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A global view of aquaculture policy

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ABSTRACT

Aquaculture is among the most dynamic sectors in the global food system, yet it remains surprisingly under-represented in the mainstream literature on food policy. This article reviews 204 published articles and reports and shows that government policies have strongly influenced the geographic distribution of aquaculture growth, as well as the types of species, technology, management practices, and infrastructure adopted in different locations. Global cross-section studies reveal a broad spectrum of under- to over-regulated aquaculture systems that correspond, respectively, to high- and low-growth areas for aquaculture. The bulk of this paper centers on aquaculture policy as it plays out six individual countries plus the EU: Bangladesh, Zambia, Chile, China, USA, and Norway. These case studies shed light on aquaculture policies aimed at economic development, aquaculture disease management, siting, environmental performance, and trade protection. Experiences from these countries point to the need to find the right policy balance between semi-subsistence farms, small and medium enterprises (SME), and large-scale commercial operations, particularly in low-income settings. The cases also highlight the importance of addressing aquaculture disease pressures and misuse of antimicrobials in many parts of the world, and identifying successful aquaculture policy instruments and institutions that can be transferred between countries. The review underscores the challenges of establishing nutrition-sensitive aquaculture policies and of incorporating aquaculture directly into food policy and global food system dialogues and action.

1. Introduction

Aquaculture is among the most dynamic sectors in the global food system, yet it remains surprisingly under-represented in the mainstream literature on food policy. Food policy and global food system dialogues are historically, and to a large degree presently, focused on terrestrial animals and plant-based commodities and the foods produced from them. This review article explores the rapidly growing literature on aquaculture policy and its connections to and importance for food policy more generally. Our objectives are twofold. The first is to review how government policies prioritizing growth in output and revenue versus policies focused on environmental protection have shaped the geographic distribution of aquaculture globally. The second, and more ambitious, objective is to examine aquaculture policy as it plays out in individual countries across the full development spectrum, with attention to policy goals, instruments, governing agencies, and outcomes pertaining to nutrition, health, equity, and the environment.

For readers who are relatively unfamiliar with the aquaculture sector, context is important.[1] Global fish consumption per capita has roughly doubled over the past half century and is now on par with poultry and pork on an edible weight basis (Edwards et al., 2019; Naylor et al., 2021b; FAO, 2022a). Aquaculture production growth has both

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[1] In this review, aquaculture, or "farmed fish", refers to the cultivation of finfish and shellfish including crustaceans and bivalves. Aquatic plants are also produced and consumed widely as food, particularly in Asia, but data on aquatic plants are generally lacking, and they are not the primary focus of aquaculture policy in any country. Seaweed, or algae, is an important source of food in some countries, especially in East Asia, but is mainly produced for industrial purposes on a global basis. See Naylor (2021a) for more details and references on aquatic plants and algae.

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met *and* stimulated this increase in fish demand and will continue to do so, offering in many cases a healthier and more environmentally sustainable alternative to red meat consumption (Golden et al., 2021; Gephart et al., 2021; Garlock et al., 2022; Falcon et al., 2022).[2] The expansion in aquaculture output has exceeded that of most other food commodities over the past 25 years—roughly tripling in live weight—and the sector has evolved into a mature international industry (Garlock et al., 2020, 2022; Naylor et al., 2021a). In 2020, aquaculture contributed 56 % of fish available for direct use as human food on a global basis (FAO, 2022a).

Inland freshwater aquaculture dominates the sector, contributing 62 % of global live-weight volume and 75 % of global edible weight volume in 2020 (Naylor et al., 2021a; FAO, 2022a). Asia is by far the largest aquaculture producer, accounting for 92 % of global live-weight production in 2020, and China alone contributes 57 % of total aquaculture volume and 59 % of global value (FAO, 2022a) (Fig. 1). Despite these patterns, most articles on aquaculture published in the English-language literature during the past two decades have focused on high-valued marine species, such as shrimp and salmon (Naylor et al., 2021a). The bulk of the aquaculture policy literature, particularly surrounding the economics of aquaculture regulation, pertains to industrial countries in Europe and North America and not to Asia where the vast majority of aquaculture occurs (Anderson et al., 2019).

We begin by setting the context for aquaculture policy and then review a set of cross-section studies focused on the relationship between aquaculture growth, institutional quality, and the rigor of environmental policies. The diversity in policy priorities and governing institutions has resulted in a broad spectrum of under- to over-regulated aquaculture systems around the world that have shaped geographic patterns of production and trade (Asche et al., 2022). Our discussion is confined to government policies and does not extend to private sector governance and certification strategies, although the latter are important for advancing the sustainability of certain aquaculture products, particularly widely traded commodities for high-end consumer markets (Jesperson et al., 2014; Bush and Oosterveer, 2019; Naylor et al., 2021a).

The paper then turns to our second objective and reviews studies focused on aquaculture policy as a tool for economic development, aquaculture disease management and siting, environmental performance, and trade protection. (Aquaculture siting refers to the physical and geographic positioning of aquaculture infrastructure in line with production performance and risk, environmental and resource protection, government regulations, supply chain location, and other key factors for business operations.) Policies across these areas influence where and how aquaculture expansion occurs, which species are promoted, and who benefits in the process. We highlight the experience of six specific countries plus the EU—Bangladesh, Zambia, Chile, China, USA, and Norway—pointing to policy successes and failures and underscoring the evolving nature of aquaculture policy as the sector develops in any given country.

Much of the discourse on aquaculture policy, particularly pertaining to future growth in the industry, focuses on the role of aquaculture in meeting rising protein demand by an expanding global population in an era of climate change. The nutritional benefits of fish, which go beyond just a protein source and include the provision of essential micronutrients and healthy fatty acids, are often overlooked. The final section of this paper highlights the challenges of establishing nutrition-sensitive aquaculture policies and of incorporating aquaculture directly into food policy and global food system dialogues and action. We conclude with a half dozen key insights and recommendations for food policy experts as they contemplate the future course of aquaculture policy.

Our approach in constructing this review was pragmatic and was based on our prior reviews and our collective knowledge of food policy and aquaculture. We first conducted a broad search of the literature (and references therein) using key words related to aquaculture policy, trade, development, regulations, food security, and nutrition, without strictly restricting our policy set or time frame of review. Given the diversity of aquaculture systems and policies across countries at different stages of development, it became clear that an examination of individual case studies would help sharpen our focus on critical policy issues in the aquaculture sector. We selected our case studies based on their representation of key policy objectives and challenges gleaned from our initial literature search and from the Naylor et al. (2021a) 20-year retrospective review of global aquaculture. The case studies were also chosen based on their role in aquaculture production and trade in each region and their coverage in the literature.

2. The policy context

Government policies have fundamentally shaped the geographic distribution of aquaculture growth, as well as the types of species, technology, management practices, and infrastructure adopted in different locations (Garlock et al., 2020). The aquaculture sector is vast and complex, with over 650 species of fish, shellfish, aquatic plant, and algal species cultivated in 2020 in a variety of marine, brackish, and freshwater systems and traded widely (FAO, 2022b).[3] Diverse aquaculture operations can be seen around the world, for example: extensive inland ponds with multiple species of small fish and plants, many of which remain unidentified; intensive commercial ponds or cages of tilapia and pangasius (catfish) raised in freshwater systems; hanging lines of mussels and macroalgae (seaweed) in nearshore coastal zones; large brackish ponds of high-valued shrimp; on-land raceways for trout; and marine netpen aquaculture, large submersible offshore cages, and land-based recirculating systems raising various high-valued species (Naylor et al., 2021a; Short et al., 2021; FAO, 2022a).

Aquaculture development in any given country hinges on four key policy domains: public investments in infrastructure and R&D; policies supporting aquaculture value chains; regulatory policies providing environmental and social protections; and trade policies. Public investments in infrastructure (e.g., ponds, waterways, roads, cages, and ports) and basic research and development (R&D, e.g., genetic improvements in fish, shellfish, and algae; research on fish nutrition and health) provide the foundations for aquaculture innovation and expansion in all producing countries. Innovation is the engine for aquaculture productivity growth and reduced input prices for producers and consumers, as emphasized by Anderson et al. (2019) in their review of key economic contributions related to aquaculture technology. Aquaculture innovation often derives from market scarcity and other constraints (e.g., declining wild fish stocks including forage fish for feeds, rising cost of fishmeal and fish oil in feeds, disease pressures) and is supported by technology and policy incentives (Asche and Smith, 2018). The scientific literature pertaining to aquaculture R&D has been reviewed extensively; for example, Kumar and Engle (2016) on technological advances in shrimp, salmon, and tilapia; Wargelius (2019) on genome editing in Atlantic salmon; Houston et al. (2020) on the use of genomics in aquaculture; Wang et al. (2021) on genetically modified fish; and Naylor et al. (2009, 2021a) and Eroldogan et al. (2022) on aquaculture feed innovations.

In low-income countries, investments in infrastructure and R&D are

[2] The anticipated increase in fish demand from aquaculture assumes constant or declining real fish prices as technology continues to improve and production expands, particularly given the significant reservoir of knowledge still to be transferred to aquaculture from the agro-sciences (Asche, 2008; Kumar and Engle, 2016; Naylor et al., 2021b).

[3] Roughly-one-fifth of all species reported by FAO are in the "nei" (not elsewhere included) category, reflecting wide species diversity in the sector and a lack of monitoring and sound reporting in many countries (Metian et al., 2020; FAO, 2022b).

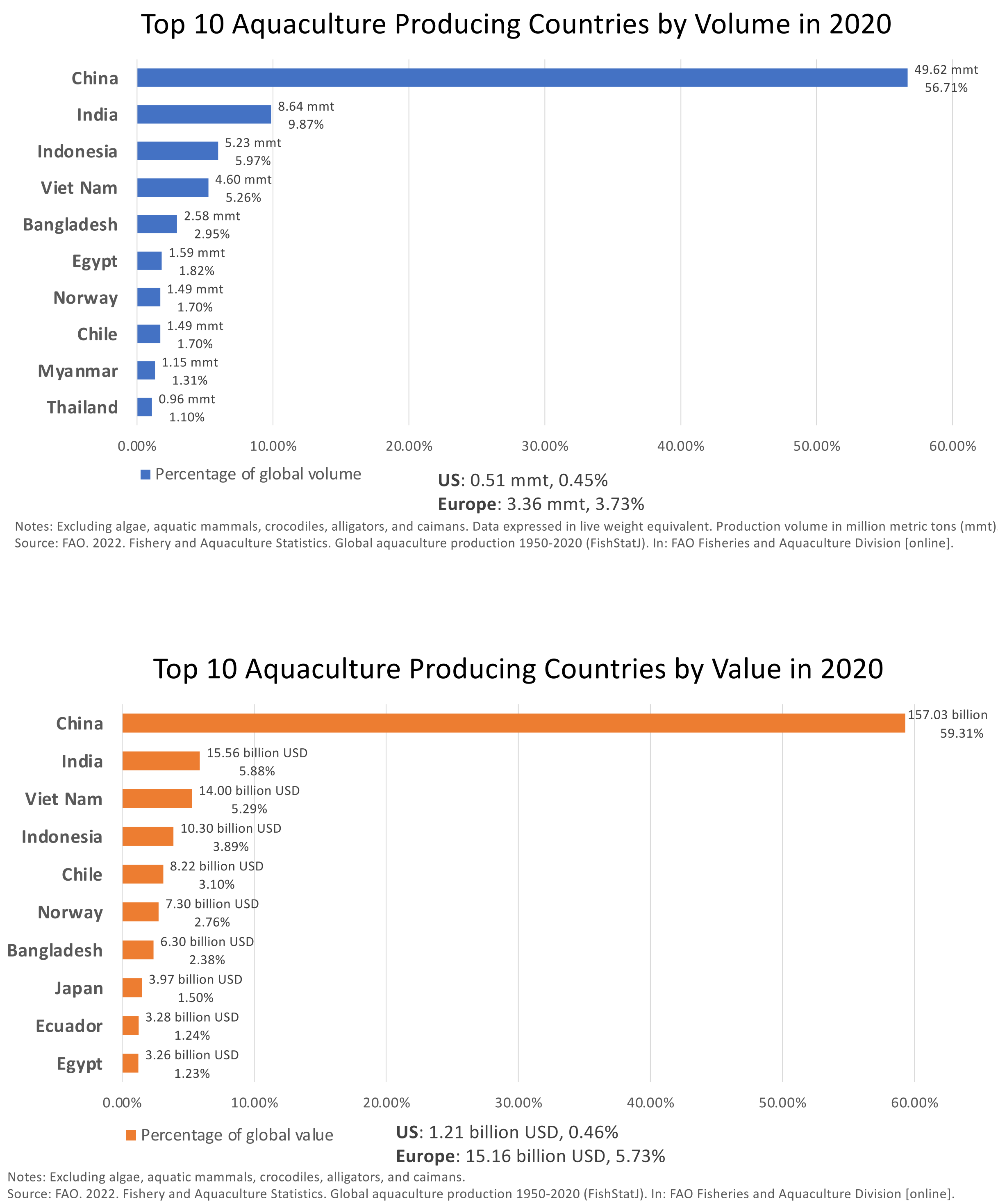


Fig. 1. Top ten aquaculture producers by volume and value, 2020.

often supported by international lending agencies and organizations, such as the World Bank and WorldFish, in line with priorities of national development ministries. In emerging and industrial economies, a wider range of national line agencies support such investments, along with the private sector in cases where financial returns can be captured (Hishamunda et al, 2014; Kumar and Engle, 2016; FAO, 2017; Love et al, 2017; Guillen et al, 2019).

