issues in low- and middle-income countries.

The study is based on a review of literature and mass media, as well as insights gained from interactions with international research and development specialists and stakeholders involved in production, investment, research, retail and advocacy of seafood and alternative seafood. The overarching objective is to develop a set of priority research questions to understand the implications of the emerging alternative seafood sector on the future of food, nutrition and livelihoods in low- and middle-income nations.

The following are the specific objectives of the study:

- Develop a report of plant-based and cell-based seafood.
    - Elaborate an overview of globally and regionally nuanced seafood production sectors: production, sources, markets, value, food and nutrition security, and future supplies and demand.
    - Synthesize a coherent picture of current alternative seafood production: technologies, products, markets and investment, based on a literature review and stakeholder interaction. Develop future growth scenarios designed to inform development specialists about how the alternative seafood sector might impact food and nutrition security, livelihoods and the environment.
- Develop a research and model development program of work that addresses priority unknowns with regards to future alternative seafood production trends and the impact on hunger and poverty.
- Identify and articulate priority research questions around alternative seafood.

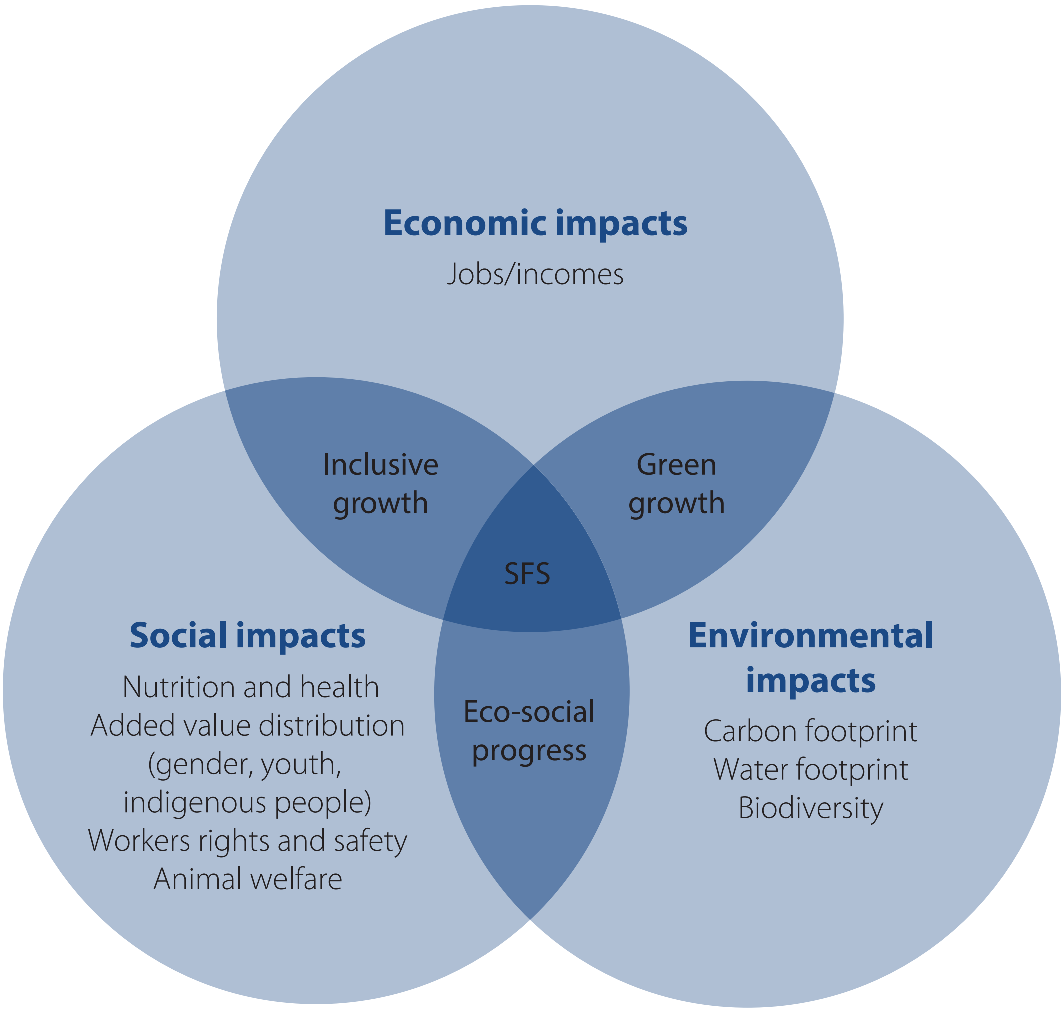
Plant-based seafood: avocado roll and soba.

3. Study methodology

3.1. Introduction

For the purposes of the study, a sustainable food systems (SFS) framework has been adopted (FAO 2018a). An SFS is central to the UN's Sustainable Development Goals (SDGs), in which major transformations in agriculture and food systems are essential to ending hunger and poverty. An SFS comprises a number of subsystems. Typically, they include farming, waste management, input supply and output systems, as well as other essential systems, including an energy system, trade system and associated drivers. SFS deliver food and nutrition security for all, without compromising the economic, social and environmental systems needed to provide food and nutrition security for future generations (FAO 2018a; HLPE 2014). The study considers all three elements essential to sustainability: social, economic and environmental.

The study is based on a combination of a literature review, interviews with representatives of key stakeholder groups, scenario development and two workshops. Certain aspects of sustainability are given greater attention than others (Figure 1).



Source: modified from FAO 2018a.

Figure 1. Sustainability in food systems.

3.2. Literature review

The review elements of the study were primarily developed through a search of peer-reviewed and grey literature and, importantly for such a rapidly developing sector, of mass media. Where possible, interactions with stakeholders were used to corroborate opinions expressed online.

3.3. Stakeholder interviews

Stakeholders were identified in the course of the review and assigned to one of the following groups to facilitate consultation: plant-based seafood or cell-based seafood producers, investors, researchers, retailers and advocates. Interviews were carried out to better understand the market trends of alternative seafood and the potential implications for consumers (including those for whom seafood is an important source of protein, lipids and micronutrients), fisheries and aquaculture (e.g. supplies, markets, employment) and the environment. This information was used to inform growth scenarios of the sector.

Structured questionnaires were developed for each stakeholder group. With the exception of retailers, at least three representatives of each stakeholder group were interviewed, for a total of 18 interviews. Anonymity was assured. Interviews were conducted by phone or video meetings over the course of 2 weeks in late June and early July 2020 (Appendix A).

Due to the small sample sizes from each stakeholder group, interview responses were used to qualify preliminary findings from the literature review and inform development of the research, including the future growth scenarios.

3.4. Future growth scenarios development

Two future growth scenarios were developed to frame plausible ranges of growth for the plant- and cell-based seafood subsectors over the next decade. These scenarios were used to provide insight about the potential of the alternative seafood sector to impact food and nutrition security and livelihoods. Key scenario parameters were determined in conjunction with IFPRI. Scenarios and ensuing market share analysis were developed from consideration of the current growth trajectory of the subsectors, specifically in terms of production volumes and value. Further validation is necessary to apply these outputs to more robust modeling exercises.

3.5. Workshops

The main goals of the workshops were to (1) share and evaluate preliminary findings from the literature review, stakeholder interviews and scenario development, (2) identify knowledge gaps, and (3) elucidate future research priorities with respect to the alternative seafood sector and development. Workshop outputs were used to help finalize this report.

The workshops participants comprised 14 alternative seafood stakeholders, most of whom had been previously interviewed, and 24 international research and development specialists, including those whose focus on eradication of hunger and poverty and the social, economic and environmental dimensions of development.

Due to COVID-19, the workshops were conducted in a virtual environment. Two 90-minute virtual workshops, one for participants in Asia and Europe and the other for those in Africa and North America, were held on consecutive days in early August 2020. Preparatory materials were circulated among participants. They included study background, key research articles and short video pieces by regional WorldFish staff (Bangladesh, Solomon Islands, Zambia) on the roles of aquatic food. The workshops were structured around a presentation of a theory of change (TOC) that outlined WorldFish's concept of how the alternative seafood sector might impact food and nutrition security, livelihoods and the environment and proposed key research questions needed to validate underlying assumptions. Breakout sessions followed, which were designed to facilitate the review, validation and prioritization of the proposed research questions. Workshop outputs were captured in templates from the breakout sessions, questions submitted by participants, and notes made during plenary discussions (Appendix C).

4. Seafood and the global food system

4.1. Introduction

Throughout recent decades, fishers and farmers have steadily increased food production, outpacing rising demand from both population and income growth. Initially, this was done by using more land and water. From 1960 onward, however, continued land conversion and intensification of production methods have allowed for increased total food production and food production per unit land area. Since then, the global population has more than doubled and terrestrial food production has more than tripled, while agricultural land use has increased less than 15% (OECD n.d.-b). Intensification of agricultural production has been achieved through improved crop and livestock varieties, increasing use of irrigation, synthetic fertilizers and crop protection chemicals, and changes in farm management practices, such as crop rotation.

Over the same period, conventional seafood production has increased more than five-fold (FAO 2020c). Between 1960 and 1990, capture fisheries were the main source of increased seafood supplies. This was largely due to greater investment in technologies, including fishing vessels able to access new offshore areas and improved methods of finding, capturing and preserving catches at sea. Since 1990, however, fisheries production has stagnated. Today, about 60% of stocks are fully fished while more than 34% are overfished (FAO 2020c), and despite numerous initiatives, stock recovery has been slow. For the past 30 years, aquaculture has accounted for the growth of seafood production and since 2014 has supplied more than half of all fish eaten. By 2021, it is expected that aquaculture will generate more than half of all seafood supplies, including seafood for non-food uses (OECD/FAO 2020). The rapid development of aquaculture has occurred due to massive private sector investment and technological innovation, including intensification of production with higher stocking densities, increased feed use and increased energy use for water management. In Sections 4.2–4.5, we consider the role of seafood in sustainable food systems and its social, economic and environmental implications, now and over the next decade.

4.2. Social impacts: Seafood, the global food system and food and nutrition security

Fish production has risen at an average annual rate of 3.1% over the past 60 years—far higher than that of other animal protein sources (2.1% for meat, dairy, milk)—and fish is one of the world's most traded food commodities (FAO 2020c). This growth and the extent of its trade have allowed seafood to assume an increasingly important role in the global food system.[1] Nevertheless, seafood consumption remains relatively understudied and underarticulated in the food and nutrition security discourse (Allison et al. 2013; Bogard et al. 2019; FAO 2018b).

The Food and Agriculture Organization of the United Nations (FAO) estimates that in 2018, 179 million metric tons of fish were produced, of which 156 million metric tons were used for human consumption (Figure 2). A further 32 million metric tons of aquatic algae, mainly seaweed, were also produced (FAO 2020c). This compares with global production of 2679 million metric tons of cereals, 2185 million metric tons of sugar, 1296 million metric tons of dairy products, 1053 million metric tons of oilseeds and 327 million metric tons of meat (OECD/FAO 2020).[2]

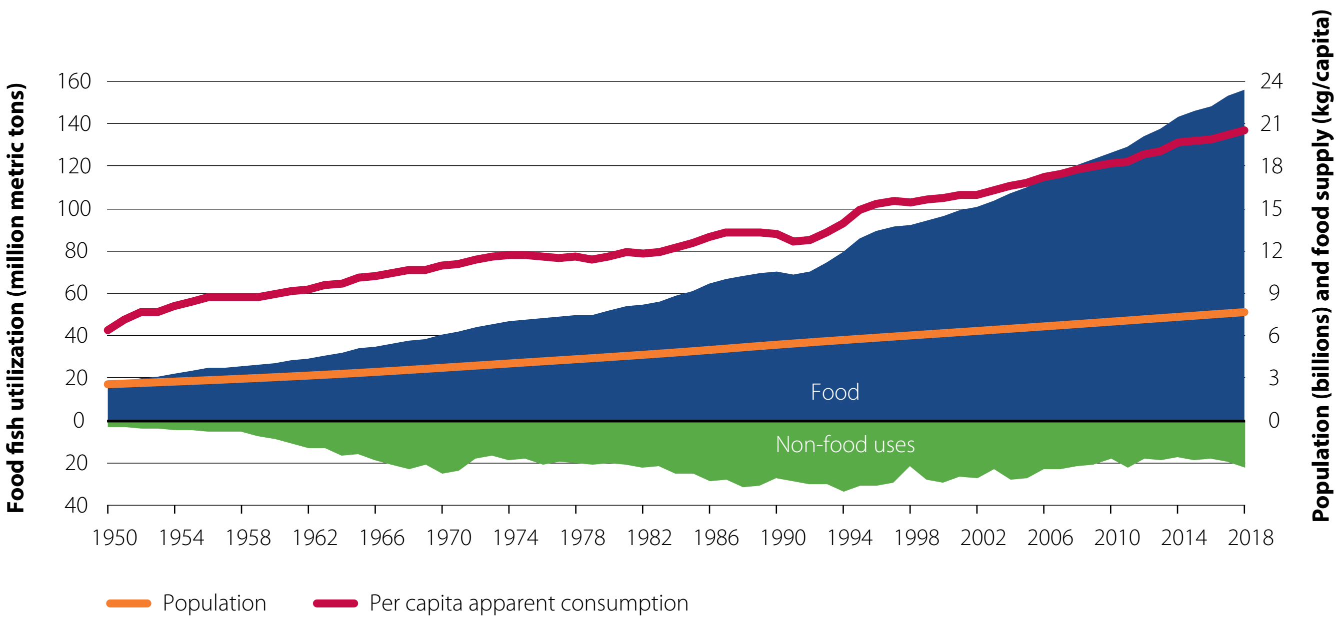
Between 2018 and 2030, global food demand is projected to grow about 17% due to population growth, growing wealth, and urbanization, and global food fish demand is projected to increase 18% over the same period (FAO 2020c). Growth in seafood demand could be greater than anticipated because of the continuing decline in total per capita red meat consumption in Europe and North America in favor of other protein sources, including poultry and seafood (FAO 2020a; Hicks et al. 2018; Santo et al. 2020).

Over the same period, conventional seafood production is expected to grow 15%, with almost all the growth anticipated to come from aquaculture (FAO 2020c). However, the projected growth rate of production is approximately half that of the previous decade. This is a result of greater adoption and enforcement of environmental regulations, increased outbreaks of aquatic animal and plant diseases, limited access to increasingly congested and contested coastal space (FAO 2020c) and, mainly in developed countries, market saturation of some farmed aquatic products.

Much of the growth of aquaculture is expected to occur in Asia, in countries including China, India, Indonesia and the Philippines (FAO 2020c). The growth of aquaculture in Africa over the next decade is predicted to be almost 50%, although it is measured against a very low baseline, just over 2 million metric tons. The continent is unlikely to account for more than 3% of global aquaculture production by 2030, even though the population is projected to grow by 32%.

Recent changes in global food production have increased per capita food consumption, including that of seafood, and decreased levels of hunger. The rate of food insecurity fell from 15% in 2000 to 11% in 2018, but this still unacceptably leaves 820 million people food insecure. This is largely due to poverty but is aggravated by conflict, which inhibits stable access to food (OECD/FAO 2020). Moreover, trends in restrictive trade practices, exacerbated by the COVID-19 disruption of both supply chains and trade (FAO 2020b), could increase the frequency of localized food shortages, especially in areas where population growth is high and opportunities to increase food production are limited (OECD/FAO 2020).

These figures say nothing about nutrition and health outcomes nor the resilience and sustainability of present food systems. Recent reviews, such as that of the EAT-Lancet Commission on Healthy Diets from Sustainable Food Systems, claim that they are threatening both (Willett et al. 2019). In addition to the 820 million food insecure people worldwide, many more consume low-quality diets. These diets cause micronutrient deficiencies and contribute to the substantial rise in incidences of diet-related obesity and diet-related noncommunicable diseases (such as coronary heart disease, stroke and diabetes) that are reckoned to be the single largest contributor to premature death and morbidity.



NOTE: Excludes aquatic mammals, crocodiles, alligators and caimans, seaweeds and other aquatic plants.

Source: modified from FAO 2020c.

Figure 2. World food fish use and apparent consumption.

Increases in seafood supplies from aquaculture have moderated seafood price rises, adding resilience to the global food system (Troell et al. 2014). Some aquaculture, however, is targeted at wealthier consumers in domestic cities or international markets rather than local rural areas (Golden et al. 2017; Thilsted et al. 2016). An important exception is the semi-intensive freshwater aquaculture of carp and tilapia. These are low-cost fish that have become increasingly essential sources of animal protein in some low- and middle-income countries in Asia and Africa (FAO Fisheries and Aquaculture Department 2018; Golden et al. 2017; Macfadyen et al. 2012; Pomeroy et al. 2014; Toufique and Belton 2014).

Nevertheless, per capita fish consumption is lowest in Africa and other low-income food-deficit countries (Table 1). Ensuring adequate access to those who most depend on seafood for food and nutrition security requires a range of measures. Aquaculture policies tend to be geared toward production and economic impacts. However, policies must also consider the sociocultural dynamics of local food systems and be aligned with nutrition and health policies and outcomes, especially with regards to the most vulnerable populations, such as children in the first 1000 days of life (Cusick and Georgieff n.d.; FAO 2020c; Hicks et al. 2019; Thilsted et al. 2016).

4.2.1. Nutrition and health

There has been a paradigm shift in food and nutrition security thinking. Rather than focusing on feeding people, the focus now moves toward nourishing people with sustainable diets, emphasizing the importance of nutrition and health as a key outcome of food systems (Global Panel on Agriculture and Food Systems for Nutrition 2016; Willett et al. 2019).

People best obtain nutrients from a varied diet. An analysis of the quality and scientific rigor of more than 200 articles published between 2003 and 2014 found that there was overwhelming and consistent evidence that fisheries and aquaculture contributed to improving food and nutrition security in low- and middle-income countries (Béné et al. 2016; Bogard et al. 2017; FAO 2018b;

Region/economic grouping	Total apparent food fish consumption (t of live weight equivalent)	Per capita apparent food fish consumption (kg/year)
World	152.9	20.3
World (excluding China)	97.7	16.0
Africa	12.4	9.9
North America	8.1	22.4
Latin America and the Caribbean	6.7	10.5
Asia	108.7	24.1
Europe	16.1	21.6
Oceania	1.0	24.2
Developed countries	31.0	24.4
Least developing countries	12.4	12.6
Other developing countries	109.5	20.7
Low-income food-deficit countries	23.6	9.3

Source: modified from FAO 2020c.

Table 1. Total and per capita apparent food fish consumption by region and economic grouping (2017).

