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REVIEW

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Scenarios for Global Aquaculture and Its Role in Human Nutrition

Jessica A. Gephart[a,b], Christopher D. Golden[c,d], Frank Asche[e], Ben Belton[f,g], Cecile Brugere[h], Halley E. Froehlich[i,j], Jillian P. Fry[k], Benjamin S. Halpern[l,m], Christina C. Hicks[n], Robert C. Jones[o], Dane H. Klinger[c,p], David C. Little[q], Douglas J. McCauley[i,r], Shakuntala H. Thilsted[g], Max Troell[s,t], and Edward H. Allison[g,u]*

[a]The National Socio-Environmental Synthesis Center, University of Maryland, Annapolis, Maryland, USA; [b]Department of Environmental Science, American University, Washington, DC, USA; [c]Department of Nutrition, Harvard T.H. Chan School of Public Health, Boston, Massachusetts, USA; [d]Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, Massachusetts, USA; [e]Institute for Sustainable Food Systems and Fisheries and Aquatic Sciences, School of Forest Resources and Conservation, University of Florida, Gainesville, Florida, USA; [f]Department of Agricultural, Food and Resource Economics, Michigan State University, East Lansing, Michigan, USA; [g]WorldFish, Bayan Lepas, Penang, Malaysia; [h]Soulfish Research & Consultancy, York, UK; [i]Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, California, USA; [j]Environmental Studies, University of California, Santa Barbara, California, USA; [k]Department of Health Sciences, College of Health Professions, Towson University, Towson, Maryland, USA; [l]National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, California, USA; [m]Bren School of Environmental Science and Management, University of California, Santa Barbara, California, USA; [n]Lancaster Environment Centre, Lancaster University, Lancaster, UK; [o]Global Provide Food and Water Team, The Nature Conservancy, Arlington, Virginia, USA; [p]Center for Oceans, Conservation International, Arlington, Virginia, USA; [q]Institute of Aquaculture, University of Stirling, Stirling, Scotland, UK; [r]Marine Science Institute, University of California, Santa Barbara, California, USA; [s]Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden; [t]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden; [u]Nippon Foundation Ocean Nexus Program, Earthlab, University of Washington, Seattle, Washington, USA

ABSTRACT
Global demand for freshwater and marine foods (i.e., seafood) is rising and an increasing proportion is farmed. Aquaculture encompasses a range of species and cultivation methods, resulting in diverse social, economic, nutritional, and environmental outcomes. As a result, how aquaculture develops will influence human wellbeing and environmental health outcomes. Recognition of this has spurred a push for nutrition-sensitive aquaculture, which aims to benefit public health through the production of diverse, nutrient-rich seafood and enabling equitable access. This article explores plausible aquaculture futures and their role in nutrition security using a qualitative scenario approach. Two dimensions of economic development – the degree of globalization and the predominant economic development philosophy – bound four scenarios representing systems that are either localized or globalized, and orientated toward maximizing sectoral economic growth or to meeting environmental and equity dimensions of sustainability. The potential contribution of aquaculture in improving nutrition security is then evaluated within each scenario. While aquaculture could be "nutrition-sensitive" under any of the scenarios, its contribution to addressing health inequities is more likely in the economic and political context of a more globally harmonized trade environment and where economic policies are oriented toward social equity and environmental sustainability.

KEYWORDS
Aquatic foods; food security; food sovereignty; globalization; nutrition security; nutrition-sensitive

1. Introduction

Achieving global food and nutrition security goals within environmental boundaries will require transformation of global food production and distribution systems. This dual challenge will become ever more critical to solve with a global population headed to 10 billion by 2050, shifting socio-economic demographics, and with dietary trends toward more resource-intensive foods (Tilman and Clark 2014; Springmann et al. 2018; Willett et al. 2019).

Fish and other aquatic foods from both freshwater and marine environments (hereafter referred to as "seafood") are central to meeting food and nutrition security goals (Béné et al. 2015; Thilsted et al. 2016;

CONTACT Edward H. Allison eha1@uw.edu; e.allison@cgiar.org WorldFish, Jalan Batu Maung, Batu Maung, Bayan Lepas, Penang, Malaysia 11960.
*Corresponding author

World Health Organization 2018; Willett et al. 2019); and potentially providing more environmentally sustainable animal-source foods (Hilborn et al. 2018; Hallström et al. 2019). Globally, per capita seafood supply increased from 9.0 kg in 1961 to 20.2 kg in 2015 (Food and Agriculture Organization [FAO] 2018a), with rising prices in capture fisheries indicative of even stronger demand (Tveterås et al. 2012). This demand for seafood will increase significantly over the medium term (2030–2050) if historical trends in income and population growth, urbanization, and diets are maintained (Willett et al. 2019).

Although wild seafood has been harvested from oceans and inland waters for millennia, large increases in fishing effort over the past century, coupled with anthropogenic pressures including habitat degradation and pollution, have placed increasing pressure on wild fish stocks (Lynch et al. 2016; Pauly and Zeller 2016). As a result, global capture fisheries production peaked in the mid-1990s and has since plateaued (FAO 2018a). Under optimal management conditions, capture fisheries output could potentially increase by about 20% (Costello et al. 2019), although this seems unlikely in practice. In contrast, over the past three decades, farmed seafood production (aquaculture) grew at a rate of more than 8% per year and now produces around half of all seafood destined for human consumption (FAO 2018a; Edwards et al. 2019). Aquaculture therefore has been, and will remain, critical for filling the seafood demand gap.

Like any food production system, increasing aquaculture production will come with environmental costs. Environmental impacts, including those associated with energy use, water reliance, feed inputs, genetic risks and nutrient and pollutant release, vary widely because production systems and feed requirements are highly diverse, with around 460 species/groups of algae, shellfish, and finfish raised in freshwater, brackish, and marine environments, using a wide range of technologies (Troell et al. 2014; Tacon 2020). Local and regional environmental factors significantly determine ecosystem impacts of production, such as those related to accumulation of effluent and sensitivity of wild species (Aguilar-Manjarrez et al. 2017). Environmental impacts depend on the species, and increasingly, strain, farmed due to varying feed requirements, differences in growing method, production intensity, input sourcing, and farm management practices (Gephart, Troell, et al. 2017; Poore and Nemecek 2018; Bohnes et al. 2019), but within this variability lies opportunities. Although it has ancient roots (Beveridge and Little 2007; Harland 2019), the rapid growth of aquaculture in the last 40 years makes it a relatively young industry with vast potential to innovate toward low environmental impact systems.