A central feature of the narrative surrounding aquaculture policy, innovation, and growth is the critical role of domestic and international value chains (Anderson et al., 2019; Bush et al., 2019). Much of this literature is focused on countries in the Global South, particularly in freshwater systems, where the expansion of value chains has reduced transaction costs and boosted aquaculture production, consumption, and livelihoods.[4] As value chains have matured, they have also blurred the distinction between small-scale producers, small- and medium-sized enterprises (SME), and commercial aquaculture operations, making it

[4] See, for example, Naylor et al. (2021a) and the full set of articles on aquaculture value chains in the special volume of *Aquaculture* led by Bush et al. (2019).

difficult to gauge the equity outcomes of aquaculture policies in certain developing countries such as Ghana and Bangladesh (Kassam and Dorward, 2017; Bush et al., 2019). Supply chains for high-valued and widely traded commodities, such as Atlantic salmon, have followed the path of the industrial poultry sector, enhancing international product competitiveness (Asche et al., 2018b).

Regulatory policies also comprise a key tenant of aquaculture policy (Anderson et al., 2019). Aquaculture regulations span environmental, property, labor, animal health and welfare, and food safety laws (Hishamunda et al., 2014). They are necessary for the development of sustainable and equitable aquaculture systems but can also become overly burdensome, curtailing entrepreneurial initiatives, innovation, profits, and growth. The regulatory environment for marine aquaculture (also known as mariculture) is especially complex given the dynamic and common property nature of operating in the marine environment (Falconer et al., 2023). Finding the appropriate balance between environmental protections and incentives for mariculture growth is often hindered by multiple competing uses and values of coastal and ocean ecosystems, potentially resulting in under-developed resource use (Knapp and Rubino, 2016; Asche et al., 2022). Regulatory systems for inland aquaculture, focused mainly on land and water rights, sustainable water use, pollution control, exotic species introductions, and animal health, are relatively immature and poorly assessed in the Global South where most of the growth in this sub-sector occurs (Hishamunda et al., 2014; Naylor et al., 2021a).

Seafood is among the most widely traded commodities in the global food system and has become increasingly globalized, with trade roughly doubling in terms of quantity and value from 1998 to 2018 (Gephart and Pace, 2015; Bellmann et al., 2016; Anderson et al., 2018; Naylor et al., 2021b). The World Trade Organization regulates seafood as an industrial product and thus, unlike agriculture, trade barriers are generally much lower for aquaculture products than for agriculture (Asche et al., 2018a). Trade in aquaculture products is key for meeting rising seafood demand globally, especially given the geographic patchiness in production associated with rapid growth in under-regulated countries and slow or declining growth in over-regulated countries (Asche et al., 2016; Belton et al., 2020; Naylor et al., 2021b).

Numerous papers on aquaculture trade policy have centered around imports by the EU and U.S. for the main traded species such as salmon, shrimp, catfish, and tilapia (e.g., as reviewed by Anderson et al., 2019). Although trade provides the opportunity for enhanced economic efficiency (Asche et al., 2018a), lower labor and regulatory costs in the Global South create a competitive edge over aquaculture production in the EU, U.S., and other industrialized countries. As Asche, Roheim, and Smith (2016) note, any attempt by wealthy countries to impose trade barriers on aquaculture imports from the Global South for industry protection is likely to have negative impacts on global poverty and food security given the importance of aquaculture as a source of employment and incomes in many developing countries. The authors argue that since the social cost is concentrated in local environmental impacts in the producing countries, imposing trade barriers due to low regulatory costs in the exporting countries effectively diminishes the sovereignty of exporting nations to decide how much they want to pollute.

The process of globalization itself has been dynamic in recent decades, with incomes and seafood demand expanding more rapidly in developing versus industrialized countries. A significant share of aquaculture production, particularly in Asia and Africa, is now destined for domestic markets, and South-South trade in aquaculture products is expanding in volume and share (Pieterse, 2017; Belton et al., 2018; Naylor et al. 2021a, Naylor et al., 2021b).

3. Balancing growth and environmental protection

Policies governing aquaculture reflect a wide range of social objectives, ranging from the promotion of economic growth, foreign exchange earnings, foreign direct investment, food security, and rural livelihoods on the one hand, to the protection of capture fisheries and environmental conservation on the other. Food safety, climate adaptation, and sustainable development have also emerged as important policy objectives. Although nutrition outcomes are rarely an explicit goal of food policy, as we discuss later in the paper, the high protein, micronutrient, and healthy fatty acid content of fish can contribute significantly to the quality of diets for populations across all income classes (Thilsted et al., 2016; Golden et al., 2021).[5] The question for this section is: How have policy priorities influenced aquaculture growth and the geographic distribution of production?

In a comprehensive report on aquaculture policy and governance by the United Nations Food and Agriculture Organization (FAO), Hishamunda et al. (2014) stress that aquaculture is a business, and for resources to be invested in this business, there must be an enabling economic environment and secure property rights to the aquatic resource base in question. The authors also underscore the need for regulations to prevent short-sighted business behavior from harming ecosystems and society in ways that may cause industry stagnation, market volatility, or inequitable and unjust resource allocation. The report reviews alternative models of governance and both supply- and demand-side policy instruments for aquaculture development.[6] Given the broad and changing nature of cultural and economic conditions across aquaculture producing countries, no single model is recommended as a permanent solution for industry development. Instead, the report emphasizes that effective and sustainable governance of aquaculture must balance environmental and human well-being, with an eye toward equity, accountability, flexibility, incentives for innovation, and predictability in the rule of law.

Somewhat counterintuitively, the quality of government institutions appears to be a weak predictor of aquaculture growth. In an empirical analysis of 74 aquaculture producing countries over three decades (1984–2013), Nadarajah and Flaaten (2017) found a weak correlation between annual growth in aquaculture volume and institutional quality as measured by governance, corruption, and competitiveness.[7] On the surface, this result is not too surprising when considering the rapid growth in aquaculture from a small base in several low-income countries of Southeast Asia and Africa where institutions are weak and aquaculture policies are generally incoherent (Brummett et al., 2008; Hishamunda et al., 2009; Munguti et al., 2014; Abate et al., 2016). At the same time, aquaculture has grown slowly in the U.S. but rapidly in Norway—two countries where institutions governing aquaculture are strong and well-coordinated (Zajicek et al., 2021; Asche et al., 2022).

Virtually all aquaculture systems rely heavily on the natural aquatic environment and thus benefit from, have negative impacts on, or contribute positive ecosystem services to the surrounding environment. The interaction between aquaculture growth and the environment in any given country depends importantly on the implementation and enforcement of government regulations. Introducing the first empirical

[5] Golden et al. (2021) compiled nutrient profiles of 3753 types of aquatic foods within the Blue Food Assessment (https://bluefood.earth) and found that several categories are, on average, richer in omega-3 fatty acids, vitamins A and B12, calcium, iron, iodine, and zinc than beef, pork, and chicken. Nutritionally vulnerable subpopulations often struggle to satisfy essential intake requirements for some of these micronutrients, particularly zinc and iron, through the available and accessible diets (Allen, 2016; Obbagy et al., 2019).

[6] Alternative models of governance reviewed in this report include top-down decision-making and implementation; market-based governance with attention to revenue generation and foreign exchange earnings; and participatory governance by multiple stakeholders and civic society.

[7] The authors proxied for institutional quality using the following data sources: the World Bank's Worldwide Governance Indicator (WGI); Transparency International's Corruption Perception Index; and the World Economic Forum's Global Competitiveness Index. They also explored the relationship between aquaculture growth rates and membership of the Organization for Economic Cooperation and Development and eco-label certification programs.

model of aquaculture expansion as a function of environmental policies, Abate et al. (2016) demonstrate a negative relationship between aquaculture growth and the stringency of environmental regulations. Their analysis, which covers 95 countries across 6 continents during the 1990s-2000s, measures both input and output regulations in the aquaculture sector. Countries in Africa, Latin America and Asia have the least stringent regulations and the highest aquaculture growth rates, whereas the opposite holds for countries in North America, Europe, and Oceania. Norway is the only exception among industrialized regions to rank in the top ten for aquaculture growth, despite having the most stringent environmental regulations in the set. The authors also show a positive statistical relationship between aquaculture growth and income and population growth across countries, indicating the important role of aquatic food demand in driving aquaculture development.

Environmental regulations are critical for sustaining aquaculture growth and profits over the long term, as over-intensification, pathogen and parasite problems, and conflicts with other stakeholders, such as capture fisheries, can adversely affect the industry. As the industry matures and new technologies are adopted, the environmental performance of aquaculture generally improves, as predicted by the Environmental Kuznets Curve model (Tveterås, 2002). Given that aquaculture is typically regulated by more than one agency within any country, the dampening effect of environmental policies on growth tends to be highest in nations where pro-environment agencies have equal or greater political clout than pro-industry agencies (Abate et al., 2018).

Defining sustainability itself remains a controversial topic. For example, Luthman et al. (2022) characterize aquaculture in the Nordic region, where environmental regulations are strong, as representing weak sustainability, because intensification, profitability, and economic growth trump environmental considerations in policy formulation. This characterization contrasts with the view that both economic and environmental sustainability are needed for aquaculture to succeed over the long term (Hishamunda et al., 2014; Belton et al., 2020; Asche et al., 2022). As in all food production systems, designing aquaculture policies with strong environmental sustainability components that do not impose too great a regulatory burden on producers is challenging, yet critical for economic viability. Experiences from specific countries along the economic development spectrum, described in the following section, help to clarify the connections between policy priorities, production growth, and environmental outcomes.

4. A spectrum of policy objectives and outcomes

It is hard to comprehend the welfare implications of different aquaculture policy strategies without delving into the details of specific producing and consuming countries. In this section, we review aquaculture policy objectives and outcomes at the national scale, drawing on experiences of selected countries where studies have shown government policy to be important in stimulating or retarding aquaculture growth. The case study countries, shown in Table 1, represent different aspects of government policy, scale of production, and supply chain function along the development spectrum, from low- to high-income, and are not intended to cover the entire global aquaculture sector. Our discussion focuses on the economic, social, and environmental dimensions of aquaculture policy, with an eye toward inclusive (e.g., pro-poor) and environmental outcomes.

4.1. Development priorities

Throughout the Global South, aquaculture has been promoted as a tool for economic development and food security, especially in countries where per capita fish consumption has been historically high, and where capture fisheries have been overfished (Naylor et al., 2021b; FAO, 2022a). In countries where fish are cultivated in large volumes, such as Bangladesh and Egypt, production growth has driven down real prices, making fish increasingly accessible to low-income consumers (Beveridge

Table 1
Aquaculture Production and Fish Consumption in Case Study Countries, 2020.