Kaimila et al. 2019; Longley et al. 2014; Thompson and Amoroso 2014). Seafood is a nutrient-dense source of high quality, highly bioavailable proteins, lipids and micronutrients. It also contains the essential amino acids required for human health. Seafood supplies an estimated 14%–16% of global animal-source protein intake (WHO 2008), and the bioavailability of protein in fish and fish products is 5%–15% higher than from plant sources. Seafood provides more than 20% of the average per capita animal protein intake for 3 billion people worldwide and more than 50% in some low- and middle-income countries, such as Bangladesh, Ghana and a number of Small Island Developing States (The Commonwealth Blue Charter 2020).[3]

Many aquatic species, particularly pelagic fatty fish (such as sardines, mackerel, herring) and salmon, are rich in long-chain omega-3 fatty acids that contribute to visual and cognitive development, especially during the first 1000 days of a child's life (Roos 2016). Seafood also provides essential minerals, such as calcium, phosphorus, zinc, iron, selenium and iodine, as well as vitamins A, D and B, helping reduce the risks of both malnutrition and noncommunicable diseases (Allison et al. 2013; Béné et al. 2015; Kwasek et al. 2020). Micronutrient and lipid contents are especially high in small fish species consumed whole and in fish parts that are not widely consumed, such as head, eyes, bones and skin (HLPE 2014).

There is enormous interspecies variation in fish nutrient composition, in part determined by environmental and ecological traits (Hicks et al. 2019). There are also notable differences between wild and farmed species. The rise of aquaculture has changed the global composition of seafood that we consume, especially of fish, from being dominated by oily, pelagic marine species to freshwater species, which differ in oil content and composition (Beveridge et al. 2013). The fat content of farmed aquatic animals is also higher than that of their wild counterparts (Barange et al. 2018; Beveridge et al. 2013). These changes have implications for countries where aquaculture is important for food and nutrition security. In Bangladesh, for example, aquaculture production grew 810% (0.2 to 1.96 million metric tons) between 1991 and 2010 while fish consumption increased 30% over the same span. Paradoxically, however, per capita intake of iron and calcium decreased significantly over that period (Bogard et al. 2017). This has been attributed in part to a change in species eaten—a shift from small, wild-caught fish that tend to be consumed whole, to large, farmed fish—and to the intensification of aquaculture production methods, with increasing reliance on plant-based pelleted feed. The increasing dominance of aquaculture production does not necessarily mean a decline in nutrition. There is considerable opportunity to fortify the nutrient content of farmed aquatic produce for the benefit of consumers (Gephart et al. 2020; Kwasek et al. 2020) as well as repurpose nutrient-rich waste streams from processing, such as bones and viscera, into nutritious consumer products.

The consumption of seafood is not without risk. Metals such as mercury and lipid-soluble organic pollutants, like polychlorinated biphenyls, can accumulate in fish, especially in longer lived species that feed at the top of the aquatic food web, which when consumed pose a potential threat to human health (Jahncke et al. 2002). Accumulation of toxins can also occur when fish consume toxin-producing algae. People who eat seafood contaminated by algal toxins can become ill, with symptoms being dependent on the amount and type of toxin ingested (Pennotti et al. 2013). Ciguatera toxin, for example, is produced by dinoflagellates and concentrated in fish organs. When ingested, even when cooked, these can cause nausea, pain, cardiac and neurological symptoms in humans (Pulido 2016). While people can avoid such problems by reducing consumption of affected species, mislabeling of fish products can expose vulnerable consumers to risk (Marko et al. 2014). Yet the positive effects of fish consumption largely outweigh the potential negative effects associated with contamination risks (FAO/WHO 2011; HLPE 2014), with the exception of vulnerable groups, such as children and pregnant women, for whom contaminant levels have greater significance than the general population (Béné et al. 2016).

Seafood consumption is thus increasingly acknowledged as beneficial for individual growth and development, and consumption of a certain amount of fish, fatty fishes in particular, is associated with reduced risk of coronary heart disease and stroke (FAO/WHO 2011). The links between seafood consumption, nutrient intake, nutritional status and health are, however, confounded by other factors in addition to the species and production

Box 1. Fisheries and aquaculture in Bangladesh

Kazi Ahmed Kabir

Bangladesh is one of the world's major producers of seafood (FAO 2020c) and a unique example of continuing this growth inclusive of smallholders (Hernandez et al. 2018). Eighteen million people directly or indirectly depend on fisheries and aquaculture for their livelihoods, which comprises more than 25% of agricultural GDP and accounts for 3.57% of national GDP (Department of Fisheries 2018b). Fish is a culturally significant part of the diet in Bangladesh. It accounts for more than 60% of animal protein intake (Department of Fisheries 2018b) and is essential to reducing malnutrition and hunger (Hernandez et al. 2018). In 2017–2018, total fish production was 4.5 million metric tons, of which 63% came from aquaculture (Department of Fisheries 2018b). Seafood, especially crustaceans, is the second-most important export commodity of Bangladesh, earning USD 520 million in 2017–2018 (Department of Fisheries 2018b).

Nutrition sensitive aquaculture, Goaldhanga, Jashore, Bangladesh.

Bangladesh is one of the few countries in the world where both aquaculture and capture fisheries (inland and marine) are growing (Department of Fisheries 2018b; FAO 2020c). This is due to deltaic agroecology and the availability of water resources, including 800,000 ha of inland aquaculture, 3.9 million ha of inland capture fisheries, 16 million ha of marine waters and 710 km of coastline (Department of Fisheries 2018b). Future scenarios indicate a continued growth of both aquaculture and fisheries in Bangladesh until 2050 (Rashid and Zhang 2019).

Local fish market in Teknaf, Bangladesh.

According to the UN's Intergovernmental Panel on Climate Change Fifth Assessment, Bangladesh is one of the most vulnerable countries to climate change (IPCC 2014). In addition, poor infrastructure and competition for land use with other agricultural and industrial growth might diminish the expected benefits from aquaculture and fisheries, as shown in Figure 3 (Parvin et al. 2017).

An in-depth analysis of multisectoral growth and a clear development plan with public-private partnership is essential to reach national targets for SDGs as well as the government's vision for 2021, when the country will celebrate its 50th anniversary of independence.

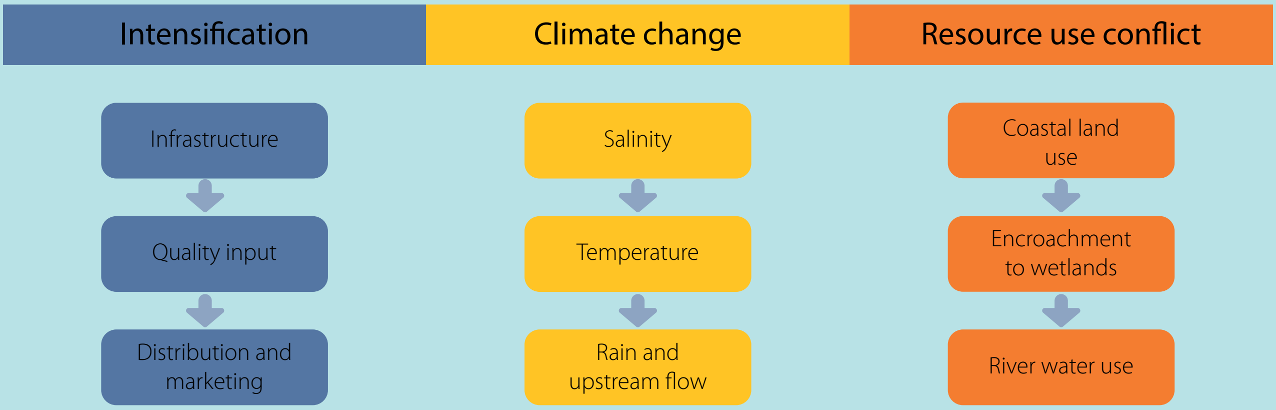


Figure 3. Major challenges for growth of aquaculture and fisheries in Bangladesh.

method. These factors include good sanitation and safe drinking water, health services and adequate housing (Willett et al. 2019).

4.3. Economic impacts: Livelihoods, employment and working conditions

About 60 million people are employed in the primary sector of fisheries and aquaculture worldwide, two-thirds of whom work in fisheries (FAO 2020c). Most are small-scale artisanal fishers and aquaculture workers in low- and middle-income countries in Asia and Africa. Women account for a higher percentage of the workforce in aquaculture (14%) than in fisheries (11%). Most often, they work as small-scale producers in postharvest industrial and artisanal processing, value addition marketing, and sales. Informal work arrangements characterize the sector, and there is an enormous diversity of seasonal, temporary and permanent occupations. The complexity and informal nature of the sector also makes estimating employment difficult. FAO estimates that 820 million people depend on fisheries and aquaculture for their livelihood, which is equivalent to about 10% of the global population. This encompasses involvement in upstream and downstream segments of the value chain, including boat building, net fabrication, fishing and fish farming, seafood processing, transportation and retail (FAO n.d.).

Yet informal work arrangements have resulted in generally low salaries and poor protection of labor rights. Even when regulation exists, enforcement is weak. Only a minority of fish workers belong to unions, associations or cooperatives, which limits their influence over decisions on access and use of fishery resources (Nakamura et al. 2018). However, certain types of aquaculture have been shown to improve the livelihoods of economically disadvantaged and socially marginalized people (Dey et al. 2013; Kassam and Dorward 2017; Pant et al. 2014). Nonetheless, serious labor abuses, including forced labor, child labor and forced child labor, have been reported in fisheries in 47 countries, which are often though not exclusively illegal, unreported and unregulated (IUU) fisheries (Nakamura et al. 2018).

Meghna River, Bangladesh.

Box 2. Fisheries and aquaculture in Solomon Islands

Delvene Boso

Solomon Islands is home to 694,619 people (SINSO 2020). The entire population lives within 100 km of the coast, with 94% living within 5 km of the coastal margins of small islands, atolls and otherwise mostly mountainous and inaccessible islands (Foale et al. 2011). Like many in the Pacific, most Solomon Islanders are defined by their relationship to the sea—they are ocean people. It is a region of spectacular diversity and is rich in natural wonders, cultures and traditional practices.

Reef fish for sale at Gizo market, Western Province, Solomon Islands.

Despite its beauty, poverty, vulnerability and inequality persist across many sectors of the society. Solomon Islands was ranked fourth among the most-at-risk societies in the world (Day et al. 2019). Extreme poverty affects approximately one-quarter of all Solomon Islanders, which is higher than any country in Asia, and is projected to rise anywhere from 2% to 12% due to the most recent external shock, COVID-19 (Hoy 2020).

Adding fertilizer to land nursery tank, Aruligo, Solomon Islands.

Solomon Islanders eat a lot of fish. It is caught, distributed and then acquired by consumers through purchase, gifting or bartering. In Solomon Islands, the per capita aquatic food consumption is 72 kg, and 98% of urban households regularly buy fish (M. Sharp, H. Eriksson, J. Scott and N. Andrew, personal communication, 2020). This system of producing and distributing fish connects remote sources of supply with urban areas of demand and generates indispensable value, both in the form of fish-based livelihoods for the many people involved and for food and nutrition security in island populations. During periods of hardship and disruption, such as the ongoing COVID-19 pandemic or natural disasters, fish and fish-based livelihoods play an important role in the resilience of community economies (Eriksson et al. 2017). Maximizing the livelihood benefits of fish is more important than ever.

In the Pacific, per capita coastal fisheries production is declining (Gillett 2016). Within a decade, an estimated additional 115,000 t of fish per year will be needed across the region for good nutrition (Bell et al. 2009). Recognizing the potential for aquaculture to contribute to food security and livelihoods, the Solomon Islands government, through the Ministry of Fisheries and Marine Resources (MFMR), developed a revised Solomon Islands Aquaculture Development Plan that focuses on importing and preparing for bringing Nile tilapia into the country. Through the support of the New Zealand Ministry of Foreign Affairs and Trade, the MFMR has built a national aquaculture facility west of the capital at Aruligo where the old International Center for Living Aquatic Resources Management (WorldFish) facilities used to be.

Current freshwater aquaculture activities are, however, minimal. There are freshwater farms of Mozambique tilapia in the outskirts of Honiara, with more developed farms in the inland communities surrounding the Auki township of Malaita Province. These provide inland communities with fish for consumption and income. With the ministry's National Fisheries Policy 2019–2029 goal to have a "sustainable fisheries sector that contributes to the socio-economic needs of all Solomon Islanders," there is a strong direction to focus on livelihood activities for socioeconomic well-being.

4.4. Environmental impacts

4.4.1. Fisheries

A combination of vessel subsidies, ineffective management, discards, habitat degradation, lost or discarded fishing gear and IUU fishing has resulted in severely depleted global fisheries, damaged marine habitats and destabilized ocean ecosystems (UN 2020). One-third of all fishstocks are being depleted faster than they are able to recover, while an additional 60% are fished at the maximum sustainable level. Only 6% of fishstocks are assessed as underfished (FAO 2020c).

Destructive fishing techniques, like bottom trawling and dredging, can cause immediate and direct damage to benthic environments and communities, including seagrass meadows, cold water corals and tropical coral and sponge reefs (FAO/UNEP 2010). Further indirect or delayed effects often also emerge as impacts are transferred through the ecosystem. This endangers the survival of larvae and juveniles of a wide variety of marine life. For example, coral reefs, which harbor an estimated 25% of marine fish species, are easily damaged by bottom trawling and take decades to recover (Althaus et al. 2009). The present private economic value of coral reefs, such as fishing, tourism and coastal construction, is estimated in excess of USD 20 billion annually, which is approximately 75% of the value they could generate if they were healthy (UN Environment et al. 2018).

Another problem is fisheries bycatch—the unwanted and often discarded fish and other marine creatures trapped by commercial fishing nets when fishing for a different species. This impacts trophic dynamics of ocean systems and poses serious ecological consequences for marine megafauna, such as turtles, seabirds, sharks and marine mammals (Lewison et al. 2004; Komoroske and Lewison 2015). FAO estimates an annual discard quantity of about 9.1 million metric tons (10.1% of annual catches), of which 4.2 million metric tons come from bottom trawls, 1 million metric tons from purse seines, 900,000 t from midwater trawls and 800,000 t from gillnet fisheries. FAO has also estimated that fisheries interact with at least 20 million individuals of endangered, threatened and/or protected species annually (Pérez Roda et al. 2019).

Because many commercial fish species take years to reach maturity, it can take decades for overfished or mismanaged areas to recover even when properly managed. By destroying habitat and driving marine species populations toward collapse or extinction, poor management of fisheries can impact entire ocean ecosystems (The Good Food Institute 2019). Removing top predators through bycatch or overfishing disrupts food webs, with worldwide ecological, economic and social costs (Pauly et al. 1998; Srinivasan et al. 2010; The World Bank 2017; World Wildlife Fund 2020).

The great majority of small-scale, artisanal or subsistence fishery landings are destined for local human consumption, thus contributing importantly to food and nutrition security in low- and middle-income countries. However, IUU fishing poses a threat to many people who depend upon fisheries for protein by exacerbating poverty, augmenting food insecurity and thwarting efforts to achieve the SDG targets. The impacts of climate change on the aquatic ecosystems is expected to hinder sustainable outcomes, and fishery-dependent low- and middle-income countries, particularly small-scale fisheries, are highly vulnerable to climate-related changes.

Reducing pressure on global fisheries is critical to allow commercial species and ocean ecosystems to recover from decades of exploitation and mismanagement. The World Bank has estimated annual net losses to global capture fisheries of USD 88.6 billion for 2012 (expressed in 2017 USD) due to overfishing, which if allowed to persist represents a lost natural capital asset worth trillions of dollars (The World Bank 2017).

4.4.2. Aquaculture

Aquaculture has its own associated environmental impacts, largely determined by species, system, production methods, location and management (Waite et al. 2014).

Seaweed and mollusc aquaculture generate food and feed ingredients, while at the same time removing human-generated nutrients. Although generally positive, seaweed farming can affect levels of light and dissolved nutrients and cause changes to kinetic energy, current regimes and sediment transport, which impact plankton and benthic communities (Campbell et al. 2019; Duarte et al. 2017; Hasselström et al. 2018). Seaweed farms also release particulate and dissolved matter, provide habitat for pathogens and release reproductive material (Campbell et al. 2019).

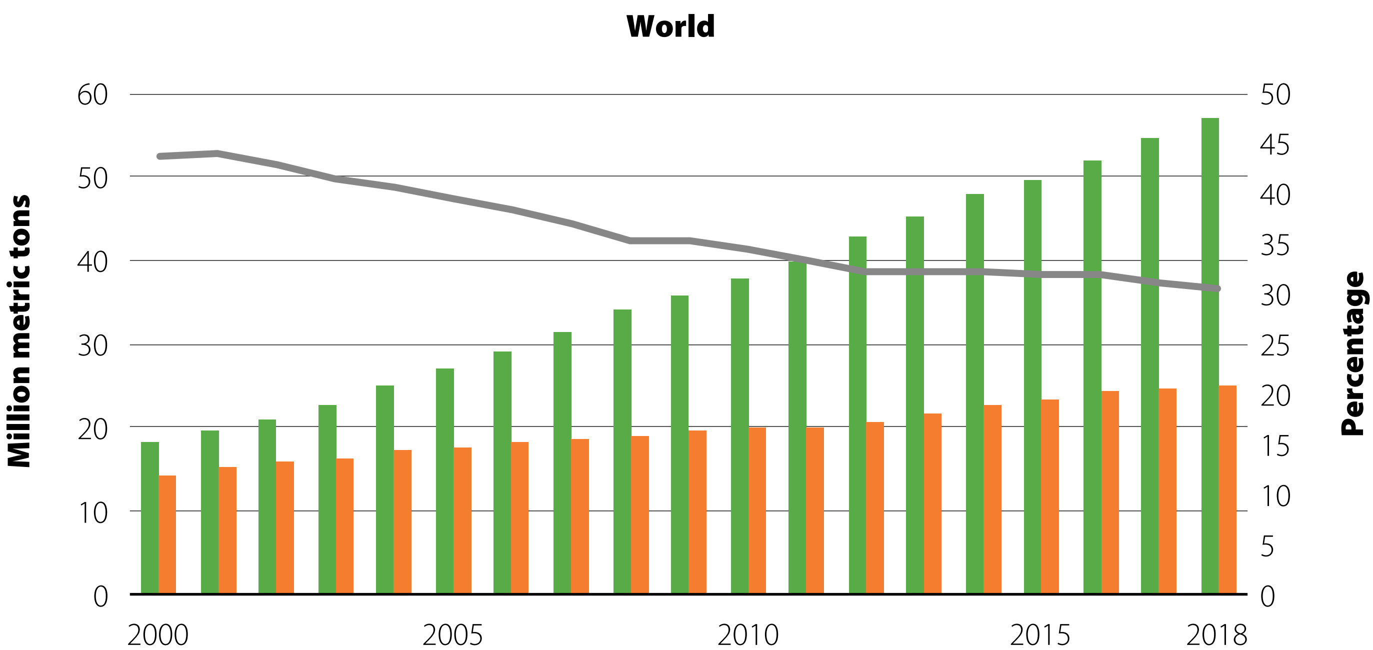
Fish and shrimp farming depend on a wide range of ecosystem services, including space, water, seed, fertilizers and feeds, and energy:

- **Space** on land or in sheltered coastal areas, lakes and reservoirs is used to establish pond, cage, longline or other production systems.
- **Water** physically supports farmed aquatic plants and animals, supplying oxygen and dispersing and assimilating wastes.
- **Seed** (postlarvae, fry or fingerlings) are used stock the farming systems.
- **Fertilizers** and feeds increase production.
- **Energy** is used to pump water and aerate ponds, transport seed and feed onto the farm, and process and move produce to markets.