Seafood currently supplies nearly 20% of animal protein and is often a rich source of vitamins, minerals, and omega-3 fatty acids essential to human health, development and cognition, with at least 845 million people estimated to be nutritionally dependent on seafood (Béné et al. 2015; Golden et al. 2016). The nutritional contribution of aquaculture varies widely, depending not only on the species produced and what it is fed (Fry et al. 2016; Tacon et al. 2020) but also on the environmental, social, and economic context of production and distribution systems. Evaluating nutritional contributions therefore requires a systems approach to understand the distribution of seafood, as well as the economic value derived from seafood along the supply chain. Both environmental and nutritional performance of farmed seafood must be considered in the context of the broader food system and local context of both production and consumption (Halpern et al. 2019). This approach avoids pitting one fish against another in search of a silver bullet and emphasizes the importance of considering aquaculture in the context of the diversity of foods in a food system (Tlusty et al. 2019).

This systems approach aligns with the concept of nutrition-sensitive food production, an emerging paradigm developed in response to perceptions that the global food system has been successful at increasing productivity to meet caloric needs of a growing population but has been less successful at supplying a healthy and nutritious diet (e.g., Krishna Bahadur et al. 2018). Nutrition-sensitive agriculture seeks to maximize the contribution of agriculture to nutrition through a strategy stressing the multiple benefits derived from diverse foods, including improving nutrition, valuing the social significance of food, and supporting livelihoods (Uccello et al. 2017). The concept of nutrition-sensitivity has recently been extended to fisheries and aquaculture sub-sectors (Golden et al. 2016, 2017; Thilsted et al. 2016; Fisher et al. 2017). Nutrition-sensitive aquaculture is defined here as a food system that (i) supports public health outcomes through production of diverse seafood, (ii) provides multiple, rich sources of essential, bioavailable nutrients, and (iii) supports equitable access to nutritionally adequate, safe, and culturally acceptable diets that meet food preferences for all populations, without compromising ecosystem functions, other food systems, and livelihoods. Key to nutrition-sensitive aquaculture is the shift from looking at aquaculture as primarily a means to produce seafood toward a means to create wellbeing, which necessitates accounting for socio-economic, environmental, and cultural dimensions.

Under what circumstances, and with what policies, could aquaculture be "nutrition-sensitive"? This question is addressed here by examining potential aquaculture development trajectories using a scenario approach and evaluating the constraints and opportunities for nutrition-sensitive aquaculture under each scenario. Previous analyses of the future of aquaculture have used supply and demand models to project production and consumption levels based on observed patterns of consumption and price elasticities of demand (e.g. Kobayashi et al. 2015; Tran et al. 2019). Although valuable for forecasting near-term demand, such projections are based on current diet patterns, trade environments, and governance contexts. Their utility can be expanded when coupled with qualitative scenarios to understand the conditions that enable or inhibit nutrition-sensitive aquaculture, such as the role of public and private investments in shaping development trajectories, the trade policy environment, technological innovation and knowledge transfer, and the response of consumers to information and marketing campaigns (Asche 2008; Thong and Solgaard 2017; Garlock et al. 2020).

Scenarios are plausible descriptions about how the future may develop, based on coherent and internally consistent relationships, but are not predictions or forecasts (Nakićenović and Intergovernmental Panel on Climate Change 2000). Here, qualitative scenarios for future aquaculture are developed through a process of expert elicitation and focused on the medium-term future (i.e. 2030–2050). The specific contexts required to support nutrition-sensitive aquaculture are examined within each scenario. Finally, while the scenarios take a global perspective, individual countries and production systems can follow diverging paths. To underscore the range of paths that can simultaneously exist, current aquaculture production systems exhibiting key elements of each scenario trajectory are described. The presented scenarios can help prompt discussions about which futures are desirable. As the current food system experiences substantial shocks to both supply and demand, there is potential for the sector to reorganize and head down an alternate scenario path. As such, it is critical to take stock of the current trajectory of aquaculture and prioritize conditions enabling nutrition-sensitive aquaculture into the future.

2. Methods

Future scenarios were developed using a version of the exploratory-strategic scenario methodology, following scenario development approaches used for socio-environmental decision-making (Reilly and Willenbockel 2010). The first step was to converge on the focal issue: the development of aquaculture and how different trajectories would likely affect its contribution to human nutrition.

The second step was to identify forces that are driving change in the aquaculture sector, with an emphasis on drivers that affect its intersection with the overall food system. Drivers are "any natural-or human-induced factor that directly or indirectly brings about change in [aquaculture] production systems" (Hazell and Wood 2008). This definition, originally applied to agriculture, was extended beyond its production sector focus to include other elements of the food system, including distribution and consumption. The perceived relative *importance* of the identified driving forces and *uncertainty of their impacts* were ranked. Importance, in this context, relates to any force or factor – environmental, social, economic, cultural, or political – that could significantly alter the trajectory of aquaculture development. The focus was on uncertainty in the magnitude and direction of the impact on aquaculture and the food system, not whether the identified driver will occur or if it will have an effect.

The two drivers identified as most important, most uncertain, and uncorrelated to each other were used to bound four contrasting scenarios. This was not a predictive exercise, meaning scenarios were not assigned probabilities. Instead, the scenarios focused on contrasting situations that are plausible given the identified uncertainties faced by aquaculture and food sectors, health, human development, and the environment. Taking these four scenarios, a storyline was developed for each using a template based on a matrix of all drivers identified as potentially important, additional to the two that formed the scenario axes. Opportunities for nutrition-sensitive aquaculture were evaluated within each scenario. Finally, current aquaculture systems were reviewed to identify examples capturing the key elements of each scenario.