Case study	Share of global volume	Volume (mmt)	Share of global value	Value (billion USD)	Share of animal protein consumption provided by fish
Bangladesh	3.0 %	2.58	2.4 %	6.30	60 %
Zambia	0.1 %	0.05	0.04 %	0.11	24 %
Chile	1.7 %	1.49	3.1 %	8.22	7 %
China	56.7 %	49.62	59.3 %	157.03	22 %
USA	0.5 %	0.45	0.5 %	1.21	7 %
EU*	3.7 %	3.26	5.7 %	15.16	11 %
Norway	1.7 %	1.49	2.8 %	7.30	23 %

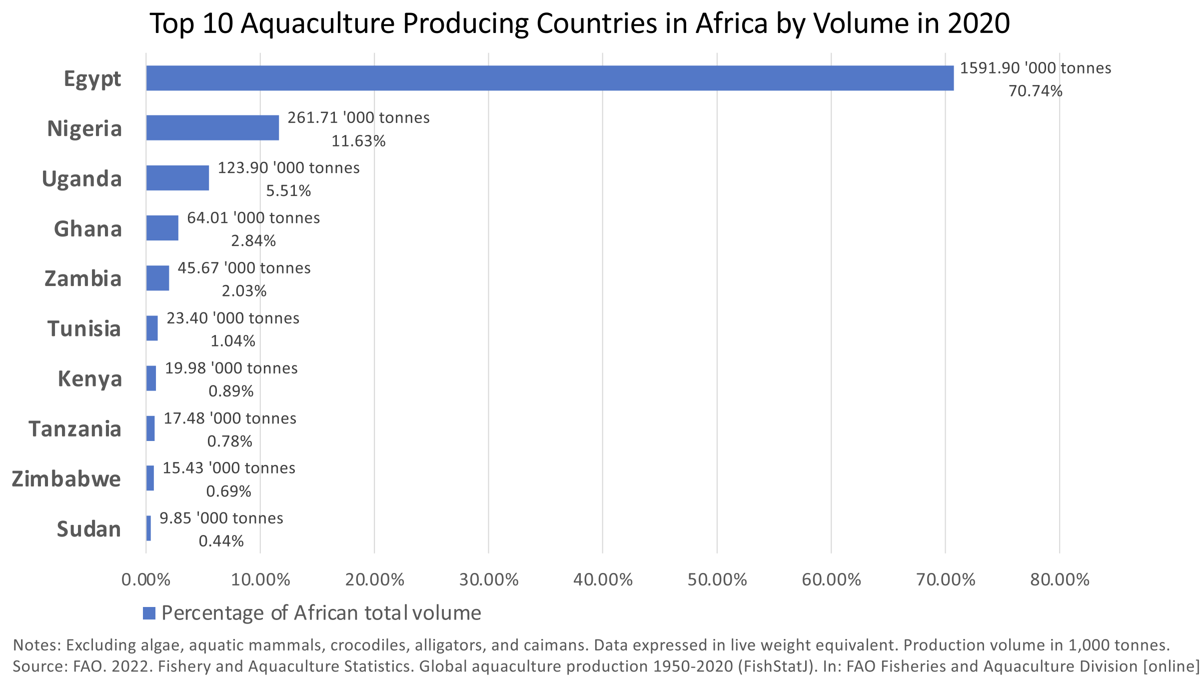
Notes: Excluding algae, aquatic mammals, crocodiles, alligators, and caimans. Production volume data expressed in live weight equivalent. Production volume is in million metric tons (mmt).
Source: FAO. 2022. Fishery and Aquaculture Statistics. Global aquaculture production 1950–2020 (FishStatJ). Food Balances (2010-). In: FAO Fisheries and Aquaculture Division [online]. Rome. Updated 2022.
* The data are available for Europe but not for the EU.

et al., 2013; Toufique and Belton, 2014; Belton et al., 2018). Africa still plays a minor role in global aquaculture output, accounting for only 2 % of global live-weight production in 2020 (FAO, 2022a). Egypt alone supplied two-thirds of Africa's total production, leaving sub-Saharan Africa with a 0.6 % share of global aquaculture output (Fig. 2). Given that nutrient-dense animal source foods are expensive to access for many households in sub-Saharan Africa (Headey and Alderman, 2019), policies supporting aquaculture growth in the region have the potential to boost food security and nutrition (Chan et al., 2019; Ragasa et al., 2022).

Despite increasing national and international attention on African aquaculture, the sector remains constrained by inadequate public and private investments in seed, feed, and extension services; disease problems associated with poor water quality; high local costs of production; and competition from inexpensive aquaculture imports, especially from China (Chan et al., 2019; Mapfumo, 2022). Meanwhile, the demand for fish in sub-Saharan Africa continues to rise with population growth, urbanization, and the emergence of a middle-income class (Tschirley et al., 2015; Naylor et al., 2021b; Falcon et al., 2022). Wild fish capture throughout the region is declining or targeted for export, placing greater pressure on fish imports to meet the growing demand (Golden et al., 2017; Tran et al., 2019; Ragasa et al., 2022). If current trends continue, 50 % of fish for human consumption in Africa is expected to be met through imports by 2050 (Chan et al., 2019).

Trade policy thus plays a major role in balancing seafood demand and supply in Africa, and throughout the world. In many aquaculture-producing countries, policies are geared toward exports, such as salmon in Chile, shrimp in India, tilapia in China, and pangasius in Vietnam. Pursuing an export strategy for aquaculture is typically aimed at augmenting foreign exchange, economic growth, and rural livelihoods. However, in a comprehensive literature review of 202 studies on aquaculture, fisheries, and development, Béné et al. (2016) found inconsistent evidence linking fish trade to food security and poverty alleviation. For example, an export strategy may compromise domestic access to fish if producers find that foreign markets are more lucrative than domestic markets (Belton and Bush, 2014; Asche et al., 2014, 2016, 2018b; Naylor et al., 2021b; Hicks et al., 2022). In other cases, aquaculture development for export adds to local aquatic food consumption and nutrition security (Mamun et al., 2021).

Bangladesh provides an interesting example because policies have supported both freshwater inland aquaculture for domestic consumption and shrimp aquaculture for export. Although farmed shrimp comprise three-quarters of the country's seafood exports and 70 % of agricultural exports (Hobbs et al., 2023), 96 % of all aquaculture production in Bangladesh is destined for domestic markets (Belton et al., 2018). In shrimp-based polyculture systems in Bangladesh, co-products such as aquatic plants and small fish are retained for local consumption,



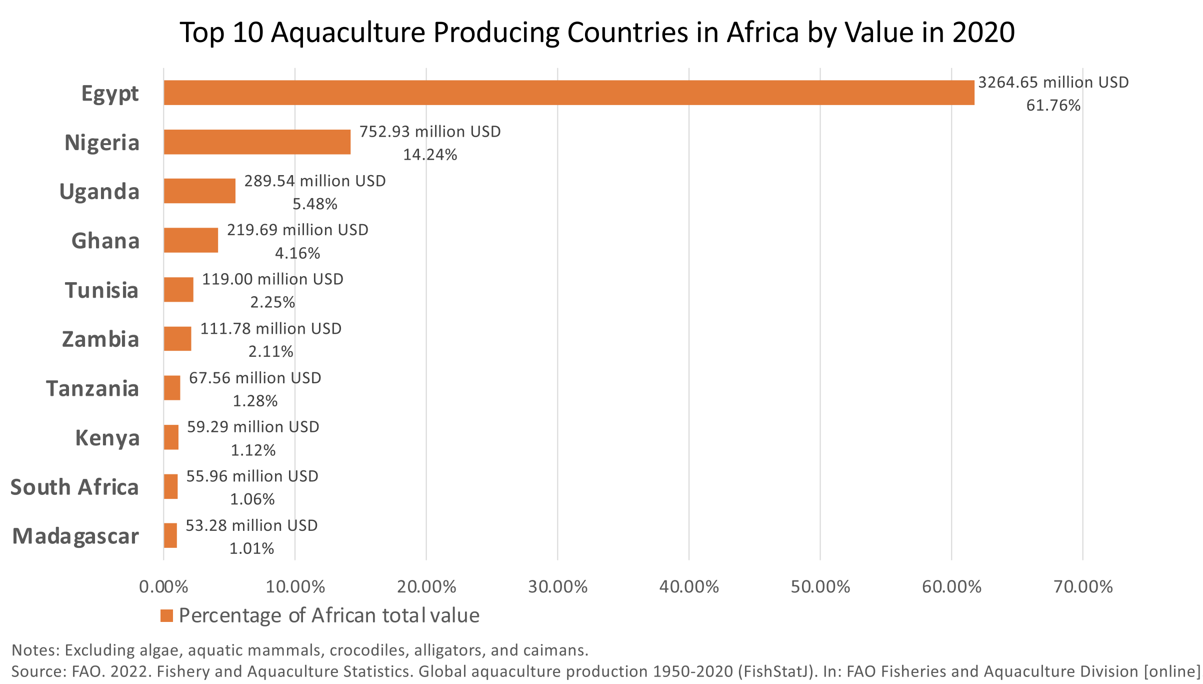


Fig. 2. Top Ten Aquaculture Producing Countries in Africa by Volume and Value, 2020.

and the sector thus contributes to food security through the domestic supply channel as well as through demand effects arising from increased export earnings (Mamun et al., 2021).

4.1.1. Bangladesh

Aquaculture in Bangladesh has grown faster than most other countries' aquaculture sectors in recent decades. The country has long been recognized as an ideal site for aquaculture development given its abundant waterbodies, propensity for flooding, strong cultural preference for fish in the diet, and declining wild fish stocks. Fish is the second highest food expenditure category in Bangladesh after rice (Toufique and Belton, 2014) and accounts for 60 % of animal protein consumption (Table 1). Several international development organizations (e.g., the World Bank, the Asian Development Bank, the United Nations Development Program, and ICLARM (now WorldFish)), as well as international and national NGOs (e.g., CARE, Grameen Bank), began working with the Bangladesh Ministry of Fisheries and Livestock in the 1980s and 1990s to promote aquaculture as a tool for economic development and food security, essentially modeling after the Green Revolution in rice (Lewis, 1997). Rice-fish systems were also introduced and trialed.

The early top-down strategy to develop aquaculture involved large public investments in infrastructure (e.g., ponds, roads, energy), seed technology (broodstock, hatcheries), and feed mills. Involvement of the private sector was more evident in coastal regions where commercial semi-intensive shrimp farming was promoted (Lewis, 1997). While early assessments of aquaculture development in Bangladesh highlighted a policy focus on production growth and income generation over equity and access to fish by low-income households (Lewis, 1997), later studies from the 2000s onward documented a process of poor-poor growth, with rising access to nutrient-dense fish consumption by extremely poor households (Toufique and Belton, 2014; Belton et al., 2018).

Four factors were responsible for this transition. First, once the basic infrastructure and R&D supporting inland and coastal aquaculture were in place, the government established a business-friendly environment that attracted foreign direct investment, generated a proliferation of small and medium enterprises (SME), and deepened domestic investments along the entire value chain (Hernandez et al., 2018; Hu et al., 2019; Kuijpers, 2020). Second, the government introduced a new nutrition policy in 2015 that spanned the entire food sector and began efforts to revitalize the Bangladeshi National Nutrition Council (FAO, 2017). The Ministries of Planning and Finance oversaw budget allocations among food and non-food agencies and included aquaculture in their nutrition planning process.

Third, the government was open to the introduction of new farmed species to meet the demands of low-income consumers, such as tilapia, pangasius, and other freshwater fish—thus moving beyond the initial policy focus on large carps, which are consumed mainly by wealthier households (Toufique and Belton, 2014; Hernandez et al., 2018). In coastal areas, shrimp polyculture systems producing small fish for local consumption also became more common (Mamun et al., 2021). Finally, the rapid growth in aquaculture production led to a decline in real fish prices, even as per capita consumption increased, enabling the lowest income groups with the highest price elasticities of demand to benefit most (Toufique and Belton, 2014). Apparent fish consumption in Bangladesh doubled between 2000 and 2019, with aquaculture supplying an increasing share of the market over capture fisheries (Hernandez et al., 2018; Falcon et al., 2022).[8] Hernandez et al. (2018) report that 94 % of fish produced by aquaculture in Bangladesh is destined for domestic markets; roughly-one-tenth is consumed at home by smallholder producers, and the remainder is split almost evenly between urban and rural markets.

Technical efficiencies, value chain expansion, and commercialization have been at the heart of Bangladesh's aquaculture success. As in all development experiences, however, there have been winners and losers. Studies in both the pre- and post-2000 development periods documented a concentration of land ownership by wealthy households, preferred access to government-owned land by elite groups, and persistent landlessness among poor households (Lewis, 1997; Paul and Vogl, 2011; Toufique and Belton, 2014; Hernandez et al., 2018).[9] Amidst the proliferation of supply chain actors, large feed mills have become more dominant, and micro-credit, while abundant in Bangladesh, has not been used widely by smallholders in the aquaculture sector (Hernandez et al., 2018). Nonetheless, smallholder producers have gained from growth in supply chains, and consumers at all income levels have benefitted from increased availability and access to fish and aquatic plants. It is important to keep in mind that absolute gains in poverty alleviation and improvements in nutrition have been achieved, even while privileged or land-owning households accumulated more wealth than poor households on a relative basis.