Freshwater ponds account for the majority of farmed fish production. Generally, they are sited in farmland, often in lower lying, poorly drained areas of marginal productive value. During the 1980s and 1990s, coastal shrimp and fishponds accounted for an estimated 40%–50% of mangrove losses that occurred in Bangladesh, Brazil, China, India, Indonesia, Malaysia, Mexico, Myanmar, Sri Lanka, the Philippines, Thailand and Vietnam, with implications not only for biodiversity, fisheries and timber but also for coastal protection (Ahmed et al. 2018; Carugati et al. 2018).

On the face of things, using coastal areas for marine aquaculture appears trivial. For example, the sea surface area occupied by cages in Scotland to produce about 200,000 t of farmed Atlantic salmon is estimated at 2 km^2. However, their requirements for adequate shelter, water depths, seabed type and proximity to transport infrastructure necessitate developments being clustered in specific areas along the coast. Without careful planning and stakeholder consultation, the social license for coastal aquaculture to operate can be withheld (Aguilar-Manjarrez et al. 2017; Billing 2018).

Aquaculture is increasingly reliant on nutritionally complete feeds (Cottrell et al. 2020; Tacon and Metian 2015). It is estimated that about 30% of aquaculture production now uses such feeds (Figure 4). The majority of aquaculture feeds have included fishmeal and fish oil produced from the reduction of forage fish, small pelagic plankton-feeding fish that are preyed on by larger fish and by seabirds and marine mammals for food. High feed prices are forcing feed manufacturers



Source: modified from FAO 2020c.

Figure 4. Fed and non-fed aquaculture production (2000–2018).

to reduce fishmeal and fish oil inclusion rates in favor of oilseeds, like soy, and to seek alternative sources, such as co-products from fish processing, micro and macroalgae, bacteria, yeasts and insects (Cottrell et al. 2020; Little et al. 2016). The volume of fish from capture fisheries reduced to fishmeal and fish oil declined by 40% between 1994 and 2014 but has since remained steady at about 20 million metric tons per year (FAO 2020c). Improved feeds and feeding practices and reductions in fishmeal and fish oil dietary inclusion rates have also helped stabilize use in aquaculture.[4] It is estimated that fishmeal produced from fish processing wastes will represent 38% of world fishmeal production by 2025, compared to 29% for 2013–2015 (Ye et al. 2017). Depending on the rate of growth of fed aquaculture, especially in China, feeds compounded from novel feedstuffs (e.g. insects, yeasts, genetically modified crops) and improved feed conversion ratios could reduce forage fish use in the sector as much as 60% by 2030 (Cottrell et al. 2020). However, increasing reliance on plant-based feeds requires substantial areas of farmland and fresh water (Troell et al. 2014) and considerable energy to produce and transport food.

Uneaten food, fecal and metabolic wastes and chemicals, including medicines, are generally released from aquaculture production units, treated or untreated, into the environment to be dispersed and assimilated. Impacts of food and fecal wastes on the quality of receiving waters and sediments are readily detected, especially close to discharge points and after feeding. These wastes can cause elevated levels of nitrogen, phosphorous and carbon and reduced levels of dissolved oxygen. Eutrophication occurs where the release of wastes is large relative to the size of the receiving environment and amount of water movement. In freshwaters, eutrophication often manifests as phytoplankton blooms dominated by Cyanobacteria, with resultant changes throughout the aquatic food web (Brugère et al. 2019) including losses in biodiversity. Sediments under and immediately adjacent to cage fish farms also typically exhibit symptoms of eutrophication: large increases in the biomass of pollution tolerant invertebrate species and a loss of sediment community diversity (Beveridge 2004). Scaling developments within the capacity of the environment while respecting broader societal objectives for the environment is key to sustainable aquaculture.

An enormous taxonomic diversity of aquatic genetic resources contributes to fisheries and aquaculture production. Global aquaculture production includes almost 600 species, though 10 species account for more than half of aquaculture production (FAO 2019). Many farmed species and strains are non-native, dominating aquaculture production in many parts of the world.[5] Escapes of non-native species and strains that become invasive threaten many wild relatives of farmed aquatic species (FAO 2019). This compounds the threats to aquatic genetic resources posed by terrestrial and aquatic environmental degradation, climate change and overfishing. Through their presence alone, aquaculture farms can also impact biodiversity and ecosystem services.[6] For example, fish and shellfish farms attract predators and noise, and the presence of people can displace more sensitive species (Beveridge 2004). Greater scrutiny of the use and exchange of aquatic genetic resources is required, as is a better understanding of risks so that policies and practices can be designed and implemented to minimize risk and optimize opportunity (FAO 2019).

In sum, consuming resources and releasing wastes into the environment impact biodiversity and ecosystem services. The type and magnitude of impacts are determined by species, system, farm location, production method (extensive, semi-intensive and intensive) management. The effects that aquaculture has on biodiversity and ecosystem services can also have social and economic consequences. Good governance, appropriate legal frameworks, strong institutions with adequate institutional capacity and adoption of adaptive management are all essential to sustainably and equitably share benefits from ecosystem services.

4.5. Discussion

Over the past 50 years, global consumption of seafood has doubled, especially due to the rise of aquaculture. With the notable exception of Africa, future growth of conventional seafood supplies is generally projected to keep pace with the rising demand created by population growth, growing affluence and aspirations for healthier diets (OECD/FAO 2020).

Seafood is an excellent source of quality protein, lipids and micronutrients and is recommended as a part of a balanced diet (FAO/WHO 2011;

Box 3. The role of aquatic foods in Zambia

Rose Komugisha Basiita

Women selling dried fish along Kasama-Luwingu Road in northern Zambia.

Zambia is a landlocked middle-income country located in the southern part of Africa. Its increasing population is currently estimated at about 8 million. In the Zambian context, aquatic food implies fish, and in a few cases, freshwater crustaceans and reptiles. Aquatic foods play an important role among Zambians. They are sourced from capture fisheries and aquaculture that produce up to 80,800 and 32,888 t, respectively (Department of Fisheries 2018a). At the national level, fisheries contribute 3.2% to the overall GDP, and up to 40% of the overall animal protein intake at the household level (Shula and Mofya Mukuka 2015; Policy Monitoring and Research Centre 2017; Ng'onga et al. 2019). Over 12,000 households are engaged in aquaculture, and rural Zambians living along rivers and lakes fully depend on fisheries for their livelihoods. Recent statistics show that up to a million people depend on fisheries and aquaculture for income, employment and food and nutrition security. Women play substantive roles (40%–80%) in production, postharvest and marketing of the fisheries industry (Kruijssen et al. 2018; Phillips et al. 2016). Like elsewhere, sustainable use of aquatic resources is vital given that they are important to many vulnerable groups in Zambia, especially infants, lactating mothers, youths and the elderly.

Silver fish (kapenta) harvested and dried on the ground in Samfya District, Lake Bangweulu.

The country's aquaculture industry faces major challenges. These include but are not limited to undeveloped market linkages, lack of quality affordable and accessible fish feeds, lack of quality fish seed and issues of biosecurity and disease. Unsustainable harvesting methods have negatively impacted the capture fisheries sector, such as nonselective fishing methods and gear that have been used to indiscriminately harvest fish of various sizes and species that are many times not intended by the fishers. For example, the use of mosquito nets and fish poisoning have been recorded in various lakes and rivers in Zambia, such as Lake Kariba. These practices have generally led to a decrease in species diversity and production and a degradation of nursing habitat, among other things.

Climate change presents new challenges as well as opportunities for the fisheries and aquaculture sector. For instance, prolonged droughts and reduced water levels directly affect breeding and spawning of fish, such as catfish (*Clarias gariepinus*) in floodplains, including the Bangwuelu floodplains in northern Zambia (Huchzermeyer 2012; Shula and Mofya-Mukuka 2015). Poor postharvest handling continues to cause problems that lead to major fish losses, which affects the vulnerable groups that depend on aquatic foods for their livelihoods. Food safety and hygiene at landing sites and fish markets is another major challenge in Zambia. Preliminary studies done on Lake Kariba have revealed the presence of zearalenone, a mycotoxin in harvested kapenta (*Limnothrissa miodon*) and in the water (Gonkowski et al. 2018).

Despite the challenges and stresses on the aquatic system, WorldFish recently did a foresight analysis in Zambia that shows fish demand will continue to grow. Demand is mainly driven by population growth, income growth and diet transformation among urban dwellers that includes more animal-based protein, particularly fish (Tran et al. 2019). The current and future fish supply deficit in meeting this demand will require a robust and multifaceted approach to make aquatic food resources in Zambia more diverse, affordable and accessible to all.

Willett et al. 2019). However, many fishstocks and the aquatic environments that support them remain in a perilous state due to overfishing, habitat destruction and eutrophication. Capture fisheries also have a poor reputation with regards to exploitative labor. Aquaculture raises other concerns regarding the nutritional value of increasingly intensively farmed species, which depend on plant-based feeds, the consequences of waste discharge and the social issues arising from the informal nature of the subsector.

These challenges are well recognized, as acknowledged in the Code of Conduct for Responsible Fisheries (CCRF) that FAO and its members elaborated 25 years ago. An ecosystem approach to fisheries and aquaculture was adopted for managing and developing the sector. Progress, however, has been slow, primarily because of low compliance (Brugère et al. 2019; FAO 2020c). A number of initiatives, including those of the Marine and Aquaculture Stewardship Councils, seek to promote sustainable fishing and aquaculture practices through ecolabeling and certification schemes that build on the CCRF. New aquaculture technologies, including novel feedstuffs and enclosed and semi-enclosed production systems (such as Recycle Aquaculture Systems and aquaponics), promise to improve the nutritional value of farmed aquatic products and address environmental footprints. But again, progress has been slow at the needed scale.

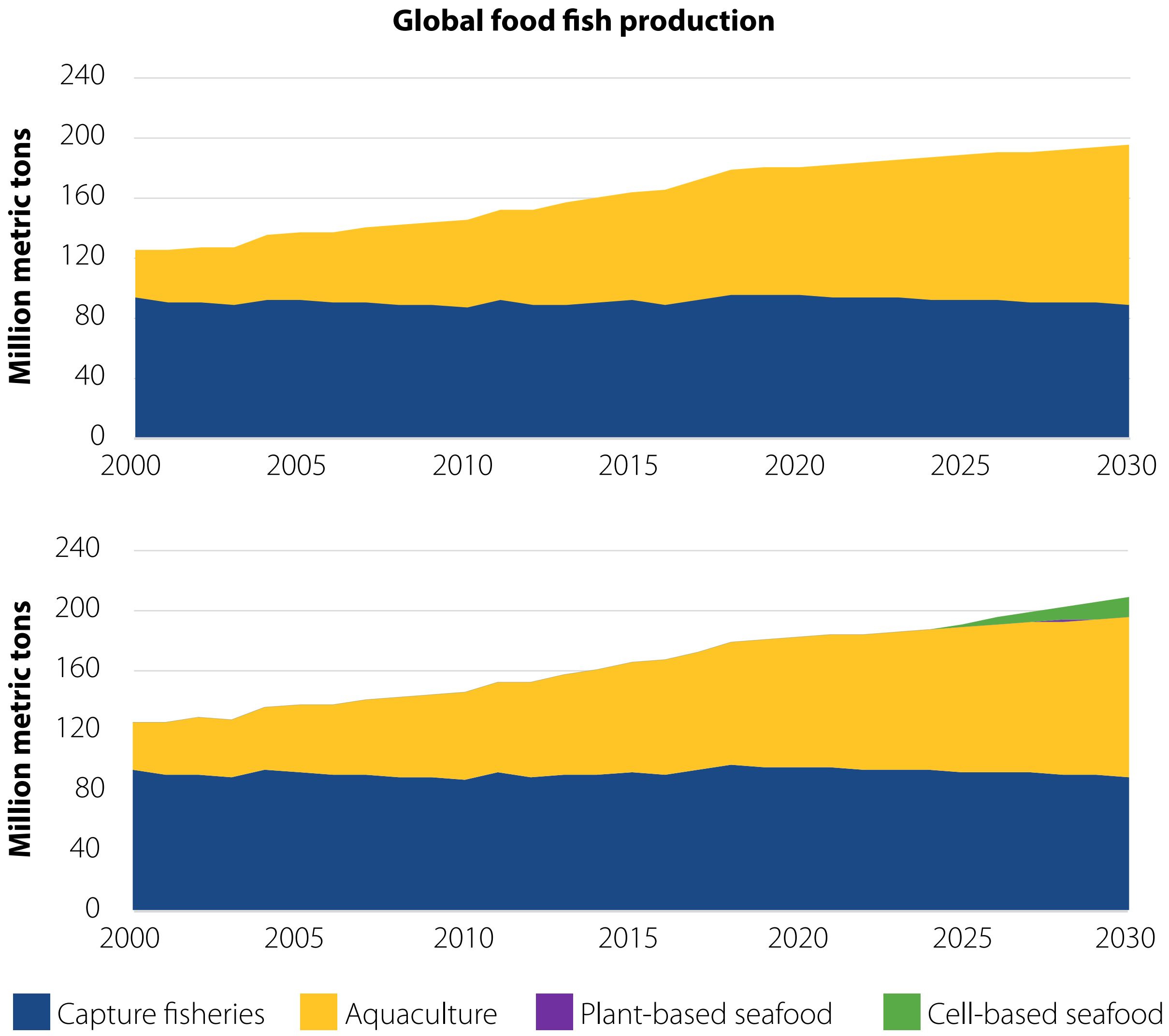
The COVID-19 pandemic has also exposed the vulnerabilities of the global food system. Many questions remain as to how the emerging alternative seafood sector will interact with the conventional seafood sector. Will the alternative seafood sector add resilience to the global food system on social, economic and environmental fronts? Will it develop in such a way that improves food and nutrition security and livelihoods for all?

Fish farmers, Kamukate Village, Luwingu District, Zambia.

5. Alternative seafood

By 2030, global food fish consumption[7] is projected to increase 18% (from 2018 levels) due to rapid population growth coupled with rising incomes and urbanization (FAO 2020c). Expanding seafood production and technological advances in fisheries and aquaculture are expected, but the majority of capture fisheries are already harvested at maximum capacity. While many believe aquaculture growth will keep pace with increased demand, with the notable exception of Africa, others believe that aquaculture growth will slow and leave many countries with unmet demand (Cai and PingSun 2017; OECD/FAO 2020). As a new seafood supply, alternative seafood is seeing increasing investment and could provide opportunities to help meet this rising demand while addressing concerns of the sustainability of the industry.

Alternative seafood is comprised of all plant-based, fermentation-derived and cell-based seafood alternatives that mimic the taste, texture, appearance and/or nutritional properties of conventional seafood. In this report, fermentation-derived seafood is grouped with plant-based seafood. Aquatic plants and algae, such as microalgae and seaweed, are widely consumed



Source: Historical data (2000–2018) from FAO 2020c and projections to 2030 from Searchinger et al. 2019.

Figure 5. Projected growth of food fish supply and potential for alternative seafood.

in Asia and the Pacific as food products. Globally, however, aquatic plants and algae are more commonly used as additives to food products (such as nutrient fortification, flavors and texturizers) and pharmaceuticals (such as antibiotic, antiviral and anti-inflammatory activities) (Aasim et al. 2018). Aquatic plants and algae as human food are not discussed further in this report of alternative seafood.

5.1. Plant-based seafood

Traditional plant-based replacements for meat and seafood, like tofu and tempeh, are generally derived from ingredients that include soybeans, wheat gluten, mushrooms, rice and legumes. These vegetable proteins mainly come from terrestrial agriculture systems and are further processed with water, flavoring, fat, binding agents and coloring agents to yield products that mimic the sensory attributes of meat and seafood (Kyriakopoulou et al. 2019).

Plant-based seafood comprises products that are structured plant-, algae- or fungus-derived foods designed to replace conventionally produced seafood either as standalone products or within recipes. Plant-based seafood is mainly comprised of a combination of the following ingredients: legume proteins, soy protein, wheat protein, rice, vegetables, mycoproteins, seaweed, algae and/or plant oils.

Plant-based seafood products that are meant to fully replace conventionally produced meat or seafood in a diet should provide a similar nutritional value, though they may lack enhancing factors. Animal-sourced protein is a complete protein, providing all nine essential amino acids. These proteins are highly bioavailable in seafood, as are essential micronutrients and fatty acids (Section 4.2.1). Efforts to mimic this can be partially achieved by integrating complete plant-based proteins, such as soy, algae and quinoa, or by using a complementary set of incomplete plant-based proteins within products. Plant-based seafood products that are meant to partially replace conventionally produced meat or seafood in a diet can be developed to meet other goals, such as balancing diets through, for example, a high dietary fiber content or vitamin and/or mineral fortification (Kyriakopoulou et al. 2019). Despite the intention, health implications regarding the number of ingredients, which can include binders, colorants and preservatives, and the degree of processing of plant-based replacements has raised concern in some quarters

Various plant-based seafood preparations (clockwise): unagi nigiri, tuna poke bowl and the concept of a salmon fillet.

(Monteiro et al. 2019). It is worth noting, however, that recent research has found that replacing conventional meat with plant-based meat products actually lowered several cardiovascular disease risk factors in generally healthy adults (Crimarco et al. 2020). Plant-based seafood companies are aware that there is currently limited evidence of the health effects of their products, so they are striving for transparency and simplicity in their recipes.

Plant-based seafood has a promising future with consumers, including those with seafood allergies, as indicated by recent demand trends for plant-based meat and dairy products (The Good Food Institute 2019). Upward of 20 well-established companies have emerged to meet this demand, and products mimicking shrimp, canned and raw tuna, fish fillets and burgers are already available for purchase at retailers, including Whole Foods, Amazon and Tesco.

The growth of the plant-based seafood industry has attracted attention from conventional animal-source food companies. This has led to a recent crossover of the industries, as seen by Bumble Bee Foods' joint venture with Good Catch, Van Cleve Seafood's launch of a plant-based seafood company, Tyson Ventures' investment in New Wave Foods, and Cargill and Nestlé's mass-market plant-based seafood products. Support from private investment and recent support from public investment (116th Congress (2019–2020), 2020) continues to signal interest in plant-based replacements for meat and seafood and funds fundamental research and development of novel products.

5.2. Cell-based seafood

Cell-based seafood is genuine animal-based seafood that aims to replicate the sensory and nutritional profile of conventionally produced animal seafood. It is comprised of the same cell types and arranged in the same three-dimensional structures as animal seafood muscle tissue.