3. Scenario results

The two key drivers identified as bounding the future of the aquaculture sector are *economic globalization* (section 3.1) and *economic growth trajectory* (section 3.2). These drivers form two dimensions of possible

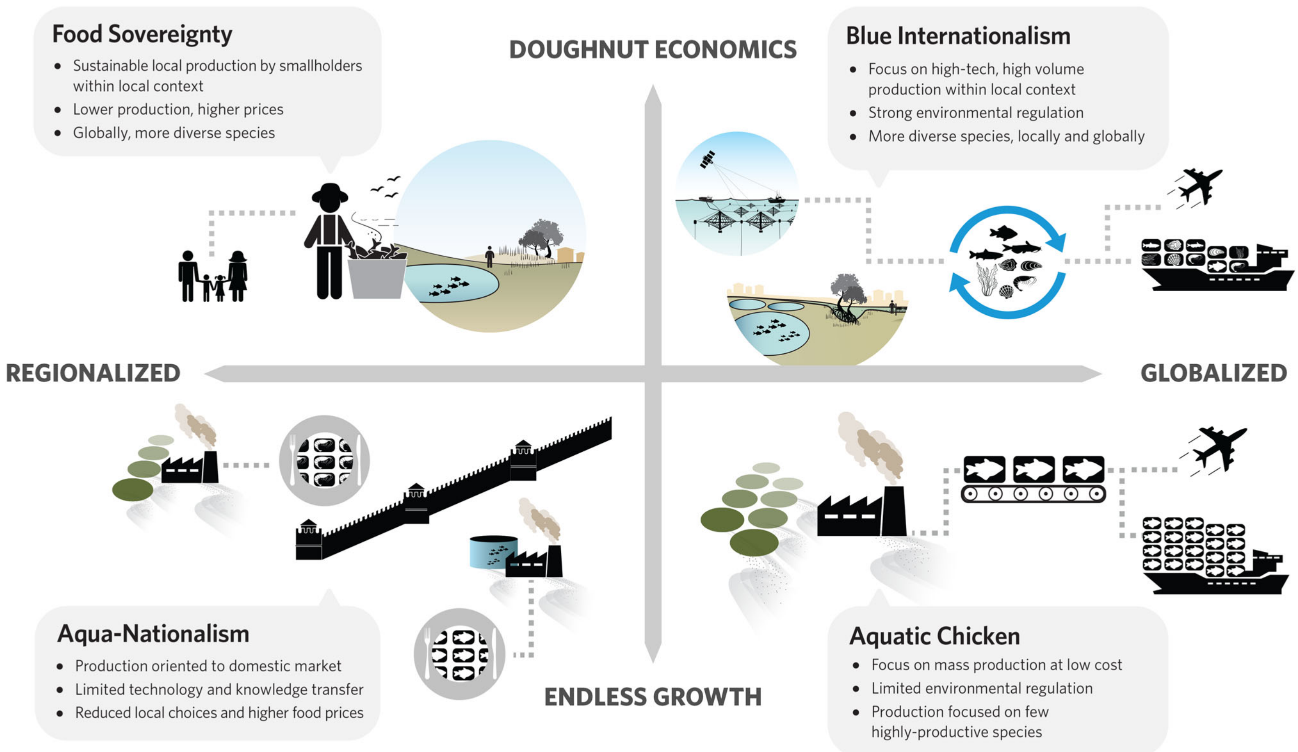

Figure 1. Visual representation of the two selected axes and four resulting scenarios.

economic development pathways that are likely to influence food sector trajectories – including aquaculture sectoral policies because of their influence on how goods and knowledge are distributed. Economic globalization refers to the structure of the global economy, within which aquaculture production and trade take place, and economic growth trajectory refers to the degree to which national, regional and global governance will influence the adjustment of the food system to emergent concerns for environmental sustainability and distributional equity. These can broadly be seen as reflecting uncertainties about: (1) whether the macro-economic architecture of global trade will remain similar to that found currently, or will fragment under the forces of populism and nationalism (Rodrik 2018a), and; (2) whether humanity commits to the environmental and distributional policies required to provide a good life for all within planetary boundaries (O'Neill et al. 2018), or whether neo-classical, growth-focused economic development strategies prevail. This second issue has been much debated in the last decade (Peck 2010; Reich 2016). These uncertainties are also identified in most macro-economic prospect and foresight documents, including the 2018 "World Economic Situation and Prospects" (United Nations 2018).

3.1. Geographical growth pattern: regionalized to globalized

Globalization describes the increased connectivity and flow of people, information, goods, and services across space (Figure 1). The horizontal axis therefore describes the spectrum of the degree of integration, from a food system in which production and consumption occur in the same geographical area (regionalized) to a food system in which production might occur in a geographically distant area from where it is consumed (globalized). The farthest left point on the axis would represent a system based on household production and consumption. Further along this axis, the regionalized systems move toward globalization and include increasingly large geographic areas, for example, through development of regional trading blocs (e.g. the European Union, the Association of Southeast Asian Nations, and the North American Free Trade Agreement countries). The farthest right position would represent a global market system where food is produced primarily for export, based on the comparative advantage of each region or country, or where food is primarily imported. When more foods and other products available in local markets come from non-local producers, markets tend to become more interconnected within global supply chains and prices become more synchronous (i.e., global market integration).

In general, globalization has increased in recent decades due to decreasing transportation costs, improved communication technology, and liberalization of trade policies. Global food trade has increased in line with this, with at least 25% of all food calories now traded internationally (D'Odorico et al. 2014), and seafood is among the most traded foods with 39% of production traded by value (Asche et al. 2015). Global trade of seafood has increased particularly rapidly, with near doubling in volume and value of seafood traded internationally from 1994 to 2012, with the largest increases in trade flows co-occurring with rapid expansion of aquaculture (Gephart and Pace 2015). The impacts of seafood trade on food security and wellbeing remain a subject of debate (Kurien 2005; Béné et al. 2010). The argument that international trade benefits food security centers on poverty alleviation from trade-induced economic growth (Béné et al. 2010). Meanwhile, the position that international seafood trade hinders food security centers on the argument that export revenues are not distributed in a way that benefits the poor (Béné et al. 2010). A meta-analysis of case studies on the impact of international seafood trade on small-scale fisheries identified three distinct syndromes, with only one resulting in increased fisher incomes in some instances (Crona et al. 2015). While these studies focused on capture fisheries, similarly mixed impacts are likely for aquaculture (Golden et al. 2017). Against the dominant trend of globalization, there have been some movements toward increased protectionism and patterns of de-globalization (Link 2018). Within the area of food production, some countries have set goals or implemented policies related to food sovereignty (Clark 2016; Desmarais et al. 2017).

3.2. Economic growth trajectory: "endless growth" to "doughnut economics"

The second axis describes different ways in which economies around the world may develop (Figure 1). One end of this continuum of possible macro-economic pathways represents a capitalist approach (Friedman 2009) that additionally posits that human inventiveness and adaptability can lead to "endless growth" (Simon and Bartlett 1985) and improved prosperity through the "rising tide that lifts all boats" (Kwon and Salcido 2019). The other represents an explicit concern for planetary boundaries and distributive justice (a "doughnut economics" approach; Raworth 2017a, 2017b). Both of these economic growth models can improve well-being, but their different intended pathways to social and environmental development would likely yield different food system configurations and therefore different aquaculture growth patterns.