The most significant social costs of aquaculture expansion in Bangladesh are related to the environment and food safety. As part of the government's general laissez-faire approach to aquaculture development, there has been no clear legal framework governing land use change and effluents in coastal and inland areas (Paul and Vogl, 2011). Saltwater intrusion, pollution, and mangrove destruction linked to aquaculture expansion have been problematic, affecting agriculture, aquaculture, inland fisheries, and the protection of coastal communities from storms and floods. Low-income households have been displaced in some aquaculture systems (e.g., large coastal shrimp operations) with consequences for livelihoods and food security (Paprocki and Cons, 2014; Didar-Ul Islam and Bhuiyan, 2016). As the aquaculture industry seeks to diversify and deepen its aquaculture exports, it faces high costs of compliance in meeting public and private quality standards and is challenged to meet food safety criteria (Hobbs et al., 2023).

The Department of Fisheries, located within the Ministry of Fisheries and Livestock, plays a leading role in governing aquaculture, with a mandate that favors aquaculture growth and industry development over environmental protection. Regulatory oversight of coastal and inland aquaculture in Bangladesh involves dozens of ministries, divisions, and agencies, often with weak institutional coordination and enforcement (Lewis, 1997; Paul and Vogl, 2011). The balance between aquaculture growth and the environment in Bangladesh is consistent with that of many developing countries (Abate et al., 2016), as reviewed earlier in this paper.

4.1.2. Zambia

Are there lessons from the Bangladesh experience that can be applied to other low-income countries where development priorities dominate food policy, most notably in sub-Saharan Africa? Zambia provides a good illustration of the opportunities and challenges faced by policymakers in sub-Saharan Africa given its long-standing history of small-scale pond systems for subsistence, local sales, and barter, and its more recent development of commercial aquaculture through large-scale and SME production systems (Kaminski et al., 2018). Zambia is a land-locked country with numerous rivers, seasonal flood plains, and lakes—including Lake Kariba, one of the world's largest artificial lakes where commercial cage culture has been established.[10] Aquaculture value chains are oriented almost entirely around tilapia, with small-scale farmers raising a mix of native and non-native species, and large-scale producers mainly cultivating non-native Nile tilapia (*O. niloticus*), including Genetically Modified Farmed Tilapia (GIFT) (Genschick et al., 2017; Maulu et al., 2019; Avadi et al., 2022).

Zambia has become the fifth largest aquaculture producer in sub-Saharan Africa and the top producer of tilapia within the South African Development Community (Genschick et al., 2017). The sector is characterized by two distinct sets of producers: small-scale, semi-subsistence

[8] Belton et al. (2014) report, however, that increased availability of fish from aquaculture in Bangladesh may not have made up for the decline in available fish supplies from freshwater capture fisheries in terms of nutrition content, as the latter are more diverse and rich in a wide variety of micronutrients.

[9] Hernandez et al. (2018) reported that 89% of aquaculture households produced 25% of total production, while the top 2.4% accounted for 50% of total output. At the same time, large farms (with 0.4 HA or more of pond area) accounted for 27% of all fish farms in Bangladesh but owned 53% of the total pond area in 2014.

[10] Lake Kariba, bordering Zambia and Zimbabwe, was initially constructed as the world's largest artificial lake by volume, four times as large as the Three Gorges Dam (World Commission on Dams, https://web.archive.org/web/20020604055823/http://www.dams.org/kbase/studies/). The lake is subject to extreme climate fluctuations associated with El Nino (warm-mode ENSO events) and thus the volume of standing water varies on an interannual basis (https://earthobservatory.nasa.gov/images/87485/the-decline-of-lake-kariba). The dam at Lake Kariba is also in need of structural upgrading, making this water source somewhat tenuous over the long term (Leslie, 2016). By comparison, Lake Volta in Ghana, where large-scale aquaculture cage culture has also been established, is the world's largest artificial lake by surface area (https://www.britannica.com/place/Lake-Volta). (Websites accessed on 18 November 2022.).

farmers who are supported by government seed and feed programs and remain essentially isolated from commercial value chains; and large-scale and SME tilapia systems that are integrated with private value chains (e.g., seed, feed, financial capital, wholesale markets) through vertical integration and contractual arrangements (Genschick et al., 2017; Kaminski et al., 2018; Avadi et al., 2022). Zambia has some of the largest aquaculture operations in Southern Africa, consisting of both land-based pond systems in the southern region of the country and cage systems in Lake Kariba. Over the past decade, the contribution of large-scale aquaculture to total live-weight production has increased from 25 % to 75 %, with two commercial companies accounting for almost one-third of the commercial output (Kaminski et al., 2018; Avadi et al., 2022).

Government policies in Zambia have contributed directly to the dichotomized nature of Zambia's aquaculture sector. Farming fish is not new to the country; national and international development programs promoting small-scale pond aquaculture date back to the 1950s and 1960s, even before the country's independence in 1964 (Kaminski et al., 2018). During the past 50 years, successive governments have directly supported small-scale farmers through the provision of seed from public hatcheries, subsidized feed, and various forms of extension services. National and international investments along the full value chain have been limited, however, and the quality of inputs and extent of training have been inadequate to support economically viable enterprises for most small-scale producers (Brummett et al, 2008; Genschick et al., 2017; Maulu et al., 2019). Long-term reliance on subsidized inputs, coupled with the absence of strong extension services, have prevented many smallholder producers from gaining access to technology and developing the skills needed to keep pace with commercial aquaculture developments in Zambia (Masuka and Musonda, 2013; Avadi et al., 2022). Overall, semi-subsistence farmers achieve low yields, direct their output to home consumption or barter, and treat aquaculture as a secondary or tertiary economic activity (Avadi et al., 2022).

The commercial sector, by contrast, has developed along quite different lines. Government policy has created a generally favorable environment for private investment, both nationally and internationally, supporting private hatcheries and feed companies for improved seed and fish nutrition (Kaminski et al., 2018). The aquaculture feed industry initially developed as an extension of existing poultry and livestock feed operations in Zambia. But pressure by large commercial aquaculture companies for higher quality feeds has led to new contractual relationships with international aquafeed companies. Policies on siting have also been favorable to large-scale commercial companies. Although both customary and statutory land rights are recognized in Zambia through the Lands Act of 1995, customary rights are often leased for large-scale development, with the government overseeing land use transactions and resettlement procedures (Avadi et al., 2022).[11] In addition, the government, through the Department of Fisheries, provides permits for large-scale aquaculture operations in Lake Kariba.

The result has been a skewed distribution of production and value added within the aquaculture sector. Avadi et al. (2022) report that in 2015–16, the semi-subsistence sector, comprised of roughly 11,000 farms, accounted for only 6.4 % of the nation's total aquaculture output, while the 12 large-scale cage operations in Lake Kariba contributed 67 %. Twenty large- and medium-scale ponds operations supplied 11 % of total output, while 853 small commercial farms contributed 6.8 %.[12] Large-scale cage producers also accounted for two-thirds of direct value added in the sector and 70 % of total aquaculture employment. However, SME aquaculture operations have emerged with higher profit margins than large-scale aquaculture producers in Zambia during the past decade (Avadi et al., 2022).

Despite hopes that the commercial aquaculture would have economic spillovers to semi-subsistence farmers through value chain development, and to low-income consumers through reduced fish prices, the process has not been inclusive to date (Genschick et al., 2017). In this regard, the process of aquaculture development in Zambia differs significantly from that of Bangladesh. Tilapia produced by the commercial sector in Zambia are typically larger and more valuable than those produced by small-scale semi-subsistence farmers, and the larger fish are sold primarily to middle- and high-end consumers in urban markets and to institutional buyers (schools, clinics, public servants) (Avadi et al., 2022). At the same time, generally unrestricted trade policy has allowed fish imports to increase, particularly for smaller fish coming from Namibia, Zimbabwe, and China, often out-competing production of semi-subsistence aquaculture producers (Kaminski et al., 2018; Tran et al., 2019).[13]

To help semi-subsistence farmers become economically viable, the Zambian government has implemented a set of National Aquaculture Development Plans (2015, 2020), as well as an Aquaculture Enterprise Development Project in collaboration with WorldFish (2017) (Genschick et al., 2017; Avadi et al., 2022). There is little evidence that this transition has been successful to date, as most small-scale producers remain in the semi-subsistence category with inadequate extension and market access to turn aquaculture into a primary economic activity (Avadi et al., 2022).

Kaminski et al. (2020) review potential ways in which small-scale aquaculture producers, in general, can benefit from inclusive business models commonly used in agricultural development, such as contract farming, joint ventures, and farmer-owned cooperatives. Piloting some of these inclusive business models in Zambia could potentially enhance the shift from semi-subsistence to SME aquaculture (Avadi et al., 2022). Large- and medium-scale companies can serve as pioneering agents for supply chain development and absorb the bulk of the production risk, as seen, for example, in plantation agriculture (Byerlee, 2014). There are still critical missing links in engaging smallholders in commercial aquaculture in Zambia, however, particularly in terms of the extent, consistency, and quality of extension services.[14] By comparison, experience from Ghana illustrates how targeted, high-quality aquaculture extension for small-scale, non-poor pond producers can contribute more to direct and indirect economic benefits than is achieved by SMEs or large-scale cage producers in Lake Volta (Kassam and Dorward, 2017; Mantey et al., 2020). Improved training in pond management could also lower the environmental impacts of smallholder production, such as eutrophication, which typically exceed damages from well-managed commercial operations (Avadi et al., 2022).

The biggest challenge for policymakers in Zambia, and throughout sub-Saharan Africa, is addressing the needs and capabilities of the lowest income tier of aquaculture producers. Drawing from the example of Bangladesh above, there may be merits in promoting diversification in fish species produced by semi-subsistence farmers—targeted for local,

[11] Details on Zambian land rights can be found in Hall et al. (2017). Rural communities in Zambia have given up land and resettled both voluntarily and involuntarily depending on the specific case. Avadi et al. (2022) report that all large-scale aquaculture companies claim to have acquired their land leases and lake area permits legally.

[12] Small-scale commercial farms differ from small-scale semi-subsistence farms in that they have acquired more training and management skills; they have access to inputs, including loans; and they often sell their product beyond the farmgate (Avadi et al., 2022).

[13] Kaminski et al. (2018) report that fish imports in Zambia rose at 30% per annum between 2004 and 2014, albeit from a small base, with 68% coming from Namibia, 20% from China, and 11% from Zimbabwe. Unofficial evidence in this paper indicates that Chinese tilapia is dumped in Namibia, often labeled as horse mackerel, and enters Zambia as "frozen fish".

[14] Building local capacity in Africa through targeted extension services is critical for aquaculture growth and equitable distribution (Munguti et al., 2014; Mantey et al., 2020)—a lesson that has been learned from Asian success stories (e.g., in West Bengal, India (Mishra et al., 2021)) and yet-to-be success stories (e.g., Lombok, Indonesia (Senff et al., 2018)).

low-income consumers—and in improving access to higher quality commercial seed and feed inputs. A critical question is whether Zambia should maintain its current trade policy for fish (e.g., largely unrestricted imports of small tilapia that help increase the availability of affordable fish) or impose a tariff on imported fish to protect small-scale commercial tilapia farmers. The stakes of improving smallholder productivity and lowering fish prices for extremely poor consumers are high, as undernutrition, particularly among children and women, remain a key impediment to the development process in Zambia (Tran et al., 2019; Avadi et al., 2022).

4.2. Disease management

As aquaculture production intensifies throughout the Global South, disease management, siting, and environmental performance require increasing policy attention (Garlock et al., 2020; Naylor et al., 2021a). Virtually all freshwater and marine aquaculture systems interact directly with the ambient aquatic environment and thus contribute to and are affected by pathogens, pests, parasites, and pollution of surrounding activities (Cao et al., 2023). Fish disease is commonly viewed as the highest risk to production in established aquaculture systems and presents a serious and chronic problem for the industry overall (Stentiford et al., 2012; Anderson et al., 2019; Naylor et al., 2021a).[15] As noted by Anderson et al. (2019), studies analyzing the efficiency, economic incentives, and economic impact on society of disease management, regulation, and biosecurity practices are essentially absent in the literature.

Disease risks are especially important for aquaculture policy for two reasons. First, disease can essentially wipe out production systems in a season resulting in loss of farm incomes, employment, and foreign exchange earnings; higher prices for consumers; and boom-and-bust cycles that destabilize segments of the industry. Examples include the devastating effects of white spot disease in Asian shrimp systems, and infectious salmon anemia in Chilean salmon aquaculture (Brummett et al., 2014; Shinn et al., 2018; Quiñones et al., 2019; Chávez et al., 2019; Asche et al., 2018a, 2021, 2022).