Cell-based seafood is based on the isolation and multiplication of stem cells (capable of differentiating into many cell types) or immortalized cell lines (differentiated muscle, fat, connective tissue cells that continue to propagate) from aquatic animals (Benjaminson et al. 2002). Cells are generally grown in closed-loop bioreactors that regulate temperatures, nutrients and other conditions, such as dissolved oxygen and pH, to optimize growth. After sufficient cell multiplication,

Various cell-based seafood preparations (clockwise): shrimp dumplings, salmon nigiri, fish maw and yellowtail.

they are harvested and concentrated to produce products like seafood burgers and fish fingers, or the integration of scaffolding (structural support for cell attachment and tissue development) is used to produce fillets and other cuts that emulate the appearance and texture of conventional seafood products. Cell-based seafood allows for several benefits in comparison to conventional production. The isolated production of valuable cuts comes without production of by-products, such as scales and bones, and there are fewer public health concerns, such as contaminants, zoonotic diseases and antimicrobial resistance. There are also reduced animal welfare issues and the opportunity for local seafood production and distribution. The production technology is being adapted from other industries, such as biotechnology and brewing. As such, current outstanding issues are those of optimized and scalable production, including the development of appropriate cell lines and scaffolding, optimized media formulations and cell culture densities, and scalable bioreactor designs, as well as the use of natural resources, specifically water and energy (Rubio et al. 2019).

Startups still dominate the nascent cell-based seafood industry, which is less than a decade old. In that short time, the industry has been able to grow carp, tilapia, bass, rainbow trout, salmon, mahi mahi, lobster, Fugu, tuna, red snapper, yellowtail and shrimp. Investment levels continue to grow rapidly with recent involvement by the public sector (National Science Foundation 2020) and the most established cell-based seafood producers have managed to secure partnerships with major food conglomerates like Nutreco and Pulmuone (The Good Food Institute 2020a). The first company was founded in 2016, and with only about 10 companies in total the subsector is still quite new. As a result, no cell-based seafood products have yet received a product license, and they are unlikely to for at least 1 to 2 years. However, rising consumer awareness regarding the impact of sustainable food choices on natural ecosystems and a willingness of regulatory authorities to work with the subsector will likely accelerate development of the industry.

5.3. Potential for impact on global food systems

Plant- and cell-based seafood could help increase the global supply of seafood to meet the growing global seafood demand, complementing existing strategies and further development in sustainable fisheries and aquaculture. In niche markets, such products could also compete with conventional seafood. New consumer research shows that alternative seafood products can have greater appeal to consumers if they fit into existing seafood consumption habits and provide similar sensory and nutritional experiences. They should also reduce barriers to seafood consumption, such as affordability and preparation, and clearly communicate the benefits of the product, including fewer health concerns and environmental sustainability (Lamy and Szejda 2020). Currently, plant-based seafood is mainly accessible in wealthier markets and the introduction of cell-based seafood will also be concentrated in wealthier markets. Despite this, there is potential for both to create shifts in global food systems that affect food and nutrition security, livelihoods and the environment in low- and middle-income countries.

5.3.1. Social impacts: Food and nutrition security

Food and nutrition security can be measured by indicators of availability, access, utilization and stability (Committee on World Food Security 2014). It is necessary to develop suitable and comprehensive indicators to measure the impact of specific events or interventions on food and nutrition security. However, it is widely accepted that increased production, decreased loss and waste, and better distribution of nutrient rich foods are required to ensure adequate food and nutrition security of growing populations (Willett et al. 2019). A combination of methods is necessary to help meet the growing global demand for nutrient-rich foods. This includes shifting protein sources up the supply chain,[8] using plant-based substitutes or extenders for animal-sourced proteins and using novel sources for both human and animal nutrition (Boland et al. 2013).

Plant-based seafood shifts plant proteins toward the consumer, and both plant- and cell-based seafood are produced at essentially 100% edible yield, thus avoiding the average 60% yield loss generally associated with conventional seafood production (Archer et al. 2001; FAO 2011; Torry Research Station 1989). These products are more accessible in wealthier countries, so their direct impacts on food and nutrition security in low- and middle-income countries is limited at present.

Plant-based seafood products presently use ingredients derived mainly from terrestrial plant sources that are already in global markets. Prices are already competitive with many conventional seafood products, which indicates wider affordability and accessibility, although they are often sold at a premium. Sales volumes are likely to increase significantly during the next few years with increasing consumer acceptance. However, cell-based seafood is not yet marketable, though it is anticipated to come to market at scale within the next 5–10 years. Production cost analysis suggests that cell-based seafood will initially target markets for higher value species and that it will be quite some time before cell-based seafood competes with lower value, mass-produced wild and farmed species, including tilapia and carps.

Alternative seafood products could, however, indirectly impact food and nutrition security in low- and middle-income countries by displacing some of the seafood imported by developed markets, including the European Union, United States of America, and Japan, that is increasingly produced in low- and middle-income countries (FAO 2020c). Rising consumption of alternative seafood combined with some decline in consumption of conventional seafood could reduce pressure on aquatic ecosystems. In turn, this could benefit small-scale and subsistence fishers whose fishing grounds have been compromised by industrial fishing operations.

If plant-based seafood and/or cell-based seafood do become accessible in low- and middle-income countries, both can act as essential nutrient delivery platforms that complement local diets and address nutrient deficiencies. Used in combination with other aquatic food-based solutions, including food waste valorization, incorporation of plant-based extenders, or the use of algae and other aquatic plants for human and animal nutrition, alternative seafood has the potential to introduce changes in food systems that extend beyond food and nutrition security.

5.3.2. Economic impacts: Livelihoods

Plant-based seafood products range from lower value products emulating canned tuna, fish burgers and breaded white fish to higher value products emulating raw tuna, salmon and shrimp. Cell-based seafood products in development are of higher value species, including bluefin tuna, fish maw,[9] mahi mahi and shrimp, but once price parity is reached products of lower value species could also be developed. The variety of alternative seafood products appeals to a range of mass and niche markets but are likely to be concentrated in the markets of wealthier countries in the near future.

Livelihoods can be measured by indicators of natural, financial, social, physical and human capital. Here, however, we focus on potential changes to financial and human capital in terms of income and employment, respectively (Carney 1998). If alternative seafood production displaces some amount of conventional seafood production, employment opportunities in fisheries and aquaculture and processing could shift. However, employment downstream in the value chain, such as packaging and distribution, will likely be less affected. The majority of change will likely occur in industrial fishing operations, but the focus on high value alternative seafood might affect small-scale fishers and farmers producing seafood like shrimp. Small-scale fishers generally react to external shocks through diversification, and they can often do this with more agility than industrial operations. However, appropriate policy or management efforts should be developed. These must support livelihood diversification or conversion that allows small-scale fishers to either retain their place within the existing value chain or be included within alternative seafood value chains. Additionally, as mentioned in Section 5.3.1, if alternative seafood can reduce pressure on aquatic ecosystems, it may further benefit small-scale and subsistence fishers whose traditional livelihoods have been hurt by compromised coastlines and declining fish populations.

5.3.3. Environmental impacts

It is estimated that 93% of global fisheries are either fully fished or fished above maximum capacity (FAO 2018b). Currently, global food fish consumption[10] is growing 3.1% annually (FAO 2020c) and the global supply is only expected to grow about 1.3% annually over the next decade (OECD/FAO 2020).[11] Plant- and cell-based seafood are novel seafood production methods that could help sustainably augment conventional production. Environmental impacts can be measured by an array of indicators that describe and track environmental progress. Here we focus on those indicative of aquatic ecosystem health and sustainability of natural resources use (OECD Environment Directorate 2008).

As mentioned in Section 5.3.1, increased consumption of alternative seafood alongside a decrease in consumption of conventional seafood may reduce pressure on aquatic ecosystems and the conventional seafood sector's rate of use of natural resources, specifically energy, water and land. This, however, is contingent on consumer action. A significant amount of consumer conversion away from conventional seafood will likely be necessary to achieve conservation benefits at scale, but smaller changes in industrial fishing operations could encourage the recovery of local and regional aquatic ecosystems. Plant- and cell-based seafood tend to have more efficient production processes than their conventional counterparts, though no formal environmental impact analyses have been published yet. Life-cycle assessment studies from the plant-based meat industry have shown plant-based meat generates about 90% less greenhouse gas emissions and requires 46% less energy, 87%–99% less water and 93%–96% less land compared to their conventional counterparts (Heller and Keoleian 2018; Khan et al. 2019). Similar studies of the cell-based meat industry have shown reductions in greenhouse gas emissions and energy, water and land use as compared to their conventional counterparts, but are limited to proposed at scale production systems since no facilities are yet producing at scale (Scharf et al. 2019). Cell-based seafood is expected to have even lower energy requirements based on the tolerance of fish muscle tissue to cooler temperatures, a wider range of pH and lower oxygen requirements during growth (Rubio et al. 2019).

Alternative seafood production inherently forgoes the energy required to fuel fleets, issues of overfishing and bycatch, and the direct release of pollutants, farmed aquatic organisms and disease in aquatic ecosystems. Although alternative seafood has potential to be less resource intensive than conventional seafood production, any research in this area should begin by developing a standardized, transparent methodology that facilitates comparison between wild, farmed, plant-based and/or cell-based seafood, given the influence of product and production specificities (Potter et al. 2020).

Cell-based seafood: salmon maki. Plant-based seafood: salmon nigiri.

6. Future growth scenarios of alternative seafood

Two growth scenarios for both the plant-based seafood and cell-based seafood subsectors were developed to better understand the subsectors' potential impact on food and nutrition security and livelihoods in low- and middle-income countries. Informed by a literature review and stakeholder interviews, the scenarios are based on assessing the pace of technological development, the number of businesses entering the market, investment, scalability of production, range of products, and likely demand and target prices. More robust data collection and stakeholder engagement are necessary to inform future foresight modeling that can provide more insight about the implications, opportunities and challenges associated with growth of the subsectors.

6.1. Scenario development

Many assumptions were required in the development of these scenarios because of the novelty of the subsectors and the lack of robust data around production, trade and consumption. Since no trade data for alternative seafood is available, it is assumed that there is negligible trade across regions, so all such production is destined for consumption in the same region. The regions considered are Asia, Europe and North America. We have not included Africa because we assume limited penetration of markets will occur before 2030. These growth scenarios have large uncertainties because limited sector data and research have not been published yet.

Alternative seafood is produced at essentially 100% edible yield, whereas on average 40% of the live weight of most fish is edible yield, excepting the relatively small but important volumes of small fish eaten whole. Production quantity of alternative seafood is presented as its equivalent quantity of conventional fish biomass, meaning only 40% of given quantities should be counted as edible. For comparison of projected growth, the annual conventional food fish production was taken as 180 million metric tons (178–184 million metric tons) by 2030 based on FAO, IMPACT fish model (Appendix B)[12] and OECD/FAO growth projections[13] (Figure 5) (FAO 2020c; OECD/FAO 2020). Projections of conventional food fish production were generated without considering alternative seafood, and projections of alternative seafood production were developed outside of model extrapolation.

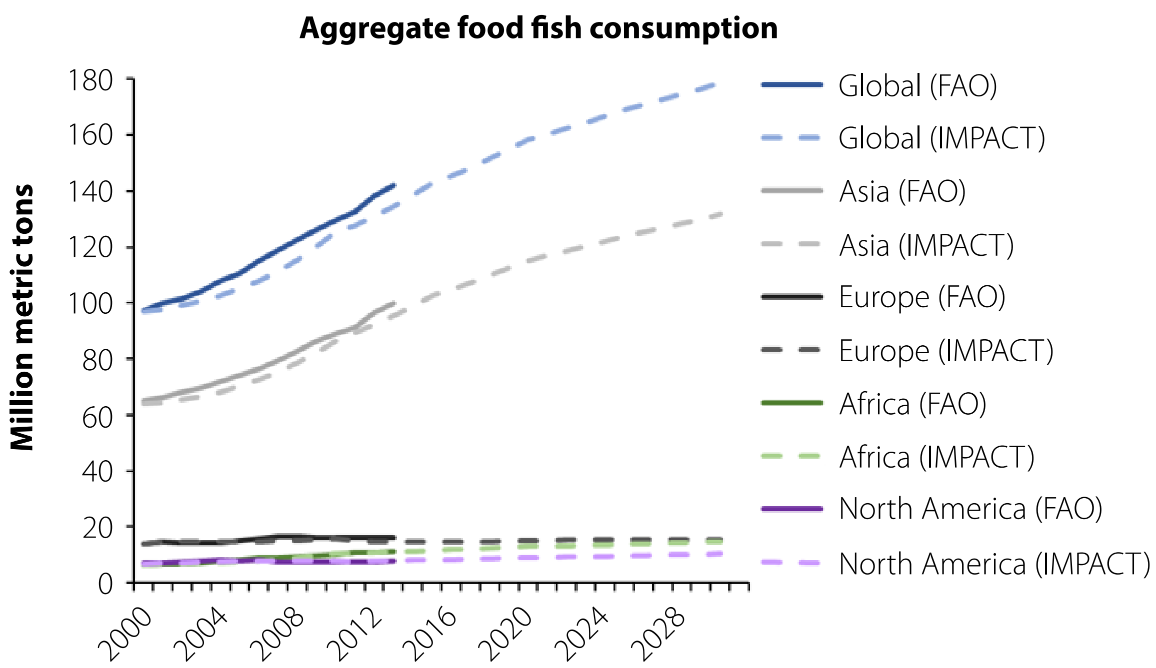


Figure 6. Historical and projected future food fish consumption at global and regional levels.

6.1.1. Plant-based seafood growth scenarios

Plant-based seafood has already entered markets in Asia, Europe and North America with an assumed geographic distribution of production and consumption of 20%, 40% and 40%, respectively. In 2030, we believe the distribution will shift to 30% in Asia, 40% in Europe and 30% in North America and assume negligible penetration of markets in Africa.[14]

The average factory gate price of plant-based seafood is estimated at USD 3/kg, which is the average farmgate price of aquaculture production with a price premium of 30% (FAO 2020c).[15] Historical figures of production are estimates. The value of the global plant-based seafood market was estimated at approximately USD 22.5 million in 2019.[16]

The business as usual (BAU) scenario assumes a modest growth trajectory of the plant-based seafood subsector with 25% biennial growth in production volume, which is a conservative estimate based on the growth of the plant-based meat sector.[17]

The high-growth scenario assumes production volumes will double every 2 years. This would require favorable market conditions that could include growing demand from consumers, a range of accessible mass-market products, increased availability in restaurants and/or fast food outlets, strong marketing from large food corporations and an introduction and pursuit of nutrition-sensitive food and climate change policies. However, even in this more optimistic scenario, we believe that by 2030 plant-based seafood will still only comprise a small percentage of seafood production.

6.1.2. Cell-based seafood growth scenarios

Cell-based seafood has not yet entered markets. Industry sources consulted during this research suggest that sales are not anticipated until 2022, when licensing is expected to be in place in key Asian and North American markets, with more substantial sales to follow within the next decade. In 2030, we expect a geographic distribution of 30% in Asia, 40% in Europe and 30% in North America, with no expected penetration of markets in Africa.[18] The average baseline factory gate price of cell-based seafood is estimated as USD 25/kg.[19]

The BAU scenario assumes production volumes will double every 2 years beyond 2022. This is feasible assuming modest market growth and continuing high production costs likely due to slow technological progress, especially with regards to producing products with similar sensory and nutritional attributes to conventional seafood at price parity. This constrains the market for cell-based seafood to higher value species and/or high-end markets.

Scenario	Biennial growth by volume	Biennial change in price	2030 production volume and value	2030 global food fish market share
BAU	25%	5% (inflation)	24,000 t; USD 94 million	0.01%
High	100%	5% (inflation)	256,000 t; USD 980 million	0.14%

Table 2. Plant-based seafood growth scenarios.

Scenario	Biennial growth by volume	Biennial change in price	2030 production volume and value	2030 global food fish market share
BAU	50%	5% (inflation)	190 t; USD 6 million	0%
High	No fixed percentage	5% (inflation); -15% (mass production)	13,500,000 t; USD 260 billion	7.50%

Table 3. Cell-based seafood growth scenarios.

Given the recent emergence of the subsector and the paucity of available data, the high-growth scenario is extrapolated from individual business growth trajectories from stakeholder interviews. This scenario assumes technological development and at-scale production resulting in a biennial 15% reduction in price until 2030, when affordable investment is readily available and there is an increasing number of market entrants.

6.1.3. Projected market shares in 2030

By conducting a market share analysis, Figure 6 shows the projected future alternative seafood global market share of the high-growth scenarios by 2030. Based on these projections, we estimate plant-based seafood will share 0.14% by volume and cell-based seafood 7.5% by volume of the global seafood market. We expect these shares will be unevenly distributed in more developed regions, with 30% of production and consumption in Asia, 30% in Europe and 40% in North America.

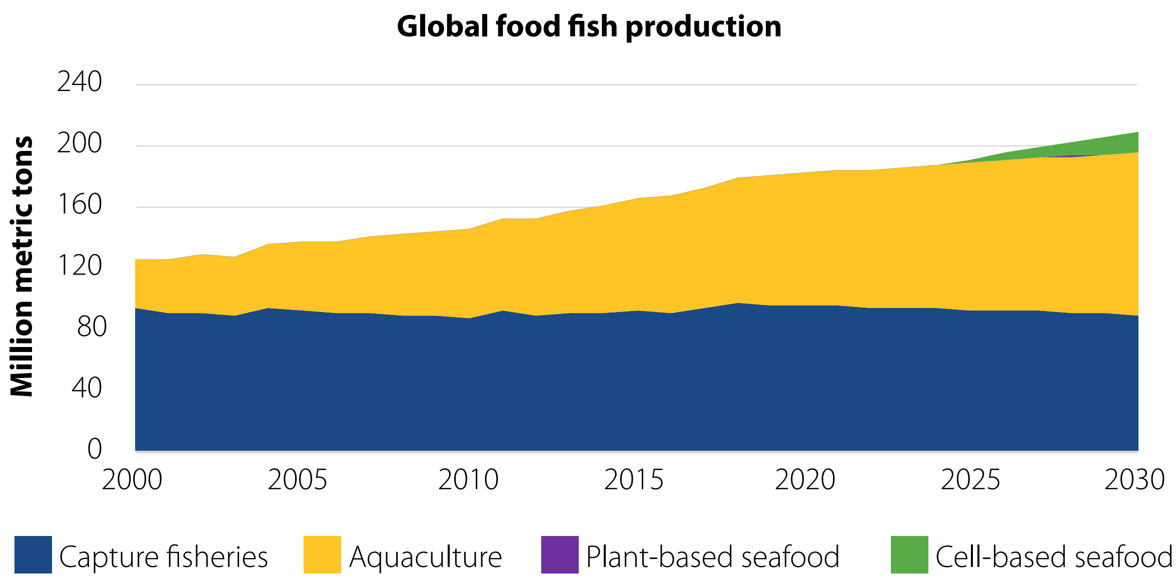
Within these three regions, it is projected that about 256,000 t of plant-based seafood will be consumed in 2030, which is an annual average of 44 g per person. A higher consumption of cell-based seafood is expected in 2030, at about 13.5 million metric tons, which is an annual average of 2.3 kg per person (Table 4).[20] These estimates are small when compared with the average annual per capita consumption of conventional seafood projected to be 21.5 kg per person in 2030 (FAO 2020c). More robust data and stakeholder involvement are required to further develop growth scenarios that can reliably inform policy development.

6.2. Discussion

Based on these growth scenarios and the projected production volumes, it is expected that the alternative seafood sector will have small or negligible impacts against key indicators of food and nutrition security and livelihoods in low- and middle-income countries in the next decade.