On the endless growth end of the spectrum, there is a key assumption that the global economy can continue to grow, if governments provide the right investment climate, through a combination of major investments in innovation, technology, infrastructure, and human capital. Under this approach, aquaculture growth may be incentivized by tax breaks to large-scale aquaculture investors, investment in skilled workforces that then benefit private-sector financed research and development, or removal of potential restrictions to aquaculture growth, such as environmental legislation that might limit expansion of production facilities, or labor laws that might reduce the profitability of commercial operations. This philosophy of economic growth posits that market forces will achieve improved well-being and technological innovation will provide solutions to environmental boundaries.

On the other end of the axis, the donut economics approach is defined by establishing a safe and just operating space for humanity that is bounded by a social foundation and an environmental ceiling, creating a donut-shaped space for sustainable development (Raworth 2012). The social foundation and an environmental ceiling are interdependent, such that environmental stress can worsen poverty and inequality, and vice versa. As a result, this approach requires a more intentional accounting for both social and environmental outcomes of economic growth. Aquaculture development under a donut economics approach might be characterized by state- or societally-set standards and criteria for sustainable production methods and labor laws and unions to ensure gender equality, decent working conditions, and fair wages. The economic extremes highlight a key difference between endless growth and donut economics approaches: donut economics treats planetary and social boundaries as the starting point for assessing how economic activity should take place, rather than treating social and environmental stresses as economic externalities (Raworth 2017b).

3.3. Aquaculture scenarios

The two axes relating to the degree of globalization and the economic growth philosophy create four quadrants, each representing a distinct future scenario, named: Aquatic Chicken, Aqua-Nationalism, Food Sovereignty, and Blue Internationalism (Figure 1). A qualitative narrative followed by a discussion of the opportunity space for nutrition-sensitive aquaculture and a current aquaculture system exemplifying the scenario is provided for each scenario.

3.3.1. Aquatic chicken

3.3.1.1. Aquatic chicken scenario narrative. Under the aquatic chicken scenario, the world moves toward further economic globalization and encourages boundless economic growth. Through genetic selection and modification, as well as technological innovations, the aquaculture industry develops intensive production systems with limited environmental regulation. The highly intensive and controlled production systems prioritize reducing production cost, raising concerns regarding environmental impacts and animal welfare. Despite this, seafood products may still be environmentally efficient compared to other animal-source foods. Production systems rely on globalized supply chains, sourcing feed ingredients internationally, taking advantage of low labor costs for processing, and utilizing coproducts and byproducts globally.

Through competition, only the most profitable system-species combinations win out, resulting in massive production of only a few species, which are highly traded and spread rapidly (akin to the dominance of four species in the meat market, led by chicken; Bennett et al. 2018). This high level of production creates low global prices for such "aquatic chickens," which occupy different price categories targeting different types of consumers and reach consumers around the globe due to low trade barriers. This enhances access to seafood for those in urban areas and areas with good logistics. Self-provisioning and local smallholder production persist as part of integrated rural livelihoods for species not dependent on externally sourced seed, but this is marginal compared to a world where production is dominated by a few large species.

The "aquatic chicken" supply chains are generally vertically integrated and only a few companies control key components of the supply chain, especially breeding and feed production. This level of consolidation has both risks and benefits. On the one hand, companies build significant knowledge with respect to production and marketing of these species and manage risk along the supply chain to reduce the probability of production disruptions, including through investment in multiple producers to minimize risk from any periodic localized disruptions. On the other hand, inherent low species diversity makes the systems vulnerable to disease, which can only partly be mitigated by improved knowledge about disease prevention and treatment.

3.3.1.2. Aquatic chicken scenario discussion. Although this scenario is likely to produce the largest quantity of food at the lowest prices, the concentration of production among large producers and reliance on cold storage supply chains can limit rural access. The high nutritional quality of the aquatic chickens could feasibly fill nutrient gaps in the markets it reaches. Therefore, maintaining or enhancing quality of the products, for example, through nutrient fortification (Tacon et al., 2020), will be important from a nutrition-sensitivity perspective, but there are currently few incentives to take nutritional quality into account when the main objective is efficient, low cost production. Targeted policy interventions would therefore be necessary to redirect aquatic chicken toward nutritionally vulnerable populations in order to be nutrition sensitive.

Farmed salmon and tilapia have to a large extent adopted production practices from intensive agriculture to an aquatic environment, following paths similar to the aquatic chicken scenario (Asche 2008; Kumar and Engle 2016; Asche et al. 2018). The "growth first" approach characterizing the aquatic chicken scenario does not consider negative environmental impacts of production. The development history of Atlantic salmon (*Salmo salar*) provides a good example of this. In the early years, local pollution and use of antibiotics and different chemicals increased even faster than the salmon production, not dissimilar to what one has observed for chicken. In addition, use of marine ingredients in salmon feeds presents a unique environmental challenge. With increased knowledge and governance systems providing incentives, these challenges can be addressed such as by using vaccines instead of antibiotics (Asche 2008) and alternative terrestrial (e.g. soy for protein) or high technology-based (e.g. microalgae and genetically modified rapeseed for omega-3 fatty acids) feeds ingredients (Klinger and Naylor 2012; Cottrell et al. 2020). While there are still environmental challenges associated with salmon production that vary with the production practices in different countries, the total environmental impact is now less than many alternatives (Froehlich, Runge, et al. 2018).

Salmon is rapidly moving to become an industry with multi-national companies in key roles. For example, there are only two or three feed suppliers present in most salmon producing countries and two leading breeding companies. The development of the salmon industry has been supported by the university and research and development infrastructure in producer countries, which facilitated knowledge transfer from agriculture. This drove significant reductions in production costs, leading to lower prices and moving salmon from a luxury to an affordable product in wealthier countries. The export patterns reflect a strategy of targeting wealthy consumers, with the greatest share heading to the largest economies, while very small quantities enter poorer and smaller countries. This highlights that while salmon may be nutritionally useful in the countries where it is consumed, it is not to any extent targeting the neediest.

While salmon is currently the aquatic species that most closely follows chicken style production and marketing strategies, the special circumstances that made it a success may also prevent it from becoming a globally produced aquatic chicken. Significant production is restricted to only a handful of countries, with two making up almost 85% of total production, and its geography is limited by sea cage production that requires specific oceanographic conditions and temperature range. This may be overcome in the future by efforts to develop land-based and offshore systems (Bjørndal and Tusvik 2019). If successful, this will allow production in many more countries and effectively remove the largest production constraints. In the long run, it is still a question if it can be price and cost competitive relative to faster growing subtropical species, such as tilapia.

