The Road to Sustainable Aquaculture

On current knowledge and priorities for responsible growth

BLUE FOOD PARTNERSHIP

FRIENDS of OCEAN ACTION

WORLD ECONOMIC FORUM

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About this report

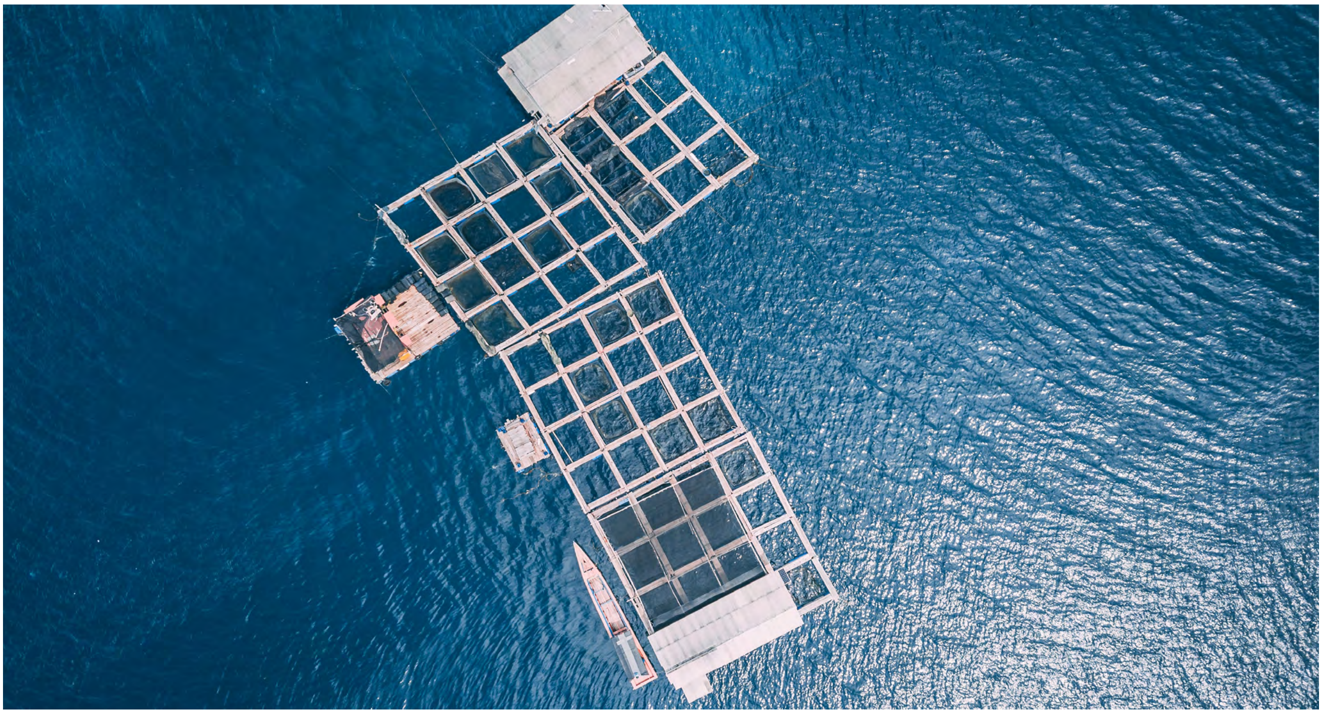
Road to Sustainable Aquaculture
This report is presented by the Sustainable Aquaculture Working Group of the Blue Food Partnership, led by the World Economic Forum's Friends of Ocean Action platform. The goal of the Working Group is to develop a science-based global roadmap to guide the growth of sustainable aquaculture. The report assesses the current context of aquaculture including frameworks that support responsible growth, the latest in scientific knowledge, governance structures and case studies. It is prepared by ThinkAqua on behalf of the Blue Food Partnership and made possible by the generous support of the UK Government's Blue Planet Fund.

The report draws on an evidence base from peer-reviewed literature, aquaculture industry and related websites, as well as broader stakeholder consultations. Members of the Sustainable Aquaculture Working Group contributed valuable expertise to the analysis. The Working Group will build on this report to identify actions and recommendations towards a global roadmap for sustainable aquaculture.

Blue Food Partnership
The Blue Food Partnership catalyzes science-based actions towards healthy and sustainable blue food value chains. The initiative is managed by Friends of Ocean Action, a platform of the World Economic Forum, in collaboration with the World Resources Institute. The World Resources Institute also acts as Secretariat for the High-Level Panel for a Sustainable Ocean Economy (Ocean Panel).

The Partnership brings together stakeholders from the private sector, non-governmental and intergovernmental organizations, scientists and governments. Connecting to policy and science, the partnership is informed by the Ocean Panel's 2030 ocean food priority areas (as outlined in the Transformations for a Sustainable Ocean Economy report) and the Blue Food Assessment, which seeks to better understand the role of blue food in global food systems and guide policies and practices accordingly.

ThinkAqua
ThinkAqua is a global non-profit organization delivering sustainability improvements for enhanced social, economic and environmental outcomes across aquaculture. It is particularly focused on identifying and scaling innovations that place sustainable aquaculture sectors at the heart of vibrant economies.



Executive summary

Demand for blue food—food from our ocean, rivers and lakes—is growing. However, the production and consumption of wild-capture blue foods are already at all-time highs in recent years, and overfishing further depletes aquatic ecosystems. Given the depletion of wild aquatic resources and ecosystems, aquaculture will play an increasingly important role in meeting growing demand. Aquaculture includes a diversity of blue food species, production systems and value chain actors, and growth in production has increased 7.5% per year since 1970. Still, not all growth is sustainable. It is vital to consider the opportunities and tradeoffs of aquaculture development to ensure truly sustainable growth. Aquaculture, if developed more responsibly, has the significant potential to meet the food demands of a growing global population in a way that is sustainable, nutritious and equitable.

This report takes a critical first step by reviewing current knowledge that is relevant to making aquaculture more sustainable. Understanding the current state of the sector will inform priorities toward sustainable growth and lead to future actions and recommendations in a global roadmap. Together, the report reflects the diversity of aquaculture species and actors, highlighting the complexities of the sector and opportunities for action on global, national and local scales. It provides information, examples and priorities to guide value chain actors, investors, non-profit organisations, policy-makers and regulators in the aquaculture sector and beyond.

Aquaculture has the potential to contribute to greater social, economic and environmental sustainability while meeting the growing demand for blue food (Section 1). Sustainable aquaculture can have a global impact and must be considered in the context of global frameworks for sustainable development (Section 2). For example, recognizing the interconnected nature of food security, human health, environmental health and livelihoods highlights the role of sustainable aquaculture in achieving numerous United Nations Sustainable Development Goals (SDGs). A diversity of aquaculture systems are also considered in global frameworks, including the Food and Agriculture Organization of the United Nations Code of Conduct for Responsible Fisheries.

With these frameworks in mind, Section 3 analyzes how the aquaculture sector currently defines criteria for sustainable production systems. It considers a broad array of sustainability criteria and evaluation programs. It also includes a review of research and funding systems in selected countries where aquaculture is either well established or set to grow significantly.

From an assessment of sustainability criteria along the value chain, we turn to a review of aquaculture governance—the current and potential role of decision-makers at multiple scales (Section 4). The section assesses different governance approaches, including legal regulations, certification schemes and community-based governance. It also provides a comprehensive database of governance resources and information. Together, value chain actors and decision-makers can guide opportunities for aquaculture in integrated food production systems (Section 5). These integrated systems can showcase holistic approaches to aquaculture, ones that recognize food security, environmental sustainability and livelihoods together.

While it is important to consider sustainable aquaculture in global frameworks, it is also vital to recognize the diversity of aquaculture systems, including the role of small-scale aquaculture. We present 26 aquaculture case studies from across the globe, highlighting examples that support responsible practices in aquaculture (Section 6). To better support decision-makers in different sectors, we define and separate these case studies by subject matter, including governance, social engagement, food security, health, technology, and markets. These case studies, alongside other insights from the report, inform a final table, focusing on important priority areas for the sustainable development of aquaculture moving forward (Section 7).

By considering global frameworks, sustainability criteria, governance strategies, integrated food system approaches and examples of responsible development in aquaculture around the world, this report provides a foundation for future action and recommendations. Increasing demand for aquaculture presents both opportunities and challenges on multiple scales. Developing our shared understanding of the current state of aquaculture will catalyze a strategic vision for a global roadmap that will guide the sustainable growth of aquaculture over time.

1 Introduction

Aquaculture has the potential to meet food security while having a low impact on the environment, fighting climate change, and providing critical nutrition to growing populations. Aquaculture species can be very nutrient-dense and, depending on the species and production method, can be more sustainable than land-based animal-source foods (Nidjam et al, 2012; Poore and Nemecek, 2018; Gephart et al, 2021; Golden et al, 2021). These aquatic systems—both freshwater and oceanic—provide vital nutrients to billions of people and can help address the challenges of malnutrition.

Alongside food security and nutrition goals, aquaculture can likewise play an important role in livelihoods and economies. Aquaculture has been the fastest-growing protein sector over the past few decades and aquaculture products are some of the most traded food commodities globally (Bush et al, 2019). Furthermore, emerging economies contribute significantly to this trade, providing opportunities for economic development in places and communities that need it most. This trade is only expanding—global fish and shellfish trade, for example, reached $153 billion in 2017, with a compound annual growth rate of 4% over the previous five years.

This evidence emphasizes the critical role aquaculture can and will play in global food systems over the next few decades. Investments in growth and innovation can support growing value chains and aquaculture development. Yet not all growth is positive. Like all food systems, there are challenges to address as we attempt to develop strong foundations. We need to understand the current state of aquaculture development and ensure that actors along the value chain and beyond have the knowledge and information they need to grow the sector sustainably.

Understanding where we currently stand with aquaculture is a broad and complex challenge. Although sustainability in aquaculture has been explored in other initiatives, these have tended to focus almost exclusively on the environmental impacts of the sector. Here, we consider a more holistic approach, one that brings together scientific research, global frameworks, previous and ongoing industry initiatives, governance strategies, integrated systems approaches and case studies.

We reviewed available information on responsible aquaculture development, including:

- Relevant global frameworks to examine how responsible and sustainable aquaculture can contribute to current food system and sustainable development decision-making (UN Sustainable Development Goals and FAO Code of Conduct for Responsible Fisheries)
- Existing evidence programmes along the value chain to identify delivery mechanisms, relevance and impact
- Governance mechanisms, taking into account national legislation and regulation, certification and other approaches
- Opportunities for integrated systems, particularly how more holistic aquaculture approaches can support increased food yields
- Case studies from numerous geographies to examine successful approaches towards the responsibledevelopment of aquaculture and lessons learned

Like aquaculture systems, this approach is diverse and far-reaching with relevance to both the public and private sectors as well as non-profit entities that build bridges between them. We build on this current knowledge to generate some key priority areas for consideration towards the sustainable growth of aquaculture.. Altogether, we have sought to develop this report in a way that highlights three pillars—social, economic and environmental sustainability—recognizing that all are essential to the growth of truly sustainable aquaculture.

2 Review of available data, information and science relating to sustainability of aquaculture globally

2.1. Potential contributions of sustainable aquaculture to the SDGs

The purpose of this review is to assess the range of contributions that aquaculture could potentially make to achieving the SDGs (see Table 1), both individually and synergistically, across food systems and for producers, communities and nations. Although SDG 14 'Life Under Water' receives a good amount of focus, aquaculture has the potential to make a broader contribution across the SDGs that has yet to be fully realized. Critical reflections on some of the key opportunities and challenges for decision-makers, practitioners and other stakeholders are presented toward the end of this section.

Aquaculture development can contribute directly to poverty alleviation (SDG 1) through the provision of affordable aquatic foods to consumers. Recent growth in commercial aquaculture for freshwater finfish by medium- and large-scale producers in Bangladesh and Andhra Pradesh, India, for example, has had a transformative impact on the accessibility and affordability of fish for poorer consumers nationally (Belton et al, 2017; Hernandez et al, 2018). It has also been shown that the consumption of a diversity of aquatic foods, produced using a wide array of farming systems and strategies (see for example Table 3), can help enhance food and nutrition security (SDG 2) by improving dietary diversity. This could play a key role in achieving healthy lives (SDG 3) and sustainable diets globally (SDG 12) (Golden et al, 2021; Key Traceability, 2021).

Aquaculture provides several million jobs across the world (SDG 8) and its development in remote and coastal areas can help maintain communities that might otherwise decline or disappear (SDG 10 and SDG 11). Increasingly, employment in the sector requires capacity building and training, resulting in high quality opportunities. Livelihoods and employment opportunities across aquaculture value chains and food systems can particularly help empower women (SDG 5). Women already provide critical labour throughout the aquaculture value chain, contributing to food security in vulnerable areas. The provision of aquaculture-based income opportunities can also help alleviate pressure on wild aquatic resources and ecosystems (SDG 14).

Responsible aquaculture can constitute an efficient and largely non-consumptive use of accessible water resources (SDG 6) and can be integrated with other food production systems to optimize the use of labor, nutrients and physical space (SDG 14 and SDG 15). Further details on the contribution that sustainable aquaculture development could make to the SDGs are presented in an evidence paper[2] prepared by Key Traceability in 2021.

Aquaculture relevant findings from the Blue Food Assessment and the SDGs

Key insights can be drawn from the comprehensive Blue Food Assessment, carried out by more than 100 researchers from leading institutions globally since 2019, with a first set of findings published in 2021. The assessment found that just 10 countries currently account for 55% of global fish consumption, and that population growth and increased household incomes are likely to see the demand for blue foods increase from 54.7 million tonnes in 2015 to 100 million tonnes in 2050 (Naylor et al, 2021). Demand across countries is influenced by socio-cultural and sub-national factors, but significantly increased aquaculture production could make nutritious aquatic foods more affordable and help avoid 166 million cases of micronutrient deficiencies by 2030 (Golden et al, 2021). The Blue Food Assessment also identified several knowledge gaps, including: a lack of data on dietary intake at a household level; uncertainty over the influence of urbanization; an absence of data on the production and consumption of potentially important blue food groups (i.e. aquatic plants and seaweed, and aquatic animals such as amphibians and reptiles); and the need to account for price dynamics and affordability.

Results from the Blue Food Assessment focusing on environmental performance and using Life Cycle Assessment (LCA) impact categories (Gephart et al, 2021) noted that:

- bivalve mollusc and seaweed cultivation were associated with the lowest environmental impacts;
- for cultured finfish, carp (bighead and silver) resulted in the lowest emissions of greenhouse gases and nutrients (nitrogen and phosphorus);
- farmed salmon and trout were the most efficient users of land and water;
- improving the Feed Conversion Ratio (FCR) for fed animal species could enhance environmental performance across all impact categories;
- attaining higher yields of fish significantly reduced land and water use.

Climate change poses high levels of risk to supplies of aquatic food at a national scale (Tigchelaar et al, 2021). Action is therefore needed on gender equality, governance enhancements, and poverty reduction to increase resilience to climate change impacts. Details of management and policy implications of four representative 'climate risk profiles' were presented and possible trade-offs concerning equity, health and sustainability that demand attention were noted in the Blue Food Assessment. People engaged in aquaculture value chains, particularly small-scale actors, face a range of threats (e.g. climate change, environmental issues, political change, and socio-economic pressures) and constraints to adaptation and these are intensifying (Short et al, 2021).

To support the sustainable development of the aquaculture sector, there is a need to recognize the diversity of livelihood opportunities provided by aquatic food production and across associated value chains, and to ensure that governance structures maximize the benefits of these opportunities.

A number of key areas where the Blue Food Assessment and other research outcomes could contribute to attaining the SDGs are referenced in Table 1.

Table 1: Sustainable Development Goals of the United Nations (UN, 2015b) and the potential contributions of sustainable aquaculture development

SDG	Title	Potential contributions of sustainable aquaculture development
1 NO POVERTY	End poverty in all its forms everywhere	• Aquaculture development can contribute to poverty reduction through livelihoods and employment opportunities throughout value chains (i.e., input production, processing, trading, wholesalers, retail and food service) and in feed production and service delivery (FAO, 2020; Short et al, 2021). • Aquaculture can provide affordable aquatic foods to poor communities and small-scale pond-based production of fish has benefited the livelihoods of millions of poor people in Bangladesh (Belton and Azad, 2012). • Medium- and large-scale production can have transformative effects, making fish more affordable to poorer consumers (Little et al, 2012; Belton et al, 2016; Bene et al, 2016).
2 ZERO HUNGER	Ensure availability and sustainable management of water and sanitation for all	• Affordable aquatic foods derived from aquaculture can contribute to enhanced food and nutrition security and can be a rich and highly bioavailable source of protein, omega-3 fatty acids and other micronutrients (e.g. calcium, iron, zinc and vitamin A and vitamin B12) (Beveridge et al, 2013; Thilsted et al, 2016; Golden et al, 2021; Key Traceability, 2021). • Avoidance of animal feed ingredients derived from fish that could potentially meet the needs for direct consumption of poor and malnourished individuals could contribute to enhanced food and nutrition security in vulnerable communities (Thiao and Bunting, 2022).
3 GOOD HEALTH AND WELL-BEING	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	• Consumption of aquatic foods derived from aquaculture at recommended levels can contribute to healthy and sustainable diets globally (Willett et al, 2019; Golden et al, 2021; Key Traceability, 2021). • Nutrition-sensitive approaches could alleviate micronutrient deficiencies in vulnerable populations. For example, acquisition and consumption of aquatic foods from aquaculture by young children and breastfeeding women can enhance nutritional, cognitive and life-course outcomes (de Bruyn et al, 2021; Ahern et al, 2021).
5 GENDER EQUALITY	Achieve gender equality and empower all women and girls	• Aquaculture production and associated value chain activities provide employment for women across value chains (Key Traceability, 2021; Short et al, 2021). • Emerging aquaculture sectors can lead to novel livelihoods and employment opportunities for women that may previously have been limited to traditional activities (Shirajee et al, 2013). • Some gender-responsive co-management approaches to aquaculture development have contributed to women's empowerment (Gopal et al, 2020).
6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all	• Aquaculture can constitute an efficient and non-consumptive use of accessible water resources that can be integrated with complimentary activities, including irrigation, navigation and recreation (Cohen et al, 2021). • Wetland-based aquaculture systems (e.g. rice-fish or mangrove-shrimp) can help bolster agrobiodiversity (FitzGerald, 2002; Ahmed et al, 2020) and bivalve cultivation can enhance water quality (Lindahl et al, 2005). • Safe wastewater-fed aquaculture practices involving appropriate pre-treatment and intermediaries or biorefinery strategies can contribute to sanitary waste management (Bunting and Edwards, 2018).
8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	• Aquaculture development can deliver productive employment opportunities and decent work (Key Traceability, 2021; Short et al, 2021). • Standardized and year-round production from aquaculture can offer consistency of supply in quality, timing and size, thus contributing to economic growth and presenting opportunities for mechanization in handling and processing which might otherwise constitute physically demanding and inefficient processes. • The need for safeguards across seafood and feed value chains to avoid human rights abuses has been highlighted (Marschke and Vandergeest, 2016). • Adopting measures to minimize use of fish-derived ingredients in animal feeds in sub-Saharan Africa, and elsewhere, could help promote inclusive growth (Thiao and Bunting, 2022).
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	• Investments in infrastructure (e.g. communications, electricity supplies, potable water and sanitation and roads) can promote establishment and growth of aquaculture, in-turn providing revenues for sustaining improved infrastructure (WorldFish, 2007). • Aquaculture operations and centres of production are usually static and thereby provide a rational and strategic focus for infrastructure development. • Maturation of aquaculture industries results in significant research and development innovation with application within and beyond these industries (Hua et al, 2019).
10 REDUCED INEQUALITIES	Reduce inequality within and among countries	• Aquaculture sector growth can stimulate social and economic development in poor, marginal and rural communities (Alexander et al, 2014). • Cooperative and community-based management structures can help share the costs and responsibilities of production and contribute to the more equitable sharing of benefits (Bunting, 2004; Haque and Dey 2016, 2017) and inclusion of cooperatives in farmer cluster arrangements might enable smaller producers to engage with certification schemes (Haque et al, 2021). • Domestic and international trade in products from aquaculture can make aquatic foods more accessible to, and affordable for poorer consumers (Belton et al, 2017).