Alternative seafood (metric tons)	Asia	Europe	North America	Total	Per capita consumption (g/person/year)
Plant-based	77,000	77,000	102,000	256,000	44
Cell-based	4,050,000	4,050,000	5,400,000	13,500,000	2326

Table 4. Projected global and regional plant-based and cell-based seafood consumption in 2030.



Source: Historical data (2000–2018) from FAO 2020c and projections to 2030 from Searchinger et al. 2019.

Figure 7. Projected growth of conventional and alternative seafood supplies based on high-growth scenarios.

However, the alternative seafood products that first appear in low- and middle-income countries may well target more affluent market segments, building on successes achieved in wealthier countries, and thus influence local or regional food systems. Greater insight regarding the potential impact of the sector can be gained from future foresight modeling with the IMPACT fish model.[21] IMPACT was developed by IFPRI, which is part of CGIAR. Consisting of multiple modules, it was developed to support analysis of long-term challenges and opportunities for food, agriculture and natural resources at global and regional scales (Robinson et al. 2015). The IMPACT fish model is one of these modules. The IMPACT fish model was first used to make projections of global food fish production, consumption and trade from 1997 to 2020, the first time fish was included in a major global agricultural production and trade model (Delgado et al. 2003). WorldFish continues to make significant updates to the IMPACT fish model to closely reflect the latest FAO historical trends and appropriately calibrate future trends for fisheries and aquaculture.

Opportunities and challenges associated with the emergence of alternative sources of protein, including alternative seafood, need to be understood in relation to rapidly evolving patterns of production and demand. For example, as incomes rise, demand for high-value and nutrient-rich foods, like fruits and vegetables and animal-source foods, will increase more rapidly than demand for staple food commodities, particularly in low- and middle-income countries. IMPACT can provide baseline projections for these future changes in demand for a wide range of agricultural commodities and food groups in 2030 and beyond, considering not only changes in income but also population, agricultural productivity, climate and other factors. These baseline projections provide a reference case for comparison against scenarios exploring the potential impacts of new foods, like alternative seafood.

The IMPACT fish model can be used to explore how alternative seafood will affect production, consumption, prices and trade of conventional seafood and other food commodities. It can also be used to examine indicators of food security, micronutrient availability and resource use to 2050. However, this is beyond the scope of the present study. To confidently conduct future foresight modeling of alternative seafood requires the collection of disaggregated historical data of production, consumption, trade, prices, inputs and nutrient content of alternative seafood products. The following questions are also essential to informing future foresight modeling of alternative seafood:

- What types of alternative seafood are in development (e.g. species, product)?
- What will alternative seafood compete with or displace? How much? Where? For whom? When?
- What market share is anticipated? Where? When?
- What agricultural inputs are required? Where are they from? How were they produced?

The development of scenarios in this report says more about the paucity of reliable data than it does about the growth of alternative seafood or its likely impacts on food and nutrition security or livelihoods. As argued in Section 7, there is a need for much better data to inform scenario modeling and to develop more robust projections that can help inform future policies for the sector.

Photo credit: Wildtype/Hattie Watson

Cell-based seafood: salmon rolls.

7. Theory of change, assumptions and emergent research questions

7.1. Introduction

WorldFish set out to study the emerging alternative seafood sector to better understand the potential implications, opportunities and challenges for food and nutrition security and livelihoods in low- and middle-income countries. The development of key research questions around the sector may be integrated into WorldFish's future research programs to assess how the sector might affect the organization's mission to strengthen livelihoods and enhance food and nutrition security by improving fisheries and aquaculture.

As discussed in Section 3.1, SFS are central to meeting the SDGs. FAO's SFS framework (FAO 2018a) was adopted as an appropriate framework for analysis because it integrates all three dimensions of sustainability: economic (e.g. profits, livelihoods, jobs and incomes), social (e.g. gender, youth, indigenous people, workers' rights and safety) and environmental (e.g. carbon and water footprints, animal and plant health, biodiversity).

A TOC was used to identify the research questions most pertinent to WorldFish. As Vogel (2012) explains, a TOC "makes explicit how and why change happens, for whom and in what context." It is often used to articulate "pathways to impact" for research, as well as to help strengthen the planning, implementation and evaluation of impact strategies for impact-oriented research (Vogel 2012).

To create a preliminary TOC, we used our analysis of the issues surrounding the alternative seafood sector in an SFS context, as developed through literature and media research, stakeholder interviews and scenario development. This TOC compels setting out assumptions and hypotheses about how alternative seafood is likely to impact hunger and poverty.

Our TOC sets out the current situation regarding alternative seafood and potential pathways we hypothesize need to occur to improve food and nutrition security and livelihoods and address environmental concerns. Each of the hypothesized causal links is underpinned by assumptions that have been identified and elaborated as preliminary research questions. These must be addressed before the TOC can be fully accepted. Alternative seafood stakeholders and members of the development community reviewed and validated the TOC and preliminary research questions via virtual workshops.

7.2. Theory of change

Our TOC only describes one potential pathway for impact in efforts to focus on broader key research questions. Additionally, some causal links have been condensed to simplify the TOC, but all associated assumptions were elaborated as preliminary research questions. Our TOC states the following:

If plant- and cell-based seafood products with equal or better sensory experience, nutritional value and pricing are sustainably produced and widely distributed, the resilience of global food systems will increase because of a slowed growth of conventional seafood demand and then production. This would relatively reduce the use of natural resources (energy, land, water) and allow aquatic ecosystem recovery to facilitate improvements in food and nutrition security and livelihoods in low- and middle-income countries.

Our TOC can be elaborated, as shown in Figure 8. For the purposes of this research, our TOC does not explicitly address issues of animal welfare, food safety, food fraud and exploitative labor, though they are recognized as legitimate areas for research.

The proposed pathway is dependent on a reduced growth rate of conventional seafood demand and, consequently, of conventional seafood production. This must happen at the scale needed to produce environmental benefits that can improve food and nutrition security and livelihoods. This is discussed at length in Section 8. If the causal links were to be expanded, our TOC would state the following:

If plant- and cell-based seafood products with equal or better sensory experience, nutritional value and pricing are sustainably produced and widely distributed and consumers increasingly consume more alternative seafood and less conventional seafood, the resilience of global food systems will increase. This would occur because of a slowed growth of conventional seafood demand and then production (fisheries and/or aquaculture). As a result, this would relatively reduce the use of natural resources (energy, land, water) and allow aquatic ecosystem recovery to facilitate the improvement of areas relied on by fishing communities for food and nutrition security and livelihoods in low- and middle-income countries.

7.3. Development of research questions

The TOC and preliminary research questions were shared with stakeholders and development professionals during two virtual workshops. Breakout groups were convened and tasked with validating, rejecting or amending them and prioritizing the preliminary research questions from a perspective of how they might impact food and nutrition security, livelihoods and the environment, in line with the SFS approach.

The participants judged 34 research questions according to their importance using four categories: high, high-medium, medium or low-high.[22] They also added 15 additional research questions of their own (Table 5). The workshop agenda, process and outputs are detailed in Appendix C.

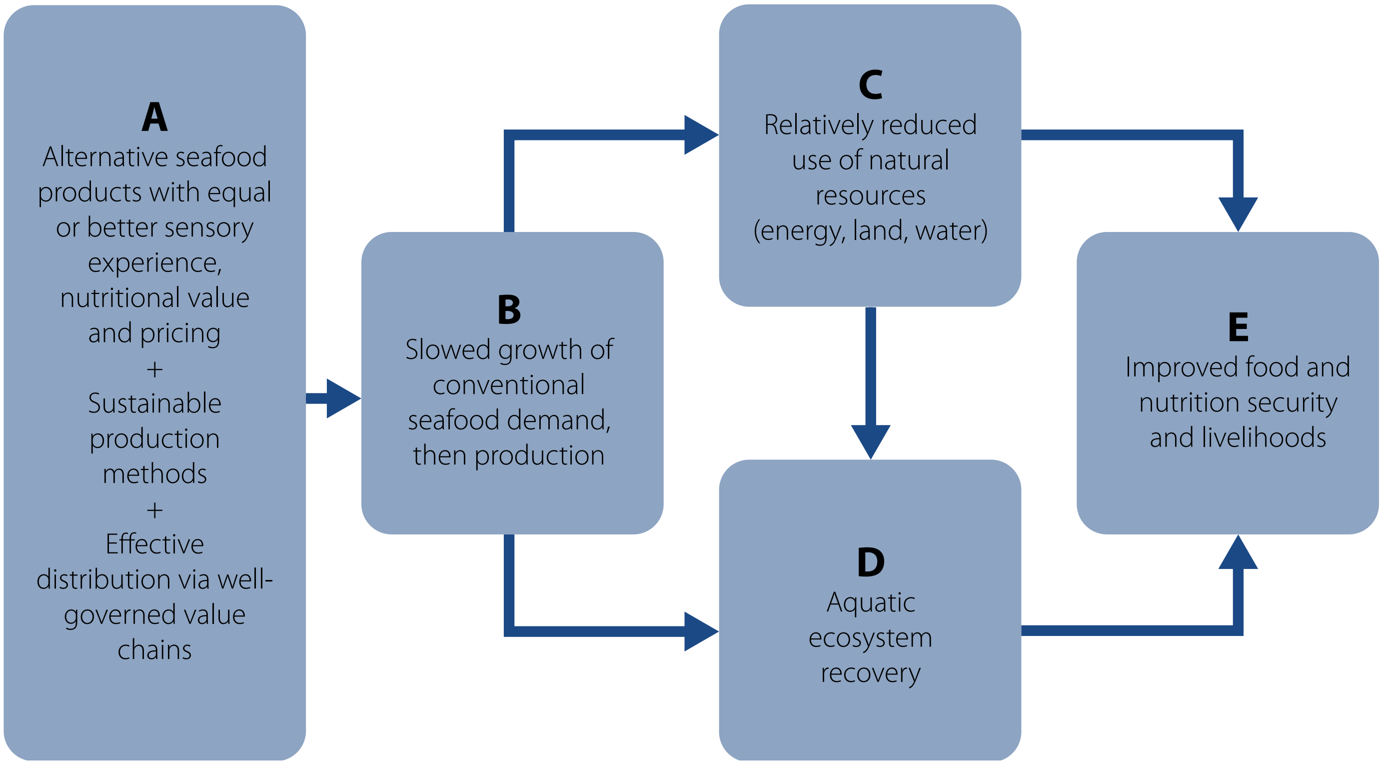


Figure 8. TOC describing how alternative seafood may impact hunger and poverty and the environment.

High importance research questions

TOC Section A

- How do the nutrient profiles of plant- and cell-based seafood compare with those of conventional seafood?
- Will plant- and cell-based seafood be accessible to all consumers?
- What sorts of policies might improve access for poor consumers?
- How might policies or stakeholders guide the development of the plant- and cell-based seafood subsectors to maximize benefits to low- and middle-income countries?

TOC Section B

- How important will price, taste, food safety, environmental concerns, ethics (e.g. human and animal rights) be as determinants for adoption of alternative seafood?
- How quickly will plant- and cell-based seafood production grow by 2030 and what will be the main drivers?
- Where will alternative seafood be produced? What are the main drivers? (amended)

TOC Section C

- How do the environmental impacts of plant- and cell-based seafood compare with those of conventional seafood?
- What are the natural resources requirements of plant-based seafood?
- How much and what type of energy, land or water will plant-based seafood require compared to conventional seafood and to plant-based meat?
- What are the natural resources requirements of cell-based seafood?
- How much and what type of energy, land or water will cell-based seafood require compared to conventional seafood production? Compared to cell-based meat?

TOC Section D

- Does the adoption of plant- and cell-based seafood contribute to the recovery of aquatic ecosystems? If so, how?
- How much must conventional seafood production and/or consumption decrease to produce a measurable recovery of aquatic ecosystems?
- How dependent is ecosystem recovery on changes in species-specific production and/or consumption?

TOC Section E

- Under what conditions can plant- and cell-based seafood improve food and nutrition security in low- and middle-income countries?

Moderate-High importance research questions

TOC Section A

- What are the industry intentions or objectives with respect to consumers, geography, pace of development, uptake? (amended)
- How can negative environmental impacts best be minimized?
- How can stakeholders equitably share risks and benefits?

TOC Section B

- Will plant- and cell-based seafood be consumed instead of conventional seafood, will it mainly replace other animal-source foods, or will it simply be eaten in addition to conventional seafood and/or meat?

TOC Section C

- What inputs are required? How much? What are the opportunities/benefits and issues/challenges of using these inputs? (amended)

TOC Section D

- How can aquatic ecosystem recovery be measured and what enabling conditions or policies will be necessary?
- How long will aquatic ecosystems take to recover?

TOC Section E

- None

Moderate importance research questions

TOC Section A

- None

TOC Section B

- From a market perspective, which species will plant- and cell-based seafood subsectors focus on producing? (amended)

TOC Section C

- None

TOC Section D

- None

Moderate importance research questions

TOC Section E

- Can plant- and cell-based seafood provide a cost-effective solution compared to food-based solutions?[23]
- How might plant- and cell-based seafood value chains differ from conventional seafood value chains?
- How much and what types of employment will be created and/or lost in low- and middle-income countries due to the plant- and cell-based seafood subsectors?
- Which areas of plant- and cell-based seafood chains offer the greatest opportunities for employment, especially among women and marginalized groups?
- How will exploitative labor conditions in the plant- and cell-based seafood subsectors be avoided?
- What are the expected indirect economic effects of plant- and cell-based seafood in low- and middle-income countries?

Low-High importance research questions

TOC Section A

- How can the nutrient content or nutritional value of plant- and cell-based seafood best be ensured?
- Is certification for production standards needed and, if so, who should develop standards?

TOC Section B

- Where will alternative seafood be consumed? What are the main drivers? (amended)

TOC Section C

- What are the most appropriate methods for evaluating the use of natural resources by this emergent sector as compared to the conventional seafood sector? Is it a life cycle assessment or are there other methods? Is it based on a company's individual practices or evaluating the field as a whole? (amended)

TOC Section D

- None

TOC Section E

- None

Additional research questions, added by participants

TOC Section A

- Does the TOC, for example, extrapolate too far?
- How can R&D at this stage in the growth of the plant- and cell-based seafood subsectors use a sustainable food systems approach that considers the target consumer both in the US and EU but also of high consumption in low- and middle-income countries, where such products are not currently being developed?
- How will plant- and cell-based seafood be adopted?
- What will alternative seafood displace? How much? Where? For whom? When?
- How safe are plant- and cell-based seafood products for human consumption?
- How will consumer preferences develop toward alternative seafood and conventional seafood? Will vegetarians and vegans eat cell-based seafoods? How will consumers react to the technology?
- What will the impact be on livestock product markets or other food sectors?

TOC Section B

- What is the historical disaggregated production, consumption, trade, prices, inputs and nutrient content of alternative seafood?
- What are current projections for demand for conventional seafood?

TOC Section C

- What goes into products (and its origin) and what comes out?

TOC Section D

- To what extent is aquatic ecosystem health a key driver of social outcomes? What is the value of aquatic ecosystems to people? (It likely depends on where you live.)
- While aquatic ecosystem recovery is good for its own sake, how does it link to food and livelihoods? (This is likely to be species dependent.)
- How might regional differences in consumer preferences affect consumption of plant- and cell-based seafood and thus aquatic ecosystem recovery?
- How important is the counterfactual in assessing the impact of plant- and cell-based seafood on aquatic ecosystem recovery rates?

TOC Section E

- Are we displacing or augmenting livelihoods?

Table 5. Key research questions, excluding those assessed as of low importance. References to TOC sections correspond to the lettering in Figure 8.

8. Priority areas for research

Throughout the assessment of the TOC and the research questions, workshop participants noted the potential for both plant- and cell-based seafood to have broader impacts on food systems as a new food, not solely as an alternative to conventional seafood. Additionally, participants stressed that future research should reflect the differences between the plant- and cell-based seafood subsectors. While the subsectors could eventually provide similar benefits, the major differences in production, regulation and marketability require some independent lines of research. As emerging subsectors, governments and/or intergovernmental organizations have a tremendous opportunity to shape the growth of the industry, especially to help achieve the SDGs.

These ideas were used to refine and appropriately frame the proposed research questions. The key research questions judged to have immediate relevance to WorldFish's mission are presented in Sections 8.1–8.3. They are organized according to the three dimensions of the SFS: social, economic and environmental. To properly explore these key research questions, we recommend developing specific TOCs for each line of research.

8.1. Social impacts

The research questions around the social impacts of sustainable food systems focus on nutrition and health. Research questions on added value distribution (gender, youth, indigenous people) through employment are addressed under economic impacts. Two key research questions are regarded as particularly relevant to WorldFish's mission.

1. How are markets for plant- and cell-based seafood likely to develop in different regions?

The objective is to increase our understanding of how plant- and cell-based seafood markets are likely to grow by 2030, the main drivers of this growth and how these markets will interact with those of conventional seafood. Stakeholder interviews helped inform us of growth trajectories of individual businesses, but they did not provide robust information on overall growth of plant- and cell-based seafood subsectors over the next decade. We have estimated that at maximum, plant-based seafood will hold 0.14% share of the global food fish market and cell-based seafood 7.5%. These estimates were extrapolated from the growth of the alternative meat sector and individual business growth trajectories (Section 6).

It is necessary to deepen our understanding of how regulatory groups and consumers in various geographic regions, economic classes or cultural and social groups will adopt plant- and cell-based seafood. Adoption can occur in many ways. These include, but are not limited to, plant- and cell-based seafood as alternatives to conventional seafood, as an alternative to conventional meat or in addition to current conventional seafood and meat consumption. As a new food, what will alternative seafood displace? How much? Where? For whom? And when? Will we see disruption in the conventional seafood or meat sectors? Additional information is needed regarding consumer preferences for adoption based on primary considerations, such as price, accessibility, convenience and taste, as well as higher order considerations, like environmental concerns and ethics. This information is essential to answer these questions that can more broadly be applied to envision changes in global, regional and local food systems. Models like IMPACT, when supplied with robust historical disaggregated data (e.g. production, consumption, trade, prices, inputs nutrient content), can be used to develop scenarios that help address these questions, further focus research and inform decision-making.

Plant- and cell-based seafood as new foods may have broader impacts on food systems. The production methods allow for more consistent, reliable and local seafood supplies that are more resilient to shocks to the food system arising from events such as the COVID-19 pandemic and climate change. However, will the influence of the alternative seafood sector be sufficient to significantly increase the resilience of the global food system? And if so, does this merit policy reviews to develop a more enabling environment for the emerging sector?

Research in alternative seafood has been heavily concentrated in the private sector. Along with the inevitable duplication of research efforts that results from such an approach, there remains a lack of open source information about the fundamental aspects of plant- and cell-based seafood technologies. Growth of the sector relies on continued investment, but how can investment from public and private sources complement one another? And what enabling conditions, such as licensing arrangements and policies, are required to secure these investments? When it comes to low- and middle-income economies, how might appropriate policies and stakeholders guide development of the sector to include and maximize benefits? Other interesting questions are how much of the value-added components of plant- and cell-based seafood production might it be possible to capture in low- and middle-income countries, compared to that of conventional seafood production? And what are the implications for low- and middle-income country economies? Might innovative financing solutions such as Blue Bonds (Ahmed 2019) be used to help maximize the social, economic and environmental benefits from the emerging sector in low- and middle-income countries?