The commoditization and global trade in tilapias took off around the millennium with a rapid rise in exports of processed individually quick-frozen tilapia from China to North America (Zhang et al. 2017). The ground for this growth was laid two decades previously through the distribution and farming of Nile tilapia (*Oreochromis niloticus*) across five continents (Kumar and Engle 2016). US-based pioneers had developed a "white tablecloth" restaurant focus for fresh tilapias produced in Latin America which had built popularity through the absence of a strong fishy flavor, a blank canvas for chefs to add flavor, and value for price in a fairly limited seafood menu of the United States. Technical advances, control of breeding and improved strains had also been developing to improve productivity and remove barriers, such as inconsistent size and "off-flavors" that had previously plagued the sector. The market developed mainly around individually quick-frozen fillets, often with value added by diversification by US based processors. Yet, even though tilapia has now entered almost every retail and food service niche in North America, including fast food, demand for tilapia has recently declined in the United States (FAO 2019), in contrast to the steady growth evident on a global basis (Tveterås et al. 2019).

Large integrated companies in China are now developing value-added products for the domestic market and are increasingly turning to new markets, such as Sub-Saharan Africa, to sell rapidly increasing quantities of frozen whole tilapia (Mapfumo 2015). As a result, nascent large-scale intensive production in countries like Ghana, Kenya, and Zambia, which largely targeted better-off urban consumers, cannot compete on price with Chinese imported tilapia, thus eroding domestic margins and market shares. The influx of cheaper substitutes has made tilapia more affordable for poorer consumers and arguably, provided strong incentives for local producers to become more efficient. But local producers are hampered by slower growing strains, expensive feeds, limited availability of quality fingerlings, lack of trained employees, and an undeveloped service sector. Tilapia production growth in other countries, such as Egypt and Bangladesh, is spurred by knowledge and technology transfer; import of feed ingredients and production equipment has also been critical in most contexts supported by increasing globalization.

3.3.2. Aqua-nationalism

3.3.2.1. Aqua-nationalism scenario narrative. In this scenario, countries throughout the world turn inward for economic growth and focus on supporting national industries to meet seafood demand. While demand within countries continues to fuel production for domestic markets, limited technology transfer, sparse development, underdeveloped regulatory systems and import barriers for feeds result in less efficient production at the country level and higher prices. Such increases in prices reduce access to seafood by the poor, and lower total global aquaculture production. Inequality in seafood supply rises: the supply to current net importers declines sharply and while domestic production gradually expands, it is unable to close the demand gap and causes prices to rise. Reduced access to imported feed ingredients increases production costs and further drives up prices. Growth of farmed seafood supply in "late adopting" countries where aquaculture development is currently in the nascent stages, is delayed, interrupted, or reversed.

Overall, diversity of seafood available in each country generally declines as production diversity is constrained by local environmental conditions and limited technology transfer among countries. In low- and middle-income countries, reduced external pressure for improvements in environmental and food safety standards to comply with demand from export markets result in fewer regulatory spillovers to domestic-oriented production and larger negative environmental and public health externalities. To meet domestic demand and bring down rising costs, countries put production growth first and lift environmental regulations along the supply chain, allowing industry to exceed local carrying capacity and push up against environmental boundaries. Collectively, the world then pushes up against or exceeds planetary boundaries. Although small initiatives promoting locally produced, environmentally conscious seafood arise in some locations (e.g. "Slow Fish," inspired by Slow Food), these systems are unsupported by economic policies and remain too niche to achieve any significant supply.

In some places, rolling back environmental and animal health regulation results in disease outbreaks and biodiversity loss due to poor siting of farms in ecologically sensitive habitats. This increases risk of periodic seafood supply reductions and increased price volatility. In instances of disruptions from localized extreme events, regions are unable to source from foreign producers to fill production gaps without open trade policies. In other cases, protectionist trade policies limit some supply shocks and the spread of transboundary diseases by preventing the import of organisms that serve as vectors for transmission. Overall, fluctuating supply and lack of governmental intervention to influence food safety and nutritional quality, together with reduced species diversity available on domestic markets and inadequate consumer awareness and education, mean that farmed fish play a limited role in contributing to nutrition and public health in many countries.

3.3.2.2. Aqua-Nationalism scenario discussion. Under this scenario, countries with mature aquaculture sectors that already supply a diversity of production technologies, species, and product types will continue to meet some nutritional needs, but for a narrower range of consumers and at increased cost, and to a more limited extent, than at present, while the development of nutrition-sensitive aquaculture in countries with emergent aquaculture sectors will stall. Availability of feed ingredients will be a major challenge for some countries, given current levels of international trade for soy, fishmeal, fish oil, and other feed ingredients. In order to overcome these challenges, national governments will need to invest more heavily in research, development, training, extension, financial support to producers, and businesses upstream and downstream of the farm in order to offset reduced innovation that could otherwise be obtained by importing equipment, inputs, and skilled personnel, or through foreign direct investment. Subsidies may be required to encourage local production of feed ingredients or to offset the cost of hikes in feed prices due to restrictions on imports if production of species dependent on formulated feeds is to remain economically viable. Public information and social marketing campaigns will be needed to inform consumers of the benefits of consuming certain fish species, and incentives may be necessary to encourage production of species deemed particularly desirable from a nutrition point of view.

Myanmar provides a good example of what an aqua-nationalism scenario looks like. Prior to the onset of political and economic reforms in 2011, the "closed" nature of the economy discouraged inward investment, while economic sanctions severely restricted access to export markets. Government policy during the 1990s and 2000s encouraged industrial-scale aquaculture by allocating land concessions for development by Myanmar companies. Expansion of aquaculture occurred without concern of social or environmental impacts and resulted in displacement of rural households from their land and conversion of large areas of biodiversity rich wetland habitat to fishponds (Mark and Belton 2020). These farms produce a very limited diversity of fish species. A single carp species – rohu (*Labeo rohita*) – accounts for around 70% of total production (Tezzo et al. 2018). Most farms use unsophisticated production technologies that generate low yields. Until recently, a single company maintained a virtual monopoly in domestic aqua-feed production, resulting in high feed prices and low rates of feed use. The high price of feeds contributed to low productivity and limited diversity of species farmed. Domestically sourced feed ingredients are insufficient to meet the needs of the industry, also contributing to high feed prices (Belton, Hein, et al. 2018).