Table 1: Sustainable Development Goals of the United Nations (UN, 2015b) and the potential contributions of sustainable aquaculture development (continued)

SDG	Title	Potential contributions of sustainable aquaculture development
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient and sustainable	• Urban and peri-urban planning can include nature-based solutions and blue infrastructure and can be designed to incorporate aquaculture production systems and strategies that can help regulate normal runoff and stormwater events, generate employment, produce fresh aquatic foods, recover nutrients and provide open spaces for the public (Leschen et al, 2005; Bunting and Little, 2015). • Aquaculture provides decent wages and livelihoods in rural and littoral communities with limited other options for year-round employment (Short et al, 2021).
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and pro-duction patterns	• Aquatic foods are recommended as key elements of healthy and sustainable diets globally, and sustainable aquaculture systems can be used to produce affordable, culturally appropriate, nutritious and safe products (Gephart et al, 2020; Shepon et al, 2021; Key Traceability, 2021).
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts*	• Aquaculture products can potentially replace foods with higher greenhouse gas emissions thus contributing to combating climate change (Gephart et al, 2021; Key Traceability, 2021). • Potential climate change mitigation actions can be identified across aquaculture value chains (Bunting and Pretty, 2007). • Aquaculture production systems can contribute to climate change resilience by providing reliable food and jobs and can enable communities to adapt to climate change impacts (Ahmed et al, 2014).
14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	• Sustainable aquaculture systems can produce diverse aquatic foods and generate employment whilst operating within the carrying capacity of supporting marine ecosystems (Gephart et al, 2021). • Culture can occur at the surface, in the water column or on the bottom of marine, brackish and freshwater ecosystems and consequently this creates diverse opportunities to use accessible areas, whilst also making aquaculture an often efficient user of space in terms of food produced per unit surface area. • Avoiding aquaculture development close to sensitive areas (e.g. mangroves and seagrass beds) can help conserve biodiversity. • Cultivation of bivalves and seaweeds can realise direct ecosystem benefits (Key Traceability, 2021).
15 LIFE ON LAND	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	• Aquaculture integrated into terrestrial agriculture systems (e.g. rice-fish and rice-prawn culture) can yield nutritious and valuable crops of aquatic foods that can contribute to food and nutrition security, healthy and sustainable diets and social and economic development (Amilhat et al, 2009; Ahmed, 2013). • Integrated systems can promote nutrient recovery and recycling and can encourage greater agrobiodiversity that contributes to enhanced social-ecological resilience (Bunting et al, 2017; Cohen et al, 2021). • Aquaculture integrated with terrestrial ecosystems (e.g. mangroves and coastal wetlands) can increase the economic value of those ecosystems to local communities, thus motivating their protection (Fitzgerald, 2002).
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	• Promotion of social development is central to the notion of sustainable aquaculture and producers can adopt measures that establish or maintain good relations with local communities (The Fish Site, 2018; and see this report Section 2.2.12). • Producer group and cluster formation can help ensure good practices are adopted widely and consistently and that issues such as sharing of water resources and countering disease problems are addressed in jointly agreed and overseen management plans (ADB et al, 2007). • Tax revenue and foreign exchange earnings resulting from the sale of aquaculture products strengthens state institution capacity.
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development	• Established international and regional institutions and discussion fora for the aquaculture sector provide an excellent means to promote responsible and sustainable development (Troell et al, 2021). • Future research and investment for development must promote responsible and sustainable practices across farmed aquatic food systems to enhance social and economic development within the carrying capacity of supporting ecosystems (Cohen et al, 2021). • National and international partnerships can help address data gaps and the poor alignment of regulations and government departments with the needs of sustainable aquaculture development (Key Traceability, 2021). • Significant private sector investment and partnerships contribute to the delivery of the SGDs, while profitability motivates further investment and scaling of positive impacts. • Building sustainable aquatic food systems will rely on resources enabling strong partnerships, particularly at the governance level to establish performance and impact metrics (Stead, 2019).

Note: *The Paris Agreement adopted under the auspices of the United Nations (UN, 2015a) is the principal international instrument for addressing climate change and setting targets in this area.

The Report of the Blue Food Assessment has a section on Blue Foods and the SDGs. For additional information see: https://re54e8libu2wprcq1nsbw051-wpengine.netdna-ssl.com/wp-content/uploads/The-Report-of-the-Blue-Food-Assessment-Digital.pdf

2.2. Realizing potential contributions to the SDGs

In the following sections, we introduce some of the considerations that are fundamental to realizing aquaculture's potential contributions to the SDGs. Considering the very specific framing and targeting of the SDGs, policies, regulations, and plans of action may be devised in isolation; however, action to achieve one target, if conceived and implemented well, could also contribute to achieving other goals. There may also be trade-offs and mitigation to consider within social, economic, and environmental limitations.

2.2.1. AQUACULTURE'S LINKS WITH CAPTURE FISHERIES: OPPORTUNITIES AND CHALLENGES

Aquaculture presents opportunities and challenges for addressing the core market drivers behind overfishing, the most obvious resilience challenge for SDG 14 'Life Below Water'. Overfishing has resulted in the significant reduction of many commercially exploited finfish stocks, with a subsequent decline of revenues for fishers and loss of an important source of nutrient rich foods for consumers. Overfishing is driven by consumer demand, which is expected to increase by 80% between 2018 and 2050. Cultured production of the most at-risk species, or their market-accepted substitutes, functions as a critical safety valve against the incentives of overfishing. One example was the entry of pangasius into the white fish markets of Europe. This was strongly criticized by captured white fish interests that were already suffering from quotas restricting their catches and then also had to compete on price with pangasius, an affordable substitute for consumers (Little et al, 2012). Conversely, a supply deficit results in higher prices, which not only impacts consumers but contributes to the incentives behind irresponsible and Illegal, Unreported and Unregulated (IUU) fishing. Supply deficits and higher market prices can, however, also provide incentives that promote the development of aquaculture where profit margins for different species can make their cultivation a realistic proposition.

2.2.2. OPTIMIZING FEED UTILIZATION AND INGREDIENTS SUPPLY

The importance of feed, particularly as a cost and in terms of its environmental footprint, has drawn significant interest and investment around impacts and alternatives. The issue is complex, but this section aims to summarize some of the key points. It is also important to keep in mind that much of global aquaculture production is not fed (e.g. molluscs, seaweed, and traditional carp culture).

Feed is often the single biggest cost to aquaculture businesses and typically makes up the largest part of the environmental footprint (Roberts et al, 2015; Bhones et al, 2018). Aquaculture already exhibits some of the best feed conversion ratios (FCR) in animal-source foods, and FCRs have continued to decline over time, but it may be possible to achieve even more efficiencies in how feed is used in aquaculture businesses to improve FCRs further. For example, this could be done through innovations in feed delivery systems or production system design in order to avoid waste and maximize feed intake. This approach would support economic and environmental sustainability by reducing waste.

Marine ingredients – fishmeal and fish oil in particular – provide nutrient-dense materials for feed manufacture and are a straightforward way of meeting the nutritional needs of farmed species. Commercially formulated diets for aquaculture (or 'aquafeeds') often contain fishmeal and fish oil derived from wild capture fisheries, which are often at, or near, their limit of production. As the supplies of marine ingredients are influenced by prevailing climate patterns, environmental changes may lead to increased uncertainty in the availability of the small pelagic fish stocks that predominate as raw material for fishmeal and fish oil. It is also important to ensure that the exploitation of wild fish biomass for aquafeed does not conflict with the nutrition and livelihood opportunities of poor coastal populations, particularly in regions such as West Africa, where the reduction fisheries sector was only recently established (Hicks et al, 2019; Thiao and Bunting, 2022). Processing waste ('trimmings') from both wild and farmed sectors already supplies an estimated 30% of marine ingredients (Tacon and Metian, 2015) and has the potential to grow further if innovation in the supply chain can be incentivized at both primary and secondary processing nodes. If this trend continues, aquaculture could even become a net producer of marine ingredients in the future.

Concerns about potential reductions in direct human consumption of some species used in fishmeal production, and resulting increases in food and nutrition insecurity, have led to calls for action to replace some of these fish-derived ingredients with alternatives to ensure wild fish is available to meet nutrition needs in certain low-income communities (Thiao and Bunting, 2022). The development of alternatives (e.g. algae, plants and insects) is already occurring and increasing the use of these materials could also create additional livelihood and insects) is already occurring and increasing the use of these materials could also create additional livelihood opportunities and provide a commercial route to recycling agro-processing by-products and organic waste streams. Currently, most of these 'novel' feed ingredients remain expensive, partly because production is at pilot scale and full commercialization is hampered by legislation, the need for further innovation, and/or energy costs.

Although the total volume of fishmeal and fish oil used in global aquafeed has increased over time with the growth of the sector (IFFO, 2020), the development of fed aquaculture has benefitted from the progressive replacement of marine ingredients with other feed ingredients, usually of vegetable origin. This has resulted in declining proportions of marine ingredients in aquafeed (Turchini et al, 2019). Aquafeed formulations for many species have already benefited from a 'head start' afforded by the salmon industry and are likely to see significant further improvements as their respective industries mature and become attractive markets for value chain investment.

All feed ingredients have a footprint across a range of impact categories. Any comprehensive analysis needs to understand this and to assess the trade-offs entailed in any substitutions. Issues with vegetable-based ingredients include: land use (e.g. deforestation); competitor markets (e.g. food, biomass for renewable energy); water use (e.g. irrigation of crops); chemical use (e.g. fertilizer); and biodiversity impacts. The science of product LCA is increasingly being applied to aquafeed. In some cases, the complete substitution of fishmeal and fish oil may not actually be a more sustainable or desirable option due to increased pressures for terrestrial crops coupled with the nutrition implications of these substitutions (Malcorps et al, 2019). Where alternative ingredients are used, it is important to secure the safety and nutritional value of the farmed end product, avoiding phenomena such as the declining concentration of long chain omega-3 fatty acids in farmed salmon as a result of replacing fish oil with vegetable oils (Sprague et al, 2016). Innovations, such as the production of oil from cultivated microalgae, has already achieved commercial reality and is enabling the production of aquafeed of sufficient nutritional quality to maintain expected omega-3 content (Auchterlonie and Bescoby, 2021). Other innovations in feed ingredient production are developing rapidly, including proteins via bacterial conversion of methane-based substrates[3], and proteins via insect meal[4], with both sectors now working towards commercially significant volumes.

Many fisheries supplying fishmeal target well-managed single-species stocks, even if they are typically from species low in the food chain. The fishmeal industry has adopted some independent actions to improve sustainability over time, including the development of an industry-specific, third-party audited, certification standard that has been active since 2010[5], as well as the more recent Global Roundtable on Marine Ingredients, which provides: "a single value chain contact point to contribute to existing platforms aimed at ensuring sustainable management of fisheries providing marine ingredients."[6]

In fed aquaculture systems in Asia, much of the fishmeal raw material comes from mixed-species trawl fisheries, a part of the catch that carries little or no value in consumer markets due to being juvenile or poor-quality fish. FAO has development guidelines for mixed-species trawl fisheries in Asia to help improve fishery management practices (FAO, 2014) and help ensure that the regional aquaculture industry has a continued supply of sustainable fishmeal and oil.

A significant proportion of that catch is also fed directly. Estimates have put the volume of this directly fed material as high as 4.95 million tonnes per annum (Greenpeace, 2017). Typically, these directly fed species, such as high-value, carnivorous snakehead and marble goby, are not produced at volumes that stimulate investment in the development of formulated diets. Direct feeding is inefficient from both a fisheries resource use perspective and because of risks to the aquaculture system. This material is often only partly consumed, leading to debris and contamination in farming units, and carries the risk of the transfer of pathogens directly from wild species to farm situations. For example, the feeding of raw herring to rainbow trout in Denmark is believed to be the cause of the introduction of Viral Haemorrhagic Septicaemia (VHS) that went on to impact the entire European trout sector (Dixon, 1999).

The economics of aquafeed production, driven predominantly by the cost of ingredients, is a major consideration. Marine ingredients are nutritionally effective, but their constrained supply results in consistently elevated prices in open markets, affecting their inclusion and use in aquafeed. Soya products, which are popular ingredients in aquafeeds, can also be influenced by the differentiation between non-GMO and majority GMO products that impacts prices in various markets, especially in Europe. The new technology and processes used in the development of novel feed ingredients, such as microalgae, bacteria, insects, and genetically modified crops, also need to achieve production volumes that can compete with marine ingredients in terms of consistency of supply and cost, and have appropriate legislative governance. Aquafeed producers continue to juggle costs, availability, and ingredient sourcing in ways that may affect aquafeed composition, and ultimately impact the quality of the resulting farmed fish product.

Life Cycle Assessment (LCA) is a standardized methodology for accounting for all the environmental impacts that result from a product's manufacture and supply chain. The 'Life Cycle' of a product refers to all the impacts that occur through raw material acquisition, manufacturing, use and final disposal. LCA has been applied to many production processes and is steadily being incorporated into policy as standardized methodology becomes developed for different products. The EU will incorporate LCA into its Green Deal in the coming years and the Product Environment Footprint Category Rules (PEFCR) are currently being finalized for many food products. LCA is also being incorporated into the certification for major aquaculture standards, especially Global Warming Potential (Carbon Footprint). The data describing various inputs and outputs of different parts of the production life cycle are collected and measured to construct a Life Cycle Inventory (LCI) for a particular final product. This data can then be cleaned and adjusted for entry into LCA software which provides the impact assessment.

There are many LCA impact categories, but usually only a few most applicable to the goals of the study are selected. For livestock production, the most commonly applied impact categories are: Global Warming Potential, Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, Photochemical Oxidation Potential, Cumulative Water Use, Cumulative Energy Use, and Land Use. For aquaculture, it is now possible to incorporate 'Fish In-Fish Out' ratios and Biotic Resource Use, which are both measures of the efficiency of marine ingredients utilization. The impacts are cumulative measures of all the emissions that contribute towards them throughout the life cycle, therefore some contextualization is often required. This is usually in the form of a 'contribution analysis' to pinpoint the parts of the supply chain where most emissions are occurring for each impact. As this may be different for each impact, the relative importance must be interpreted.

Data collection for LCAs can be a time-consuming process. The practitioner must fully understand the manufacture and supply chain of the product and know where efforts must be directed to gather appropriate data. Primary data collection is usually necessary from the production facility and, in the case of livestock, from any processing facilities. Data must also be provided on feed formulations as this is usually the most influential part of the LCI. Data related to the production of a particular feed ingredient is usually collected from literature sources or LCA databases, whereas all data on national energy mixes and direct emissions from different types of industrial machinery are held on LCA databases connected to the software. After primary data collection, there is usually a period of data cleaning and validation, involving further communication with the data providers to address data gaps and identify any parts of the production process that may not be clear.

2.2.3. LOCAL ENVIRONMENTAL INTERACTIONS

The impacts of effluent from aquaculture production units have been modelled for several decades. It is now possible to predict the emission of nitrogen and phosphorus from different systems across freshwater, brackish and marine environments based on species, biomass, feeding rate, feed composition, and other factors. In some instances, these impacts may be managed via system design (e.g. partial or full recirculation, semi-enclosed floating structures) and by feed formulation (e.g. low phosphorus feeds for freshwater use).

Extensive and semi-intensive aquaculture routinely occurs in water bodies that have received nutrient-rich runoff from agricultural land, urban areas, or river deltas and the production of aquatic plants and animals can contribute to the capture and recycling of phosphorus and nitrogen. Formal wastewater-fed aquaculture systems around cities in Asia traditionally provided significant volumes of fish and aquatic plants to poorer urban consumers, but these have largely disappeared due to the significant expansion of urban areas and degradation of wastewater infrastructure. The use of waste streams is a valuable component of circular economies as they can produce valuable products while also addressing the problem of nutrient loss to the biosphere (Willett et al, 2019).

Aquaculture systems can have conservation value as wetland systems – mitigating the risk of flood events and increasing nutrient use within freshwater systems, as well as influencing local biodiversity and providing refugia in marine systems (e.g. increased fish availability around fish cages, mollusc and seaweed cultivation longlines). These, and other benefits, are beginning to be recognized among the broad range of ecosystem services provided by aquaculture (Willer et al, 2021), and may provide a foundation for ethical investment in the industry.

2.2.4. SEED SUPPLY

Many parts of the aquaculture sector rely on juveniles supplied from hatcheries, but a significant proportion of shellfish and seaweed production, and some fish production, still relies on wild-caught juveniles. Some hatchery-raised species rely on wild-caught broodstock to replenish or rejuvenate stock, in some cases when inbreeding has occurred because of poor stock management. Collection of seed/spat/juveniles from the wild is a major constraint to development because of the natural variation in supply and the risk of disease introduction. The continual collection of wild-caught material has ecosystem impacts because of the removal of juveniles or breeding adults, and it also removes the opportunity for farming operators to undertake genetic selection programmes, thereby missing out on the potential to increase yields over time. For some species not enough is known about the reproduction, breeding, or provision of juveniles for a continuous hatchery supply. For example, this information would be useful in the case of the European eel, that holds high value in global markets but is a significantly threatened species that is easy to farm from the juvenile stage. Restrictions in availability certainly occur with this species because hatchery techniques are not sufficiently developed and because associated legal controls are in place in Europe.

There are international selective breeding programmes for some species, for example the Genetically Improved Farmed Tilapia (GIFT) strain development conducted by WorldFish, and major commercial breeding programmes for salmon and whiteleg shrimp. These programmes take many years and require significant investment. In the case of tilapia, this came from public and foundation funding. For salmon and shrimp, the initial investment may have come from the public purse, but the programmes are now the focus of large, vertically integrated farming companies like Mowi and Charoen Pokphand.

2.2.5. AQUATIC HEALTH AND WELFARE

Aquatic health must be at the heart of sustainable aquaculture development because healthy plants and animals improve farm productivity and resource-use efficiency. Animal welfare standards are also increasingly demanded by certain consumer groups, most notably in Europe. In this section, we introduce a range of health management techniques and outline their importance. Improved aquatic health and animal welfare requires providing farming conditions that increase survival rates and farming efficiency. Disease management is a large component of this. Disease outbreaks in fish farms (e.g. salmon, tilapia) have been one of the main challenges for finfish aquaculture, causing significant stock and economic losses, and problems with animal welfare (Ma et al., 2019). The extent of antibiotic use as for treatment or preventive health management has led to increasing concerns regarding antimicrobial resistance (Matsuura et al., 2019). Due to the risks associated with antimicrobial resistance and consumer health, the sector has been adopting other preventative measures (Gudding and Van Muiswikelet, 2013; Hwang et al., 2020).

Understanding that 'prevention is better than cure', the aquaculture sector's ideal approach to disease management is through reducing disease risks. Coordinated actions like zoning and area management (that would include agreements for coordinated disease management and stocking from disease-tested sources and at common ages) can be a vital first step. Actions for individual enterprises (hatcheries, nurseries and farms) to prevent disease and maintain optimal health are considered below:

1. Maintaining an optimum farming environment, including optimum water quality, including temperature and water chemistry, appropriate for the cultured species. Water quality test kits can be used to understand environmental stressors.