2. How can plant- and cell-based seafood best contribute to food and nutrition security?

The objective is to increase our understanding of how plant- and cell-based seafood can be developed to include and benefit consumers in low- and middle-income countries. To achieve this, the subsectors may consider integrating or adapting objectives in their existing production plans to reach these markets. Actions taken by governments and/or intergovernmental organizations have great potential to influence these decisions. To reach these markets, there is first a question of accessibility of plant- and cell-based seafood to consumers in various geographic regions, economic classes and cultural and social groups. Decisions regarding seafood species, product form and required inputs are tied to the markets that plant- and cell-based seafood producers aim to enter and can be selected with intentions to reach low- and middle-income economies. The production method of plant- and cell-based seafood lends itself to localized production schemes and franchising, which could enable access in places where seafood is currently inaccessible. Creating local markets, production and value chains has implications for food sovereignty, the way food is produced, traded and consumed.

There remain, however, a number of technological hurdles to overcome. These mainly pertain to the cell-based seafood subsector and center around the development of a comparable sensory experience and the scalability of production. These obstacles need to be solved before alternative seafood products challenge those from conventional seafood sources.

An understanding of the required inputs and their origin, especially for the plant-based seafood subsector, is essential to determine if the sector might compete directly and in any significant way with their use as human food or animal feed and whether this reduces the resilience of the global food system. Currently, most of the input materials come from land-based agriculture. However, stakeholder interviews indicate that producers are exploring a wider range of inputs, especially novel aquatic foods, such as microalgae and seaweeds, some of which could require new licensing for use in food.

Likewise, there are important questions regarding the nutritional potential of plant- and cell-based seafood, how the nutrient profiles compare with those of conventional seafood and how they might be best used as nutrient delivery platforms. Plant- and cell-based seafood can be developed with specific nutrient profiles that complement local diets and address nutrient deficiencies expected in the consumer base. Further research exploring optimal nutrient profiles and the nutritional potential of alternative seafood would need to inform these decisions. Given mounting debate around the growing prevalence of processed foods in diets, the types and degree of processing, especially of the plant-based seafood subsector, also need to be investigated. To ensure and communicate the nutritional value of these products, the development of transparent, consistent certification and labeling will likely need to occur. While food safety is likely to prove less of an issue than it is with conventional seafood, it still merits research.

For WorldFish and the development community, it remains to be determined what the potential and feasibility are of plant- and cell-based seafood to provide cost-effective solutions to food and nutrition security in comparison with other food-based solutions, like increasing the availability or nutritional value of staple crops.

8.2. Economic impacts

The research questions around economic impacts focus on employment and incomes, especially as it pertains to gender, youths and marginalized groups. The two key research questions are regarded as particularly relevant to WorldFish's mission.

3. How much and what types of employment are likely to be created and/or lost in low- and middle-income countries by the plant- and cell-based seafood subsectors?

The conventional seafood sector currently employs more than 800 million people. Coupled with the projected growth trajectories of plant- and cell-based seafood, it is unlikely that major changes in employment will occur in either sector over the next decade. Employment per unit production and in associated value chains in the emergent plant- and cell-based seafood subsectors is likely to be considerably less than it is in fisheries or aquaculture. Our most optimistic scenarios estimate some few million metric tons of both plant- and cell-based seafood production by 2030, so employment is likely to be in the hundreds of thousands. However, the subsectors will likely generate employment opportunities in skilled and semi-skilled professions, including food technology, biotechnology and marketing. It will be important to determine which areas of plant- and cell-based seafood value chains offer the greatest opportunities for employment, especially for women, youths and marginalized groups, and for governments to establish policies and other measures that ensure such posts are realized.

Job losses in fisheries and aquaculture as a direct result of market competition by the emerging alternative seafood sector are amenable to assessment through IMPACT. However, we do not anticipate it to occur by 2030. It is worth noting, though, that if alternative seafood sufficiently reduces pressure on aquatic ecosystems, it could actually benefit small-scale and subsistence fishers whose livelihoods have been disrupted by problems including compromised coastlines and declining fish populations.

4. How can development of the subsectors be guided to generate well-governed value chains that maximize societal benefits?

To answer this question requires an understanding of how plant- and cell-based seafood value chains are likely to differ from those of conventional seafood. The former are likely to have shorter, localized and more efficient market chains. In terms of value chain governance, it is important to determine how markets, policies or stakeholders might guide the development of the plant- and cell-based seafood subsectors to maximize benefits to realize the SDGs. This research is essential as consumers, governments and stakeholders have the opportunity to guide the growth of the emerging subsectors.

8.3. Environmental impacts

The research questions around environmental impacts focus on investigating alternative seafood as a more sustainable means of seafood production than fisheries and aquaculture. It assumes, however, that the former will substitute for the latter in the marketplace, an assumption that needs rigorous testing. Two key research questions are regarded as particularly relevant to WorldFish's mission.

5. How do the environmental impacts of plant- and cell-based seafood compare with those of conventional seafood?

Plant- and cell-based seafood production have the potential to be less resource intensive than current animal protein production systems. But these systems and standard methods for comparison need to be further developed. Research into this question must be guided by the subsectors as they currently exist. To do so, comprehensive baseline data about plant-based seafood, cell-based seafood, fisheries and aquaculture must be acquired and standardized. This data should include species, product types, production systems, natural resources requirements, including energy, water and land, and other input requirements, including nutrients and feed. Research must also inform plausible future scenarios that explore consumer uptake, technological development and governance in both the rapidly evolving alternative seafood sector as well as fisheries and aquaculture. Mechanisms to incentivize the uptake of more sustainable production methods and management systems should be further explored with stakeholders and policymakers.

Research must encompass development of appropriate robust and accepted environmental impact assessment indicators and methodologies, such as carbon footprint or opportunity cost (Chami et al. 2019; Hayek et al. 2020) or life cycle assessment. These must capture key trade-offs and impacts and facilitate valid comparisons between the production and trade of conventional seafood and alternative seafood. This comparison could also be extended to the conventional or alternative meat sector as a better understanding around the adoption of alternative seafood is developed. These assessments could then be used to promote technologies (including the use of decarbonized energy), management systems, policies and incentives to minimize environmental impacts of both conventional and alternative seafoods. Developing standards for environmental sustainability and impact assessment would also help properly assess the contribution of the alternative seafood sector within the context of overall aquatic food systems performance.

6. How can changes in conventional and alternative seafood production and/or consumption generate observable improvements in aquatic ecosystem health?

The mechanisms by which adopting alternative seafood might lead to environmental improvements are proposed in the TOC. However, research is required to first validate the underlying assumptions and then explore the potential for impact on aquatic ecosystems.

The proposed mechanisms depend on a reduced growth rate of conventional seafood demand and, consequently, a reduced growth rate in conventional seafood production. The reduced rate of production must occur at a scale needed to produce measurable recovery of aquatic ecosystems. Research around the indicators used to measure recovery and the scale required has begun.[24] However, it can be developed to encompass further questions around various indicators of recovery and their associated timelines, the impact of species-specific changes in production, and enabling conditions or policies that allow for aquatic ecosystem recovery, including control of overfishing and IUU catches. This line of research could also complement research around conventional seafood production. For example, might alternative production of nonfarmable species, such as bluefin tuna, help wild stocks recover? And how contingent is recovery on implementing stock management plans?

Cell-based seafood: salmon maki. Plant-based seafood: unagi nigiri.

9. Conclusions

The emerging alternative seafood sector is characterized by rapid innovation. There is also a real sense of excitement about the possibilities to sustainably and responsibly develop novel, safe, nutritious seafood with universal consumer appeal. Evidence from literature, media reports and discussions with stakeholders show that the sector has potential to help meet growing seafood demand. This would complement the ongoing development of initiatives to increase the sustainability of fisheries and aquaculture.

To evaluate how the alternative seafood sector might impact Agenda 2030 and the SDGs, which guide CGIAR research, an SFS approach was used to capture perspectives on its potential broader social, economic and environmental impacts, with an emphasis on food and nutrition security and livelihoods. Developing a TOC proved useful in determining possible paths by which the alternative seafood sector might impact food and nutrition security and livelihoods in low- and middle-income countries. The proposed path and underlying assumptions associated with each step were used to draft research questions that alternative seafood stakeholders and the development community then evaluated and refined.[25]

The six key research questions identified, together with the subsidiary research issues, are regarded as the most relevant to WorldFish's mission. Fundamental research is essential to understand regional differences in seafood supply-demand gaps, nutrient deficiencies and the environmental value of specific seafood species. This information could then be used in conjunction with IMPACT outputs and the IMPACT fish model to inform discussions with the public and private sectors as well as civil society. Such discussions could inform where innovative investment solutions, like Blue Bonds, might be used to generate maximum social, economic and environmental benefits.

Other research areas outside the scope of the present exercise will likely influence the growth of the alternative seafood sector and merit research. These include but are not limited to seafood waste valorization, use of plant-based extenders in seafood, and substitutes or alternative production methods for high-quality feedstuffs, such as fishmeal and fish oil.

The amount and direction of growth in the sector will influence the outcome of many of these research questions, so collaboration with alternative seafood stakeholders is essential to ensure poor and marginalized people are included. We recognize that some important issues, including exploitative labor, animal welfare, food safety and food fraud, play a smaller role in the research questions identified, but they should not be ignored. Collaboration with other research entities is also essential as some of the priority research identified is already underway. Most notably, researchers at the University of California, Santa Barbara are exploring the potential conservation impacts of cell-based seafood.[26]

Accelerating the development, commercialization and widespread availability of alternative seafood is of growing interest for many whose vision includes responsible stewardship of both land and water while ensuring human well-being. WorldFish is committed to strengthening livelihoods and enhancing food and nutrition security in low- and middle-income countries by improving fisheries and aquaculture, and will continue to consider the implications, opportunities and challenges alternative seafood might introduce.

Notes

[1] Nearly 67 million metric tons (38%) of seafood production was traded in 2018, making it one of the world's most traded food commodities. However, the aquaculture portion of traded seafood contributes little to food and nutrition security because it is largely of high market value products targeted at wealthier consumers (Asche et al. 2015; Golden et al. 2017).

[2] The OECD/FAO production estimates are average values from 2017 to 2019.

[3] The importance of seafood with regard to protein intake can be overstated, as the vast majority of people get most of their protein from plants (Béné et al. 2015).

[4] For example, even as the share of Atlantic salmon diets, rates of fishmeal and fish oil inclusion between 1990 and 2013 fell from 65% to 24% and from 19% to 11%, respectively (Ytrestøyl et al. 2015). Food conversion ratios (ratio of biomass of feed to fish produced) for farmed Atlantic salmon over the past 25 years have fallen from about 3:1 to around 1.3:1 (Ye et al. 2017).

[5] Farming non-native species is a proven means of increasing productivity and profit. There are demonstrable markets, indigenous and/or export, for the product, and the investment in production technologies has already been made.

[6] Ecosystem services include production services (e.g. food, water, energy), regulating services (e.g. climate regulation, bioremediation, carbon sequestration), cultural services (e.g. cultural heritage and identity, recreation) and support services (e.g. flood retention, nutrient cycling). Biodiversity is closely associated with the provision of ecosystem services.

[7] The term "consumption" here refers to apparent consumption, which is the average food available for consumption, which is not equal to food intake for many reasons, such as waste at the household level.

[8] Shifting proteins up the supply chain refers to moving protein sources, often traditionally used for animal feed, toward consumption by humans, likely as ingredients for extending or replacing animal-derived proteins.

[9] The term "fish maw" refers to the dried swim bladder of certain marine fish species, including croakers or sturgeons, which are a delicacy in some Asian cultures.

[10] The term "consumption" here refers to apparent consumption, which is the average food available for consumption, which is not equal to food intake for many reasons, such as waste at the household level.

[11] FAO estimates the average annual growth rate of global fish food consumption will decrease to 1.4% for the period of 2019 to 2030, mainly due to reduced production growth, higher fish prices and a deceleration in population growth.

[12] All IMPACT fish projections in this report refer to production or apparent consumption (the average food available for consumption) as of August 2020. Projections for apparent consumption also account for the food balance (i.e. exports, imports), the data for which often lags several years behind production data. IMPACT fish projections should be considered preliminary and may differ slightly from those to be released in future publications.

13 The OECD/FAO production estimate is for 2029.

14 These geographic distributions are assumed based on the locations of plant-based seafood producing organizations and their current and near-future target markets, as informed by stakeholder interviews.

15 As informed by stakeholder interviews.

16 Plant-based seafood made up 0.06% of the total US seafood market in 2019, which is equivalent to USD 9 million of the USD 15 billion market (The Good Food Institute 2020a). We assume North America currently has 40% of the plant-based seafood market, so the global 2019 baseline should be valued at approximately USD 22.5 million.

17 Growth in the plant-based meat sector has been 16%, 18% and 24% of value in 2017–2018, 2018–2019, 2019–2020, respectively (Plant Based Foods Association 2018; The Good Food Institute 2020b). We know the current momentum in growth of plant-based meats is high, but we prefer to be more cautious in our estimates with a 25% biennial growth rate in production quantity. Additionally, we impose a 5% biennial price increase to account for inflation.

18 These geographic distributions are assumed based on the locations of cell-based seafood producing organizations and their near-future target markets, as informed by stakeholder interviews.

19 As informed by stakeholder interviews.

20 Population projections for 2030 used in this report are 4,485,177,000 for Asia (East Asia and Pacific, South Asia), 930,755,000 for Europe (Europe and Central Asia) and 389,191,000 for North America (World Bank 2020).

21 For more information about IMPACT see https://www.ifpri.org/project/ifpri-impact-model.

22 Where a consensus was not reached, breakout groups submitted a range of scores of importance. The scores also reflect responses from two workshop breakout groups (Asia-Europe and Africa-North America). Questions judged of low importance were considered no further.

23 Improving food and nutrition security can be achieved in a number of ways, including the adoption of rights-based approaches, better education about food and nutrition, improved intra-family division of food (prioritizing pregnant and lactating female household members) and improved access to nutritious foods (improved economic access, food markets, transport infrastructure). If it is decided that increased economic access to nutritious foods is the solution (e.g. food banks, food for work programs) then the issue arises of whether plant- and/or cell-based products are cost-competitive in relation to other food-based solutions (e.g. dried fish, nutrient supplement powders).

24 For more information see https://ucsbcellbasedfish.weebly.com/

25 It should be noted that a few workshop participants felt inadequately informed about plant- and cell-based seafood to feel entirely comfortable reviewing and evaluating the draft research questions.

26 For more information see https://ucsbcellbasedfish.weebly.com/

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Appendix A. Stakeholder interviews

The purpose of the interviews was to better understand the market trends of alternative seafood and the potential implications, opportunities and challenges for food and nutrition security and livelihoods in low- and middle-income countries. This information was used to inform estimated growth scenarios of the sector.

Stakeholders were identified in the course of the study and categorized by roles into groups: producers, investors, researchers, retailers and advocates. Apart from retailers, these groups contained representatives from the plant- and cell-based seafood subsectors, and at least three representatives of each group were interviewed.

Structured questionnaires were developed for each stakeholder group. Five to 12 representatives of each group were identified and contacted by email to determine their willingness to participate. Anonymity was assured. Interviews were conducted virtually or by email over the course of 2 weeks in late June and early July 2020.

Table 6 summarizes the questions that formed the basis of the interviews. Eighteen interviews were conducted and generally involved both researchers (Nisha Marwaha and Malcolm Beveridge). On three occasions, however, time differences constrained the interview to only one researcher. Three interviewees chose to complete the questionnaire by email. The researchers compiled notes from the interviews separately and then combined and used them as a resource to inform the research. Further information can be found in Section 3.

Interview components

Each interview was prefaced by the following:

- Thank you
- Introduction to WorldFish
- Scope of interview
- Introduction to WorldFish researchers
- Introduction by stakeholder (background, motivation, role)
- Definitions of terms as used in the interview: "alternative seafood," "plant-based seafood," "cell-based seafood."

Question	Producer	Investor	Researcher	Retailer	Advocate
How familiar are you with (i) alternative meat, (ii) alternative seafood, (iii) plant-based seafood and (iv) cell-based seafood?		X	X	X	X
What is your organization's age, nature, stage?	X				
What products do you produce? Why? What is your current turnover, production volume and employment?					
How has production and product diversity changed?	X				
What markets do you target (age; geography [developing, developed]; dietary preferences [vegan, vegetarian, flexitarian, omnivore])?	X				
How do you think the availability of your product changes consumption patterns in your customer base?	X				
What marketing advantages and disadvantages do you see for plant-based/cell-based seafood?	X				
What impact has COVID-19 had, and is it likely to have longer term effects on your organization?	X				
What technical and licensing constraints does your organization face?	X				
What are the key research gaps from your perspective?	X	X	X		
How do you see your organization changing in 2 years and 5–10 years (in terms of product range, volume and markets)?	X				
Do you invest in the alternative seafood sector? Why or why not?		X			
Do you see any major competitive advantages or disadvantages of the sector vis-à-vis other foods, such as conventional seafood and alternative meat?		X		X	
How is COVID-19 changing your attitude toward investing?		X			
Can you summarize your research?			X		
What do you see as the biggest technical challenges in your field? What do they depend on? How quickly will they be addressed?			X		
WorldFish's mission targets improving nutrition, livelihoods and environment in the developing world. What are your views on the role of alternative seafood in achieving such goals?			X		

Question	Producer	Investor	Researcher	Retailer	Advocate
Do you stock alternative seafood products? Why or why not?				X	
What existing or conventional products do the alternative seafood products compete with?				X	
How is COVID-19 affecting your conventional and alternative seafood sales?				X	
What main facets of the alternative seafood (or protein) sector do you focus on? What are your main findings?					X
Based on your experience, how important are issues of (i) taste, (ii) price, (iii) ethics (e.g. animal or human welfare), (iv) food safety and (v) environmental concerns to production and/or consumption of alternative seafood?					X
Have you noticed changes in the sector due to COVID-19?					X
How important do you see alternative seafood products in addressing key social, economic and environmental issues, now and in the future?	X	X	X	X	X
Do you have any other comments or concerns about the alternative seafood industry?	X	X	X	X	X

Table 6. The questions that formed the basis of each interview for each stakeholder group.

Interview results

The main findings from the interviews with each stakeholder group were as follows. These findings are only representative of the stakeholders who were interviewed.

- Producers: The producers of alternative seafood are all relatively new. Plant-based products range from high-end to mass market, and cell-based seafood producers focus on higher value products to reach price parity. Both groups of producers mainly cater to consumers who already eat seafood, such as omnivores, flexitarians and pescatarians, but they aim to complement conventional seafood supplies. Both groups also emphasize transparency, traceability, environmental sustainability and food safety of their products, but they do find that consumers often categorically reject novel or nontraditional foods. The COVID-19 pandemic slowed some research and development activities and forced producers to revaluate their business models. But it also increased public awareness of meat and seafood supply chains, the vulnerability of food systems to shocks and the need to transition protein sources. Fundamental research and regulatory support are needed to develop better and more accessible products, especially regarding novel ingredients and production technologies for plant-based seafood, and cell lines, cell culture media, scaffolding/texture and scalability for cell-based seafood. Alternative seafood could improve food and nutrition security (through nutrient fortification, more efficient protein sources and recovery of coastal and other subsistence fisheries), livelihoods (through recovery of coastal and other subsistence fisheries) and the environment (through lower use of natural resources and reduced pressure on terrestrial and aquatic ecosystems). However, this will require partnerships with animal-source food companies, cooperation with conventional seafood producers, public research funding and continued transparency.