Second, the management of fish diseases in aquaculture varies widely within and between countries, with profound consequences for human health and the environment when improperly done. By far the most worrisome aspect of aquaculture disease management, in our view, is the liberal and unrestricted use of antibiotics and other antimicrobials (antivirals, antifungals, antiprotozoal substances) as a first line of defense in many countries outside of Europe and North America.[16] Antimicrobials are used in aquaculture to promote growth as well as to treat disease prophylactically and therapeutically (Mortazavi, 2014; Lulijwa et al., 2020). Several of the most widely used antibiotics are also used in human medicine, and thus the emergence of antibiotic resistance bacteria presents a serious threat to global health (Schar, 2020). There are no comprehensive, standardized data on the amounts and types of antimicrobials applied throughout the global aquaculture industry, and thus addressing the full scope of this problem is far from reach. Moreover, there are serious gaps in national action plans focused on preventing antimicrobial resistance in aquaculture in most countries (Caputo et al., 2022).[17]

Antimicrobials in aquaculture are administered mainly through medicated feeds and spread through the aquatic environment via uneaten feed, urine, and feces. Many of these compounds are non-biodegradable and accumulate in sediments, often remaining in the environment in an unmetabolized form (Mortazavi, 2014). Residues in the aquatic environment can lead to resistance in local and endemic bacteria, creating reservoirs for antimicrobial resistant genes and, in some cases, to multi-antimicrobial resistance (Schar et al., 2020; Lulijwa et al., 2020).[18] Antibiotic resistant genes can persist in the environment for several years after actual use of drugs (Tamminen et al., 2011).

Reverter et al., (2020) calculated a Multi-Antibiotic Resistance Index (MAR) for aquaculture-related bacteria for 40 countries (accounting for 93 % of global production) and found that 70 % of those countries exceeded the threshold of high-risk antibiotic contamination. Zambia, Mexico, and Tunisia ranked highest, while Canada, France, U.S. ranked lowest. In industrialized countries, antimicrobial use in aquaculture is tightly regulated (Mortazavi, 2014; Lulijwa et al., 2020). Governments in high-income countries generally permit a limited number of explicitly approved antimicrobials for use in aquaculture, which must be prescribed by certified veterinarians according to strict labeling procedures (Henriksson et al., 2017).[19] Limiting the number of compounds for use in aquaculture—as opposed to assessing the risks of numerous antimicrobials as they enter the sector—is considered an effective approach for controlling antibiotic use, but this strategy only works in countries that produce a small number of species and where a strong, consolidated industry exists (Henriksson et al., 2017).

Trade policies can also be used to control the misuse of antibiotics in the global aquaculture sector. Failure to meet European Council or the U.S. Food and Drug Administration (FDA) regulations on antibiotics typically results in strict import barriers by the EU and U.S., with a significant loss in export revenue by violating countries (Henriksson et al., 2017; Lulijwa et al., 2020). Trade regulations do not address the use of antibiotics throughout the life cycle, however, and in some countries, including China, regulatory programs on antibiotics are enforced only for export products but fail to cover aquaculture products for domestic consumption (Boison and Turnipseed, 2015). International

[15] Disease risks differ for finfish versus crustacean and bivalve aquaculture. As reviewed by Naylor et al. (2021a), invertebrates lack the adaptive immunity of finfish. Their innate immune systems, which are complex and heterogeneous, are not fully understood. The gut is an important component of the immune system for finfish, which allows diet and alterations in the microbiome to influence disease susceptibility and resistance, while disease risks for invertebrates depend critically on external microbial communities. As a result, vaccines can be highly effective in preventing disease in finfish but not in crustaceans (Henriksson et al., 2017). Shrimp aquaculture has been especially susceptible to booms and busts in production from disease outbreaks (Brummett et al., 2014; Asche et al., 2021).

[16] In a comprehensive review of antibiotic use for the top 15 aquaculture-producing countries over the period 2008–2018, Lulijwa et al. (2020) found that 67 different compounds were used in 11 of the 15 cases—a 2.5-fold increase from the earlier period of 1990–2007 when 27 compounds were documented. Their study found that countries used an average of 15 different antibiotic compounds, with Vietnam, China, and Bangladesh applying 39, 33, and 21 different antibiotic compounds, respectively, in their aquaculture systems. The large number of different antimicrobials in aquaculture is not too surprising given the diversity of species and systems, and lax oversight of antimicrobial use in most developing countries.

[17] Existing studies on antimicrobial use, resistance, and environmental impacts typically rely on national and international surveys of aquaculture practices. Schar et al. (2020) estimate, based on survey data from 2000 to 2019, that Asia accounts for 94% of global antimicrobial use in aquaculture, and China alone accounts for 58%—the latter most likely being an underestimate given that antimicrobial use is poorly documented for even the most widely produced species, such as carps.

[18] Multi-antimicrobial resistance (MAMR) is the most disastrous outcome as it can potentially lead to uncontrolled epidemics and epizootics (Lulijwa et al., 2020). Although the data on MAMR is scarce, it has been reported in global catfish production (Chuah et al., 2016).

[19] For example, the U.S. regulates antimicrobial use through the Food and Drug Administration (FDA), permitting a few targeted antibiotics for immediate disease control. There are no antibiotics approved for use as a growth promoter, for prophylactic use to prevent the outbreak of a disease, or for use in marine fish for offshore aquaculture (Zajicek et al., 2021). Norway has virtually eliminated the use of antimicrobials in salmon aquaculture through an aggressive vaccination program and strict regulations and veterinary programs (Henriksson et al., 2017; Lulijwa et al., 2020).

coordination of policies and regulatory practices is needed to control antibiotic use and mitigate antibiotic resistance in aquaculture (Lulijwa et al., 2020). Implementing such coordination is extremely difficult given the lack of reliable data on chemical use for most aquaculture species and regions (Naylor et al., 2021a).

The best avenue for reducing antimicrobial use and antimicrobial resistance in aquaculture is to prevent diseases from occurring in the first place; once diseases have been established, they are extremely difficult to eliminate (Mortazavi, 2014; Brummett et al., 2014; Houston et al., 2020; Okoli et al., 2022). Naylor et al. (2021a) review the literature on aquaculture disease pressures and mitigation strategies and note that science-led disease strategies, while used widely in high-valued aquaculture systems in the Global North, remain largely unavailable for many low-value aquaculture species in the Global South due to high costs and the lack of product development. Disease issues are therefore a particularly serious problem in middle- and low-income countries where aquaculture is expanding most rapidly.

4.2.1. Chile

Chile serves as a cautionary tale of disease and antibiotic challenges in a rapidly expanding aquaculture industry. It also serves as an example of a country that has been forced to adjust policies to high-risk disease conditions and to re-orient its strategy toward greater environmental sustainability. Chile is the second largest producer of farmed salmon after Norway (FAO, 2022b). The sector accounts for over one-third of all food exports and ranks only behind copper in terms of primary exports and is thus of great importance to the Chilean government. Salmon aquaculture in Chile is geared toward exports rather than domestic consumption (Naylor et al., 2021b), but the industry employs at least 70,000 people directly or indirectly, many residing in low-income rural settings (Avendaño-Herrera, 2018). The commercialization of salmon aquaculture in the 1980s and 1990s led to early improvements in rural poverty alleviation and income equality in certain remote coastal areas, such as Los Logos where the industry began in Chile (Ceballos et al., 2018; Cárdenas-Retmal et al., 2021).

Salmon aquaculture was introduced in Chile in the 1970s, but commercial production did not take off until the 1980s-1990s. The most significant growth occurred in the early to mid-2000s following the enactment of the Aquaculture National Policy in 2003 (Brummett et al., 2014). This policy aimed to double aquaculture production by 2012, with few restrictions on environmental or disease control. By the mid-2000s, Chile was the fastest growing salmon producer in the world, set to overtake Norway. However, in 2007–2008 the industry was also besieged by a massive disease outbreak of Infectious Salmon Anemia (ISA), a virus that nearly decimated the industry and caused total salmon production to decline by two-thirds (Asche et al., 2009; Brummett et al., 2014). The ISA crisis cost the industry over $2 billion in financial losses, and tens of thousands of jobs were eliminated.

Reviews of Chile's ISA case (Asche et al., 2009; Brummett et al., 2014; Avendaño-Herrera, 2018; Quiñones et al., 2019; Bachmann-Vargas et al., 2021) point to several accumulated management and policy flaws by the mid-2000s that led to the industry's collapse: a high concentration of farms in certain locations; the absence of zone management programs; poor sanitary control, including insufficiently regulated importation of fish eggs, and no fallowing or disinfection protocols; a lack of biosecurity measures between farms; poor control over the use of antibiotics dating to the 1990s; and the absence of comprehensive government regulations and control over salmon aquaculture more generally. These shortcomings permitted multiple routes of transmission for the ISA virus (Mardones et al., 2009). Prior to the ISA crisis, the industry benefitted from high prices and increasing production, and despite efforts to create a regulatory structure for farmed salmon, industry growth simply outpaced the implementation of regulatory controls (Brummett et al., 2014). The government played a passive role on regulation in favor of industry growth—priorities patterned after three decades of rapid expansion (Bachmann-Vargas et al., 2021).

ISA was not the first, nor the last, significant disease to affect Chilean salmon aquaculture (Figueroa et al., 2019). In more recent years, the emergence of an endemic bacteria, *P. salmonis,* has led to widespread infections of salmon rickettsial syndrome, causing 50 % to 97 % of all disease-related mortalities in the industry (Avendaño-Herrera, 2018; Avendaño-Herrera et al., 2023). Liberal use of antibiotics in salmon aquaculture in Chile—greater than in any other salmon farming country—has resulted in continued deposition of antibiotic resistant bacteria in sediments (Buschmann et al., 2012; Quiñones et al., 2019). As a result, therapeutic treatments of *P. salmonis* have largely failed, and the situation portends further problems for aquaculture production and human health in Chile as the antibiotic compounds persist in the environment.

Chile has undergone successive policy changes in response to its disease challenges in salmon aquaculture, and researchers call for a One Health approach to management (Lozano-Muñoz et al., 2021; Avendaño-Herrera et al., 2023). Ongoing policy changes include the introduction of monitored sanitary zones, improved spatial planning of aquaculture concessions, mandatory environmental impact assessments, and environmental and sanitary sanctions and fines for non-compliance (Quiñones et al., 2019; Bachmann-Vargas et al., 2021). These policy changes pertain mainly to the seawater fattening stage and largely overlook the freshwater juvenile stage of salmon farming. The lack of policy focus on freshwater systems is a major gap in the strategy for disease control, as the industry is not vertically integrated for the most part between fresh- and salt-water farming systems (Avendaño-Herrera, 2018; Quiñones et al., 2019). Moreover, attempts to measure success by tracking the overall amount of antibiotics used hides the fact that some producers use much more antibiotics and others use less.

A key governance problem in Chile is that environmental regulations are often adopted from the country's leading trading partners, such as the U.S, partially as a means of advancing exports, but corresponding laws are not always implemented or enforced. More generally, Chile's neoliberal political and economic model means that environmental regulations typically have a market-enabling quality as opposed to a market-regulating quality (Barton, 1997; Barton and Fløysand, 2010; Tecklin et al., 2011). Policies addressing aquaculture carrying capacity and disease control in Chile are generally not grounded in strong science (Quiñones et al., 2019). Moreover, the financial system supports growth over industry closure, as banks seek loan repayments in this dominant and dynamic sector of the Chilean economy (Brummett et al., 2014).

Where Chile goes from here with its salmon aquaculture sector will have important implications for human health and the environment. The national policy discourse, attempting to legitimize continued salmon aquaculture growth, is currently oriented around the concepts of biosecurity, sustainable protein, and "the Promise of Patagonia" — a phrase coined by the Chilean Salmon Marketing Council to link salmon production to pristine waters in Patagonian territory to quell consumer distrust (Bachmann-Vargas et al., 2021). However, an integrated and effective ecosystem plan for development has yet to be established. Debates over spatial planning are pervasive: for example, aquaculture farms vs artisanal fisheries; mussel farms vs salmon farms; tourism and conservation vs fish and seaweed production (Chávez et al., 2019). Policy priorities and operations often differ among agencies, and tension among these groups has yet to be resolved.

4.3. Siting

Effective spatial planning and regulation of aquaculture siting are critical components of policy as the industry increases in scale and production intensifies. Careful siting is important not only for the control of disease, parasites, and pests, but also for mitigating pollution, balancing the allocation of land and water resources among different users, and protecting natural ecosystems. As climate change progresses, there is mounting concern in drought-prone regions about the use of scarce freshwater resources for aquaculture; in Egypt, for example, water quality and quantity constraints have increasingly limited aquaculture growth (Soliman and Yacout, 2016).