2. Ensuring adequate nutrition is in place for the stock is also critical for supporting immune functions. Aquafeeds should include the necessary macronutrients (protein, fats, and carbohydrates) as well as micronutrients (vitamins and minerals) (also see Section 3.4). These feeds must also be palatable for the fish to encourage consumption.

3. Prophylactic methods: Use of immunoprophylactic methods, which enhance the immune system of farmed animals, has been one of the key approaches for optimal health management in fish and shrimp farms. Vaccines, immunostimulants and probiotics are the main strategies used:

    - Immunostimulants can be derived from plants, algae, animals, microbial or synthetic sources (Subramani and Michael, 2017). Prebiotics are the most used immunostimulants as they increase intestinal beneficial bacteria, which improves animal health (Ringo et al., 2010).

    - Probiotics are widely used in fish and crustacean farming due to their positive effect on improving immune response, gut health, growth and efficiency (e.g. lower Feed Conversion Ratios) of animals (Chai et al., 2016; Tabassum et al., 2021), and helping control potentially pathogenic microorganism and nutrients in water (Faisal et al., 2017; Kewsharoen and Srisapoome, 2019).

- Vaccines have become an important health management tool and have contributed significantly to the expansion of fish farming worldwide. There are currently 26 licensed fish vaccines commercially available for use with different fish species (e.g., carp, catfish, tilapia, trout, salmon, seabass and seabream) (Ma et al.,2019). The growing interest in vaccinations has been supported by the positive results observed in the Norwegian salmon farming industry. Between 1987 and 2003, salmon production in Norway doubled, in part due to effective use of vaccines, and antibiotic use was almost eliminated (Gudding et al., 2014).

  Although there is a wide range of commercial vaccines, some diseases remain a major problem for the farmed salmon industry, as the current vaccines used do not provide adequate levels of protection, forcing farmers to rely on antibiotics (e.g., piscirickettsiosis in Chile; Flores-Kossack et al., 2020). In Japan, challenges with some farmed fish species (e.g., Pacific bluefin tuna and slippery fish), which are vulnerable to handling stress, is driving innovation in vaccine administration methods (Matsuura et al., 2019).

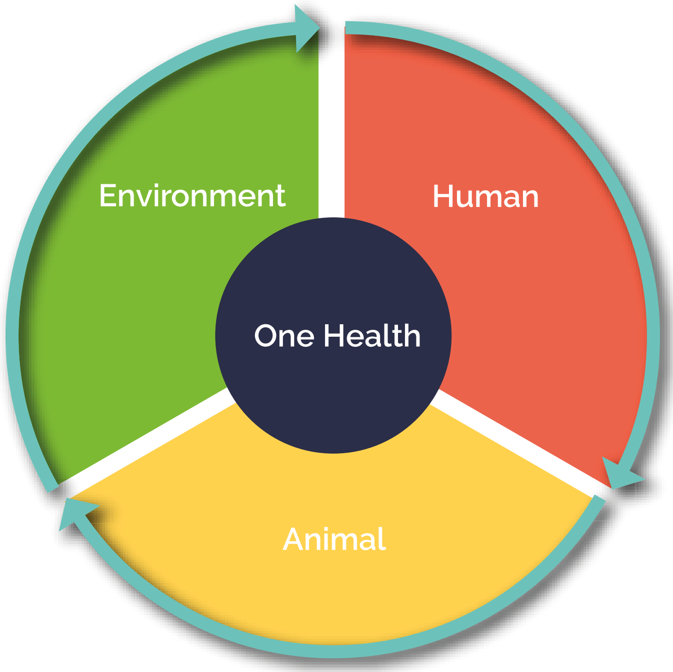
  - Lessons from salmon shared with tilapia: Many of the vaccination techniques, technologies and procedures from the salmon industry are now being applied to commercial tilapia farming in West Africa. In the past two to three years, commercial hatcheries and cage sites in Lake Volta, Ghana have been developing vaccination programmes as a management tool against increasingly financially-impactful bacterial pathogens. Although this technology and practice is in its infancy, results are encouraging.

  - China's increasing use of vaccines: China uses six domestic vaccine products and one imported vaccine that has obtained a national veterinary medicine certificate. However, these vaccines have not yet achieved widespread use due to limitations with the delivery route, the need for new methods for immune antigen screening, and high availability of relatively ineffective inactivated vaccines (Wang et al., 2020).

4. Breeding program and genetic improvement: Selective breeding programs for domesticated stock aim to produce animals and plants with desirable traits for aquaculture. Selective breeding programmes and genetic improvement to produce more disease-resistant or robust animals is currently being used in the aquaculture sector as an optimal health management strategy (Lhorente et al., 219). Such programs also address other traits, such as growth rates, pigmentation of flesh (in salmonids), and edible yield. Genetic selection and improvement of farmed stock generally is a feasible method to improve productivity and can help to address animal welfare through offering cumulative and permanent benefits of improved resistance (Yáñez, et al., 2014) (also see Section 7.7.2).

Traditional small-scale farmers with limited access to technology, infrastructure and disease diagnostic-capacity often face greater risk of disease impacts and can increase transmission, although lower-density farms also often have lower rates of disease. FAO, OIE, WorldFish and several companies are exploring approaches to ensure small-scale farmers are able to access diagnostic services - either through a government-supported service or commercial providers. Overall, maintaining optimal farming environments and using immunostimulants not only improves animal health but also contributes to wider environmental health when less antibiotics are used and less water exchange is required.

Evaluating the sustainability of aquaculture development through a 'One Health' Approach



A 'One Health' approach considers that animal, environmental, and human health are interlinked, where sustainable food systems depend on all three (Berry et al., 2015). While human, animal, and environmental health are all extensively studied within their respective disciplines, attempts at quantifying them in conjunction are limited. For example, authors have compared carbon emissions with antimicrobial resistance (Reverter et al., 2020) or protein production (Nijdam et al., 2012), disregarding the array of other benefits and impacts of aquaculture production.

A large challenge is choosing and incorporating the right indicators that appropriately illuminate the whole picture. Aquaculture can impact on the environment in numerous ways beyond carbon footprint, which is still the most commonly-used metric in life-cycle analysis that estimates environmental impact (e.g., through waste water or through preserving biodiversity) (Gephart et al., 2021). Aquaculture can also provide benefits to local ecosystems, such as with filter feeders, and these positive attributes must also be quantified and considered.

Effects on human nutrition are even more complex, requiring understanding beyond the micronutrient composition of the fish. Consumer preferences, preparation and cooking habits, hygiene and sanitation, affordability and the role of aquatic foods in the individuals' broader diet all influence the impact of aquaculture on 'healthy' outcomes for humans (Pounds et al., 2022, in review). In addition, economic growth indicators do not always reflect wellbeing, and even countries with economic growth may continue to experience poverty and food insecurity (Stewart 2019). Attempts at framing aquaculture under the One Health lens have suggested alternative indicators to production or economic measures, including: nutritious and safe food, gender equalization, quality employment, healthy stock, biosecure farms, optimized water usage and quality, and protected biodiversity (Stentiford et al., 2020).

While a 'One Health' Approach is a step in the right direction, we still lack a comprehensive framework to understand the multitude of ways in which aquaculture development is fit for purpose and sustainable (Pounds et al., 2022, in review). This framework should include environmental, human, and animal health outcomes and extend throughout the value chain.

2.2.6. INVESTMENT OPPORTUNITIES CONTRIBUTING TO THE SDGS

Investments in aquaculture can promote broader economic and social development within surrounding communities (Belton and Filipski, 2018). Investments in upstream (e.g. feed, feed ingredient manufacture and delivery, veterinary medicines) and downstream (e.g. processing facilities, markets infrastructure, distribution and logistics) businesses provide similar benefits and extend aquaculture's socio-economic contributions even further through the value chain.

The degree of investment into aquaculture varies depending on the system. Many aquatic foods derived from aquaculture can be among the least demanding in terms of capital investment, supplementary nutrient additions, and management, making such systems accessible to small-scale farmers. On the other hand, some aquaculture systems (e.g. recirculating aquaculture systems - RAS) carry significant CAPEX and OPEX related to the purchase of highly technical engineered solutions and the need for energy inputs. Investments in aquaculture necessarily reflect the multitude of the different production system types and species that are currently farmed.

Infrastructure investments and aquaculture development often proceed in tandem and can be mutually supportive. With careful planning, appropriate provisions can be made within infrastructure and urban-development schemes for aquaculture to be an integrated part of urban and peri-urban food production. Aquaculture development faces challenges, however, especially concerning licensing, as it often needs to fit into broader regulatory frameworks that are not designed with the sector in mind. The consequences of this are discussed further in Section 4.

Environmental, Social, and Governance (ESG) criteria are standards for company operations that conscious investors can use to screen investments. More than 25 countries (including China) have already introduced mandates for firms to disclose ESG information. The EU is at the vanguard of this trend; as well as enhancing transparency, from 2023 new Corporate Social Reporting Disclosure (CSRD) laws will include obligations to address ESG issues connected to companies' businesses. Globally, investors held $17.1 trillion in assets chosen according to ESG criteria at the beginning of 2020 (up from $12 trillion just two years earlier). These include high-growth specialist funds for sustainable animal protein production, under which the sustainability attributes of aquaculture compared to land-based alternatives are drawing positive investor sentiment. Salmon farming companies were in the top 10 of a recent ESG risk assessment (the Coller FAIRR Protein Producer Index) of 60 of the world's largest meat, fish and dairy producers (FAIRR, 2022).

2.2.7. INSURANCE IN AQUACULTURE

Perception of performance risk is one of the main barriers blocking investment capital from expanding aquaculture production. In particular, interested investors cite under-structured projects (high perceived risk) and lack of familiarity with the sector (inability to price technical risk) as the biggest challenges (Credit Suisse, 2019).

Reduced downside variability and a more confident, narrow spectrum of future performance scenarios cuts the costs of financing. Salmon aquaculture is sufficiently developed that firms are able to finance growth through public offerings and with the support of specialized banks. Outside of salmon, this is largely not the case, because industries are either too nascent (e.g. marine finfish) or too distributed (e.g. shrimp, mollusks, freshwater finfish).

Insurance offers one tool to help break down this risk barrier. In theory, reduced downside performance volatility should more than cover the price of insurance from a cost-of-capital perspective: after all, that is why crop insurance is widespread in terrestrial farming. In emerging aquaculture sectors, paucity of data points, and an uneven track record of precedent producers results in policies that are more expensive than businesses can afford: a chicken-and-egg challenge typical of new industries. In sectors characterized by distributed small-scale activity, high transaction costs are the barrier, and the site-specific nature of production risks complicates standardized approaches to pricing risk. Farmers are priced-out when their business's small capital footprints cannot absorb underwriting costs — especially given the low margins characteristic of systems with low barriers to entry.

2.2.8. PROMOTING NUTRITION-SENSITIVE PRODUCTION PRACTICES

Adopting nutrition-sensitive aquaculture practices, such as integrated agri-aquaculture and polyculture, can help tackle food and nutrition insecurity and promote diets that result in better nutrition outcomes. Systems that produce an array of foods encourage dietary diversity and nutrient intake. Co-culture of aquatic animals in flooded fields used to cultivate rice, and growing vegetables on raised embankments, are two widespread practices that have been promoted by international organizations, sometimes based around local knowledge and practice. These types of systems can help ensure food and nutrition security and resiliency for local communities while producing valuable crops to bolster financial returns and promote regional economic and social development (Amilhat et al, 2009). Polyculture (producing more than one aquatic species) remains widely adopted in semi-intensive pond farming systems across South and South-East Asia, for a variety of species reflecting local production, household consumption, and market needs (e.g. small local fish species for domestic consumption grow in ponds alongside larger carps destined for market). Selected production practices (e.g. deepening ponds) can also help adapt to and mitigate climate change and bolster agrobiodiversity.

2.2.9. OPPORTUNITIES AND CONSTRAINTS TO THE TRADE OF AQUATIC FOODS

Local and international consumers benefit from the enhanced trade of aquatic foods originating from aquaculture, providing them with greater choice when buying seafood and more options for obtaining affordable and nutrient-rich products. Aquaculture exports can also be an important source of foreign exchange earnings for emerging economies; however, the level of earnings may depend largely on whether primary and secondary processing occurs within a country. Export markets tend to be increasingly supplied by vertically integrated value chains able to readily meet certification, food safety, and other market requirements. This creates significant barriers to small-scale participation in the international seafood trade.

2.2.10. ACHIEVING AND MAINTAINING GOOD SECTOR AND SOCIAL RELATIONS

Since aquaculture systems are often located in shared spaces or dependent on shared water resources, it is vitally important that good relations are maintained with local communities and other stakeholders. This is often referred to as the 'social licence to operate' (SLO). Engaging with stakeholders in decision-making processes and going beyond compliance is important for producers to attain SLO from communities surrounding aquaculture (McGhee et al, 2019; Vince and Haward, 2019). Effective communication of the science surrounding aquaculture also improves SLO (Carrassón et al, 2021). Most importantly, cooperation among producers is crucial to effectively countering the risk of diseases spreading and to governing the wider cumulative environmental impacts, including eutrophication of multiple production units at landscape levels. And the benefits achieved via SLO are directed back into local communities. The clearest and most-evidenced example of this is through enhanced livelihoods and employment opportunities, as well as increased access to fish in certain contexts (e.g. the case study on Victory Farms, Kenya). Other benefits may include improved investment in shared infrastructure.

2.2.11. CRITICAL ROLES FOR REGULATION AND GOOD GOVERNANCE[7]

Regulation and governance of aquaculture are essential for ensuring environmentally sustainable practices that operate within local ecosystem carrying capacities. Aquaculture industries have often developed ahead of the regulation needed to effectively manage them, with some leading operators working with regulators to ensure sustainable development. In many jurisdictions, regulation infrastructure is still catching up with industry development, especially as longer-term sustainability ambitions replace shorter-term economic development goals. This historic vacuum of regulation was one of the drivers behind market-based governance through certification standards, enabling quality control at the farm level where more holistic regulations were lacking. In some jurisdictions, regulations are helping to drive innovation. For example, in China concerns over public water quality is reducing traditional pond culture and increasing the use of recirculation systems; in Norway new salmon farming licences have been given to companies investing in new production methods. Novel offshore activities, notably wind farms, could provide an opportunity to establish new aquaculture facilities, but there are likely to be logistical and legislative barriers that limit the scope of this (Buck et al, 2017), especially if future developments occur beyond the 12-nautical mile limit of territorial waters, a prospect that is currently mainly hypothetical. Legislation will need to adapt quickly to support the uptake of such novel technologies.
Stricter statutory and civil society demands related to sustainability are driving businesses and brands to internalize environmental costs. This is, in turn, fuelling investor interest in a range of closed-containment possibilities that may mirror similar evolutions in terrestrial feed-lot livestock systems.

Governance will also be required to assure social standards. While jobs in processing aquatic foods from aquaculture are welcomed in low-income communities, these are likely to be physically demanding and relatively low paid. Human rights abuses have been reported in selected cases within seafood value chains and appropriate safeguards are required to ensure that such practices are eliminated (Marschke and Vandergeest, 2016).

2.2.12. CERTIFICATION IN INTERNATIONAL TRADE

More valuable, internationally traded aquatic food products are more likely to adopt certification schemes. These schemes serve to document and demonstrate quality assurance for higher-income buyers and consumers and to reduce reputational risk for large retailers[8, 9]. Cooperative-style group certification programmes have enabled processors to supply whiteleg shrimp from some small- and medium-sized producers into international markets. Grow-out in such systems constitutes the lowest-margin, highest-risk value chain phase. As big companies benefit from devolving this risk to farmers, there may be power imbalances to consider. Only a small proportion (3%) of global aquaculture production is covered by the main Aquaculture Stewardship Council (ASC) and Global Aquaculture Alliance Best Aquaculture Practices (GAA-BAP) certificate programmes (Henriksson et al, 2021, p.1227), though the portion of certified product is significantly higher for salmon (60%). Production innovations and norms developed in pursuit of sustainability certification are likely to spill over into wider categories of production, and the scientific advances resulting from these programmes can also influence norms adopted by market regulators.

Currently, third-party schemes do not comprehensively or consistently address, for example, landscape-level cumulative impacts and risks or an appropriate range of LCA impact categories.

2.3. Alignment with the FAO Code of Conduct for Responsible Fisheries

The SDGs provide an overarching framework for action internationally, but separate agreements are required to address the complex issues of global significance. Specific objectives and targets to address climate change have been agreed internationally in the Paris Agreement on climate change (UN, 2015a). Measures agreed globally to halt and reverse biodiversity loss and rehabilitate ecosystems are contained in the Convention on Biological Diversity (CBD) (UN, 1992b). Both of these international treaties are legally binding.

Strategies and actions to promote responsible aquaculture development were agreed globally and specified in "Article 9 - Aquaculture Development" of the FAO Code of Conduct for Responsible Fisheries (CCRF) that was adopted by the FAO Conference in October 1995 (FAO, 1995). These measures were endorsed by the Member States of the FAO Committee on Fisheries (COFI), but they are not legally enforceable. Consequently, at a national level the degree to which these commitments are translated into legislation and regulations for a particular sector (e.g. aquaculture development) can vary and work is ongoing to review the coverage and effectiveness of measures to implement the CCFR (FAO, 2022b).

Details of the contents of Article 9 of the CCRF are presented in Table 2, together with a review of the current status of implementation and promising areas for further action.

Table 2: Content analysis of "Article 9 - Aquaculture Development" of the FAO Code of Conduct for Responsible Fisheries (*source FAO, 1995) and implementation status review

Sub-section*	Status of implementation and promising areas globally
9.1. Responsible development of aquaculture, including culture-based fisheries, in areas under national jurisdiction.	
9.1.1. States should establish, maintain and develop an appropriate legal and administrative framework which facilitates the development of responsible aquaculture.	• States often do not have legal and administrative frameworks to effectively promote the development of responsible aquaculture. • Guidelines may be so strict, complex and expensive as to significantly limit aquaculture production, or so overly loose as to permit development with excessively negative impact footprints risking unsustainable boom-and-bust development. • Competing vested interests around water use, outdated understanding of industry advancement among lawmakers and/or the wider electorate, and resistance by established sectors who view aquaculture as a threat to vested interests are among the drivers of overly restrictive regulatory frameworks. • Prioritization of short-term economic opportunity over long-term sustainability is usually the driver in cases of insufficient regulation. • The FAOLEX database provides an overview of policies, national legislation and bilateral agreements that are relevant to aquaculture in a particular country (FAO, 2022a) (see Section 2.3 for more details). • Guidelines have been published to assist with improving planning and policy development in aquaculture (FAO, 2008; FAO, 2017). • Recent FAO Aquaculture Legal Assessment and Revision Tool (ALART) initiative aims to develop a standardized protocol for aquaculture regulation review and revision (FAO, 2022b).
9.1.2. States should promote responsible development and management of aquaculture, including an advance evaluation of the effects of aquaculture development on genetic diversity and ecosystem integrity, based on the best available scientific information.	• States do not generally carry out or require an evaluation of the effects of a specific aquaculture development on genetic diversity and ecosystem integrity, although some have risk assessments at national levels. • Tools and protocols have been developed for Environmental Impact Assessment (EIA) and LCA for aquaculture production facilities or process evaluations across value chains (Newton and Little, 2018; Gephart et al, 2021). • Standardized approaches to EIA have been developed to help gauge and regulate aquaculture development, but even where there is some commonality across legislative background for this approach the application of EIA and associated monitoring has been seen to be inconsistent (Telfer et al, 2009). • Similarly, LCA protocols have become an established means of analysis for the likely consequences of an aquaculture system or sector across a similar range of impact categories, although they were originally developed for industrial products and processes, and only later for food products, and so not specifically constructed for aquaculture systems (Henriksson et al, 2012). • As a result, serious limitations in the application of LCA to aquaculture systems have been noted. However, with additional recommendations for development, the assessment of possible impacts on biodiversity, genetic diversity, and ecosystem integrity in standardized models may be possible.
9.1.3. States should produce and regularly update aquaculture development strategies and plans, as required, to ensure that aquaculture development is ecologically sustainable and to allow the rational use of resources shared by aquaculture and other activities.	• Development strategies and plans often focus on setting targets for production volume increases while not specifying jointly agreed steps and actions across sectors and food systems or allocating funding to supporting research and development. • National aquaculture development plans tend to focus on established sectors and species with a higher market value, as opposed to species that could contribute most to tackling food and nutrition insecurity.