- Investors: Investments in alternative seafood, especially with regards to cell-based seafood, require a lot of money and a long investment horizon. Investment in technologies that can reduce production costs is worthwhile because costs must fall for alternative seafood to compete in the market, though there is potential to carve out a separate market for seafood-like products. Alternative seafood is attractive because of the potential to produce products, including nonfarmable species, with increased transparency and traceability, reduced public health concerns, reduced ethical concerns and greater efficiency overall. Primary factors such as taste, convenience, price and access all continue to drive consumer food choices, but there is increasing importance placed on healthy, sustainable and ethical food. Alternative seafood could improve food and nutrition security (through nutrient fortification), livelihoods (through opportunities for livelihood diversification or conversion) and the environment (through more efficient protein conversion and reduced pollution). But there are also other solutions to explore, including food waste valorization.

- Researchers: Plant-based seafood research focuses on novel ingredients and processing technologies, while cell-based seafood research focuses on cell lines, cell culture media, scaffolding and bioreactors. Research is also being pursued to better understand the potential for impact on social, economic or environmental systems. It is widely agreed that publicly funded research would help advance the sector. There do remain questions about the future accessibility of alternative seafood, but insufficient production and distribution of nutritious food will need to be addressed in a variety of ways—alternative seafood and other novel aquatic food, like algae, start to do this. The disruptive potential of alternative seafood depends on consumer action. But if there is a sufficient decline in conventional seafood consumption and more harmful forms of fishing stop, the environment would greatly benefit. Stakeholders and governments should clearly define desired outcomes of the industry to determine if alternative seafood is an appropriate part of the solution to reducing hunger and poverty.

- Retailers: Retailers are aiming to reduce the environmental impact of the average consumer by encouraging reductions in meat, specifically red meat, intake. However, for nutritional purposes retailers are promoting increased seafood consumption. Currently, there is a small showing of alternative meat and seafood products. Many of these products target the modern consumer while few target the average consumer. The COVID-19 pandemic has caused challenges in conventional seafood supplies for retail, but the uptake of alternative foods has decreased as consumers are tending to choose more familiar foods. Alternative seafood could help absorb future demand growth but might prove more useful in the feed industry.

- Advocates: There has been rapid progress in the development of animal-source food alternatives, but growth of the alternative seafood sector depends on consumer actions. The main determinants of size and type of market are primary factors, including food safety, taste, convenience and price. Other altruistic factors, such as environmental concerns and ethics, are less compelling. The COVID-19 pandemic has increased consumer awareness of supply chains and their susceptibility to shocks. Because of the size of the conventional seafood industry, if alternative seafood augments even a small portion of conventional supplies over the next couple of decades it could be very influential. This augmentation could improve food and nutrition security (through recovery of coastal and other subsistence fisheries and reduced geographical barriers to consumption), livelihoods (through opportunities for livelihood diversification or conversion) and aquatic ecosystems. However, these will likely require support from the seafood industry and/or governments.

Appendix B. Future foresight modeling

Chin Yee Chan, Timothy B. Sulser and Keith Wiebe

International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)

IMPACT was developed by IFPRI, part of CGIAR, to support analysis of long-term challenges and opportunities for food, agriculture and natural resources at global and regional scales (Robinson et al. 2015). IMPACT is an integrated modeling system that combines information from climate models, crop simulation models and water models linked to a core global, partial equilibrium, multimarket economic model focused on the agriculture sector. This model system supports medium- and long-term scenario analysis to 2030 and 2050. It integrates these multidisciplinary modules to provide researchers and policymakers with a flexible tool to assess and compare the potential effects of changes in a number of areas: biophysical systems, socioeconomic trends, technologies and policies on agricultural production, consumption, prices, trade, resource use and food security. IMPACT is continually being updated and improved to better inform the choices that decision-makers face today, and it currently covers over 60 agricultural commodities (including crops, livestock and fish) in nearly 160 countries. The IMPACT team at IFPRI works closely with colleagues throughout CGIAR, including at WorldFish, and in other leading global research institutions, such as Oxford University, Wageningen University, the European Union's Joint Research Centre and others. Together, they explore alternative futures for food systems, diets, health and sustainable resource use.

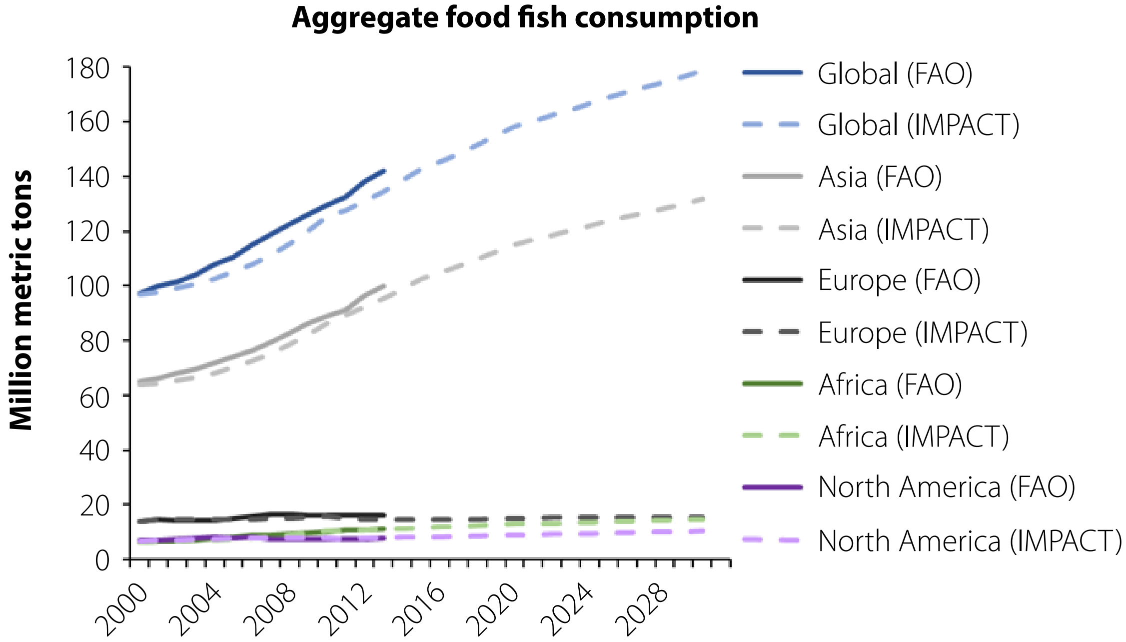
Opportunities and challenges associated with the emergence of alternative sources of protein, including alternative seafood, need to be understood in relation to rapidly evolving patterns of production and demand. For example, as incomes rise, demand for high-value and nutrient-rich foods like fruits and vegetables and animal-source foods will increase more rapidly than demand for staple food commodities, particularly in low- and middle-income countries. IMPACT can provide baseline projections for these future changes in demand for a wide range of agricultural commodities and food groups in 2030 and beyond, considering not only changes in income but also population, agricultural productivity, climate and other factors. These baseline projections provide a reference case against which to compare scenarios exploring the potential impacts of new food technologies like alternative seafoods.

IMPACT fish model

Delgado et al. were the first to use the IMPACT fish model to produce projections of global food fish production, consumption and trade from 1997 to 2020 (Delgado et al. 2003). This was also the first time that fish was included in a major global agricultural production and trade model. Approximately 10 years after IFPRI and WorldFish published the Fish to 2020 report (Delgado et al. 2003), the World Bank commissioned a follow-up study in collaboration with the IMPACT modeling team at IFPRI, the Fisheries and Aquaculture Department of FAO and the University of Arkansas at Pine Bluff. Incorporating the lessons learned in Fish to 2020, a new fish module of the IMPACT model was developed and used to create the Fish to 2030 report (World Bank 2013) covering 2000–2030. Fish to 2030 also incorporated new developments in global seafood markets and the aquaculture sector. Under the auspices of the Global Futures and Strategic Foresight project, IFPRI shared the IMPACT fish model with WorldFish in 2015. The project was funded by the Bill & Melinda Gates Foundation, the CGIAR Research Program on Climate Change, Agriculture and Food Security, and the CGIAR Research Program on Policies, Institutions, and Markets. WorldFish made further significant updates to the model to closely reflect the latest FAO historical trends. These updates were also used to calibrate future trends to 2050 considering specific biophysical and socioeconomic factors for fisheries and aquaculture and fish management and production targets defined by national governments. Using the updated model, WorldFish and IFPRI released the Fish to 2050 in the ASEAN Region report (Chan et al. 2017) in 2017 and a foresight special issue paper on the prospects and challenges of fish in Africa in 2019 (Chan et al. 2019).

Past, present and future seafood demand

Figure 9 presents the past, present and future global and regional fish consumption status using the latest FAO dataset (FAO 2017) and the latest IMPACT fish model projections. Globally, fish consumption reached 142 million metric tons in 2013. Among the four regions presented in Figure 9, Asia has the highest fish demand of 100 million metric tons, which is about 70% of the global seafood market by volume, followed by Europe (11%), Africa (8%) and North America (5%). North America and Africa started at almost the same level of fish consumption in 2000; however, Africa surpassed North America in 2007 onward. Using the IMPACT fish model projection, by 2030 global fish consumption is likely to reach 179 million metric tons, which will likely increase about 36 million metric tons compared to 2013. Asia continues to lead fish consumption globally, while Africa is likely to consume as much fish as Europe by 2030. Overall, total fish consumption increases at different growth rates in all the regions by 2030. The main drivers of this are increasing income and the surging population, particularly in Africa where the annual population growth is more than double compared to global growth.



NOTE: IMPACT fish projections should be considered preliminary and may differ slightly from those to be released in future publications.

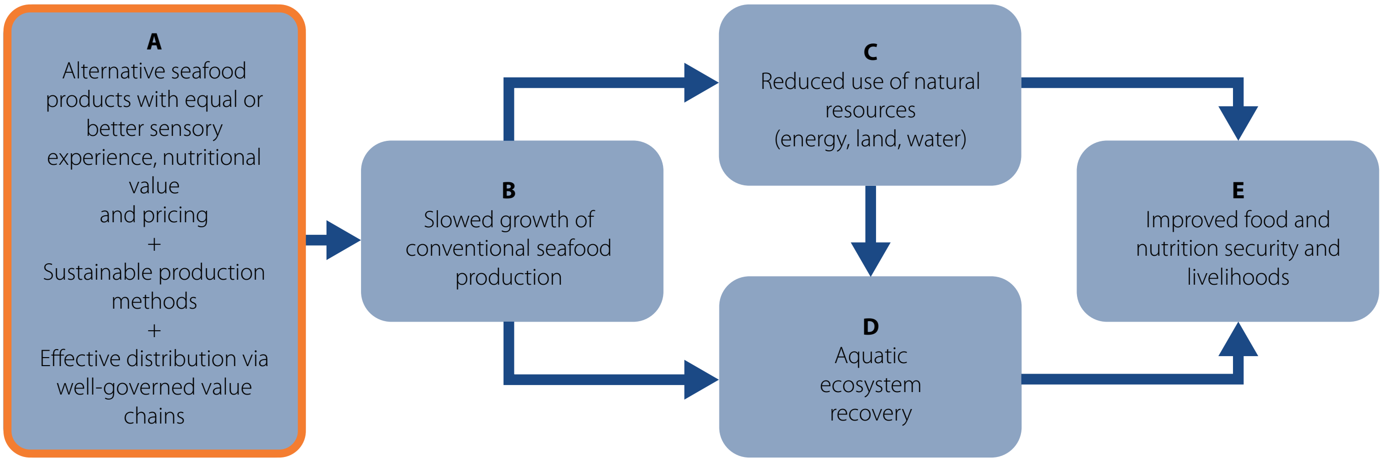
Figure 9. Historical and projected future food fish consumption at global and regional levels.

Appendix C. Workshops

Table 7 summarizes the research questions elaborated from the theory of change as well as notes, amendments and prioritization recorded during the workshop breakout groups (Section 7).

Breakout groups convened during each workshop (Asia-Europe and Africa-North America) reviewed the research questions. The orange circled statement in the TOC diagram identifies the TOC element from which research questions were developed. Each breakout group reviewed the associated set of research questions. The "Validity/Notes" column contains the breakout groups' assessment of the validity of the research questions, modifications to the research questions ("amended") and key notes to be considered when addressing the questions. The breakout groups also identified missing research questions. Note that the outputs from the two workshops, Asia-Europe and Africa-North America, have been combined.

Breakout Group 1. Research questions arising from the statement of initial assumptions

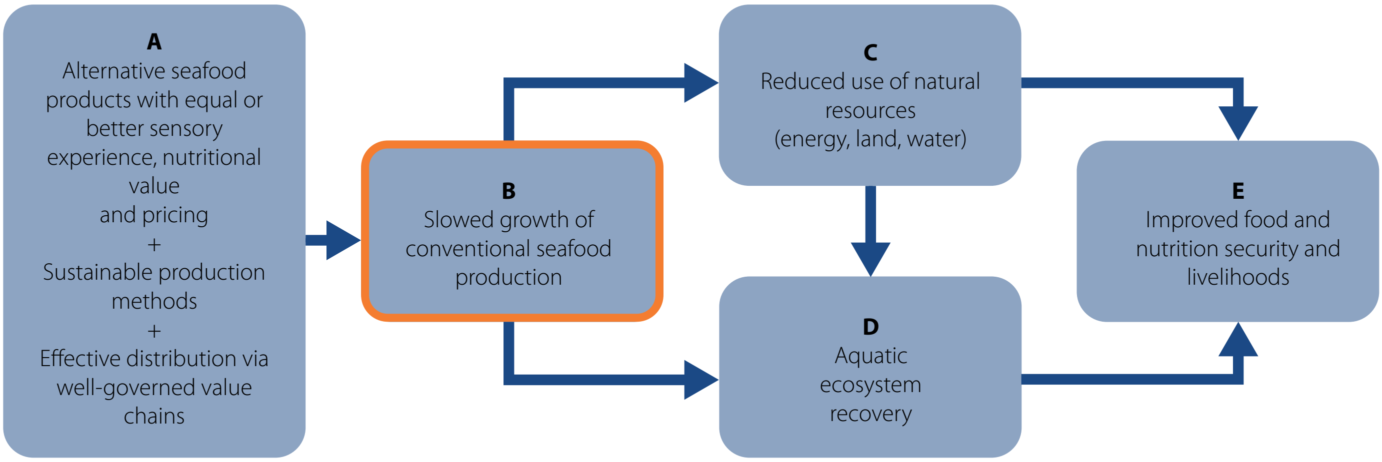


Statement	Research questions	Validity/Notes	Importance*
Alternative seafood products with equal or better sensory experience, nutritional value and pricing	How do the nutrient profiles of plant- and cell-based seafood compare with those of conventional seafood?	**Valid**, but only in certain contexts. • Targets depend on seafood species. • There is a difference between what is technologically possible and commercially acceptable/marketable. (Consumer preference and perceptions are key.) - Is it possible to genetically modify plant cells to produce long chain fatty acids? If so, then changes in consumer preferences and regulatory aspects must be considered. - It might prove hard to get regulatory approval for gene edited crops for human consumption.	**H**
	What are the optimal nutritional profiles in accordance with industry intentions/objectives regarding target markets and the pace of development? (amended)	**Valid** • Sensory experience must simulate conventional traits, but nutritional profiles can be improved/ changed. • *What is the optimal nutritional profile?	**M–H** (in relation to nutrient quality and price)
	How can the nutrient content/nutritional value of plant- and cell-based seafood best be ensured?	**Valid** • Research must be specific to plant-based seafood and cell-based seafood.	**L–H**

Statement	Research questions	Validity/Notes	Importance*
Alternative seafood products with equal or better sensory experience, nutritional value and pricing	Is certification for production standards needed and, if so, who should develop them?	**Valid** • Any certification must apply globally and be separate for both plant- and cell-based seafoods. Plant-based standards are more established and can be adapted to new products. No Codex standards exist yet, but public standards are a priority (no countries have yet requested them). • What technologies will gain regulatory approval and be commercially accepted? • There are unanswered questions regarding food safety, other product standards, differences at stages of development, etc.	**L–H**
Sustainable production methods	How do the environmental impacts of plant- and cell-based seafood compare with those of conventional seafood?	**Valid**	**H**
	How can impacts best be minimized?	**Valid** • Must be clear about resource use/efficiencies: specific food replacements in existing food systems, market growth/proportion, relations across products and fisheries systems.	**M–H**
Effective distribution via well-governed value chains	How might policies or stakeholders (such as research organizations, nongovernmental organizations and large animal-source food/protein companies) guide the development of the plant- and cell-based seafood subsectors to maximize benefits to low- and middle-income countries?	**Valid**	**H**
	How can stakeholders equitably share risks and benefits?	**Valid** • This is hard for the industry to control.	**M–H**
	Will plant- and cell-based seafood be accessible to all consumers?	**Valid** • Further research is clearly needed in relation to the overall market.	**H**
	What policies might improve access for poor consumers?	**Valid**	**H**
Additional research questions			
How safe are plant- and cell-based based seafood products for human consumption? How do the distribution and value chains of plant- and cell-based seafood compare with those of conventional seafood?			