In many parts of Asia (e.g., Bangladesh, Cambodia, China, Myanmar, Nepal, Vietnam), expansion of inland aquaculture has occurred either by converting rice ponds to aquaculture, or less commonly, integrating aquaculture into rice ponds (Edwards, 2015). This process has raised concerns over the availability of staple crops for food security in some countries. Myanmar, which now ranks among the top 10 global aquaculture producers (Fig. 1), has strictly enforced laws against converting rice fields to fishponds in smallholder areas despite potential employment and income gains (Belton et al., 2015; Filipski and Belton, 2018; Belton and Filipski, 2019). Vietnam, by contrast, has encouraged the conversion of low-quality rice land to fishponds to enhance farm incomes, but the government also maintains a reserve of 4 million ha of rice fields nationally for food security (Edwards, 2015). Diversification from staple crops into higher-valued production systems, including aquaculture, is key for rural economic growth and improvements in nutrition as countries develop and diets evolve, yet the political mindset around grains for food security is often difficult to change (Pingali, 2015).

Mariculture and inland cage culture in lakes and reservoirs help to offset pressure on land and water resources, yet pollution, antimicrobial dispersion, climate impacts, and competing uses (e.g., drinking water, wind and hydro energy facilities, navigation, tourism, and aesthetic preferences) can become problematic as the industry expands. As a result, parts of the global aquaculture industry are moving toward on-land recirculating aquaculture systems (RAS) and large offshore cage technologies to reduce exposure to and impact on aquatic environments. These systems are expensive and complex, however, and require innovative financial and environmental management to scale successfully (Klinger and Naylor, 2012; Edwards, 2015; Naylor et al., 2021a).[20] As aquaculture continues to develop in both marine and freshwater environments (Costa-Pierce et al., 2021) careful siting represents one of the most important issues that policymakers face throughout the world.

4.3.1. China

China serves as a good example in the discussion of aquaculture siting policy given the expanse of its operations in both inland and marine environments, the rising competition for water and land in the Eastern and Southern regions of the country, and the incremental shift in national policy attention toward environmentally sound systems. China is also a valuable case study for aquaculture policy overall due to its oversized role in all aspects of the industry (Cao et al., 2015; Naylor et al., 2021a) and the inability of many aquaculture and food policy scholars to access literature in the Chinese language. China is the world's largest seafood producer, processor, consumer, exporter, and importer (Cao et al, 2015; Naylor et al., 2021b; FAO 2022a) and by far the leading contributor to global aquaculture volume and value (Fig. 1). Changes in aquaculture policies in China can thus have significant impacts on the state of world aquaculture (FAO 2022a).

The policy environment in China, with its centralized governance structure, differs significantly from that of most other countries. Policies are designed from the top down through Five Year Plans and are implemented at the state and local levels by appointed officials. A brief history of Chinese aquaculture policy over time can be divided into three stages: (1) under-regulating aquaculture for economic development; (2) regulating aquaculture for stable growth; and (3) promoting responsible aquaculture for environmental and social good.

From the 1980s to the early 2010s, following the political reform in 1978 and the opening of the national economy, China encouraged and supported the intensification of aquaculture production with minimal regulation (Broughton and Walker, 2010; Jia et al., 2018; Lulijwa et al., 2020). Although the main national legislations governing aquaculture—e.g., the Fisheries Law, Regulations on Aquaculture Quality and Safety, the Marine Environment Protection Law —set some basic guidelines, they were not implemented or enforced strictly (Cao et al., 2017). Jia et al. (2018) summarized the core of public sector policy in Chinese aquaculture during this period: use available resources fully, support the sector through government-led technical assistance, and let markets determine production.

The intensification of under-regulated aquaculture escalated the loss of natural habitats, further depleted overharvested fishery stocks, and altered the livelihoods of coastal communities (Cao et al., 2015; Wang et al., 2018; Herbeck et al., 2020). Although many inland fishponds were converted from rice fields in the 1970s and 1980s, this practice was later banned due to government concerns about national food security as defined by the availability and affordability of staple grains (Edwards, 2015).

During the past decade, China has re-envisioned its aquaculture policy to promote sustainable growth. The concept of "ecological civilization," written into the Chinese constitution in 2012, has served as a guiding principle of policy reform. Ecological civilization refers to an ethical ideology that realizes harmonious coexistence between nature and society (Zhu, 2016), and can be broadly interpreted as sustainable development that involves political, economic, educational, and other societal reforms. China's 13th Five Year Plan initiated this transition at the national level, placing sustainable development and environmental protection as priorities on par with economic development for the first time (Zhao, 2021; Zhao et al., 2021; Cao et al., 2017). At the same time, the Fisheries Law underwent initial revision, with substantial shifts towards the "green development" of Chinese fisheries and aquaculture (Ministry of Agriculture and Rural Affairs of PRC, 2019). The newest draft amendment of this law stated its goals "to strengthen the protection, proliferation, development and rational use of fishery resources, develop artificial breeding, protect the legitimate rights and interests of fishery producers, promote the sustainable development of fisheries, and adapt to the socialist modernization construction and people's growing needs for a better life" (Ministry of Agriculture and Rural Affairs of PRC, 2019). It marked the first time that the word "sustainable development" appeared in any version of the law.

Chinese aquaculture policies began to target environmental performance in the early 2020s. China's 14th Five Year Plan and the subsequent 14th Five Year Plan of Aquaculture and Fisheries contain policies that focus on "high-quality growth" and modernization of the industry (Ministry of Agriculture and Rural Affairs of PRC, 2022; National People's Congress of PRC, 2021). Among the policy initiatives from the Ministry of Agriculture and Rural Affairs, the promotion of compound feed to replace the direct feed of wild juvenile fish is likely to have the largest impact on the sustainability of the fisheries sector (Zhang, 2022). Additional policy incentives for innovation in the aquafeed sector are needed, however, for a full transformation to sustainable feed in China (Dong, 2019).

As Chinese aquaculture develops in volume, quantity, safety, and sustainability, it has encountered two major issues that require more targeted policy instruments than previously used: siting and disease management. Policies in these areas have had varying degrees of success and setbacks, and their long-term effects remain to be seen.

Siting designation and regulation is a key feature of Chinese aquaculture's transition to sustainability, and it is one of the major aquaculture policies introduced in China's 13th-14th Five Year Plan period of 2016 to 2025 (Ministry of Agriculture and Rural Affairs of PRC, 2021). Well-designed policies on aquaculture siting are essential for ensuring the sustainable growth of aquaculture operations, maximizing ecosystem services provided by aquaculture, and mitigating critical challenges to the industry, especially habitat loss, disease, and pollution

[20] RAS systems are constrained by large energy requirements, high production costs, waste disposal challenges, and risk of catastrophic disease failures and are thus used mainly for the cultivation of broodstock or fish at vulnerable early life stages where the economic returns are high (Naylor et al., 2021a).

(Herbeck et al., 2020; Naylor et al., 2021a). In 2014–16, China carried out a nationwide comprehensive spatial planning process for aquaculture siting, designating "aquaculture areas" for aquaculture production, "restricted aquaculture areas" for limited production, and "prohibited aquaculture areas" to protect coastal habits (Ministry of Agriculture and Rural Affairs of PRC, 2017). Aquaculture siting regulations have been significantly more rigorous than those in Chile. Implementation of siting policies have shown promising signs of environmental improvement in China, but also a loss of aquaculture farmers' livelihoods across the country in the late 2010s (Wang, 2020).

In addition to improved siting for the control of fish diseases, the use of antibiotics is common in Chinese aquaculture, but is poorly documented and quantified. China has authorized 13 antibiotics for aquaculture use and bans others, but about 33 antibiotics are used in practice, one of the highest numbers of antibiotic compounds used globally (Liu et al, 2017; Lulijwa et al., 2020). Some antibiotics used in Chinese aquaculture were originally designed for human medical treatment, and their residuals in fish and in sediments surrounding fishponds and cages may cause bacterial resistance and other human health complications (Van Doorslaer et al, 2014).

The transition in Chinese aquaculture policy from prioritizing production volume and revenue to emphasizing environmental performance has important implications for aquaculture growth, environmental protection, food security, food safety, and the livelihoods of aquaculture farmers (Zhang and Ma, 2020). Aquaculture production in China expanded at an annual average rate of 9.77 % from 1980 to 2020, but growth rates have been declining over the decades, from 17.7 % in the 1980s to 3.44 % from 2010 to 2020 (FAO, 2022b). Moreover, despite significant progress, policies aimed at environmental performance are often difficult to design and implement. The main challenge for Chinese policymakers is to identify effective and efficient regulations and rules for farmers and other actors along the supply chain, especially for small- and medium-scale producers, that guide them toward better environmental outcomes without sacrificing their economic viability (FAO 2022a).

4.4. Environmental priorities

Aquaculture policies throughout the Global North have generally prioritized environmental and resource protection, leading to over-regulation and slow aquaculture growth in several industrialized countries (Abate et al., 2016; Belton et al., 2020; Asche et al., 2022). The share of global aquaculture produced in Japan, the EU, the U.S., and other OECD (Organization for Economic Co-operation and Development) countries fell from 55 % in 1950 to 11 % in 2019 (OECD, 2022). Norway is an exception and is the world's largest salmon producer and exporter, controlling over half of global farmed salmon output (Iversen et al., 2020; Hersoug, 2021).

In a review on the economics of aquaculture policy, Anderson et al. (2019) emphasize the constraining role of complex regulatory systems on aquaculture growth in the U.S. and Europe dating back more than thirty years. In Canada, establishing national legislation to regulate aquaculture has been stymied by political silos across agencies and territories, challenges in implementing a science-based approach to aquaculture management (e.g., chemical treatment of sea lice), and a failure to honor Indigenous rights (Howlett and Rayner, 2004; Wiber et al., 2021). Throughout North America, Europe, and Oceania, there is strong public interest in developing national legislation that supports economically competitive, environmentally sound, and socially responsible aquaculture (Lester et al., 2022). Yet meeting multiple objectives across government agencies remains difficult, and few nations have viable strategies for long-term growth (Osmundsen et al., 2017; Garlock et al., 2020; Bohnes et al., 2020; Froehlich et al., 2021b). Regulatory and economic constraints act as a barrier even for systems widely considered to be environmentally sustainable, such as Integrated Multi-Trophic Aquaculture (IMTA) and seaweed culture (Alexander et al., 2015; Naylor et al., 2021a).

4.4.1. USA

The U.S. ranked as the world's third largest aquaculture producer in the 1970s but now accounts for only 0.5 % of global live-weight production and value (Table 1). American aquaculture producers confront a complex set of federal and state regulations spanning multiple areas (e.g., environmental protection, food safety, labor standards, fish health, husbandry practices, interstate transport), resulting in high compliance costs, delays in permitting, and vast economic uncertainty (Engle and Stone, 2013). Marine aquaculture is subject to especially stringent environmental and spatial regulations and wide variation across states (Knapp and Rubino, 2016; Lester et al., 2022). The perceived regulatory burden has been shown to play a major role in aquaculture firms' decisions to move their operations abroad (Chu and Tudur, 2014). Moreover, the increasingly complex regulatory system has curbed the ability of the sector to innovate in ways that are essential for international competitiveness, sustainability, and climate resilience (Zajicek et al., 2021). Federal government investment in R&D for aquaculture has been a fraction of that devoted to agriculture in the U.S., despite an estimated 37-fold private return on investment over the period 2000 to 2014 (Love et al., 2017).[21]

One of the most controversial regulatory issues in U.S. aquaculture has revolved around the approval of genetically engineered (GE)[22] salmon for commercial production and sale. GE food products in the U.S. are regulated by the FDA, and GE fish fall under the animal drug division for food safety considerations (Marden et al. 2006). GE salmon, introduced by AquaBounty Technologies (known as AquAdvantage salmon), are engineered to grow twice as fast as wild salmon, reaching market size in half the time and requiring significantly less feed over the life cycle.[23] Smith et al. (2010) stress that regulators should evaluate the risks relative to potential health and ecological benefits from the commercial production and sale of GE salmon. Public controversy surrounding the product stems from general distrust of genetically engineered foods, market competition with non-GE salmon, environmental risks to wild salmon populations and indigenous fisheries, transboundary issues between Canada and the U.S., and the need for clear labeling (Marden et al. 2006; Le Curieux-Belfond et al., 2009).[24] Based on an online choice experiment survey of approximately 1,000 U.S. seafood consumers, Weir et al. (2021) concluded that consumers are willing to pay a higher price for non-GE and organic fish, particularly when information on the GE content is presented as a warning.