Table 2: Content analysis of "Article 9 - Aquaculture Development" of the FAO Code of Conduct for Responsible Fisheries (*source FAO, 1995) and implementation status review (continued)

Sub-section*	Status of implementation and promising areas globally
9.1. Responsible development of aquaculture, including culture-based fisheries, in areas under national jurisdiction.	
9.1.4. States should ensure that the livelihoods of local communities, and their access to fishing grounds, are not negatively affected by aquaculture developments.	• Potential impacts, both positive and negative, of aquaculture development on the livelihoods of local communities are not routinely evaluated, although FAO has created guidance in this area within the Ecosystem Approach to Aquaculture. • Some third- and second-party certification schemes do include criteria related to community relations, but impacts in terms of sustainable livelihood outcomes (other than employment generation) are not routinely assessed (see Table 5).
9.1.5. States should establish effective procedures specific to aquaculture to undertake appropriate environmental assessment and monitoring with the aim of minimizing adverse ecological changes and related economic and social consequences resulting from water extraction, land use, discharge of effluents, use of drugs and chemicals, and other aquaculture activities.	• Environmental assessment and monitoring procedures are in place in many locations, but are often limited in scale (focused on larger farmers) and reach (individual operation impacts, rather than cumulative impact considerations). • Pioneer or high-profile operators may be required to undertake extensive EIAs and comply with stringent environmental monitoring requirements. • Once the apparent success of a production system has been demonstrated, there is a tendency for poorly regulated operations to proliferate and cumulative impacts can overwhelm the carrying capacity of supporting ecosystems.
9.2. Responsible development of aquaculture including culture-based fisheries within transboundary aquatic ecosystems.	
9.2.1 States should protect transboundary aquatic ecosystems by supporting responsible aquaculture practices within their national jurisdiction and by cooperation in the promotion of sustainable aquaculture practices.	• Regional trade and economic cooperation bodies and agreements provide an umbrella mechanism for States to jointly address issues of concern regarding the development of responsible aquaculture practices in transboundary aquatic ecosystems. • Where such agreements are absent or do not match the geography of transboundary aquatic ecosystems, dedicated agreements and undertakings are often developed.
9.2.2 States should, with due respect to their neighbouring States and in accordance with international law, ensure responsible choice of species, siting and management of aquaculture activities which could affect transboundary aquatic ecosystems.	• Regional Fisheries Bodies and Aquaculture Networks provide guidance to States on considerations relating to transboundary issues in aquaculture, although many countries continue to develop regulations in isolation. • Recent work by FAO continues to highlight the need for greater regional cooperation (FAO, 2019).
9.2.3 States should consult with their neighbouring States, as appropriate, before introducing non-indigenous species into transboundary aquatic ecosystems.	• There is limited evidence of effective processes, although regional Aquaculture Networks like NACA (Network of Aquaculture Centres in Asia Pacific) and LVFO (Lake Victoria Fisheries Organization) provide guidance in these areas.
9.2.4 States should establish appropriate mechanisms, such as databases and information networks to collect, share and disseminate data related to their aquaculture activities to facilitate cooperation on planning for aquaculture development at the national, subregional, regional and global level.	• States collect data on aquaculture production volumes and the species produced and in which environment culture takes place. • States collect data on the trade (export and import) of aquaculture products and this data is made available at a global level through online databases. • States collect data on the alignment of production practices with the principles of responsible aquaculture and this data could potentially be made publicly available to demonstrate progress in achieving responsible aquaculture development.
9.2.5 States should cooperate in the development of appropriate mechanisms, when required, to monitor the impacts of inputs used in aquaculture.	• Regional Fisheries Bodies provide mechanisms for collaboration on inputs from fisheries into aquaculture value chains. • APFIC (Asia Pacific Fisheries Commission) has produced guidelines to improve the management of multi-species trawl fisheries that are the source of much of the fishmeal in Asian aquaculture feeds.

Table 2: Content analysis of "Article 9 - Aquaculture Development" of the FAO Code of Conduct for Responsible Fisheries (*source FAO, 1995) and implementation status review (continued)

Sub-section*	Status of implementation and promising areas globally
9.3. Use of aquatic genetic resources for the purposes of aquaculture including culture-based fisheries.	
9.3.1 States should conserve genetic diversity and maintain integrity of aquatic communities and ecosystems by appropriate management. In particular, efforts should be undertaken to minimize the harmful effects of introducing non-native species or genetically altered stocks used for aquaculture including culture-based fisheries into waters, especially where there is a significant potential for the spread of such non-native species or genetically altered stocks into waters under the jurisdiction of other States as well as waters under the jurisdiction of the State of origin. States should, whenever possible, promote steps to minimize adverse genetic, disease and other effects of escaped farmed fish on wild stocks.	• FAO is currently undertaking significant work on aquatic genetic resources for food and agriculture (AqGR) that aims to: strengthen global governance; promote development and sustainable use; improve management and technical capacities; lead consensus-building towards improved conservation and responsible use in Member States. • In 2019, FAO launched the first report on "The State of the World's Aquatic Genetic Resources for Food and Agriculture".
9.3.2 States should cooperate in the elaboration, adoption and implementation of international codes of practice and procedures for introductions and transfers of aquatic organisms.	• The International Council for the Exploration of the Sea (ICES) "Code of Practice on the Introductions and Transfers of Marine Organisms 2005" (ICES, 2005) provides a suitable model.
9.3.3 States should, in order to minimize risks of disease transfer and other adverse effects on wild and cultured stocks, encourage adoption of appropriate practices in the genetic improvement of broodstocks, the introduction of non-native species, and in the production, sale and transport of eggs, larvae or fry, broodstock or other live materials. States should facilitate the preparation and implementation of appropriate national codes of practice and procedures to this effect.	• Global conventions relevant to this area include the Convention on Biological Diversity, Convention on International Trade in Endangered Species of Wild Fauna and Flora, Ramsar Convention, United Nations Framework Convention on Climate Change, United Nations Convention on the Law of the Sea, The Barcelona Convention, and The Convention on the Conservation of Migratory Species of Wild Animals. • "The State of the World's Aquatic Genetic Resources for Food and Agriculture" identified an overarching need to promote development, monitoring and enforcement of policies and good governance that adequately consider issues affecting conservation, sustainable use and development of aquatic genetic resources.
9.3.4 States should promote the use of appropriate procedures for the selection of broodstock and the production of eggs, larvae and fry.	• States generally have some legislation in this area, although it may not always be aquaculture specific. • Challenges remain in implementation. • Broader questions to consider include whether governments should technically deliver these actions or regulate and drive best practice through the private sector.
9.3.5 States should, where appropriate, promote research and, when feasible, the development of culture techniques for endangered species to protect, rehabilitate and enhance their stocks, taking into account the critical need to conserve genetic diversity of endangered species.	• Guidelines have been produced to aid effective and responsible stock enhancement and States should ensure these are adopted in practice (Lorenzen et al, 2010). • Stock enhancement programmes can be effective but, unless States act to address the underlying causes of aquatic habitat degradation and stock depletion, such measures will not yield long-term improvements (Liu et al, 2019).

Table 2: Content analysis of "Article 9 - Aquaculture Development" of the FAO Code of Conduct for Responsible Fisheries (*source FAO, 1995) and implementation status review (continued)

Sub-section*	Status of implementation and promising areas globally
9.4. Responsible aquaculture at the production level	
9.4.1 States should promote responsible aquaculture practices in support of rural communities, producer organizations and fish farmers.	• Many States have promoted responsible aquaculture through development aid and projects and conducive legislative arrangements supporting small businesses. • Several have also produced Good Aquaculture Practice programmes (e.g. ThaiGAP, VietGAP) that provide specific guidance to farmers of key commodities.
9.4.2 States should promote active participation of fish farmers and their communities in the development of responsible aquaculture management practices.	• Active participation can be difficult to achieve, especially for small-scale producers and individuals from poor and marginal communities, who face other pressures on livelihoods (Bunting, 2010).
9.4.3 States should promote efforts which improve selection and use of appropriate feeds, feed additives and fertilizers, including manures.	• States promote research and development programmes that help in identifying and refining appropriate feeds and feed additives and fertilizers (including manure) but often farmers are unable to implement recommended feeding and fertiliser regimes to maximize production owing to limited access to financial and nutrient resources.
9.4.4 States should promote effective farm and fish health management practices favouring hygienic measures and vaccines. Safe, effective and minimal use of therapeutants, hormones and drugs, antibiotics and other disease control chemicals should be ensured.	• Small-scale producers in developing countries may not have access to healthy animals and plants to stock their farms and may not be able to exert sufficient control over entry to culture areas to ensure good biosecurity. • Vaccines have been developed for several conditions affecting salmon and trout and are used widely. • There are fewer vaccines for carp and tilapia and they are less accessible and suited to use with large numbers of small animals typically stocked in small-scale fishponds. • Producers in developing countries often have limited knowledge and information on diseases and appropriate treatments and pre-treatments and therefore may be persuaded to use inappropriate substances that are ineffective.
9.4.5 States should regulate the use of chemical inputs in aquaculture which are hazardous to human health and the environment.	• FAO is working with States to manage risks of antimicrobial resistance developing in the aquatic environment as part of the One Health framework. • Seafood Watch is engaging production associations in Chile and India to address this directly using market leverage in salmon and shrimp sectors.
9.4.6 States should require that the disposal of wastes such as offal, sludge, dead or diseased fish, excess veterinary drugs and other hazardous chemical inputs does not constitute a hazard to human health and the environment.	• Small-scale production systems with limited and often discontinuous levels of throughput are challenged in their economic ability to collect secondary products and supply secondary markets at an economically attractive scale. • Effective prebiotics and probiotics and vaccines help to avoid the use of veterinary drugs and hazardous chemicals (Haque et al, 2021).
9.4.7 States should ensure the food safety of aquaculture products and promote efforts which maintain product quality and improve their value through particular care before and during harvesting and on-site processing and in storage and transport of the products.	• Examples from countries like Thailand show how food safety, product quality, and improved value can be maintained across value chains by using a certification approach to confirm compliance. • Nutrition sensitive measures across food systems maintain and can potentially enhance the nutritional value of aquatic foods and food security and achieve better human nutrition outcomes (Golden et al, 2021).

2.4. The sustainability of different production systems

Considering the wide array of production systems that are used to culture aquatic foods (see Table 3), it is important to reflect on the negative and positive economic, environmental and social impacts associated with important freshwater, brackish and marine ecosystems globally. The majority of aquaculture production (i.e. marine algae, bivalve molluscs, herbivorous and omnivorous finfish species, freshwater aquatic plants, and extensive and semi-intensive pond-based systems) is relatively benign environmentally. Algae, aquatic plant, and bivalve mollusc production can even result in the net removal of nutrients from local ecosystems (Troell et al, 2003; Neori et al, 2004; Troell et al, 2009), thereby potentially mitigating the risk of eutrophication.

In Table 3, we first introduce production systems used predominantly in freshwater settings, where most global aquaculture production currently occurs, and is likely to continue to do so (Zhang et al, 2022). We then consider the systems best suited to brackish water and marine settings. Examples of production systems combining different aquatic and terrestrial crops are also presented.

The various production systems described within Table 3 represent a spectrum of capital cost profiles for farmers, ranging from low-capital expenditure extensive systems (e.g. using existing reservoirs and lakes) to capital-intensive production models such as cage culture and RAS. Each model has advantages and drawbacks. The selection of the most appropriate system is a decision that requires weighing the balance of market demand requirements, species culture requirements, the profile of available sites, and the quantum of available financial resources – among other factors.

Following Table 3, we describe key characteristics of production systems operated at different levels of management intensity and requiring different levels of investment. We then discuss important opportunities across the full range of available production systems that could foster global aquaculture sector growth.

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems

Production system	System Domain		
Ponds	**Social**	**Economic**	**Environmental**
	• Ponds managed by families in LMICs are often multi-purpose and may be used for irrigation, washing and watering livestock; production of aquatic animals is often not the priority. • Aquatic foods from household ponds can contribute to food and nutrition security, but incomes generated often constitute a relatively small portion of the overall livelihood strategy (Belton and Azad, 2012). • Commercial production of freshwater finfish in medium- and large-ponds in Asia has had a transformative impact on the provision of affordable fish for poorer communities (Belton et al, 2017; Hernandez et al, 2018).	• Good site selection can help minimize construction costs, while taking advantage of available cut-and-fill opportunities can reduce excavation costs and avoid the need to transport soil. • Natural productivity can be enhanced using organic and inorganic fertilizer inputs (Xinglong and Boyd, 2006). • Dependence on biological processes limits production intensity and yields and consequently financial returns per unit area; use of mechanical aerators can increase costs and add to production risks. • Low barriers to entry for pond culture limits opportunities for long-term profitability.	• Ponds are relatively easy to construct where soil conditions permit forming sides and embankments with desirable profiles and where the soil type is suited to holding water (FAO, 2022c). • Dissolved oxygen dynamics often dictate the carrying capacity for stocked animals; when water exchange is absent or limited, toxic compounds can accumulate in ponds. • Intensification through use of formulated diets increases the need for aeration and can entail higher levels of greenhouse gas emissions.
Flow-through ponds and raceways	• Development of flow-through systems can create employment in remote and rural areas where other livelihood options may be severely limited. • Production of fish to stock angling venues can enhance the amenity value of lakes and reservoirs and create opportunities for recreation.	• Flow-through ponds and raceways are relatively easy to construct. • Producers may have limited scope to increase or intensify production and therefore may tend toward producing high value species and look to add value. • Contamination of water upstream or disruption to water inflows can pose serious production and financial risks.	• Flow-through ponds and raceways use water drawn from reservoirs or diverted from streams and rivers to replenish oxygen and remove waste. • Drum-filters or screens can be used to pre-treat water entering farms and discharge water can be treated with drum-filters or settlement ponds. • The permissible standing stock of aquatic animals may be dictated by the volume of water available throughout the year.

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems (continued)

Production system	System Domain		
	Social	Economic	Environmental
Tanks	• Tanks can typically be made from plastic, corrugated metal sheets and concrete. • Tanks can be used effectively in urban and peri-urban settings where space and freshwater supplies may be limited, and this has potential to provide employment opportunities for young people (Miller and Atanda, 2011).	• With good maintenance and careful attention to the scheduling of stocking and harvesting, and feeding and grading regimes, it is possible to produce several crops of tilapia per year, generating more frequent cash inflows and maximizing returns on capital investments (Cai et al, 2018). • Water flow in tank systems needs to be maintained either by gravity (implying sufficient water head height), or by pumping, both of which may add to cost. • Poor water quality can result in depressed growth rates and off-flavours in harvested fish that are disliked by consumers.	• Multiple tanks provide scope to grade fish into distinct size categories to promote uniform growth and avoid the cannibalism and competition that can lead to production inefficiencies. • With limited water exchange, tanks can be used effectively to culture catfish and other air-breathing species. • Water quality monitoring can help identify issues that could be mitigated with partial water changes or a temporary cessation of feeding.
Recirculating Aquaculture Systems (RAS)	• RAS can be established in diverse locations with a reliable energy source and adequate water supplies. • Farms can provide new employment opportunities and a novel source of nutritious aquatic foods for local consumers. • RAS systems can deliver closely regulated conditions in which to conduct research and development to inform and guide commercial decision-making and sector growth.	• Capital and operating costs associated with RAS are relatively high. RAS have proven cost-effective at producing larger juveniles to stock into grow-out facilities in farmed salmon, but their success for the full life-cycle production of other species is relatively limited. • At high stocking densities, production risks can be significant and should be mitigated by appropriate backups and safeguards . • Very few large-scale successes –and well-publicized large-scale failures – highlight significant technical risk, though the industry has recently enjoyed significant investment. • The geographic flexibility of RAS systems has made them popular for high-value niche markets distant from ordinary cultural sites. • The same geographic flexibility may be a factor behind investor interests since country risk can potentially be avoided.	• Tank-based systems where process water is treated to remove waste products in separate units are described as RAS. • High stocking densities are possible under closely controlled environmental conditions and this can help optimize feed conversion efficiencies and maximize growth rates. • Uncomplicated systems can be constructed from affordable materials and use simple water treatment and aeration processes to maintain water quality. • Sophisticated systems can require detailed design and engineering specifications but with appropriate safeguards can produce large numbers of valuable juveniles to supply specific aquaculture sectors. • Solid waste can be removed from the system without entering the local environment (and may also have value as a crop fertilizer).

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems (continued)

Production system	System Domain		
	Social	Economic	Environmental
Aquaponics	• Combined production of aquatic animals and terrestrial plants in the same growing medium is termed aquaponics. • Nutrients derived from the feeds supplied to the aquatic animals can stimulate the production of plants in the system. • Aquaponic systems can be developed at a range of scales to match the available human capital and financial resources, and to produce salad and herb plants and ornamental and aquatic food animals (Love et al, 2015) that can be selected to align with prevailing food cultures and demand.	• Plants with rapid growth rates can help generate relatively quick and frequent cash inflows and supplement the overall finances of the system. • Selection of animals and plants with established or growing markets can be crucial to the success of aquaponics (Love et al, 2015). • Competition from specialist growers and products traded internationally can represent major barriers to success and deter the production of affordable crops. • Competing interests and varying economic value across the cultured species (plant and animal) can make it difficult to successfully maintain and manage the finances of aquaponic systems.	• Aquatic animals and terrestrial plants may have different optimal growing conditions with regards to temperature and light regimes, for example, and suffer from different pests and diseases that may place additional demands on producers. • Aquaponics systems can be housed in buildings and greenhouses to carefully regulate the culture environment.
Integrated Agriculture-Aquaculture (IAA)	• On family farms and small-holdings, IAA can present opportunities for sustainable intensification and diversification that can make farming a more attractive livelihood option. • Co-culturing staple and cash crops can contribute to poverty alleviation and enhance human nutrition through direct consumption and improved purchasing power. • IAA systems can supply diverse food crops to markets, contributing to food and nutritional security in local and regional communities.	• Combining aquatic food production with terrestrial crop or livestock farming can optimize the use of available resources (e.g. labour, land, nutrients and water) and generate more regular cash flows. • Utilization of by-products and waste resources can stimulate natural productivity and help avoid expenditure on feed and fertilizer inputs. • Complex and competing economic interests across multi-product systems can deter use by commercial operators, especially for systems at scale.	• Production of cultured and wild aquatic animals in rice fields is practised in Asia. • IAA strategies, notably wetland-based systems such as rice-fish and mangrove-shrimp culture can help enhance and sustain ecosystem services and biodiversity. • Configuring fields to culture both rice and fish can present practical problems depending on the soil type and prevailing hydraulic regime. • To keep cultured aquatic animals healthy, producers must avoid using potentially harmful agrochemicals and instead adopt appropriate integrated pest management strategies.