An export-oriented shrimp farming sector began to develop in the 1990s but collapsed in the 2000s in the wake of sanctions. The shrimp sector was also weakened by disease outbreaks, partly attributable to poorly sited ponds lacking biosecurity, and dependence on a declining supply of wild shrimp post-larvae, exacerbated by a ban on imports of shrimp post-larvae from neighboring Bangladesh, and a lack of investment and knowhow in the domestic shrimp hatchery sector (World Bank 2019). Myanmar is able to produce a substantial quantity of farmed fish for the domestic market, but the predominant focus on production of large-sized rohu in large, semi-intensively managed farms means that aquaculture serves a more limited range of consumers and producers than it could if the sector were organized around a diverse set of farming systems, farm sizes, and species (Belton, Hein, et al. 2018). As a result of this history of de facto "aqua-nationalism," farmed fish is more expensive and less accessible to poor consumers than it might otherwise be, and the diversity of nutrients is limited. Total seafood production and consumption per capita fall well below their potential. Recent efforts by development institutions to promote a more diverse and nutrition-sensitive aquaculture sector in Myanmar have focused on working with smaller farms to raise productivity, encouraging production of small micronutrient-rich indigenous fish species as part of polycultures with carp species, and educating rural households about the benefits of consuming these species. To date, these efforts have been implemented at a limited scale through development projects.

3.3.3. Food sovereignty

3.3.3.1. Food sovereignty scenario narrative.

Countries throughout the world adopt sustainable local food production approaches focused on smallholder production. While some traditional production systems are highly productive, in general, global aquaculture production grows at a relatively slow rate – if at all – and total production is relatively low. Without efficiency and scale in production, there are fewer investments in production and distribution technology. While low production, in combination with high trade barriers, results in higher prices, the food production systems that arise in each country tend to be in line with local cultural preferences and environmental contexts, resulting in moderate species diversity at local levels and high species diversity globally.

Throughout rural areas, fairly high seafood access exists for the large number of small-scale producers and their communities, but higher prices for seafood sold in urban markets reduce access for the urban poor. Since countries pursue a sustainable development path, production accounts for environmental limits, thus reducing risk of environmental disruptions, but when producers do experience losses, regions cannot fill the gap from foreign suppliers due to trade barriers. For those able to access farmed seafood, a variety of nutritious and culturally preferred species are available, albeit at a price. As a result, the sector contributes to nutritional diversity and quality in diets, and seafood is included in national dietary guidelines and is available to people at critical life stages, with the help of state subsidies or incentives, to state-run schools, hospitals, and elder care facilities. Regulations on food quality and incentives to maintain high nutrient content ensure that nutritional quality of farmed fish equals or exceeds that of wild-caught fish.

3.3.3.2. Food sovereignty scenario discussion.

Under this scenario, countries that have retained a cultural history of developing small-scale aquaculture will see an increase in these production systems, supported by government-backed schemes and extension services. Within low- and middle-income countries and in rural areas, there will be a growth in widely distributed household pond culture systems that support a diversity of species. These systems will likely complement existing small-scale capture fisheries. When production is at the household scale, women are more likely to play a key role in this sector, increasing the likelihood that nutritional benefits flow directly to the most vulnerable. Efforts to coordinate cooperatives and support larger scale aquaculture production will be supported through government ownership or loans, but with limited success, as operational costs and prices remain high, limiting access to cheap and nutritious fish for the most vulnerable in urban settings.

High-income countries with a history of aquaculture development will continue production, though likely scaled back, due to lack of supply of fingerlings and export markets. Within urban settings, aquaponic and recirculating aquaculture systems are likely to be promoted along with broader urban gardening initiatives, and locally produced slow food movements that reconnect consumers to food cultures. As a result, fish prices will increase, and fish consumption will decline. In these settings, aquaculture is likely to lead to an increase in the diversity of species produced, and benefits of production are likely to be felt by the wealthy. This effect may be counteracted by governments developing redistributive policies and subsidies to support the production and supply of seafood at reduced prices for targeted socio-economic groups.

A current example analogous to the former situation is found in South and Southeast Asia, where millions of rural households maintain small ponds in homesteads and rice fields. These are often stocked with hatchery-produced seed of species such as Indian and Chinese major carps, and tilapia and also tend to attract wild self-recruiting fish species from the surrounding environment (Edwards et al. 2002). Such ponds are usually managed extensively or semi-intensively, receiving relatively low levels of feeds and inputs such as rice bran, oil cake, and fertilizers. Ponds managed in this way produce correspondingly low yields of fish and generate limited negative environmental externalities, though there is some evidence that intensification is taking place in Bangladesh through greater use of pelleted feeds (Jahan et al. 2015; Hernandez et al. 2018). Depending on household preferences, fish produced in this way may be eaten by household members or sold. Most ponds generate a small surplus of fish that is sold in markets local to the area where the farm is located, as well as contributing to home consumption needs (Belton 2013). The location of such ponds close to home compounds means that they are often managed by women, even in South Asia where cultural norms that restrict the mobility of women sometimes limit their participation in other forms of aquaculture. NGO-led extension projects in Bangladesh and India have successfully introduced micronutrient rich small indigenous species such as *mola* into carp-based homestead pond polycultures (Thilsted et al. 2016). Including small indigenous species in polycultures has been demonstrated to increase intakes of micronutrient-rich small fish by women and children, (Castine et al. 2017), and to cost-effectively reduce the burden of micronutrient malnutrition (Fiedler et al. 2016). Unfortunately, these ways of farming no longer contribute a large share of total fish production. Intensive and increasingly specialized small and medium scale commercial farms provide the majority of farmed seafood eaten throughout Asia, especially for urban areas (Belton, Bush, and Little 2018). This means that return to a heavy dependence on more traditional forms of small-scale aquaculture would entail reduced supplies of seafood, and higher consumer prices.

3.3.4. Blue internationalism

3.3.4.1. Blue internationalism scenario narrative. The world fully embraces the application of sustainable development principles, taking advantage of the benefits of globalized food systems while strengthening environmental governance to ensure the world does not exceed planetary boundaries. Global competition and high levels of technology transfer lead to relatively high global inland and marine seafood production. Favoring production of seafood in line with local environmental contexts, this world leads to moderate global species diversity, with the local species diversity depending on the specific approach in a given country. High global seafood production and low trade barriers enable low seafood prices, improving seafood access in urban areas and areas with transportation infrastructure connections and access to electricity for refrigeration.