[21] Love et al. (2017) assessed U.S. federal spending on aquaculture, using a large database of almost 3000 U.S. federal research grants awarded from 1990 to 2015. The study conservatively estimates a total of $1.04 billion invested in aquaculture as compared to $41 billion invested in agriculture over the same period. Total return on investment is calculated as the total gain from the investment minus the total cost of the investment divided by the total cost of the investment from 2000 to 2014. The private rate of return excluded returns on algal research for biofuels (roughly-one-third of federal investment) and did not estimate social returns on investment (e.g., employment, economic, and ecosystem service gains).

[22] In this paper, GE salmon is synonymous with genetically modified (GM or GMO) and transgenic salmon. In our view, classical breeding of fish also leads to modification of the genetics over generations. Other authors may prefer the using GM or GMO terminology for foreign gene insertion, and GE to denote modern genetic engineering techniques such as CRISPR/Cas.

[23] Genetically engineered Atlantic salmon, first constructed in 1989, contains a growth hormone gene from Chinook salmon and is controlled by an antifreeze protein promoter and a terminator gene from ocean pout. Details on GE salmon can be found in Waltz (2016) and FDA (2022a).

[24] The USDA regulates the labeling of GE salmon under the National Bioengineered Food Disclosure Standard, which requires companies to disclose genetically modified ingredients in food, but the rules do not apply to restaurants or food services (FDA, 2022a).

AquaBounty's GE salmon was approved by the FDA in 2015 under the Federal Food, Drug, and Cosmetic Act, more than two decades after the company first opened its investigational new animal drug file with the FDA in 1995 (FDA, 2022a, 2022b).[25] The FDA determined that GE salmon is safe to eat and has a comparable nutritional profile to that of non-GE farmed Atlantic salmon (FDA, 2022a). The agency also evaluated the potential environmental impacts of the GE salmon and issued its final "Finding of No Significant Impact" in compliance with the National Environmental Policy Act (NEPA), stating that the probability of the GE salmon escaping into wild and impacting wild fish populations is very low due to multiple forms of redundant physical, biological, and geographical containment measures (FDA, 2022a,b). Despite these rulings in 2015, AquaBounty was not granted approval to produce the salmon in the U.S. until 2019, and thus began its operations in Canada and Panama. The first commercial production and sale of GE salmon in the U.S. came from land-based tank operations in Indiana—not from marine-based cages—in 2021.[26]

Going forward, breeding programs for commercial aquaculture species will benefit from rapid advances in genomics and bioinformatics, including genome editing and surrogate broodstock technologies to improve selection and accelerate the timeline of genetic gains (Gratacap et al., 2019; Houston et al., 2020). As in all aquaculture producing countries, the regulatory process will need to keep pace with genetic innovations for fish improvement (Okoli et al., 2022).

Zajicek et al. (2021) dispel several common myths associated with U.S. aquaculture, particularly regarding the unsustainable nature of mariculture, underscoring the role of sound science in designing regulations. In contrast to early assessments that identified a lack of coherence across regulatory agencies as a major constraint on aquaculture productivity, the authors suggest a relatively high degree of coordination among federal and state agencies, but also point to the absence of a clear lead agency on permitting. Governing agencies also differ across aquaculture systems, with NOAA responsible for mariculture and USDA responsible for freshwater aquaculture, thus diluting the strength of institutional support for the industry, as discussed later in this section for the case of Norway. The authors conclude in their assessment of U.S. marine aquaculture: "The current federal permitting process is thorough, complex, time consuming and expensive. We believe this is as it should be. As we collectively gain experience, knowledge, and environmental data, the time and expense may lessen but the permitting process should always be rigorous. We, as citizens of the U.S., are desirous of protecting and conserving the oceans for the next [several] generations." (Zajicek et al., 2021).

4.4.2. EU

As in the U.S., aquaculture in the EU has not flourished in recent decades, despite government funding of more than Euro 1 billion for the sector, raising questions as to whether these subsidies can be justified (Guillen et al., 2019). The decline in output has been caused partially by bureaucratic red tape, stringent environmental and food safety regulations, and inefficient and inflexible command-and-control policies (e.g., input and output quotas) that stifle innovation (Abate et al., 2016, 2018; Bostock et al., 2016).

Guillen et al. (2019) assess the allocation of various structural funds across EU member states from 2000 to 2020 to understand the connection between public funding and social benefits of aquaculture. Their analysis reveals that the decline in EU aquaculture production, caused mainly by a drop in mussel harvests (with heavy shell weight), has been matched by an increase in overall aquaculture value due to the expansion of high-valued marine finfish aquaculture.[27] Public funding for aquaculture is diverse across EU member states, targeting a small set of freshwater (e.g., trout, carp) and marine (e.g., salmon, seabass/seabream) systems. Most of the public funding supports small-scale, family enterprises that comprise over 90 % of firms in the industry. The authors argue that increasing returns on public investments could be achieved through larger-scale operations in marine environments, where technological innovation and the control over inputs and environmental outputs are higher than in small-scale rural systems. Shifting policy priorities from small-scale microenterprises to large-scale commercial firms and from land-based freshwater ponds to marine cages is advocated to promote EU aquaculture goals of international competitiveness, quality, food safety, and environmental sustainability.

Innovation hinges on the regulatory environment. EU regulations in some areas of the industry, particularly regarding GE fish, are more stringent than U.S. rules. The EU does not permit GE animals, or food or feed from GE animals, to be sold in the market, and there have not yet been applications by the aquaculture industry in the EU for GE approval (Bruetschy, 2019; EFSA, 2022). Gene editing is also highly restricted, and no applications for use in aquaculture have been advanced.[28] Some EU members have advocated for less stringent regulations on gene editing, especially for use in disease prevention, and support a multi-tiered process of regulation proposed by the Norwegian Biotechnology Advisory Board, which balances opportunities for genetic innovation with government oversight and control (Bratlie et al., 2019).

4.4.3. Norway

Important policy lessons can be learned from Norway's history of salmon farming over the past half century.[29] Norway differs from the U.S. and EU in two important dimensions: it has a long, relatively unpopulated coastline comprised of fjords with strong currents and sheltered waters near modern infrastructure; and salmon accounts for over 95 % of the aquaculture industry (Bjørndal and Salvanes, 1995; FAO, 2022a). Salmon aquaculture in Norway is internationally competitive and has become one of the nation's most important economic sectors, second only to oil (Iversen et al., 2020; Hersoug, 2021). It has not experienced the sort of negative public perceptions and social resistance that has been seen in the U.S. and EU (Kaiser and Stead, 2002; Froehlich et al., 2017). Producer groups have become well established and represented by the government, and aquaculture policies have evolved with a balanced and flexible approach toward aquaculture development and environment protection (Hersoug, 2021).

Norway's initial licensing scheme for salmon aquaculture, introduced in the 1970s, was focused on the dispersion of small-scale operations along the entire coastline with the goal of enhancing rural employment and incomes.[30] Policy incentives were designed to limit production at each site and prevent large, capital-intensive systems from dominating the industry. The distributed coastal siting scheme, coupled with production controls (measured in tons), were soon seen as barriers

[25] AquaBounty began discussions with regulators in 1993 when no defined regulatory pathway existed for GE animals in the U.S. The formal guidelines that were required in a GE animal application process were not finalized by the FDA until 2009 (Waltz, 2016).

[26] See: https://apnews.com/article/whole-foods-market-Inc-lifestyle-health-coronavirus-pandemic-technology-a4ef4f24801f62ac65918e4560d7eb8a.

[27] The study indicates that from 2008 to 2016, mussel aquaculture declined in the EU due to disease pressure and low profitability. The value of marine finfish aquaculture increased in nominal terms and remained stable in real terms over the period, and the average gross value added to the EU aquaculture sector rose by 71% (Guillen et al., 2019).

[28] See the Global Gene Editing Regulation Tracker, compiled by the Genetic Literacy Project, 2022: https://crispr-gene-editing-regs-tracker.geneticliteracyproject.org/european-union-animals/ (Accessed 18 November 2022).

[29] Norway is a member of the European Free Trade Association but is not a member state of the EU.

[30] This brief history of salmon aquaculture regulation in Norway is reviewed in full by Hersoug (2021), and the key points in the following paragraphs are extracted from that review. The initial licensing scheme was introduced by the Norwegian Directorate of Fisheries and regulated through the Fish Farming Licensing Act (Bjørndal and Salvanes, 1995).

to innovation and efficiency, leading policymakers to adopt new forms of volume controls that captured production intensity (tons/m^3) (Asche et al., 2009).

The evolution in Norway's salmon policies allowed innovation and productivity to surge; in the decade from 1992 to 2002, salmon production increased from 147,800 tons to 546,000 tons with no new licenses provided. As in virtually all food systems that intensify quickly, the environmental impacts of salmon aquaculture growth also rose (e.g., farmed fish escapes, sea lice, nutrient and chemical effluents). In response, the government introduced a Maximum Allowable Biomass (MAB) program in the early 2000s to control fish density in line with carrying capacity targets (Hersoug, 2021). What made the MAB program so successful was that it was supported by science, farming organizations, and the Directorate of Fisheries.

Responsibility for production and environmental outcomes of the MAB program is split between the Directorate of Fisheries and County Governors, respectively. Although the lack of coordination between government agencies and the dynamic nature of the industry create challenges for sustainable growth in Norway, strong institutional support and a stable administrative framework for the aquaculture sector persist (Abate et al., 2016; Osmundsen et al., 2017; Garlock et al., 2020). While maintaining the MAB as the core regulatory program, new policy initiatives have been trialed to provide predictable environmental guidelines for the industry. Policy incentives have also been introduced for the innovation of capital-intensive technologies to avoid coastal impacts, such as large offshore, submersible salmon cages and on-land recirculating aquaculture systems.

Norway's policy strategy has both stimulated and responded to industry consolidation over the past half century; 10 % of aquaculture companies in the country are now responsible for roughly 70 % of production (Hersoug, 2021). Even with consolidation, the industry supports the government's licensing scheme and environmental regulations, yet it has resisted excessively punitive tax policies, including the 40 % resource tax rate proposed by the government on the salmon aquaculture sector in 2022 (Holland, 2022; White, 2022). The unique policy approach to production controls in Norway is widely accepted by the industry because, as a large producer in the international market, salmon prices have risen as a result, and the country's reputation has become established as the world's most sustainable salmon producer.

4.5. Trade policy

Stringent environmental regulations in many industrialized countries have resulted in a high dependency on fish imports, mainly from aquaculture in countries where environmental regulations are lax (Asche et al., 2016; Garlock et al., 2020; Froehlich et al., 2021a). In response to competitive pressure in the international market, it is not uncommon for countries to impose trade restrictions on imports to protect their domestic aquaculture sectors (Asche et al., 2016; Anderson et al., 2019). Experiences from the U.S., EU, and Norway help to illustrate this point.

A prominent example from the U.S., dating back two decades, involved freshwater catfish culture—the traditional and leading farmed species in the U.S. Catfish production in the U.S. has faced serious competition from lower-cost aquaculture producers in Asia where environmental regulations are less stringent (Dey et al., 2017; Surathkal and Dey, 2020; Engle et al., 2022). In response, the U.S. imposed anti-dumping duties and high tariffs on Vietnamese catfish (pangasius) exports to the U.S. in 2003 (Asche and Khatun, 2006; De Silva and Phuong, 2011). These restrictive trade measures raised the U.S. price of catfish and lowered the international pangasius price, resulting in an estimated loss of $24 million to fish farm owners and employees in Vietnam in the short run (Asche and Khatun, 2006; Brambilla et al., 2012). The reduction in pangasius prices, in turn, caused market demand for pangasius to increase outside of the U.S., boosting Vietnam's overall export volume over the long run (De Silva and Phuong, 2011; Duc, 2010). Over the past 20 years the U.S. catfish industry has continued to compete with lower-priced imports from countries other than Vietnam (some of which may be trans-shipments originating in Vietnam) (Scuderi and Chen, 2017). Imports of other aquaculture products to the U.S., such as tilapia, shrimp, and salmon produced in countries with a more laxed regulatory structure, have also continued to rise.

Like the U.S., the EU has been involved in various trade disputes with countries exporting fish at low cost. Although trade restrictions have kept some aquaculture products out of the EU market, they have generally not improved the EU's international competitiveness over the long run (Anderson et al., 2019). Many EU nations lack long-term strategies for aquaculture growth, particularly in a changing climate, and depend increasingly on fish imports to meet demand (Froehlich et al., 2021b).