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems (continued)

Production system	System Domain		
	Social	**Economic**	**Environmental**
Reservoirs and large lakes	• Community-based groups are often best suited to manage these systems, but care is needed not to exclude other user groups. • Companies can lease access to such waterbodies and benefits can be shared with local communities. • When large water bodies are used for other purposes (e.g. navigation and recreation) appropriate controls on access may be required to protect the interests of producers. • For reservoirs developed for irrigation and hydroelectric schemes, the needs of aquaculture operators may be a secondary consideration in routine operations.	• Fish can be stocked successfully in reservoirs and large lakes and recaptured using frequent and sustained netting once a stock of market sized animals has been achieved (De Silva, 2003; De Silva et al, 2006). • Continuous stocking and harvesting can help spread production cost and achieve more regular cash inflows. • Returns from daily netting operations may be variable and unpredictable. • Inland markets often offer advantageous pricing but competitive market access may have a geographically limited range.	• Surveillance of large water bodies can be difficult and necessitate the use of guards to prevent theft and carry out frequent checks to deter and scare predators. • Feeding stations can be used to supplement natural production. • Nutrient runoff and animal waste discharges in catchments may cause excess eutrophication and contaminate cultured animals with pathogens. • When drainage and drying is not possible, unwanted invasive species (e.g. sailfin armoured catfish [Pterygoplichthys spp.] in the East Kolkata Wetlands, India) and predators, parasites, pathogens and pests can become a problem (Hussan et al, 2021).
Pens	• Wooden framework and bamboo screens and monofilament nets can be used to construct pens that partition off part of a larger water body to culture fish, prawns or shrimp (Luong et al, 2005). • Simple, low-cost barriers can be used by poorer community members in shallow marine areas to contain sea cucumbers (Arnull et al, 2021).	• For pens in large water bodies, initial capital costs may be significant and systems may only be financially viable when higher value species are being cultured. • Breaches in pens may lead to substantial losses of stocked animals and the ingress of predators.	• Barriers used to construct pens are susceptible to accidental mechanical and storm damage and appropriate safeguards may be needed to avoid negative impacts on local ecosystems and genetic diversity in wild stocks.

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems (continued)

Production system	System Domain		
	Social	Economic	Environmental
Intertidal and on-bottom culture	• Cooperative management of yesso scallop (Patinopecten yessoensis) culture in Japan has been practiced for 60 years (Gosling, 2003) and is an excellent example of socially, economically and environmentally sustainable production. • In France, the socio-cultural importance of oysters fattened in shallow ponds on the Atlantic coast is recognized through their 'protected geographical indications' (PGI) and 'label rouge' designations.	• Traditional culture of bivalve molluscs (e.g. oysters, mussels and scallop) routinely involve seeding juveniles directly onto the bottom of suitable areas of estuaries, lagoons and bays (Gosling, 2003). • Grow-out can take two to three years, so the initial lack of cash inflow can constitute a barrier to new entrants.	• Removal of predators (e.g. sea urchins and starfish) through dredging may be required prior to seeding. • Seeding and the introduction of spat or juveniles (especially bivalve molluscs) into areas for farming may increase the risk of translocation of alien species if it is not effectively managed. • Racks and trestles can be used to raise stocked bivalves off the bottom to help avoid predation and fouling with sediments. • Cumulative stocking rates must not exceed the carrying capacity of the ecosystem. Uncertainty over the recruitment of juveniles from wild stocks is a notable production constraint.
Longlines and rafts	• Simple rafts and longlines can be used to suspend nets and lines to support the culture of bivalves and seaweed (Gosling, 2003); these can be useful to enable small-scale producers to carry out cultivation in part of a shared bay or lagoon. • Large-scale systems can create employment opportunities in farming and processing for coastal communities where other work may be unavailable or highly seasonal.	• Continuous longline systems have been developed that permit efficient management procedures and harvesting and can constitute a cost-effective way to produce aquatic foods in open-water settings. • Some firms produce dedicated workboats equipped for continuous longline systems, but capital costs can be significant. • Cash inflows from farming bivalves may take one to two years, depending on the size of juveniles stocked.	• Ensuring good anchorage is often the most challenging aspect as the depth of water increases. • Self-shading can be a significant issue when farming seaweed. • Longline systems may also act as refugia for a range of marine species, providing nursery areas with biodiversity benefits.

Table 3. Social, economic and environmental attributes of the main production systems in freshwater, brackish and marine ecosystems (continued)

Production system	System Domain		
Cages	**Social**	**Economic**	**Environmental**
	• Cages permit operators, often located in coastal or rural locations, to engage in farming in open-water settings (e.g. large lakes, rivers and the sea) that may otherwise be regarded as unproductive. • Cage farms can promote economic activity and maintain communities in remote and coastal areas. • In Asia, medium-sized cages in peri-urban areas may incorporate storage facilities and living accommodation and can be used to transport fish closer to market. • Cage culture is challenged by a perception of negative environmental impacts that were more common in the early days of the salmon industry but which continue to be repeated by a smaller share of operators today. • Due to the governance challenge in limiting cage numbers to the carrying capacity of ecosystems shared with other operators and users, China has largely banned the practice in freshwater lakes and reservoirs.	• Unit costs of production in cage systems are often extremely competitive when viewed against other production systems. • Fish cultured in cages depend on supplies of formulated feed. • The means of feed delivery and feeding regime can be fundamental to the efficiency of feed conversion to marketable biomass. • Large-scale cage operations can represent a significant capital investment, with feed routinely accounting for most of the operating costs, as well as a large share of capital costs associated with grow-out of the initial cycle before first sale. • Cage culture is among the most established farming systems for high-value fish species and offers a precedent on which investors can forecast and price performance risk when evaluating financing prospects.	• Cage construction can range from wooden frameworks and bamboo slatted sides to steel frames and heavy-duty rigid polymer mesh nets (Beveridge, 2004). • Typical volumes for medium- and large-sized cages range from several hundred to several thousand cubic metres, respectively. • Poor feeding practices can result in direct losses of feed and have negative environmental impacts. • Without sufficient industry coordination, cumulative impacts associated with the proliferation of cages in promising areas can exceed the carrying capacity of supporting ecosystems, leading to oxygen depletion and water quality problems that can cause mass fish kills and the failure of businesses (Taskov et al, 2021). • Mechanical damage can lead to large numbers of escapees and ecological perturbations (e.g. harmful algae blooms and jellyfish proliferations) can cause acute problems and fish kills.
Integrated multi-trophic aquaculture (IMTA)	• IMTA combines the culture of fed and extractive species in open-water or land-based systems. • Opportunities to develop diverse production systems create livelihood opportunities for individuals with different levels of wealth and experience. • Culturing multiple species from different trophic levels places added demands on managers and employees who must carry out effective husbandry.	• Capital costs of establishing integrated production systems can be significantly higher than those for monoculture. • Multiple crops can generate more regular cash-flows but the fed animals cultured in IMTA systems that command the highest prices often take several years to reach market size. • Costs of pumping water into land-based marine systems, and to a sufficient height to supply multiple integrated production units, can be prohibitively expensive. • It may not be possible to identify fed and extractive species that are in demand in local or domestic markets, so producers may be exposed to competition internationally.	• Nutrients released from fed animals that dissolve in the water can enhance the growth of algae and plants, while nutrients in particulate matter can be captured and used by filter feeders (e.g. bivalve molluscs). • Key technical challenges include: matching capacity for nutrient assimilation to the rate of release; identifying the optimal location and position in marine ecosystems to cultivate extractive species; maintaining appropriate temperature regimes in land-based systems. • Provision must be made to maintain, treat or harvest production units without adversely affecting the water quality for, or supply of nutrients to, the other species and cohorts of similar species being cultured.

2.4.1. SEMI-INTENSIVE PRODUCTION MODES

Semi-intensive production of finfish covers a broad range of productivity that includes the efficient use of largely natural productivity in ponds, lakes and reservoirs, as well as systems that use significant amounts of feed. This in turn gives rise to a wide range of environmental impacts, but in general these are lower than those of intensive poultry and livestock production (Poore and Nemeck, 2018). Inefficiencies in the use of space and water tend to encourage moves towards greater intensification, which can be sustainable when activities are within the carrying capacity of supporting ecosystems (both locally and globally) and environmental health is protected (Bunting, 2001; Little and Bunting, 2016). Owing to the large volumes of affordable aquatic foods (e.g. Indian major carps, Common carp, Grass carp, Nile tilapia and Striped catfish) produced across a range of semi-intensively managed production systems, they have been termed 'accessible commodities' (Henriksson et al, 2021, p.1225).

2.4.2. INTEGRATED FARMING SYSTEMS

Combined production of terrestrial crops or livestock with aquaculture has been termed Integrated Agriculture-Aquaculture (IAA) and can produce a synergistic effects in terms of mobilizing and utilizing nutrients, thereby generating more regular cash-flows for operators and sustaining biodiversity and ecosystem services (Nhan et al, 2007). Rice-fish culture is an established practice that could be extended to new locations where prevailing conditions are deemed favourable. In Bangladesh, an effective system for rice-prawn farming has been devised by farmers that routinely produces vegetable crops grown on the embankments and a crop of self-recruiting fish species as a second aquatic crop. Nutrient-dense aquatic foods and vegetables that originate from these systems are often important for food and nutrition security in local communities.

2.4.3. RESILIENCE THROUGH DIVERSITY OF PRODUCERS AND PRODUCTION SYSTEMS

Overall, the aquaculture industry requires a rich ecosystem of both small-scale and industrial-scale actors to supply the global seafood market that spans many product categories and a diverse consumer base with myriad requirements. Smallholders create resilience within aquatic animal value chains due to their ability to pivot quickly with dynamic markets; however, smallholders are also most vulnerable (Short et al, 2021). In the best cases, the two systems successfully play off one-another, with prime examples including grow-out programmes and research and development spill-overs. Combining the culture of finfish in cages and bivalve molluscs and seaweed in the same location has been termed Integrated Multi-Trophic Aquaculture (IMTA). This is conceptually appealing as particulate and dissolved nutrients released from the fed part of the system could enhance production of extractive species, for example blue mussels and kelp (Troell et al, 2009). In these systems there may be several different products cultures in one location. Despite a significant amount of research and development, however, outside of China, few commercially viable operations have so far been established (Kleitou et al, 2018). Several practical and financial limitations have arisen when a single operator or production site has tried this approach.

The logistics of raising two species with different and sometimes competing requirements pose several challenges. In a commercial setting, the higher-value culture species is likely to absorb the bulk of attention – especially when the value differences are significant. This can also lead to financial disincentives to maintain the necessary balance for IMTA systems to function successfully. There may also be biosecurity (e.g. potential entry to the local system of pathogens with the stocking of juveniles of the different species) and food safety (e.g. farming of bivalve molluscs in close proximity to finfish that may be treated with veterinary medicines) risks that need to be managed.

Synergies between operators can mimic the benefits of IMTA systems. For example, where multiple operators are using different production systems to produce diverse crops for established markets, synergistic effects across bays in Asia have been observed (Ferreira et al, 2008). When extractive systems are co-located with intensive production units to mitigate environmental impacts, this might assist in securing a licence to operate from the statutory authority. Conversely, when systems rely on a degree of effluent build-up within the ambient water column or benthic environment to stimulate growth of the paired cultured species, their benefits may be severely restricted or impractical in 'low impact' sites where adequate depth and current result in no measurable effluent within an extremely short distance.

2.4.4. OPPORTUNITIES AND CONSTRAINTS ASSOCIATED WITH RESPONSIBLE DEVELOPMENT

Responsible aquaculture development[10] in tanks and small to large ponds can promote economic and social development, even in vulnerable coastal communities (e.g. small pond-based tilapia production in the Solomon Islands and shrimp-fish production in earthen ponds in Bangladesh). Inclusive business models[11] for aquaculture (see Kaminski et al, 2020) have also evolved in peri-urban locations, for example catfish culture in tanks in areas close to large markets in Nigeria and in large wastewater-fed fishponds in Kolkata, India. These are areas where people can suffer from multiple burdens of poverty, including food and nutrition insecurity, insecure living arrangements, poor environmental conditions, and relatively high costs of living (Adeogun et al, 2007; Bunting et al, 2010; Miller and Atanda, 2011; Cleasby et al, 2014; Faruque et al, 2017). High-level and global drivers of change are exerting pressure on producers in both lower middle-income countries (LMICs) and more developed countries to intensify production. Against a backdrop of cost-of-living increases and higher opportunity costs for the time and resources they must invest, producers intensify production to maintain returns for their enterprises, in pursuit of more efficient use of accessible water resources, and to counter a range of competitive pressures.

2.4.5. DEVELOPMENT OPPORTUNITIES ASSOCIATED WITH MARINE FINFISH AQUACULTURE

Although aquaculture now supplies the majority of most seafood categories (e.g. freshwater finfish, algae, molluscs, crustaceans and diamorous fish), it contributes only a small proportion of the overall marine finfish market, which is the largest category of global seafood measured by both volume and value (FAO FishStat, 2019). In 2019, aquaculture supplied only 3.2 million tonnes of marine finfish compared to 66.6 million tonnes supplied from capture fisheries (FAO FishStat, 2019). Assuming marine finfish demand between 2018 and 2050 grows at the same 80% projected for overall seafood – and assuming capture fisheries landings neither expand nor contract – aquaculture will be required to supply more than 55 million tonnes of new farmed marine finfish annually by 2050: nearly 20 times the throughput of today's global salmon industry. This would represent a 17.4 times growth in marine finfish aquaculture production over the period, as compared to an average 0.9 times growth for all other categories of aquaculture (excluding marine finfish) under the same market assumptions. These calculations assume that there would be no substitution for wild caught marine fish by freshwater or brackish farmed products. Historically, there has been widespread and often fraudulent substitution of various red snappers by red tilapia, and of marine white fish with pangasius catfish.

Access to new sites, together with the challenge of financing capital-intensive 'blue economy' systems (Credit Suisse, 2019) are among the main bottlenecks for producers. Issues concerning systems design and species-specific biological requirements may also constitute constraints to sector growth. In addition, it has been noted that a lack of local education and experience in most regions outside of Asia may constrain large-scale, sustained aquaculture development in 'new geographies' (Costa-Pierce and Chopin, 2021, p.23). When marine finfish sectors develop at scale – and are profitable – this can stimulate private and public sector investment in research and development to sustain and enhance production and ensure economic sustainability.[12]

Cage-based production of salmon in marine waters is well established as a highly efficient sector, with notable levels of production in Europe, North America, and South America. Production of Atlantic salmon in cages is typically carried out by large, vertically integrated companies. Economic activity stimulated and sustained by large commercial salmon farming operations has helped maintain communities in remote areas of Canada, Chile, Norway and Scotland, especially as other livelihood options have declined. The salmon sector is a notable success in the development of marine finfish aquaculture (noting that juveniles are raised in freshwater).

An appreciable growth in the market for marine finfish is likely to be driven by higher income and more informed consumers. A critical issue likely to limit market growth is the purchasing power of poorer consumers. The prevailing economics of offshore production mean that production typically favours higher value carnivorous species that are generally not affordable for lower-income consumers. These developments are therefore unlikely to contribute to food and nutrition security in communities at risk of malnourishment (Belton et al, 2020).

2.4.6. LOW-CAPITAL EXPENDITURE SYSTEMS

Low capital expenditure systems are more accessible to small-scale farmers. Limited investment requirements and low barriers to entry make for a high elasticity of supply. These models can therefore be particularly attractive within less developed markets, and play a key role in rural livelihoods and food security. However, that same elasticity of supply constrains profitability potential – particularly in low-value product markets where such systems often exist (e.g. aquatic plants, freshwater finfish, and molluscs). These profitability limitations – together with small possible investment levels – make it difficult for farmers in low capital expenditure systems to obtain external financial resources that might otherwise enable further growth. The need to coordinate a large number of small, independently operating systems also poses regulatory and enforcement challenges.

2.4.7. HIGH-CAPITAL EXPENDITURE SYSTEMS

Systems requiring high levels of capital investment require larger and more sophisticated financing structures and are therefore more often the domain of corporate actors. The high up-front capital costs, combined with common operating cost efficiencies, make these projects highly scalable in their economic structure, with a path to significant profitability where market demand is sufficiently large. Production risks, however, are often significantly increased in these systems. This often results in a focus on high-value product categories (e.g. salmon and marine finfish) and/or export markets, although there are examples of successful industrial-scale operations in lower-value sectors, such as tilapia. Where industrial production overlaps with small-scale market activity, the scalability advantages and superior economic resources of industrial operators can make it difficult for small-scale farmers to compete.

2.4.8. ADVANTAGES OF LARGE-SCALE PRODUCTION

Industrial-scale production play an important and positive role in the aquaculture industry. The long-term investment nature of these projects helps to align the incentives of longer-term performance (and thus sustainability of the local ecosystem) with economic rewards. This alignment is strengthened by a close link between a producer's individual behaviour and consequences for ambient water quality – which may be lost in distributed systems with many small-scale plots. A sophisticated and international financing structure typically requires formalized corporate governance systems. And a large economic footprint motivates investment in value-adding activities, such as research and development, sustainability-label certification, and corporate social responsibility activities, since their costs are amortized over a much larger revenue base. Finally, industrial-scale systems are less likely to fly under the radar of industry and environmental regulators or local media – therefore encouraging compliance, especially where these institutions are strong. A key element of this scenario, however, is the need for a functional duration of the licences granted to aquaculture production business operators to allow them to achieve a return on longer-term investments, illustrating at least one important nexus between investment and regulation.

3 Mapping social, economic and environmental evidence programmes

3.1. Introduction

Reporting on the performance of aquaculture sectors is key to understanding current impacts and unlocking the potential of increased investment. The assessments, programmes and reports reviewed in this section provide evidence of aquaculture's current performance and identify the information that governments, investors and the market need to scale future production. It is important to map these programmes in order to provide more effective ways of linking this knowledge in support of macro-scale ambitions for development. Much of the understanding of aquaculture sustainability is driven by scientific evidence programmes that exist at national, regional and global scales. Programmes are often supported to develop public information that can improve the environmental impact, health, and food safety of aquaculture. Such knowledge frequently feeds into national legislation and subsequent regulatory frameworks. Corporate entities increasingly report on their performance across ESG categories and provide a leading example for others to follow.

3.2. Evidence programmes globally

3.2.1. PROGRAMMES SUPPORTING REGULATION

Imperatives for sustainable development and responsible aquaculture production have been established and agreed internationally (FAO, 1995; and see Table 2). National bodies and international organizations have established portals to disseminate information on the relative sustainability of specific sectors. Regulation and legislation have been developed within counties to varying degrees and institutions and programmes have been designed to target aquaculture research.

3.2.2. PROGRAMMES SUPPORTING CERTIFICATION

Third parties have devised global certification schemes to enable producers, processors, and feed supply chain actors to demonstrate that they are adhering to specific guidelines and reporting requirements (Tacon et al, 2021). Second-party organizations have formulated national certification schemes (e.g. VietGAP). National bodies and international development banks and NGOs (e.g. Asian Development Bank, NACA and WorldFish) have formulated Better Management Practices (BMPs)[13] for various sectors and issues of concern. These programmes are generally built on the current level of knowledge at the time of commissioning and often include regular review processes to take into account the continual developments in knowledge about aquaculture management.

3.2.3. PROGRAMMES SUPPORTING OTHER APPROACHES

At international and national levels, members of producer organizations representing specific sectors have committed themselves to codes of conduct and adhering to best practices. Such approaches are generally based on evidence programmes developed through a range of drivers for regulation and certification, as well as independently. There are also examples that combine this information into risk-based approaches that are directly relevant to managing aquaculture's environmental impacts.