By accounting for environmental boundaries and diversifying production systems, this world reduces risks of environmental and disease disruptions to production. When disruptions do occur, trade openness allows regions to source from other regions to meet seafood demands and efficient and cooperative global surveillance systems enable disease outbreaks to be quickly contained before they erupt into pandemics threatening the sector. The Voluntary Guidelines to Support the Progressive Realization of the Right to Adequate Food in the Context of National Food Security are adopted by most States and ensure that nutrition information on farmed fish is available and State policies align with the Human Right to Food (FAO 2005). Regulations and fiscal incentives ensure that powerful food sector actors align their production, processing and marketing with dietary guidelines; they develop aquatic species strains with different nutrient "signatures" such that they can reach all sectors of the market with healthy food at affordable prices.

3.3.4.2. Blue internationalism scenario discussion. A key assumption that must be realized for nutrition-sensitive aquaculture to be delivered in this scenario is that businesses are incentivized and able to produce a diversity of nutritious products that are available at a range of price points, including relatively inexpensive products that are accessible nutritionally vulnerable populations. The aquaculture sector is primarily composed of businesses that must be profitable to sustain long-term production. As such, governments must be able to adequately subsidize, regulate, or otherwise incentivize producers so that they can profitability supply seafood at low price points. Further, this scenario assumes governments or markets can incentivize species diversity, where producers forgo the near-term benefits of consolidation for longer-term benefits of resilience (from market, environmental, disease or other shocks). Both interventions require political will and resources that may be constrained due to scarcity or high opportunity costs.

The aquaculture sector in the Netherlands exhibits many of the characteristics associated with Blue Internationalism, despite its relatively low total production. Blue mussels (*Mytilus edulis*) make up the majority of production (86% by tonnage in 2017), but other bivalves and finfish are produced, including north African catfish (*Clarias gariepinus*, 5%), cupped oysters (*Crassostrea gigas*, 5%), European eel (*Anguilla anguilla*, 3%), and several other species (1%; FAO 2016). Production systems in the Netherlands range from extensive, capture-based production of blue mussels to highly intensive recirculating systems for yellowtail (*Seriola lalandi*). In capture-based blue mussel systems, farmers dredge natural mussel beds or use suspended seed collectors to capture wild juveniles and then transfer them to protected plots for grow-out (Bostock et al. 2016). Farmed blue mussel production in the Netherlands has decreased by about 50% since highs in the late 1990s due to contraction of permitted sea-bottom grow-out area as a result of competition from other users, including environmental conservation, and periodic recruitment decreases. Collection of wild seed is regulated (Wijsman et al. 2019). Recirculating systems for yellowtail and other finfish utilize hatchery produced fingerlings, manufactured feeds, on-land tanks, and high stocking densities (Sicuro and Luzzana 2016). The Dutch aquaculture sector is composed mostly of small companies, but the sector is supported by inputs supplied by regional and international supply-chain companies.

Species are produced at a range of price points, based on first-sale value, including \$1.4/kg for blue mussels (*Mytilus edulis*), \$1.7/kg for cupped oysters, \$2.3/kg for North African catfish (*Clarias gariepinus*), \$8.7/kg for European eel (*Anguilla anguilla*), \$10.1/kg for yellowtail, and even more for sturgeon (*Acipenser gueldenstaedtii*) caviar. Further, production is largely consumed in the region. Blue mussels are consumed fresh in the Netherlands and exported to nearby France and Belgium. In general, most Dutch seafood products are consumed in the European Union (USDA 2019). The aquaculture sector in the Netherlands has contracted in recent years, largely due to high input costs (e.g., labor) and falling prices due to competition and production from abroad. Despite this, seafood production and imports target multiple market segments and price points and making seafood readily available in Dutch markets.

The first and second largest aquaculture producers, China and Indonesia, both demonstrate movement toward attributes of the blue internationalism scenario. China participates in a globalized food system (Cao et al. 2015) and there are early indications that it is attempting to realign parts of its aquaculture sector within environmental limits (e.g. Godfrey 2019; Szuwalski et al. 2020). While the long-term comprehensiveness, precision, and effectiveness of these efforts are uncertain, competing economic sectors and changing social forces may drive improved regulation of the sector. Further, China produces for a range of market segments from high-value marine finfish to lower value marine plants and the sectors utilize high species diversity (Gui et al. 2018). Aquaculture in Indonesia is similarly diverse and the Indonesian seafood sector is highly connected to global food systems (Gephart and Pace 2015). Current practices and growth goals for the sector often do not account for environmental boundaries (Henriksson et al. 2019), but the government has made commitments to improving both environmental performance and nutritional sensitivity of the sector.

4. Discussion

As a young and rapidly expanding industry, the future of aquaculture and its role in nutrition remains highly uncertain. The factors bounding plausible futures identified through a structured scenario development process center on major macroeconomic drivers: globalization and the prevalent economic growth philosophy. These factors generate four contrasting scenarios of a boundless growth, globalized world (Aquatic Chicken), a growth first, nationalistic approach (Aqua-Nationalism), a sustainable growth, localized approach (Food Sovereignty), and a sustainable growth, globalized world (Blue Internationalism). Despite the deep differences among the scenarios, there are elements of each of these scenarios in current production systems from around the world.

Across the four scenarios, there is room for nutrition-sensitive aquaculture in each, but nutrition-sensitivity is not a given under any scenario. As discussed above, some scenarios are more strongly associated with the enabling conditions for nutrition-sensitive aquaculture (adoption of pro-sustainability policies that emphasize achievement of the sustainable development goals and equity of access to healthy, nutritious food), while others (emphasis on macroeconomic growth with little high-level attention or effective commitment to environmental sustainability and health equity) would likely require targeted policies to promote nutrition-sensitive aquaculture. These policies could include (i) initiatives that directly target behavior change and communication and other aspects of nutrition promotion (Ruel et al. 2018); and (ii) conditional cash transfer programs and support for family/homestead food production (e.g., *Bolsa Família* and *Programa de Aquisição de Alimentos* in Brazil, Rocha 2009). These types of initiatives have been demonstrated to improve nutrition-sensitive food production systems and would likely lead to improved nutritional outcomes.