Norway, by contrast, has remained competitive in international markets and currently supplies over 50 % of the global salmon market. When salmon production started ramping up in in the early 1990s, both the U.S. and the EU imposed anti-dumping duties on Norwegian salmon to protect their domestic salmon aquaculture industries (Hersoug, 2021). These policies altered global trade patterns but had little impact on Norway's trajectory for salmon production. Norway shifted its salmon exports to Japan in response to duties by the U.S. and EU, while Chile expanded its salmon export market to the U.S. (Anderson et al., 2019).[31] Similar to the case of U.S. antidumping duties on the Vietnamese pangasius industry discussed earlier, unilateral trade restrictions are a weak tool for reducing global competition in fisheries and aquaculture (Anderson et al., 2019; Duc, 2010). These examples underscore the effects of national policies on the global distribution of aquaculture production and trade.

5. Policy gaps in nutrition security

The case studies presented above show how aquaculture policy priorities and outcomes differ among countries, with varying degrees of success as measured by growth in fish supplies and exports, value chain development, environmental and disease consequences, and the distribution of benefits. The literature highlights the potential role of aquaculture for food security, particularly among low- and middle-income countries and consumers (Belton et al., 2018, 2020). Human nutrition priorities in aquaculture policy—and in food policy more generally—are generally overlooked, however, despite high rates of stunting, wasting, overweight, and obesity in countries across income groups, as illustrated in our case studies in Table 2. Fish and other aquatic foods supply protein, omega-3 fatty acids, and vital micronutrients that are essential for human health (Thilsted et al., 2016; Golden et al., 2021). They also serve as a healthy and nutrient-dense substitute for environmentally- and energy-intensive animal-sourced foods, such as beef and pork, raised in agriculture production systems (Froehlich et al., 2018; Gephart et al., 2021; Gephart and Golden, 2022).

In many countries in both the Global North and Global South, health concerns related to obesity and diet-related non-communicable diseases, such as diabetes and cardiovascular disease, now exceed those of calorie-deficient hunger. Chile has been considered a leader in the policy space for regulating unhealthy foods through their national food law that encompasses labeling, restricted advertising, and taxes (Quintiliano Scarpelli et al., 2020). Nonetheless, vested interests and long-standing political representation of the staple commodity and livestock sectors in Chile, as in many countries, have impacted the priorities of food

[31] In 1990, prior to the anti-dumping duties, two-thirds of Norwegian farmed salmon production was exported to the EU, at a time when EU countries such as the UK and Ireland were trying to develop their salmon aquaculture sectors. Similarly, Norway's market share in the U.S., where salmon aquaculture was beginning to be developed, was 60% in 1989 and dropped to 5% after the anti-dumping duties were imposed in 1991 (Hersoug, 2021).

Table 2
Nutrition Health Indicators of Case Study Countries (*circa* 2020).

Case study	Nutritional Status of Children Under the Age of Five Years (%)			Adult Overweight and Obesity	
	Stunting	**Overweight**	**Wasting**	**All adults overweight** (BMI 25–29.9 kg/m^2)	**All adults obesity** (BMI $\geq$ 30 kg/m^2)
Bangladesh	30.2 %	2.1 %	9.8 %	20.5 %	5.4 %
Zambia	32.3 %	5.7 %	4.2 %	16.7 %	7.5 %
Chile	1.6 %	9.8 %	0.3 %	39.8 %	34.4 %
China	4.7 %	8.3 %	1.9 %	33.1 %	6.5 %
USA	3.2 %	8.8 %	0.1 %	31.2 %	42.7 %
Norway	not reported	not reported	not reported	35.0 %	14.0 %

Note: The data are not available for the EU.
Sources: UNICEF/WHO/World Bank. Joint Child Malnutrition, 2021 edition. UNICEF: New York: https://www.who.int/data/gho/data/themes/topics/joint-child-malnutrition-estimates-unicef-who-wb.
Global Obesity Observatory: https://data.worldobesity.org/tables/prevalence-of-adult-overweight-obesity-2/.

policy to date, with relatively little weight given to the nutrition benefits of seafood (Naylor, 2014; Pingali, 2015; Swinnen, 2018).

It is not just food policy that has overlooked aquaculture's importance for nutrition. Public health authorities typically design policies without input from the agriculture and fisheries sectors (including aquaculture) and vice versa. In Zambia, for example, stunting prevalence, albeit high, has declined over the past decade, partially due to multi-sectoral planning, but the Ministry of Agriculture and the Ministry of Fisheries and Livestock do not consider nutrition their priority and leave that mandate to the Ministry of Health (Harris et al., 2017; Harris, 2019).[32] On the flip side, the global public health community has discounted the importance of fish or aquaculture as a public health asset in alleviating hunger and malnutrition (Vianna et al., 2020). In a global analysis of 165 national public health nutrition policies (PHN) and 158 national fisheries policies, Koehn et al. (2022) showed that 59 % of PHN polices contained no or low inclusion of aquatic keywords, and 51 % of fisheries policies had no or low inclusion of food security and nutrition keywords, indicating very minimal coherence across both sectors.

A rich literature has emerged around the topic of policy integration for challenging, cross-cutting issues, such as aquaculture development and its role in food security and nutrition. This literature, with roots in marine policy (Underdal, 1980), focuses on governance problems of compartmentalization, fragmentation, competing and incoherent objectives, and conflicting policy instruments (Candel and Biesbroek, 2016; Candel and Pereira, 2017). Although identifying these problems conceptually presents opportunities for improvement, many countries in the Global South lack the human, institutional, and organizational capacity to take on multi-sectoral responses across food policy, particularly complex cases that span human nutrition (Fanzo et al., 2015; Jerling et al., 2016; Farmery et al., 2020). Capacity gaps include inadequate knowledge, data, and analytical skills, as well as a lack of institutional support to build those capacities.

To promote better policy integration in food systems, experts from FAO have advocated for a political economy approach toward understanding and solving the problems of operational isolation, or silos, in food policy (FAO, 2016, 2017). Specifically, they find that most problems related to inequitable, environmentally unsustainable, or unsafe food systems stem from battles for leadership, information, and financial resources among agencies. Ultimately, the report identifies the Ministry of Finance as being the key to inter-sector allocations of budgetary resources, and the Minister of Planning—in those states that have such a Ministry—as playing a central role in negotiating sectoral outcomes. Together, leaders in the Ministries of Finance and Planning, or equivalent institutions, have the potential to galvanize cooperation and synergies among agencies. In some cases, such as Indonesia during the Soeharto era, a coordinating Minister of Economics can play a pivotal role in advancing an effective food policy strategy across sectors (Falcon, 2014).

From an institutional perspective, the devil is in the detail in terms of what works in which country. Farmery et al. (2021) share examples of practices that helped different countries integrate, or de-silo, policies to support the role of aquatic foods in food security and nutrition. They caution, however, that what works for one country may not work for another. Food systems are highly dynamic, requiring new approaches as value chains evolve and consumer demand and tastes change and adapt. Integrating aquaculture into food policies in any given country depends importantly on agro-climatic conditions, the structure of political and economic institutions, and the cultural orientation surrounding aquatic foods (Tigchelaar et al., 2022).

6. Conclusions and policy implications

Two major themes emerge from our review of the literature related to aquaculture policy worldwide: (1) resource endowments and socioeconomic conditions play an important role in shaping aquaculture policy objectives, incentives, and instruments; and (2) policy challenges and priorities change over the course of economic development. Following these themes, we conclude with a half dozen insights from the wide body of literature reviewed herein on aquaculture policy.

First, given the rapid growth in the global aquaculture sector and its significance for economies, human health and nutrition, and the environment, it is critical to adopt food system thinking and integrate aquaculture directly into mainstream food and nutrition policies. This point is particularly true in the context of climate change. Placing aquaculture policy in a food systems context requires an understanding of how aquaculture, terrestrial crops, and livestock can work together in meeting food, feed, and fuel demands while minimizing environmental and social damages. It also requires attention to the relationship between aquaculture and capture fisheries. In most countries, agriculture and fisheries ministries and agencies are siloed, meaning that there is little strategic or operational coordination across capture fisheries and aquaculture, aquaculture and agriculture, and crops and animal systems. There is much to be gained, for example, in the transfer of knowledge from livestock to aquaculture, particularly in breeding, nutrition, and animal health. Failing to embed both aquatic and terrestrial systems into national food policy seriously limits the ability of countries to achieve food security and nutrition targets in line with the United Nations Sustainable Development Goals (SDG).

Second, the exploration of case studies reveals the benefits of learning from history and experience in the design and implementation of aquaculture policies. For example, the rapid expansion of aquaculture throughout Asia in recent decades, particularly in Bangladesh over the past 15 years, provides insights into value chain development and policies supporting aquaculture for domestic consumption versus exports. Whether or not African countries seeking to grow their aquaculture sectors can benefit from the experience of Asian countries is an

[32] Ongoing research by Kaminski and colleagues is focused on incorporating nutrition objectives into aquaculture planning in Zambia. The research entails the use of intervention trials in small-scale pond aquaculture (Kaminski et al., 2022).

interesting and open question. Each region has a unique set of natural resource endowments, climate dynamics, and cultural and institutional conditions that determine the most sensible path for aquaculture policy.

Third, across all levels of economic development, there are policy debates over the pros and cons of supporting small-scale aquaculture operations versus large-scale commercial enterprises. Throughout Africa, for example, the aquaculture sector typically consists of two distinct sub-sectors: semi-subsistence farms that are subsidized by the government, and SME and large-scale commercial farms that benefit from a business-friendly policy environment and that contribute to most of the production growth. The focus of policy should be on both, not either/or, as small-scale aquaculture in low-income communities can be important for pro-poor growth but will not succeed without a commercial sector that includes larger firms. It is clear from the literature that commercial operations play an important role in advancing production capacity, developing aquaculture supply chains, and driving innovation through gains in efficiency. Larger commercial firms can be especially important in contracting with or developing high-quality feed and seed inputs, which are essential for aquaculture success. If regulated appropriately, they can also lead to sustainable and food-safe practices. However, policymakers and donors in the aquaculture space need to keep a careful watch over the size and power of individual commercial operations to prevent worsening income distribution and regulatory capture.

Fourth, there is a clear pattern within the global aquaculture sector that countries with the most rapid growth are generally those that lack stringent environmental regulations. A key exception is Norway, which has introduced innovative policy instruments for salmon aquaculture (e.g., Maximum Allowable Biomass) to incentivize innovation and minimize environmental impacts. There is merit in exploring whether Norway's policy instruments for aquaculture can be adopted successfully by other countries. The catch (no pun intended) is that Norway is unique in its combination of biophysical conditions (deep, high-flushing fjords), aquaculture species composition (almost entirely salmon), and institutions that support salmon aquaculture growth as a leading industry in the country's economy.

Fifth, a major challenge for the global aquaculture sector is the management of pathogens, parasites, and pests. Farmers in virtually all aquaculture systems face disease pressures that evolve over time. Preventing disease outbreaks through careful siting and spatial planning, as well as the use of best management practices (e.g., attention to stocking densities, feed and broodstock quality, cage cleanliness, species rotations) and vaccines should be a top policy priority, as once diseases enter an aquaculture system, they are difficult to control. Adapting regulations for the approval of GE fish, including the use of gene editing techniques for host resistance to pathogens, is critical for preventing the misuse of antimicrobials, which are often used by aquaculture producers as a first line of defense. Our review highlights the significant public health risk associated with the misuse of antimicrobials and the emergence of antimicrobial resistance in many aquaculture settings. The case of salmon disease in Chile over the past 15 years serves as a warning for other countries that intensify their aquaculture systems too quickly. The U.S. and Europe, on the other hand, have adopted strong policies to control fish disease and antimicrobial applications in aquaculture, and could be instrumental in transferring knowledge to lesser developed regions. To date, information and training in disease detection and management remain a weak link in the global aquaculture sector.

Finally, the wide diversity in aquaculture systems, production practices, and policies within and between countries has not yet lent itself to a cohesive framework for food policy analysis along the economic development spectrum. The dominant pattern of structural transformation that characterizes agricultural development and policy—stimulating agriculture in the early stage of development, taxing agriculture directly or indirectly in the middle stage to extract revenue for economy-wide growth, and subsidizing agriculture at advanced economic stages when the sector has vested interests and strong political representation—does not appear to hold for aquaculture policy. Price data for most aquaculture species are lacking at the national and subnational levels, which hinders comparative policy analysis. Moreover, freshwater aquaculture is typically assessed in the context of economic development and food security, while marine aquaculture is viewed more often as a natural resource issue. In comparison to terrestrial agriculture, the global aquaculture sector is still young and growing fast. Its dynamic nature is reflected in a burgeoning literature on aquaculture policy that begs for further analysis.

Author contributions

RLN led the review and drafted the manuscript. JF contributed to the policy material on nutrition security and created the tables. SF contributed to the section on Chinese policy and created the figures. All authors agreed on the contents of the review and edited the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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