3.2.4. GENERAL POINTS

In this section, we review the information that is currently publicly available on the main evidence programmes that support and promote responsible aquaculture. An analysis of the coverage of criteria and issues relevant to sustainable aquaculture production by individual schemes within different types of evidence programmes has been undertaken in detail and a summary is presented in Table 4. By conducting a comprehensive assessment across a broad array of schemes, general gaps can be identified within a particular type of evidence programme. By visualizing the coverage of each scheme, it is possible to see which ones provide the most comprehensive public reporting on their performance.

Regarding producer organizations, of the ten schemes assessed, six reported on certification and five covered social issues. None of the schemes shared information on food quality and nutrition, sustainable livelihoods, risks, or recommendations. The most comprehensive scheme made information available for 10 of the 22 criteria evaluated, whereas one initiative addressed only 3.

Regarding aquaculture sustainability and production portals, the most comprehensive initiative included 14 of the criteria being reviewed, while the majority only addressed between 1 and 3. Of the twenty initiatives evaluated, nine reported the level of production or the number of farms, and five covered licensing and water quality. In the group classified as aquaculture and fisheries regulation and research bodies, the two most comprehensive schemes covered 6 of the criteria evaluated.

Variations in the public reporting of performance criteria by aquaculture certification bodies was notable, with one presenting 14 and the remaining three addressing 3 or less. All four of the initiatives reviewed covered certification and the volume of production or number of farms, but 7 criteria (food safety, food quality and nutrition, escapees, sustainable livelihoods, animal welfare, risks and recommendations) were not addressed by any of them.

As shown in the sustainability assessment and aquaculture ratings reviewed in Table 4, the Sustainable Fisheries Partnership (SFP) FishSource Aquaculture profiles and MBAq Seafood Watch reports were the most comprehensive – covering 15 and 13 criteria, respectively. None of the reports included information on food quality and nutrition, sustainable livelihoods, or economy.

Among the company sustainability reports assessed, the most comprehensive covers 12 key aspects and two schemes cover 10. However, aspects of legislation, licensing, health (mortalities), and recommendations were not covered by any of the 14 reports evaluated.

Table 4: Evidence programmes that report on the performance of sustainable aquaculture[14]

Evidence programme	Certification	Legislation	Licencing	Production/farm number	Food safety	Food quality and nutrition	Environmental surveys (inc. EIA)	Health (diseases)	Health (mortalities)	Chemical use / Disease treatments	Water quality	Escapees	Feed	Sustainable livelihoods	Social	Economy	Animal welfare	Habitat	Energy/GHG	Risks	Recommendations	Others
Producer Organisations																						
Global Salmon Initiative - Sustainability Report	X	X						X	X	X		X	X		X							
SalmonChile - Sustainability report	X							X	X	X		X			X							
Scottish Salmon Producers Organization (SSPO)								X	X						X							X
Sustainable Shrimp Partnership	X									X	X											X
Vietnam Pangasius Association - Smart Pangasius map	X			X																		X
A+ New Zealand Sustainable Aquaculture	X				X		X				X		X		X		X	X	X			X
BC Salmon Farmers Performance Dashboard and map	X		X	X				X		X		X	X		X	X			X			
Aquaculture Sustainability and Production Portals																						
Scotland's Aquaculture			X	X			X	X	X	X	X	X										
Scotland's seas											X											
BarentsWatch - Fish health			X					X		X												
BarentsWatch - Sustainability in aquaculture			X	X	X	X	X	X	X	X		X	X		X	X			X			X
Vann-nett Portal											X											
Certs and ratings - Data tool	X			X																		
SFP's T75 Initiative dashboard	X			X																		X
Satu (One) Data																						
Agri Map				X																		X
FAO Fishstat J				X																		
FAO National Aquaculture Sector Overviews		X		X																		
FAO National Aquaculture Legislation reviews		X	X		X		X	X		X	X		X					X				X
FishBase				X		X	X	X					X									
AquaScape				X							X											X
AP Aquaculture Information System			X																			
ITC Trade Map																X						
EU Inform Risk Portal														X								X
indexmundi																X						
Department of State - Trafficking in Persons report														X								

Table 4: Evidence programmes that report on the performance of sustainable aquaculture (continued)

Evidence programme	Certification	Legislation	Licencing	Production/farm number	Food safety	Food quality and nutrition	Environmental surveys (inc. EIA)	Health (diseases)	Health (mortalities)	Chemical use / Disease treatments	Water quality	Escapees	Feed	Sustainable livelihoods	Social	Economy	Animal welfare	Habitat	Energy/GHG	Risks	Recommendations	Others
Aquaculture and Fisheries Regulation & Research Bodies																						
Scottish Pollutant Release Inventory (SPRI)*										X	X											X
SEPA Compliance Assessment Schemes - Assessment reports*			X																			
Marine Scotland Science - Locational guidelines for the authorization of marine fish farms in Scottish Waters			X				X				X											
Fiskeridirektoratet - Figures and analysis: aquaculture			X	X						X		X				X						X
Fiskeridirektoratet - allocation and permits		X	X				X	X														
Yggdrasil				X			X	X				X						X				X
Coastal Aquaculture Authority (CAA) - Farms	X	X	X	X																		
FDA Import Alerts					X																	
European Commission - Rapid Alert System for Food and Feed (RASFF) Portal					X																	
Fish Health Inspectorate case information (farms and hatcheries)								X														
World Organisation for Animal Health - OIE World Animal Health Information System								X	X													
National surface water quality automatic monitoring real-time data											X											
DFO Regulations and compliance							X	X														
BFAR fisheries and aquaculture statistics				X																		
OpenSTAT - Philippine Statistics Authority - Agriculture, Forestry, Fisheries				X																		
World Bank Open Data							X							X	X	X			X			
IMR - Sea lice Map			X	X				X														
Norwegian Veterinary Institute health status of farmed fish								X	X	X												
Aquaculture Certification Bodies																						
ASC Impacts Dashboard	X			X												X						
ASC Find a Farm	X	X	X	X			X	X	X	X	X		X		X			X	X			X
BAP - Certified facilities				X																		
GlobalG.A.P database	X																					
Fisheries Commodity Standard System and Traceability Division -certification database	X			X																		
Department of State - Trafficking in Persons report														X								

Table 4: Evidence programmes that report on the performance of sustainable aquaculture (continued)

Evidence programme	Certification	Legislation	Licencing	Production/farm number	Food safety	Food quality and nutrition	Environmental surveys (inc. EIA)	Health (diseases)	Health (mortalities)	Chemical use / Disease treatments	Water quality	Escapees	Feed	Sustainable livelihoods	Social	Economy	Animal welfare	Habitat	Energy/GHG	Risks	Recommendations	Others
Sustainability Assessments & Aquaculture Reports																						
SFP FishSource Aquaculture profiles	X	X	X	X	X		X	X	X	X	X		X		X			X		X	X	
MBAq Seafood Watch reports		X	X	X			X	X	X	X	X	X	X					X		X	X	
Marine Conservation Society - Good Fish Guide	X	X					X						X				X					
Ocean Disclosure Project	X	X	X				X	X		X	X		X								X	
China Blue				X							X											
Kontali - Seafood Tip - sourcing intelligence	X			X			X								X					X		X
FAO State of Fisheries and Aquaculture reports (SOFIA)		X		X											X				X		X	X
AIP Directory				X											X					X	X	X
SeaFish aquaculture profiles	X	X		X				X		X	X	X	X					X			X	
iFISH	X				X		X															
Company Sustainability Reports																						
MOWI Sustainability Policies					X		X	X		X	X		X		X		X		X			
MOWI Sustainability Strategy and annual/quarterly reports	X					X		X		X	X	X	X		X	X	X		X			X
Biomar Sustainability report and KPIs	X				X						X		X		X		X		X			X
Skretting - a Nutreco company - Sustainability reporting	X										X		X		X				X			X
Cargill	X			X							X		X	X	X		X	X	X			X
CP - Sustainability and sustainability reports										X	X		X		X		X	X	X			X
Thai Union - Sustainability and reports	X						X				X				X	X			X			X
Walmart Environmental, Social & Governance Reporting and summary	X				X	X								X	X	X	X	X	X			X
Asda - Better Planet	X														X				X			X
Co-op - Sustainability and the Future of Food and sustainability reports																						X
Tesco - Sustainability webpage and annual reports and fact sheets	X							X			X				X	X	X		X			X
Marks & Spencer - Sustainability and sustainability reports & Interactive map	X			X										X	X				X			X
El Corte Ingles Spain Sustainability and reports															X				X			X
Shoprite South Africa - Sustainability report															X	X		X	X	X		X

3.2.5. COVERAGE OF CERTIFICATION SCHEMES

Globally, third-party voluntary certification schemes are primarily targeted at meeting the requirements of buyers and consumers in North America and Western Europe (Bush et al, 2013). When certification is not a prerequisite for accessing a particular market there may be little incentive for producers to engage with voluntary certification schemes. Some producers may also be deterred from joining selected schemes due to the costs of certification, especially for smaller businesses, or difficulties in understanding the requirements. For example, the Global Good Agricultural Practice (GlobalGAP) and ASC standards for sludge tank provision and management requirements are difficult to follow and audit (Kalfagianni and Pattberg, 2013). Second-party schemes (e.g. VietGap, ThaiGAP, IndoGAP) have been developed to encourage producers and processors to engage with a national certification scheme designed to improve the food safety standards of aquaculture products destined for export markets.

The consequences of third- and second-party certification for small-scale producers in LMICs and local communities have not been comprehensively studied. Certification bodies understand this challenge and are attempting to be more inclusive by developing improvement project models and group certification, although uptake has so far been limited (Bottema et al, 2021). Small-scale producers can be marginalized in export markets, as they are unable to meet expensive certification requirements, but are not eliminated due to their ability to supply local demand and to pivot quickly within dynamic markets (Belton et al, 2011; Belton et al, 2019). A more nuanced categorization is required, depending on the degree of commercialization, as some small-scale production is specifically commercially oriented (Bush et al, 2019) and may enter certified supply chains.

3.2.6. ANIMAL WELFARE CONSIDERATIONS

Standards aimed at improving animal welfare (throughout production and slaughter) are increasingly receiving attention, particularly in Western markets. These new scientific insights are not yet consistently included in aquaculture standards, but the need for welfare considerations is included in the FAO Code of Conduct for Responsible Fisheries and in some specific retailer standards. Concern among consumers regarding this issue varies significantly, as does the evidence of producers using best practices, with action often driven by market demand.

Welfare standards in aquaculture are not only motivated by altruism: improved aquatic animal welfare increases product quality and reduces the risk of disease. Without access to appropriate knowledge of best practices, or the establishment of sector-specific rules and regulations, producers may not be aware of which husbandry and harvest strategies are essential to adopt from an animal, environmental or human health perspective. Consumers may be placed at greater risk from food safety hazards and receive suboptimal-quality products in terms of appearance, freshness, nutrition, odour or taste. A further complication is that recognized animal welfare standards do not exist for 70% of farmed aquatic species (Franks et al, 2021).

3.2.7. ZONING AND POLICY DEVELOPMENT

Guidelines have been proposed for aquaculture planning and policy development (FAO, 2008), enacting an ecosystem approach to aquaculture (FAO, 2010), and the establishment of zoning arrangements to regulate development, maximize the use of land and water resources, and minimize conflicts (FAO, 2017). Questions remain, however, regarding how best to incorporate evidence from the most recent scientific findings, and insights from third - and second-party certification schemes, into these guidelines – as well as into Better Management Practices (BMPs) and other policies, legislation and regulations – in order to:

- engender responsible practices across aquatic food systems, from production to consumption, waste reduction, and reuse;
- address cumulative impacts and risks across landscapes;
- protect animal, environment and human health;
- address the legitimate concerns and interests of stakeholders, especially local communities and consumers;
- encourage contextually appropriate management changes and technology adoption.

3.3. Research systems in selected countries

3.3.1. INTRODUCTION

This section summarizes the current status of aquaculture research systems in a selection of countries with strong or rapidly developing aquaculture sectors. The assessment provides a measure of the new knowledge being developed that can inform policy, support commercial development, drive innovation, and help ensure sustainability. It also reviews funding systems, availability of government research institutes and/or universities, the involvement of NGOs and companies, research topic priorities, and drivers of research topics. The 13 countries are: Australia, Bangladesh, Chile, China, Ecuador, Egypt, India, Norway, Saudi Arabia, South Africa, Thailand, United Kingdom and Vietnam.

3.3.2. FUNDING AND RESEARCH SYSTEMS

Australia, Chile, China, India, Norway and the UK have well established funding systems, as indicated by at least four diversified government institutions providing funds for research (see Table 5). Thailand, Vietnam, Bangladesh, Ecuador, South Africa, Egypt and Saudi Arabia have one or two government funding bodies. However, it is often challenging to identify clear, publicly available information on the funding that goes to aquaculture research.
Some government funding programs (e.g. Sustainable Aquaculture Innovation Centre – SAIC and Biotechnology and Biological Sciences Research Council in the UK) have company consortium members across the value chain which contribute to their funding system. Funding is awarded up to a maximum of 50% of the total project cost to companies, 80% to Higher Education Institutions. Both the UK and Norway participate in collaborative projects funded through the European Union (e.g. Horizon 2020, Horizon 2021-2027), but Norwegian institutions also benefit from the Nordic Research and Innovation Programme for Sustainable Aquaculture.

Table 5: Government institutions funding aquaculture research and innovation

Country	Government Funding Institutions
Australia	**1)** Australian Research Council, **2)** Fisheries R&D Corporation; **3)** Australian Centre for International Agricultural Research; **4)** Cotton Catchment Communities CRC; **5)** Australian Department of Agriculture, Fisheries and Forestry; **6)** The National Aquaculture Council
Bangladesh	**1)** Ministry of Fisheries and Livestock
Chile	**1)** Fishery and Aquaculture Research Fund **2)** National Commission for Scientific and Technological Research; **3)** The National Fund for Scientific and Technological Development; **4)** Fondo de Financiamiento para áreas Prioritarias; **5)** The Production Development Corporation
China	**1)** Chinese Academy of Fishery Science; **2)** China Academy of Science; **3)** Ministry of Rural Agricultural and Rural Affairs; **4)** Ministry of Science and Technology
Ecuador	**1)** Secretariat of Higher Education, Science, Technology and Innovation; **2)** National Research Fund for Fishery and Aquaculture
Egypt	**1)** Agricultural Research Centre
India	**1)** Indian Council of Agricultural Research; **2)** Ministry of Science and Technology; **3)** Ministry of Fishery, Animal Husbandry and Dairying; **4)** Indian Agricultural Research Institute
Norway	**1)** Norwegian Seafood Research Fund; **2)** The Nordic Research and Innovation Programme for Sustainable Aquaculture; **3)** The Norwegian state v/Ministry of Trade, Industry and Fisheries; **4)** The Research Council of Norway; **5)** The Fishery and Aquaculture Research Fund; **6)** The research funding for agriculture and food industry and partner companies; **7)** European Union- HORIZON 2020
Saudi Arabia	**1)** Ministry of Environment, Water & Agriculture; **2)** National Fisheries Development Program; **3)** National Industrial Development and Logistics
South Africa	**1)** National Research Foundation
Thailand	**1)**Thailand Research Fund
UK	**1)** Sustainable Aquaculture Innovation Centre; **2)** UK Seafood Innovation Fund; **3)** UK Aquaculture Initiative (joint of Biotechnology and Biological Sciences Research Council, and Natural Environment Research Council); **4)** Centre for Applied Marine Sciences; **5)** European Union - Horizon 2020
Vietnam	**1)** Ministry of Agriculture and Rural Development

As Table 6 shows, China and the UK have more non-profit and other institutions involved in their aquaculture research and funding systems than any other countries. In Chile, Norway, Saudi Arabia and the UK, the non-profit and other organizations supporting the aquaculture sector are primarily based locally, while in other countries (e.g. Bangladesh, China, Egypt, India, South Africa, Thailand and Vietnam), most of the organizations involved are international. Overall, aquaculture research and innovation in developing and emerging countries is financially supported by international organizations and government development agencies from developed countries. Furthermore, some higher education and research institutions in developed countries (e.g. the Centre for Environment, Fisheries, and Aquaculture Science (CEFAS) in the UK, James Cook University in Australia, and the University of Stirling in the UK have research projects in developing and emerging countries in collaboration with local institutions or organizations.

Table 6: Other organizations involved in aquaculture research and innovation funding

Country	Other organizations
Bangladesh	**1)** WorldFish; **2)** USAID; **3)** Consultative Group on International Agricultural Research(CGIAR); **4)** Asian Development Bank (ADB); **5)** UK Aid Direct; **6)** Danish International Development Agency (DANIDA); **7)** World Bank; **8)** FAO; **9)** International Fund for Agricultural Development (IFAD)
Chile	1) Centro Experimental Quillaipe - Salmofood-Vitapro; 2) Club Innovación Acuícola
China	**1)** The Pew Charitable Trusts; **2)** German Ministry of Education and Research; **3)** Asian Fisheries Society; **4)** Network of Aquaculture Centres in Asia Pacific (NACA); **5)** FAO; **6)** United Nations Industrial Development Organization (UNIDO) **7)** World Organisation for Animal Health; **8)** The Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR); **9)** The North Pacific Marine Science Organization (PICES)
Ecuador	
Egypt	**1)** WorldFish Center; **2)** USAID; **3)** Centre for Environment, Fisheries, and Aquaculture Science (ESRC), UK; **4)** FAO
India	**1)** WorldFish; **2)** FAO; **3)** ESRC - UK; **4)** Network Program on Antimicrobial Resistance (AMR)
Norway	**1)** The Royal Norwegian Society for Development (Norges Vel); **2)** WWF; **3)** NCE Seafood Innovation
Saudi Arabia	**1)** Saudi Aquaculture Society, FAO
South Africa	**1)** French National Research Institute for Sustainable Development (IRD); **2)** European Union- Horizon 2020
Thailand	**1)** Worldfish; **2)** Shrimp-pathogen interaction (SPI) Laboratory; **3)** International Development Research Centre (IDRC) Canada; **4)** UK Research and Innovation (UKRI); **5)** Australian Centre for International Cultural Research; **6)** The British Council
UK	**1)** Marine Conservation Society; **2)** WWF; **3)** European Union - Horizon 2021-2027; **4)** Thinkaqua; **5)** Global Seafood Alliance; **6)** Worldfish; **7)** Commonwealth Scholarship scheme; **8)** FAO; **9)** Fish Health Inspectorate; **10)** Environment Agency; **11)** Marine Management Organisation; **12)** Animal and Plant Health Authority; **13)** The Crown Estate; **14)** Agri-Food in Biosciences Institute; **15)** Scottish Environment Agency; **16)** British Aquaponics Association; **17)** Association of Scottish Shellfish Growers
Vietnam	**1)** WWF; **2)** USAID; **3)** Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

3.3.3. GOVERNMENT RESEARCH INSTITUTES, UNIVERSITIES, AND COLLEGES

Each country assessed has at least three government research institutions involved in aquaculture, except in Bangladesh, Chile, Egypt and South Africa which have fewer (see Table 7). Among developed and emerging countries, there are at least seven higher education institutions, while in developing countries there are fewer, except in Bangladesh where there are 13. Information on institutions from developing countries and the source of some research funding is occasionally not available. Institutions from developed countries generally have stronger internal (within the country) and external (overseas) collaborative research projects. For example, the University of Stirling in the UK and the James Cook University in Australia contribute significantly to global sustainable aquaculture research through projects across Asia, Europe, Africa and South America. In addition, CEFAS (UK), Nofima (Norway), and the Australian Centre for International Agricultural Research all play a key role in international research work.