International trade and its interaction with sustainable development and equitable distribution of seafood is central to the scenarios. International trade agreements and certification programs both shape the impacts of globalization. International trade agreements began with an emphasis on trade liberalization (opening markets by reducing tariff and non-tariff barriers) and non-discrimination (equalizing treatment of goods and services) under the World Trade Organization, but have expanded to include bi- and multi-lateral agreements that include provisions about domestic policy, health and safety rules, labor standards, and environmental practices (Rodrik 2018b; Friel et al. 2020). Notably though, international trade agreements to liberalize food trade are legally binding, while international agreements or policy recommendations targeted at addressing malnutrition are not (Friel et al. 2020). Some Low and Middle Income Countries have challenged the dominant free trade approach to addressing malnutrition, pushing for exemptions from trade liberalization in order to pursue greater food sovereignty (Friel et al. 2020). Certification schemes, on the other hand, signal production standards to consumers, often related to human rights and environmental health (Derkx and Glasbergen 2014). These arrangements are initiated through a collaborative process between businesses and NGOs, sometimes with the involvement of governments, but generally without the sanctioning power of governments (Glasbergen 2013). Certification schemes have become increasingly important for aquaculture and generally focus on environmental and governance, while rarely covering aspects such as wealth distribution, equity, or employee interests and wellbeing (Osmundsen et al. 2020).

The primary drivers of future aquaculture scenarios in the medium term identified here deal with macroeconomic factors that are uncertain in their evolution but highly influential. These drivers likely interact with other prominent drivers of aquaculture production, such as climate change. Unlike globalization or sustainability policy, the mid-term direction related to climate change is fairly certain. Nevertheless, the scenarios which embrace a donut economics approach to economic development (Blue Internationalism and Food Sovereignty) bound the safe operating space for growth with a social floor and an environmental ceiling. As a result, these scenarios prioritize carbon emissions reductions to limit progression of global climate change, which would shift opportunities and risks for aquaculture within these scenarios.

Climate change is already reshaping our food systems by redistributing crop and fishery potential (Challinor et al. 2014; Lam et al. 2016; Myers et al. 2017; FAO 2018b; Free et al. 2019) and through extreme event disturbances (Gephart, Duetsch, et al. 2017; Biela et al. 2019; Cottrell et al. 2019). Comparatively, climate change impacts on aquaculture are less understood than consequences for agriculture and wild capture fisheries (Froehlich, Gentry, and Halpern 2018). Some studies and governing bodies, past and present, see aquaculture as part of the solution to food and nutrition security and livelihood woes of climate change, particularly for declining fisheries (e.g. Troadec 2000). Yet, emerging research is starting to show just how vulnerable aquaculture may be to changing climate conditions. At the global scale, impacts are likely to be heterogenous across the land- and seascape, but average warming temperatures and extremes (i.e., heat waves) could potentially lower overall production of finfish and bivalves, which may be countered, to some extent, by genetic and species selection and ability to relocate (Klinger et al. 2017; Barange et al. 2018; Froehlich, Gentry, and Halpern 2018). Species, however, have physiological limits (Reid et al. 2015) and it is a multi-stressor world where phenotypic tradeoffs likely exist (Froehlich et al. 2016). Further, some species/groups may be more susceptible to the suite of co-occurring stressors (e.g., ocean acidification, hypoxia) anticipated to worsen in the coming decades (Barange et al. 2018; Froehlich, Gentry, and Halpern 2018). At the local scale, extreme weather events of droughts and floods are increasingly recognized as current and future challenges to aquatic farming, including in Malawi (Limuwa et al. 2018) and Thailand (Lebel et al. 2015). Ultimately, climate change will influence the scale, type, and quality of aquaculture production heterogeneously around the world. How such impacts will affect goals for addressing nutrition-sensitive aquaculture is unknown but is no doubt critical for future research to classify and understand the role of aquaculture in food and nutrition security.

In the shorter term, shocks and crises can prompt reorganization of complex systems. This could push aquaculture onto alternate scenario trajectories. For example, the 2008 grain crisis, wherein high grain prices driven by a combination of regional droughts, biofuel demand, high oil prices, and the depreciation of the US dollar triggered a series of export bans (Headey 2011). The vast consequences of the crisis, which drove 130 million people into poverty and 75 million people into malnourishment, prompted governments to reconsider reliance on foreign foods (Headey 2011; Friel et al. 2020). This crisis prompted countries throughout Asia and Africa to turn toward greater food sovereignty, creating or expanding public staple crop stocks (Friel et al. 2020). Other recent sudden policy changes hint at a turn inward. For example, the United States has recently made reducing the seafood trade deficit a policy priority, pushing for changes to aquaculture, capture fisheries, and trade policies (Gephart et al. 2019). Such moves cast doubt in the reliability of foreign trade partners and can prompt further emphasis on domestic foods.

The realization of systemic risks stemming from globalization can also push countries onto alternate trajectories. As the global COVID-19 pandemic is still unfolding, the full scope of damage to food systems in the longer term is unknown. Yet, it is already clear that portions of the aquaculture industry are suffering major setbacks, as some exports are being halted, workers are being laid off, food service segment demand has dramatically decreased, production units are incurring large losses (FAO 2020) and some countries are reconsidering their reliance on foreign seafood. Such setbacks can be particularly long-lasting for a budding sector, with many young farms that potentially lack the capital to weather the storm and the political clout to secure sufficient recovery aid. While it is unclear whether any of these events represents a momentary response or a lasting change, it is insightful to consider the presented scenarios and what the future of aquaculture may look like if nations refocus inward for food and nutrition security or if the crisis drives further consolidation of the sector.

5. Conclusion

As nations, investors, and development organizations look toward aquaculture to meet growing seafood demand, the macro policies, especially the degree of globalization and the economic growth strategy, will shape the form of aquaculture that takes hold. While each scenario presented here holds the potential for contributing to nutrition-sensitive aquaculture, each requires some degree of public policy commitment. It appears more likely that such commitments will be made and maintained into the future if countries orient their policies toward sustainability than if they prioritize growth, though growth in production could lower prices and make fish more available to all. It is also more likely that such policies will be globally harmonized in a world in which liberal internationalism prevails over nationalist individualism. Given that countries are at different levels of development with respect to aquaculture, food sovereignty policies may work in places with capabilities and resources to grow their aquaculture sectors – but an overly rapid retreat from global markets may leave states with nascent or unrealized aquaculture potential behind, to the nutritional detriment of their citizens. As aquaculture production continues to grow, there is an opportunity to use policies, market instruments, and consumer education to guide development toward more nutrition-sensitive and healthy environmental futures. As the world now appears to sit at a crossroads for the future of aquaculture and its role in contributing to global food and nutrition security, these scenarios can prompt discussion among researchers, policymakers, and advocacy groups about desirable futures for nutrition-sensitive aquaculture to help chart a course for how to get there.

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ORCID

Jessica A. Gephart http://orcid.org/0000-0001-6836-9291
Frank Asche http://orcid.org/0000-0002-1540-9728
Cecile Brugere http://orcid.org/0000-0002-1412-1044

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