**High (H), Moderate (M), Low (L), as it pertains to the potential for impact on food and nutrition security, livelihoods and the environment.*

Breakout Group 2. Research questions arising from the statement of assumptions around desired short-term change

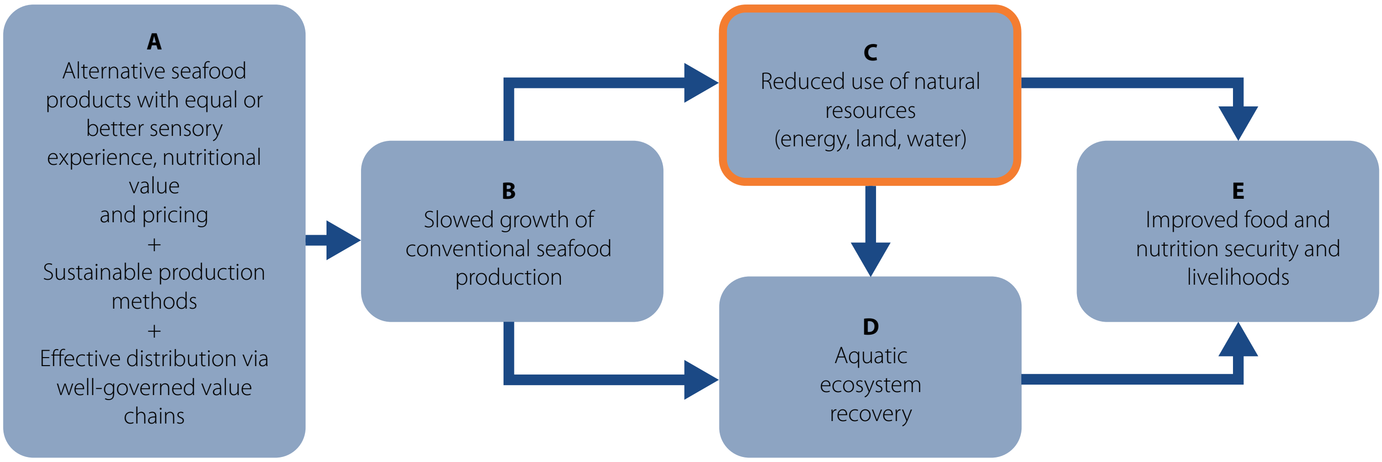


Statement	Research questions	Validity/Notes	Importance*
Slowed growth of conventional seafood production	Will plant- and cell-based seafood be consumed instead of conventional seafood, will it mainly replace other animal-sourced foods or will it simply be eaten in addition to conventional seafood?	**Valid** • Consider aquaculture's impacts on seafood consumption. It might be eaten in addition to existing seafoods, but this depends on the species, product form, regulations and categorization. • Estimated production of alternative seafood is unlikely to fill the 2030 demand gap. • Surimi might be used as a case study: - If it can be made cheaper, it could have a price point that works for larger buyers and institutional settings. - However, a lot of human culture is associated with consumption. Appeals will need to be made with respect to form. There are limitations on the types of alternative seafood products, which cannot mimic the form of a whole fish/crab but could work for fish sticks/sushi. - Most of the industrial fisheries that this could replace are already on a downward trend, so it might not have a big impact. • Compare this to what is already occurring with livestock. • This will depend on the form ("chunk meat") and price. If it is competitive, the replacement might not lead to a proportionate reduction in the competitor. Rather, the price will drop, some producers will go out of business and consumption will generally increase in both. • The focus will be on what can be eaten as processed foods. It might be at most 15% of the market.	**M–H**
Slowed growth of conventional seafood production	Where will alternative seafood be consumed? What are the main drivers? (amended)	**Valid**, but will probably need to work back from the next question. • It depends on the price point of plant- or cell-based seafoods. They are likely to be introduced in highly developed countries with the ability to purchase them, but could also be produced in developing countries in forms like canned goods. They could also be used in terms of food aid in, for example, alternative product forms like powder. With declining capture fisheries, prices will increase, but it still needs to be competitively priced, and price points will be changing. • Canning will depend on price point. At least in the mainstream, the majority of producers aim for the high-end markets, such as top restaurants with an educated consumer base that cares.	**L–H**

Statement	Research questions	Validity/Notes	Importance*
	How important will price, taste, food safety, environmental concerns, ethics (human and animal rights) be as determinants for adoption of alternative seafood?	**Valid** • Add a consumer lifestyle analysis of where the gaps are in markets and opportunities, such as young urban populations and increasing protein demand: This is *the* question. These are the pivotal concerns to determine. • Geographical location must be considered in relation to a potential new supply to landlocked countries. • Education is needed about environmental concerns and the lower levels of impact in alternative seafoods. • As a firm, we selected alternative seafood because it is a lot easier to create a cell-based fish fillet than beef (veins and marbling) in addition to the supply chain being so vulnerable to changes in environment/regulations, etc. All these concerns did factor in. • Taste, texture, product form and waste (which are important for food preparation) are initial concerns. Higher order benefits include health and ocean sustainability.	**H**
	How quickly will plant- and cell-based seafood production grow by 2030 and what will be the main drivers?	**Valid** • Plant- and cell-based research questions must be addressed separately. • We must identify facilitative conditions for production. R&D, access to capital and labor costs (including location of demand) will answer this question. • R&D is still ongoing, but it will be difficult to hit model forecasts for production, at least from a cell-based perspective because it is capital intensive (factories, labor). • This depends on the technology used. Cell-based seafood will have a shorter supply chain.	**H**
Slowed growth of conventional seafood production	Where will alternative seafood be produced? What are the main drivers? (amended)	**Valid** • Important to distinguish potential market niche/product forms, such as high-end products, versus nutrition supplements for the vulnerable. • Research question should focus on identifying underlying drivers rather than outcome of where production will occur.	**H**
	From a market perspective, which species will the plant- and cell-based seafood subsectors focus on producing? (amended)	**Valid** • This assumes that alternative seafood producers aim to mimic particular species, rather than general "fishy" attributes like taste, nutrition, appearance and mouthfeel. • It indicates which market niche producers are aiming for.	**M**
	What changes will be seen in conventional seafood production?	**Not valid** • Too peripheral. University of California, Santa Barbara has attempted to answer this, with marine biodiversity conservation potential as its focus.	**L**
Missing research questions			
We question the underlying assumption that alternative seafood will lead to a decrease in farmed or wild seafood production. What will the impact be on livestock product markets or other food sectors? Will vegetarians and vegans eat cell-based seafoods? How will consumers react to the technology?			

**High (H), Moderate (M), Low (L), as it pertains to the potential for impact on food and nutrition security, livelihoods and the environment.*

Breakout Group 3. Research questions arising from the statement of assumptions around desired medium-term change

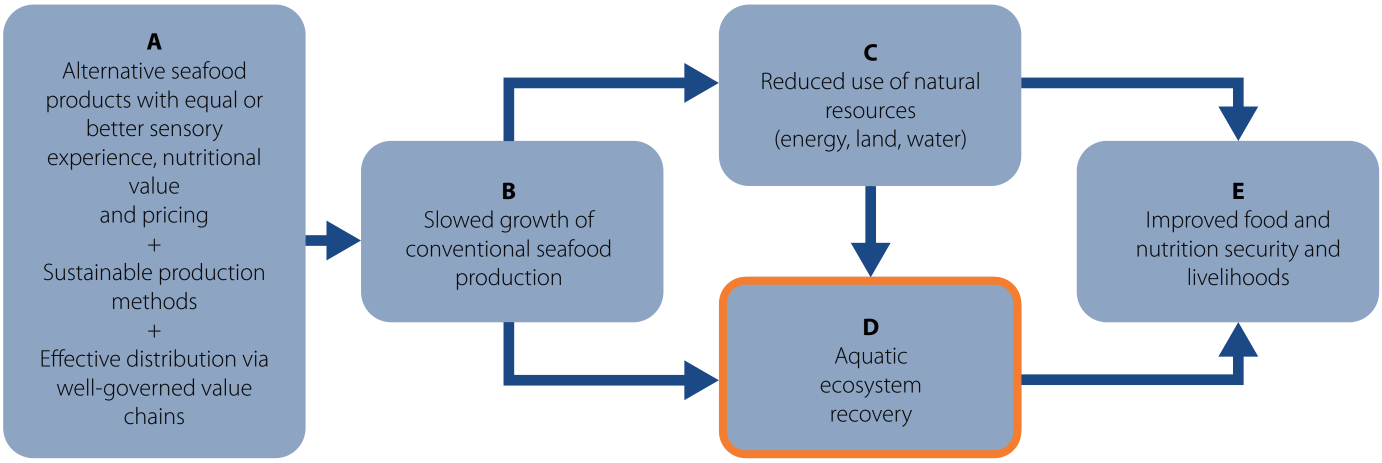


Statement	Research questions	Validity/Notes	Importance*
Reduced use of natural resources	What are the natural resource requirements of plant-based seafood?	**Valid**	**H**
	What inputs are required? How much? What are the opportunities/benefits and issues/challenges of using these inputs? (amended)	**Valid,** with amendment. • Originally, will using input material compete directly with their use as human food or animal feed?	**M–H**
	How much and what type of energy, land and water will plant-based seafood require as compared to conventional seafood? Compared to plant-based meat?	**Valid** • The life cycle assessment of foods is a big issue regarding food system sustainability and marketing foods with lower environmental costs. • Any research in this area would first have to develop a sound, transparent methodology that facilitates product comparisons.	**H**
	What are the natural resource requirements of cell-based seafood?	**Valid** Same concerns as above.	**H**
	How much and what type of energy, land and water will cell-based seafood require compared to conventional seafood production? Compared to cell-based meat?	**Valid** Same concerns as above.	**H**
	What life cycle assessment protocols should be used to evaluate conventional and alternative seafood production?	**Valid** • It is important that protocols are good. • Adopt standards of the International Organization for Standardization. New seafood-specific protocols are probably not needed.	**L–H**

Missing research questions
What are the most appropriate methods for evaluating the use of natural resources by this emergent sector? Is it life cycle assessment or are there other options? Is it based on a company's individual practices or evaluating the field as a whole?

**High (H), Moderate (M), Low (L), as it pertains to the potential for impact on food and nutrition security, livelihoods and the environment.*

Breakout Group 4. Research questions arising from the statement of assumptions around desired medium-term change



Statement	Research questions	Validity/Notes	Importance*
Aquatic ecosystem recovery	How does adopting plant- and cell-based seafood contribute to the recovery of aquatic ecosystems?	**Valid** • There may be less conventional exploitation, less fishing and fewer resources to support aquaculture. Also, slower growth of conventional seafood supply will lead to the recovery of marine systems. Access to new branded plant- and cell-based seafood might not be universally available for many places with supermarkets.	**H**
	How can recovery be measured?	**Valid** • Indicators should include fish number, diversity (e.g. oyster cages can decrease biodiversity due to the introduction of structure into a non-exploited system) and well-being of aquatic organisms. • However, ecosystems can also be affected by aquaculture practices (e.g. run-off) and how the alternative production chain (e.g. seaweed) can be used as for remediation (e.g. water quality). • We do not have baseline data for consumption.	**M–H**
	What enabling conditions or policies will be necessary?	**Valid** • Examples to consider: microbial load, raw material processing (seaweed), potential contaminants and indirect supply (e.g. landscape gets into the supply chain). • Economics and costs. For example, an Irish company buys seaweed-based feed from Vietnam to reduce costs. • Policies and conditions to consider are those necessary for governance, such as no-fishing zones and marine protected areas. Policies that encourage alternative seafood production must align with ocean protection. • Regarding social license, consultations with local communities are needed to encourage consumption of alternative resources to secure buy-in. • Adopt policies that encourage using alternative resources. Reduce public support for or even tax resource-intensive practices, and shift from fossil fuel to green energy sources.	**M–H**

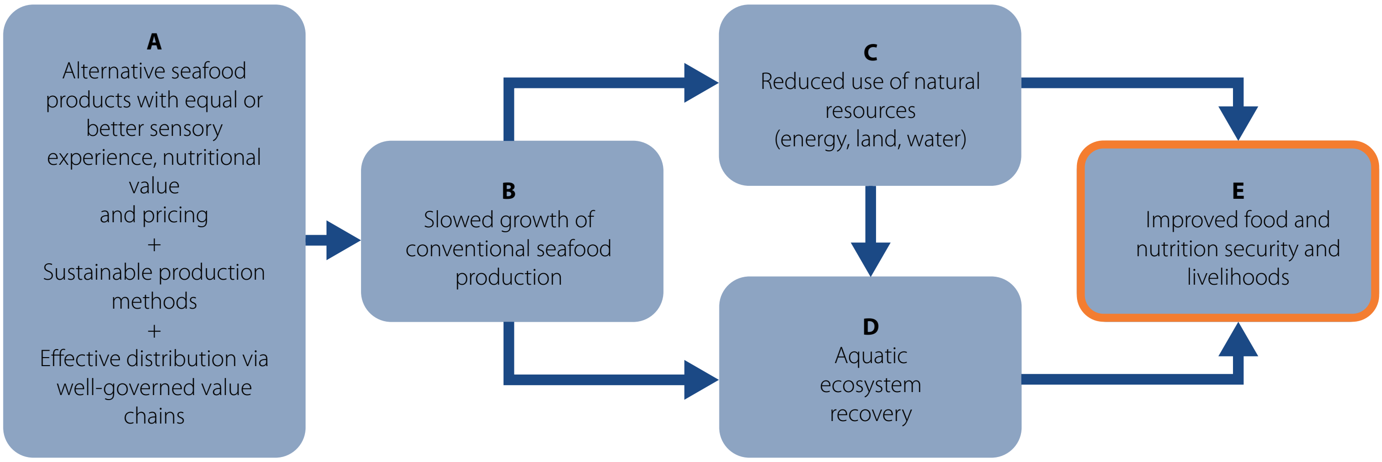
Aquatic ecosystem recovery	How long will recovery take?	**Valid**, to some extent. • This depends on assumptions around temporal evolution of consumption patterns. • It might take 2 or more years. For example, coral reefs take longer than other ecosystems to recover.	**M–H**
	How much must conventional seafood production and/or consumption decrease to produce a measurable recovery of aquatic ecosystems?	**Valid**, but only modest levels of recovery are likely.	**H**
	How dependent is recovery on changes in species-specific production and/or consumption?	**Valid**, but also very regionally dependent.	**H**

Missing research questions

Does the TOC extrapolate too far?
How will plant- and cell-based seafood be adopted (there are many types of food adoptions)?
How might regional differences in consumer preferences affect consumption of plant- and cell-based seafood and thus aquatic ecosystem recovery?
How important is the counterfactual in assessing the impact of plant- and cell-based seafood on aquatic ecosystem recovery rates?
How can R&D at this stage in the growth of the plant- and cell-based seafood subsectors use a sustainable food systems approach that considers the target consumer both in the US and EU but also of high consumption in developing countries where such products are not currently being developed?
To what extent is aquatic ecosystem health a key driver of social outcomes? What is the value of aquatic ecosystems to people? (It likely depends on where you live. Refer to marine ecosystems paper in Conservation Letters to calculate dependence.)
While aquatic ecosystem recovery is good for its own sake, how does it link to food and livelihoods? (This is likely to be species dependent.)

**High (H), Moderate (M), Low (L), as it pertains to the potential for impact on food and nutrition security, livelihoods and the environment.*

Breakout Group 5. Research questions arising from the statement of assumptions around desired medium-term change



Statement	Research questions	Validity/Notes	Importance*
Improved food and nutrition security and livelihoods	Under what conditions can plant- and cell-based seafood improve food and nutrition security in developing countries?	**Valid** • It depends on how stable conventional seafood supply is in the study location. For example, TVP vegetable protein is popular in Sir Lanka and has a long shelf life under ambient temperature conditions. It is more convenient and cheaper than fresh seafood, so it can be more readily adopted in diet. Also, spirulina, dried fish, dried seaweed are cheap protein sources in Africa. • This relates to price, accessibility, etc. For example, could alternative seafood be distributed similarly to micronutrient powder to enhance nutrition? • How does gender relate to food and nutrition security? Right now, there is division about who eats specific parts of the fish. • Acceptability of plant- and cell-based seafood products could be a big challenge, especially in areas where people are vulnerable. How can we address that with promotion? • It is very different from traditional seafood, especially in an African context. • Assuming the TOC is accurate, there are three issues: consumer side, producer and value chain (i.e. the connection between the two): Will consumers eat or not? Will the technology be accessible? Will artisanal fisheries in some regions be displaced? • Even when a new technology hurts production, consumers might benefit. • Also, plant-based seafood could be a very high-volume fish feed alternative since it could be low tech and easy to adopt.	H
	Can plant- and cell-based seafood provide a cost-effective solution compared to alternative food-based solutions?	**Valid**, but depends on scale and price. • A large part of cost structure goes to brand building (marketing and distribution channels), not helping the mass public. Maybe local production can help with reducing the costs. • Local production might allow local people to access more conventional seafood. One example is tofu, which is very accessible to the public with respect to price. • There is space for both alternative and conventional seafood. • Potential consumers need to be able to afford alternative seafood. Is it likely to be economically accessible to all? Producers, consumers, value chain operators? • Solutions can complement each other seasonally.	M

Statement	Research questions	Validity/Notes	Importance*
Improved food and nutrition security and livelihoods	How might plant- and cell-based seafood value chains differ from those of conventional seafood?	**Valid** • Who is participating in the value chain? If it is an industrial process, who will determine who gets to participate? - Artisanal chains often aggregate up from smaller boats. Would that be replaced by a high up-front investment value chain? - If done on a large scale and if competing with particular products coming from artisanal markets, then this would influence the importance of this question. - Would it be possible to make it small-scale artisanal? • Attitudes toward alternative seafood (thinking about attitude issues with aquaculture) are important across the board from value chain to producers to consumers.	**M****
	How much and what types of employment will be lost in developing countries due to the plant- and cell-based seafood subsectors?	**Valid** • Raw materials must still come from somewhere, but it will be from plants and crops rather than animals. • Livelihood substitution may occur. People working in fisheries and aquaculture may be able to shift to farming raw materials, like soy and pulses. • Food and nutrition should be considered separately from livelihoods in the TOC. • It is essential to unpack livelihood at various levels to understand what is going on, because livelihood is different from employment. If only employment is considered, this will miss key parts of analysis.	**M****
	How much and what types of employment will be created in developing countries due to the plant- and cell-based seafood subsectors?	**Valid** Same concerns as above.	**M****
	Which areas of the plant- and cell-based seafood value chains offer greatest opportunities for employment, especially among women and marginalized groups?	**Valid** • This is valid for areas that do not rely on terrestrial feedstock, such as seaweed and microbial-based materials. • Fermentation relies on a glucose supply; anything replacing petroleum-based industry that everybody needs. • Understanding the value chain will inform opportunities for employment and livelihoods. • There is a complex question of trade-offs between livelihoods and nutrition. • It is important to consider the role of women more broadly in the plant-based industry.	**M****
	How will exploitative labor conditions be avoided?	**Valid**	**M****
	What are the expected indirect economic effects in developing countries?	**Valid**, but more nuanced. • It is more difficult to predict effects on culture, psychology, etc., than effects on the economy.	**M****
Missing research questions			

* *High (H), Moderate (M), Low (L), as it pertains to the potential for impact on food and nutrition security, livelihoods and the environment.*

** *This question was not given a High (H), Moderate (M) or Low (L) prioritization, likely because the breakout group ran out of time to discuss. This question was assigned a prioritization of Moderate (M).*

WorldFish

About WorldFish

WorldFish is a nonprofit research and innovation institution that creates, advances and translates scientific research on aquatic food systems into scalable solutions with transformational impact on human well-being and the environment. Our research data, evidence and insights shape better practices, policies and investment decisions for sustainable development in low- and middle-income countries.

We have a global presence across 20 countries in Asia, Africa and the Pacific with 460 staff of 30 nationalities deployed where the greatest sustainable development challenges can be addressed through holistic aquatic food systems solutions.

Our research and innovation work spans climate change, food security and nutrition, sustainable fisheries and aquaculture, the blue economy and ocean governance, One Health, genetics and AgriTech, and it integrates evidence and perspectives on gender, youth and social inclusion. Our approach empowers people for change over the long term: research excellence and engagement with national and international partners are at the heart of our efforts to set new agendas, build capacities and support better decision-making on the critical issues of our times.

WorldFish is part of One CGIAR, the world's largest agricultural innovation network.

For more information, please visit www.worldfishcenter.org