Table 7: Government research institutes and universities and colleges involved in aquaculture research

Country	Government research institutes	Universities and colleges
Australia	**1)** Australian Genome Research Facility; **2)** Fisheries Research and Development Corporation; **3)** South Australian Research and Development Institute; **4)** Australian Centre for International Agricultural Research; **5)** Australian Seaweed Institute	**1)** James Cook University; **2)** University of Queensland; **3)** University of Tasmania; **4)** Deakin University; **5)** Queensland University of Technology; **6)** University of NSW; **7)** Newcastle University; **8)** University of Sunshine Coast; **9)** Flinders University; **10)** Victoria University; **11)** Macquarie University; **12)** University of Western Sydney
Bangladesh	**1)** Bangladesh Fisheries Research Institute; **2)** Bangladesh Agricultural Research Council	**1)** Bangladesh Agricultural University; **2)** Sher-e Bangla Agricultural University; **3)** Anowara College of Bioscience; **4)** Khulna University; **5)** University of Dhaka; **6)** Rajshahi University; **7)** Hajee Mohammad Danesh Science and Technology University; **8)** Noakhali Science and Technology University; **9)** Sylhet Agricultural University; **10)** Jessore University of Science and Technology; **11)** Patuakhali Science and Technology University; **12)** Bangabandhu Sheikh Mujibur Rahman Agricultural University; **13)** Chittagong Veterinary and Animal Sciences University
Chile	**1)** Interdisciplinary Center for Aquaculture Research; **2)** Fundación Chile	**1)** Universidad Austral de Chile; **2)** Universidad Santo Tomás; **3)** Pontifica Universidad Catolica de Valparaiso; **4)** Universidad de Chile; **5)** Universidad Catolica de Temuco; **6)** Universidad de Antofagasta; **7)** Universidad Andres Bello; **8)** Universidad de Magallanes
China	**1)** South China Sea Fisheries Research Institute; **2)** Chinese Academy of Fishery Science; **3)** Yellow Sea Fisheries Research Institute; **4)** Freshwater Fisheries Research Center; **5)** Pearl River Fisheries Research Institution	**1)** Ocean University of China; **2)** China Agricultural University; **3)** Huazhong Agricultural University; **4)** Southwest University; **5)** Nanchang University; **6)** Hainan University; **7)** Hunan Agricultural University; **8)** Ningbo University; **9)** Shanghai Ocean University; **10)** Anui Agricultural University; **11)** Guangdong Ocean University; **12)** Dalian Ocean University; **13)** Tianjin Agricultural University; **14)** Huaihai Institute of Technology; **15)** Shanghai Jiao Tong University; **16)** Sun Yat-sen University
Ecuador	**1)** National Center for Aquaculture and Marine Research - CENAIM; **2)** The National Fisheries Institute; **3)** Instituto Público de Investigación de Acuicultura y Pesca - IPIAP	**1)** Littoral Polytechnic School (ESPOL); **2)** Universidad Técnica de Manabí; **3)** Universidad Técnica de Machala; **4)** Universidad Estatal Peninsula de Santa Elena; **5)** Universidad Técnica Estatal de Quevedo; **6)** Instituto Tecnológico Superior Luis Arboleda Martinez
Egypt	**1)** National Institute of Oceanography and FIshery; **2)** Central Laboratory for Aquaculture Research	**1)** Arab Academy for Science, Technology and Maritime Transport; **2)** Arish University; **3)** Suez Canal University; **4)** The American University in Cairo

Table 7: Government research institutes and universities and colleges involved in aquaculture research (continued)

Country	Government research institutes	Universities and colleges
India	**1)** Central Marine Fisheries Research Institute; **2)** Central Inland Fishery Research Institute; **3)** Central Institute of Fisheries Technology; **4)** Department of Biotechnology; **5)** Central Institute of Freshwater Aquaculture; **6)** Central Institute of Brackishwater Aquaculture; **7)** Directorate of Coldwater Fisheries Research	**1)** Acharya Nagarjuna University; **2)** Adikavi Nannaya University; **3)** College of Science and Technology; **4)** Government Arts College for Men (Autonomous); **5)** Patna University; **6)** Sacred Heart College; **7)** Sri Venkateswara University; **8)** Vidyasagar University
Norway	**1)** The Research Council of Norway; **2)** Institute for Marine Research; **3)** Nofima	**1)** Norwegian College of Fishery Science; **2)** Norwegian University of Life Sciences; **3)** University of Bergen; **4)** Norwegian University of Science and Technology; **5)** Norwegian University of Life Sciences; **6)** University of Nordland; **7)** Norwegian Veterinary Institute
Saudi Arabia	**1)** Fish Culture Project of the King Abdulaziz City for Science and Technology; **2)** National Fish Farming Center; **3)** Jeddah Fisheries Research Center	**1)** King Abdulaziz University; **2)** King Faisal University; **3)** King Saud University; **4)** King Abdullah University of Science and Technology
South Africa	**1)** South African Institute for Aquatic Biodiversity	**1)** University of Cape Town; **2)** Rhodes University; **3)** Stellenbosch University; **4)** University of Limpopo; **5)** University of the Western Cape; **6)** University of Kwazulu Natal
Thailand	**1)** Inland Aquaculture Research and Development Division; **2)** Coastal Aquaculture Research and Development Division; **3)** Aquatic Animal Genetics Research and Development Division; **4)** Aquatic Animal Genetics Research and Development Division, Aquatic Animal Feed Research and Development Division; **5)** National Center for Genetic Engineering and Biotechnology; **6)** The National Science and Technology Development Agency	**1)** Asian Institute of Technology – Aquaculture; **2)** Chulalongkorn University
UK	**1)** Marine Scotland Science; **2)** Freshwater lab Pitlochry; **3)** Marine lab Aberdeen; **4)** The Centre for Environment, Fisheries and Aquaculture Science	**1)** University of Stirling, **2)** University of St Andrews; **3)** Scottish Association of Marine Science; **4)** University of the Highlands and Islands; **5)** North Atlantic Fisheries College; **6)** University of Edinburgh; **7)** Swansea University; **8)** University of Exeter; **9)** University of Plymouth; **10)** Aberdeen University; **11)** Bangor University; **12)** Bridgewater College; **13)** Easton and Otley College; **14)** Glasgow University; **15)** Hadlow College; **16)** Harper Adams University; **17)** Heriot-Watt University; **18)** Liverpool University; **19)** Napier University; **20)** Newcastle University; **21)** Queens University; **22)** Sparsholt College; **23)** Southampton University; **24)** York University; **25)** Scottish Rural College
Vietnam	**1)** Research Institutes for Aquaculture 1 (Hanoi); **2)** Research Institutes for Aquaculture 2 (HCMC); **3)** Research Institutes for Aquaculture 3 (Nha Trang)	**1)** Can Tho University; **2)** An Giang University; **3)** Nong Lam University; **4)** Nha Trang University; **5)** Vietnam National University

3.3.4. COMPANIES INVOLVED IN AQUACULTURE RESEARCH AND COLLABORATING INSTITUTIONS

Many companies in developed countries (e.g. UK, Norway and Australia) are actively involved in research projects through funding, setting up research and development facilities, and running in-house research and collaborative works with other institutions (see Table 8). Although China, India, Chile, Ecuador, Thailand, Vietnam, Egypt are among the key global aquaculture producers, information regarding the commitment of companies in these countries to research work is not widely available, although some examples are known (e.g. Inve Aquaculture – Thailand, Syaqua Siam – Thailand, Skretting – Ecuador, Vitapro Chile – Chile).

Table 8: Companies and other institutions involved in aquaculture research

Country	Organizations
Australia	**1)** Mainstream Aquaculture Group; **2)** Seafarms Group; **3)** Cygnet Bay Pearls; **4)** The Company One; **5)** Sea Forest; **6)** Select Oyster Company; **7)** Southern Cross Shellfish Ltd; **8)** United Soybean Board; **9)** Ridley Aquafeeds; **10)** Australian Seafood Industries; **11)** Hunter Central Rivers Catchment Management Authority; **12)** Waratah Power and Energy Australia; **13)** Huon Aquaculture, Seafood CRC; **14)** Cotton Catchment Communities CRC
Chile	**1)** Vitapro Chile; **2)** Aqua Pacífico - Centro de Inovación Acuícola
China	**1)** AquaBiotech Group; **2)** MingBo Aquatic
Ecuador	**1)** Skretting; **2)** Inve Aquaculture; **3)** Aquatropical; **4)** Aquagen
Egypt	**1)** Skretting; **2)** MSD
India	**1)** Coastal Aquaculture Research Institute Private Limited; **2)** Skretting; **3)** AS Agri and Aqua LLP
Norway	**1)** NCE Seafood Innovation has several company members across the value chain: feed, engineering, fish producers, processors, algal companies, health, genetics
Saudi Arabia	**1)** National Aquaculture Group; **2)** Tabuk Fisheries; **3)** Tharawat Seas; **4)** Aquabridge
South Africa	**1)** Marine Research Aquarium
Thailand	**1)** Inve Aquaculture (Benchmark Animal Health); **2)** Syaqua Siam; **3)** CP Foods
UK	**1)** SAIC has 240 company members across the value chain: feed, engineering, fish producers, processors, algal companies, health, genetics
Vietnam	**1)** Shrimp Vet company/lab; **2)** Bo De Fisheries Group Joint Stock Company

3.3.5. DRIVERS OF RESEARCH TOPICS

Regardless of the region where the research is conducted, the main drivers determining which topics are focussed on are industry development, advancing knowledge and developing technology that is important for aquaculture sustainability, and addressing any challenges the industry faces. Overall, the key drivers of research topics across the 13 countries include:

- Industry
- Policy and regulation
- High-quality basic, strategic and applied research
- Advancing knowledge and technology
- Product development
- Market and consumers

3.3.6. RESEARCH TOPICS

According to Engle, et al. (2018), market and consumer demand, diet ingredients and additives, genetics, health and survival, economics and regulation, technology and systems, and climate change and sustainability will be the aquaculture research priorities for the next decade. The countries assessed were found to share similar research topics, including:

- Environmental issues
- Health and welfare
- Feed and nutrition
- Nutrition and livelihood
- Environment carrying capacity
- Governance
- Feed alternatives
- Circular economy
- Artificial intelligence
- Food security
- Food safety
- Breeding and genetics
- New farming practices
- Integrated aquaculture
- Potential of new species for aquaculture
- Suitable areas for aquaculture (e.g. offshore areas)
- Water quality and treatment
- Farming technology (e.g. RAS and Biofloc technology - BFT)

4 Knowledge base relating to aquaculture governance

4.1. The role of governance in aquaculture

Governance of aquaculture is important to support the goal of sustainable intensification (Garrett et al, 2013). Good governance of aquaculture can be defined as: "a supportive state whose regulations and policies provide security for stakeholders to prosper while maintaining social harmony and stewardship of the natural environment" (Davies et al, 2019). Understanding demand (i.e. consumer needs) is critical for developing more sustainable aquaculture value chains and legislation (Little et al, 2018). As aquaculture sustainably grows and intensifies, a key considerationis that governance should be framed around the 'One Health' lens (Stentiford et al, 2020). Under this lens, aquaculture governance should support food safety and quality, the environment, animal health and welfare, competitive marketplaces, equitable societies, and human health (Krause et al, 2015).

4.1.1. THE AIMS OF GOVERNANCE

Governance is important to ensure that aquaculture complies with broader values. The main purposes of governance for aquaculture production are to:

- ensure environmental management and animal welfare standards;
- provide safety, quality and health assurances for consumers;
- support national food security and economic targets;
- encourage competitive markets with equitable access;
- promote long-term, sustainable industry success and positive contributions to local economies.

4.1.2. ENVIRONMENTAL AND MARKET IMPACTS OF INSUFFICIENT GOVERNANCE

A lack of governance has been associated with environmental degradation throughout the world. For example, the lack of spatial planning and governance in the shrimp industry has had a negative impact on mangrove forests in India (Belton et al, 2017), Thailand (Belton and Little, 2008) and Ecuador (Parks and Bonifaz 1994). Governance and policy can influence both the growth rates and environmental impact of aquaculture, as exemplified in these two contexts:

- In Vietnam's Mekong Delta, land policies were driven by economic incentives, such that mangroves were rapidly converted into aquaculture farms throughout the 1980s. Although the government realized the impact that the intensification was having on mangroves, and put restrictions into place in the 1990s, aquaculture continued to grow, fuelled by the initial explosion supported by government policies (Liu et al, 2020);

- In Bangladesh, both mangrove degradation due to shrimp production and subsequent reforestation has been attributed to changes in regulatory frameworks (Islam et al, 2018; Islam et al, 2019).

Globally, mangrove destruction from shrimp production has decreased dramatically in recent years due stricter government regulations (Boyd et al, 2021; Davis et al, 2021). Yet, despite the improvements in practice the public continues to have a negative perception of shrimp aquaculture's environmental impact, driven by the overwhelmingly negative media portrayal of aquaculture (Newton et al, 2019). Because of this, many consumers still may choose 'wild-caught' shrimp over cultured shrimp because they believe it to be a more ethical alternative. Consumers' misconception that 'wild' aquatic foods are better than 'cultured' is pervasive. Aquaculture is still criticized for its reliance on fisheries, even though aquaculture is now a net producer of fish (Kok et al, 2020).

4.1.3. SOCIAL IMPACTS OF INSUFFICIENT GOVERNANCE

Governance that neglects stakeholder engagement in the decision- and policy-making process has contributed to poor social sustainability (Krause et al, 2015). In order to provide equitable access to markets, property and labour rights should always be considered in the governance and management of aquaculture (Belton et al, 2011).

Governance should encourage competitive aquaculture markets by supporting equitable access to suppliers of all scales. The importance of smallholders to resilient aquaculture value chains is clear: smallholders' unique ability to pivot supports dynamic markets (Short et al, 2021). The aquatic food value chain in Bangladesh is overwhelmingly serviced by smallholders. Collectively they produce a vast amount of fish to supply the massive domestic market, including millions of very low-income households. Large-scale industrial farms play important roles as well, and their significant economic footprint attracts substantial investment capital to the sector (Credit Suisse, 2018). Their ability to deliver large volumes of seafood to international markets also makes a significant and positive contribution to the challenge of feeding the growing global demand for seafood.

Aquaculture governance has been criticized for being inequitable, and the lack of gender responsive legislation has impacted negatively on the performance of aquaculture value chains (Kruijssen et al, 2018).

4.1.4. EXCESSIVE GOVERNANCE LIMITS DEVELOPMENT

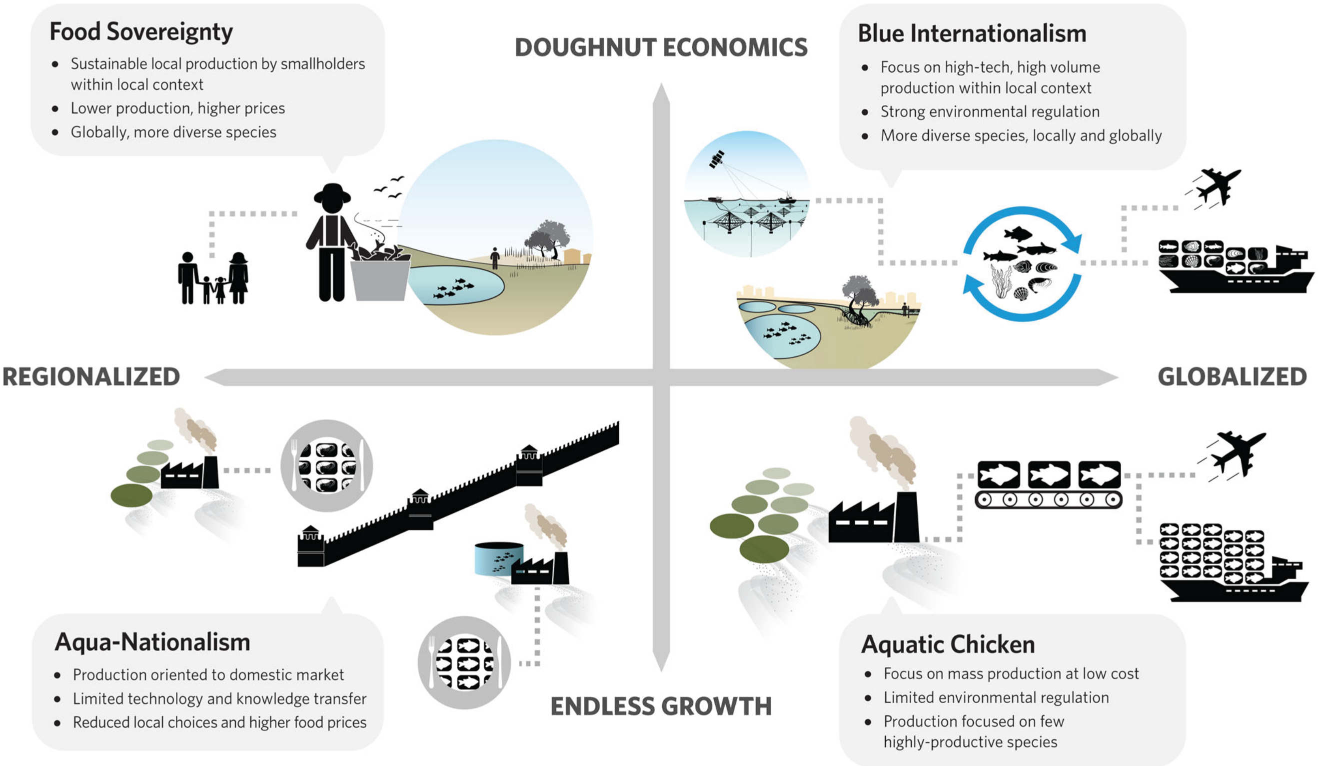
Overly restrictive governance can also create challenges by restricting even responsible aquaculture production in places where it could otherwise have positive impacts, including by supplying markets with alternative production that lowers net negative impacts. This occurs mainly in developed countries, such as the United States and the United Kingdom, where public opinion tends to be more negative. In contrast, media and public perception of aquaculture is increasingly positive in developing nations (Froehlich et al, 2017a). Concerns are often based on farming practices that have now been discontinued by many or most operators, and ecological damage by farms in poorly-selected sites that could be avoided by following current industry science. Reduction in the use of marine ingredients in feeds is a good example of where public understanding has not caught up with current practice (Kok et al, 2020).

Blanket prohibitions on new production by overly restrictive governance reduces the potential of responsible aquaculture to positively contribute to host ecosystems by providing associated ecosystem services and economic opportunities.

4.1.5 CONCERN OVER LOCAL IMPACTS SHIFTS THEM ELSEWHERE

Furthermore, in high-income countries without well-established aquaculture traditions, competing interests for waterway use can preclude nearly all forms of production. These interests often include leisure and lifestyle considerations which, while valid, can result in negative net outcomes. Competing interests among leisure and other users can drive lobbying efforts, whether explicitly or tacitly, but these dominating preferences may lead to overreliance on importing products from LMICs. Continual import of aquaculture products, while useful for supporting socio-economic priorities in many of the LMICs that produce these fish, essentially just translocates the environmental impact of those products outside the high-income countries. This creates an economic model similar to an 'aquatic chicken', focused on mass production at low costs for only a few high-performing species with limited environmental regulations (Gephart et al, 2020). A better model would be 'blue internationalism', focused on high-tech, high-volume production across a variety of species specific to the context in which they are grown, and strong environmental regulations (ibid). Figure 1 (from Gephart et al, 2020) compares various scenarios for the global aquaculture trade and recommends 'blue internationalism' as the best outcome.

Figure 1: Four extreme scenarios for the global aquaculture trade, with indicated benefits and tradeoffs (reproduced from Gephart et al 2020).



4.2. Considerations on governance

The three main levels of aquaculture governance are: (1) national (legal) regulations; (2) certification schemes; and (3) alternative and voluntary schemes. In this section, we summarize each type.

4.2.1. NATIONAL REGULATIONS

National regulation refers to the legal framework and legislation that oversees the functioning of aquaculture production. For effective regulation, these elements must be in place, implemented, and enforced. Generally, more efficient governments may also have more thorough implementation and enforcement of legislation that encourage sustainable aquaculture practices (Davies et al, 2019). In most countries, legislation is developed nationally, but often needs to take into account regional directives (for example within the European Union), agreements within trade blocs, compliance with international standards and processes (e.g. Codex Alimentarius, the World Animal Health Organisation), or the legal requirements for trade with customer countries.

National regulation of aquaculture varies greatly between countries, depending on the degree to which aquaculture contributes to the national economy and consumption, which species are cultured, and how effectively governance is enforced. The impact of regulations also varies. Government policies can legally ensure that specific standards are met for quality assurance, but too stringent legislation may inhibit industry development. For example, research into regulations on water use has described regulations in high-income countries as restraining aquaculture development, whereas regulations in lower-income countries are "fewer, less demanding, or not implemented" (Lebel et al, 2018). Indeed, the main barriers to aquaculture growth in Europe include strict environmental regulations and bureaucracy (European Commission, 2009). Similarly constricting African policies, that emphasize central planning over encouraging private industry growth, have been held partially responsible for the aquaculture industry's slow growth across the continent (Brummett et al, 2008). In contrast, increased domestic regulations in Asia were driven by food safety concerns about 'contaminated' farmed seafood exports to North America and Western Europe and the increasing concerns of domestic consumers (Little et al, 2012; Little et al, 2018). Policies in many Asian countries, Chile, and Norway have facilitated and encouraged the expansion of aquaculture (Naylor et al, 2021).

Aquaculture regulation has generally lagged behind the rapid development of the industry. Some countries overcompensated for this delay, creating overly stringent and precautionary regulations that inhibited further growth (e.g. the UK). In most contexts, aquaculture is governed by overarching laws for agriculture, forestry, or coastal management, rather than having legislation specific to its unique operations. Yet, aquaculture requires specific regulations for its effective governance (Hishamunda et al, 2014), and will likely benefit from centralization, where all aquaculture regulatory responsibilities are housed in the same location. New frameworks will be necessary as the industry and its technology continue to develop, for example with the emergence of large offshore operations that integrate aquaculture and renewable energy generation.

Even within countries with aquaculture-specific regulations, many issues concerning governance of aquaculture stem from overgeneralization of production methods, despite a large variety of aquaculture systems (Jentoft and Chuenpagdee, 2013). Sustainable production practices in aquaculture are difficult to define due to the broad range of species and production systems (Gephart et al, 2020), and regulations have generally struggled to address the variety of species, systems, geographies and volumes of production (Naylor et al, 2021). In addition, aquaculture impacts both positively and negatively on many aspects of the environment, meaning that multiple metrics are required to assess its impact.

Negative environmental impacts of aquaculture include energy use, water use, feed inputs, genetic risks, eutrophication, pollution and wastewater discharge, land use, among others. The degree of impact of these factors will depend on the particular aquaculture production system (ibid). Environmental benefits include improved water quality (Gifford et al, 2007; Theuerkauf et al, 2019), wastewater treatment (Bunting 2004; Bunting and Edwards, 2018), improved biodiversity (Visch et al, 2020), habitat creation (van der Schatte Olivier et al, 2018) and reduced pressure on fisheries through restocking (Bell et al, 2006) and as a net positive producer of food fish (Kok et al, 2020). Framing aquaculture development through a conservation lens has the potential to provide greater ecosystem services through targeted cultivation methods, such as integrated systems (Froehlich et al, 2017b).

Aquaculture regulations also need to consider socio-economic questions, as markets can be oriented towards export or local markets, and farms may be intensive or extensive, commercial or subsistence oriented, vertically integrated or specialized, large-or smallholders. Regulations must consider the large variety of actors throughout the value chain and how they interact with each other. Centralized production value chains will require different types of governance to decentralized ones, as will consolidated versus non-consolidated industries. A sector made up of many smallholders and numerous companies at each point along the value chain will have different needs than a sector made up of vertically integrated and/or large-holder corporations. This diversity within the aquaculture industry calls for a specialized and nuanced approach to its governance (Jentoft and Chuenpagdee, 2013).

As aquaculture spans so many different systems and has implications for animals, the environment, as well as livelihoods and well-being, clearly defining the responsible regulatory body can be difficult (Jentoft and Chuenpagdee, 2013). In countries with separate ministries for fisheries, agriculture and the environment, responsibility for oversight of sustainable aquaculture practices may be shared, as policies and objectives of each ministry can impact on production. As an example, both fisheries and terrestrial crops supply feed ingredients for aquaculture use (e.g. pelagic fish as fishmeal or fish oil, soy as a protein source), with associated sustainability implications (Malcorps et al, 2019). Fisheries can also supply broodstock or seed for aquaculture in many areas (e.g. collection of wild Penaeus monodon), with disease transmission implications (Dey et al, 2020). In areas where fish are a predominant nutrient source, public health ministries may also need to be involved in planning national objectives (Pradyumna et al, 2019). Public health bodies may recommend a minimum consumption of fish products, which will need to be supplied through markets. However, currently, public health and aquaculture management remain separate (de Roos et al, 2019). Even where aquaculture regulatory responsibilities are centralized under a specialized administrative body, there is a need for communication and coordination between these ministries regardless of the country, although the specific characteristics of the coordination will depend on the context.

Fundamentally, regulations for aquaculture are created and enforced by governments at national, regional, and local levels. National-level production goals (e.g. export goals) should align with regulations at the local level, but often may not due to limited resource availability or poor communication between levels. For example, Ecuador's coastal management system was limited by inadequate coordination between state agencies and municipalities (Manrique et al, 2018). As another example, Vietnam's government had conflicting policies that encouraged aquaculture intensification as well as mangrove preservation. As a result, mangrove degradation continued (Ha et al, 2014). Effective communication between levels of government is important, as problems within aquaculture (and fisheries) operate at various scales, and, for example, problems at the grass-roots level can be symptoms of higher-level issues (Jentoft and Chuenpagdee, 2013).

Consolidated and updated information regarding the existence, quality, and implementation of aquaculture-specific legislation is lacking and, as such, it is difficult to understand where the development of legislation is required. This will likely need to be tackled on a country-by-country basis, where legislation development requirements will depend on the status and orientation of the aquaculture industry (e.g. export or local market orientation, species and systems produced, etc.). Countries with export production will have specific legislation, but few have an aquaculture development strategy.

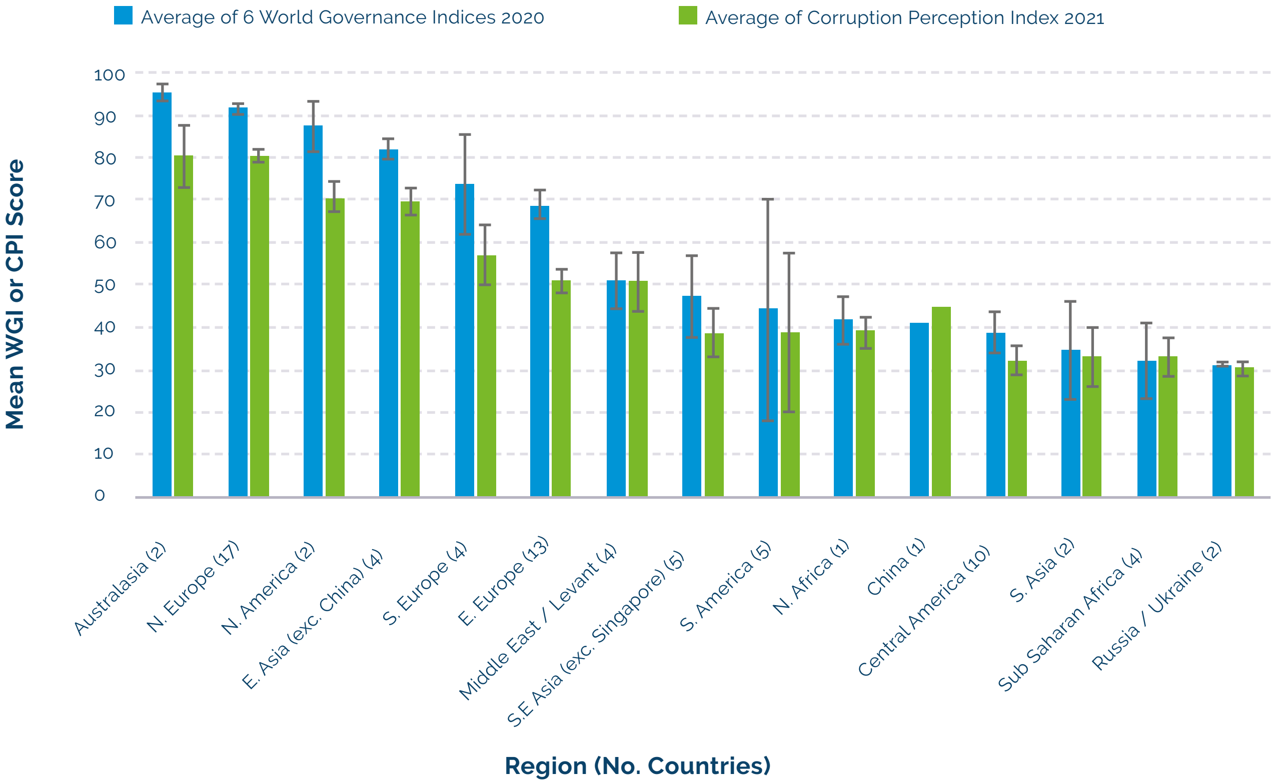
4.2.2. THE IMPORTANCE OF AQUACULTURE-SPECIFIC REGULATION, AND ENFORCEMENT OF REGULATIONS

Governance encompasses the traditions and institutions by which authority is exercised. Governance effectiveness, in turn, shapes the capacity to formulate and implement sound policies for the regulation and development of aquaculture. Corruption and/or insufficient resources for the appropriate management and enforcement of regulations can be a major limitation for the efficiency of governance at all levels. For example:

- China's regulations on antibiotic use in aquaculture have been described as largely ineffective, and their inability to supervise the distribution and use of antibiotics in the field was linked to low numbers of government staff and the high expense of antibiotic testing (Shao et al, 2021).
- In Ecuador, coastal management of mangrove areas was given disproportionate attention and resources from the government due to political turnover, competing items of political interest, and general policy changes (Manrique et al, 2018).
- Similarly, despite Vietnam's efforts to mitigate the impact of aquaculture intensification on mangroves, poor enforcement contributed to their continued decline (Primavera 2000; Ha et al, 2014).

Meaningful comparisons are complicated by the multiple dimensions of governance, accountability and data transparency conditions, which are themselves governance attributes. Consequently, global comparisons rely heavily on perception surveys of independent experts, civil society bodies, industry, and the general public. The World Bank's six Worldwide Governance Indicators (WGI) and Transparency International's Corruption Perception Index were selected for analysis based on their systematic nature, geographic scope and established provenance[15]. Data was compiled for a total of 77 countries based on their inclusion in GSA-BAP and ASC aquaculture certification programmes (covering feed, seed, production and processing value chains, see Figure 2).

Figure 2. Mean World Governance Index* (WGI) in 2020 and Corruption Perception Index (CPI) in 2021 scores for 76 countries in the ASC and GSA-BAP aquaculture certification programmes in 2022



*Note: World Governance Index (WGI) score is the mean of 6 separate governance indicators: (1) Voice and accountability; (2) Political stability and violence; (3) Governance effectiveness; (4) Regulatory quality; (5) Rule of law; (6) Control of corruption. Scores from 0-100; lower scores indicate poorer governance levels. Error bars indicate standard error of the mean (SEM).

The key findings of the data analysis are:

- countries or regions with poorer governance scores are likely to face greater barriers to participation in international trade;
- this has been a key driver of demand for second- and third-party assurance systems (certification and ratings schemes) and is consistent with net trade flows from emerging to developed economies;
- this also accounts for divergence in regulatory implementation performance between domestic and export-oriented sectors in emerging economies and associated industry dynamics.

4.2.3. THE ROLE OF CERTIFICATION SCHEMES

Certification programmes have risen to fill in the gaps in governance, in a 'hybrid regulatory networks' format (Vince and Haward, 2017). Assurance of food safety has been a primary concern and driver in the evolution of public and private regulatory standards for aquaculture. These generally provide additional quality assurance to consumers and support traceability systems. The more recent growth of private social and environmental standards arose from a perceived deficit in statutory regulation.

Certification schemes allowing for industry self-regulation, external to legislation, are often seen as important in relation to market access, but they are voluntary and carry a cost to aquaculture production businesses. According to Havice and Iles (2015): "Certification programs create rules that specify what sustainable production entails and what practices producers must follow to qualify to affix a 'sustainable' certification to their product… [they] aim to link production and consumption practices, and many span national and global scales." Certification supports the need of exporters in developing countries to meet the standards of importing countries, with net seafood flows to higher-income countries with more demanding requirements than local consumers. For example, shared safety notifications by member states via the EU rapid alert system for feed and foods (RASFF) became a legal requirement in 2002 (Article 50 of Regulation (EC) No 178/2002). This requirement is also driving improved regulation in many emerging economies, even though major implementation differences remain for domestic versus export-oriented goods.

4.2.4. CERTIFICATION SCHEMES' THEORY OF CHANGE

Certification schemes' Theory of Change is based on consumer demand for certified products as a driver for sustainable practices. As consumers choose to purchase certified products, more providers will seek to obtain sustainable practices, over time leading to increased sustainability throughout the industry. As an example, the Aquaculture Stewardship Council's Theory of Change can be viewed here. The standards are generally reviewed at regular intervals and versions are updated, taking on board new developments in sectors, industry, and research. ISEAL is an independent organization that assesses agriculture certification schemes themselves, with managerial input from certifiers and stakeholders across the agriculture and fisheries industry.

4.2.5. SOCIAL LICENCE TO OPERATE

Certification schemes support trust between consumers and the industry. However, they do not necessarily support a company's social licence to operate (SLO), which is dependent on trust between the business and community local to production (Vince and Haward, 2019). A lack of SLO and stakeholder engagement can lead to political barriers for the industry (Mather and Fanning, 2019). Obtaining and preserving their social licence should be a key consideration for regulators (Vince and Haward, 2017).

4.2.6. LIMITATIONS OF CERTIFICATION SCHEMES

Certification schemes are mainly focused on environmental and governance indicators (many of which are also environmental indicators) and do not usually encompass social and economic issues (Osmundsen et al, 2020). In developed countries, pro-environment agencies have relatively high power, which may inhibit industry development. By contrast, pro-industry agencies have relatively high power in developing countries, with negative implications for the environment (Abate et al, 2017). Definitions of 'sustainable systems' should encapsulate environmental, social and economic dimensions, as defined by the Rio Declaration (UNCED, 1992). Certification schemes may also encourage circular economy principles, such as the use of fish by-products in aquaculture feeds (Little et al, 2018).

Currently, the impacts of certification are positive at the farm-level, but limited in scope. Despite their focus on minimizing environmental impacts, certification schemes have not yet significantly influenced broader sustainability indicators (Kalfagianni and Pattberg, 2013). Since certification only covers approximately 3.5% of the world's aquatic produce, this broader impact has yet to be realized, though it should increase with the proliferation of certified producers. Furthermore, certification only addresses impacts and activities at the production site rather than across the value chain (Little et al, 2018; Amundsen et al, 2019). Reducing the negative environmental impact of production will require a life-cycle approach, measuring the impact of inputs, production, processing, transportation, and marking, all the way through to consumption.

Other criticisms include: variations in the quality of audits, that environmental standards are not sufficiently stringent, and that discrimination in access exists (Kalfagianni and Pattberg, 2013; Bush et al, 2013). Compliance capabilities vary between farms based on financial capital (e.g. ability to pay for third party certification and meet standards), physical capital (e.g. access to equipment and land), and human capital (e.g. education level of the farmer, support from neighbours) (Samerwong et al, 2020). Audits can be expensive and costly, particularly since they must be repeated every one to three years (Amundsen & Osmundsen, 2020). This has led to claims that certification may lead to the marginalization of smallholders unable to invest in the certification process (Belton et al, 2009; Tran et al, 2013; Jespersen et al, 2014; Marschke and Wilkins, 2014). In addition, the potential economic benefits of certification may not be realized for smallholders (Kaminski et al, 2020). Indeed, compliance is greater among vertically integrated industries, with sufficient capital to achieve the required standards (Naylor et al, 2021).

This is leading to consolidation and concentration of value chains serving more demanding affluent markets, as larger farms are able to afford the costs of certification, driving out and marginalizing smallholders. Conversely, more fragmented commodity chains dominated by small-scale entities remain more prevalent in emerging markets. While concentration pressures are less acute in high-unit value commodity sectors (e.g. shrimp), a 'value chain-shortening' approach has generally been a common feature of export-oriented development programmes able to face the greater quality assurance and traceability and chain of custody challenges of fragmented sectors. The benefits and challenges of such linkages for improved regulation in emerging-economies more generally should be considered.

4.2.7. OVERLAPS BETWEEN GOVERNANCE AND CERTIFICATION

Overlaps can exist between governance and certification to various degrees. In some situations, certification is voluntary, whereas in others, it is required through legislation. GlobalGAP has set the benchmarks for several national-level certification programmes, including IndoGAP and VietGAP (other national-level GAP certifications do not include aquaculture guidelines, such as ChileGAP, MexicoGAP "México Calidad Suprema", or NewZealandGAP). As these national standards are benchmarked against the GlobalGAP standards, they provide quality assurance for any product under the national standard. VietGAP, for example, is a legal requirement for all Vietnamese-produced aquaculture products destined for export. This scheme attempts to protect the international reputation and image of Vietnamese food products like pangasius (Nyugen and Jolly, 2020). VietGap was developed by the National Department of Fisheries in alignment with the Aquaculture Stewardship Council as the export standard, avoiding the development of complex legislation. This will be discussed in more detail in the section on Codes of Good Practice.

4.2.8. CERTIFICATION AND MARKET ACCESS

The popularity of certification is driven by North American and Western European market demand, where certification can support branding efforts and sustainability reputations (Olsen et al, 2021). Indeed, aquatic products aimed at these markets have higher levels of certification: 57% of salmon, 17% of shrimp and prawns, 17% of pangasius, and 11% of tilapia are certified. Increased trade between countries in the 'Global South' is often overlooked, but it has increased (Bush et al, 2019). Difficulties in achieving the complex certification standards demanded by Western countries may be driving producers towards markets without such requirements (Nguyen and Jolly, 2020), particularly since the cost implications of certification can restrain uptake (Tran et al, 2013; Jespersen et al, 2014; Belton et al, 2017). For example, most Bangladeshi pangasius farmers would not meet certification standards, but they have no motivation to do so because they are part of a booming industry, with products destined for local and regional consumption that do not demand certified products (Haque et al, 2021). These types of markets generally demand alternative criteria to certification labels, such that the sustainability of the system is dependent on adherence to government regulations (Bush et al, 2019).

4.2.9. TYPES OF CERTIFICATION SCHEMES

Approximately 30-50 aquaculture certification schemes exist (Naylor et al, 2021a). The most prevalent and value chain oriented certification bodies for aquaculture are: GlobalGAP, Aquaculture Stewardship Council (ASC), and Best Aquaculture practices (BAP), yet these only cover only approximately 3.5% of all global production (Seafood Watch provides ratings for over 30% of global production). These schemes are described in detail below.

- **GlobalGAP** originated in Germany for validating the performance of European agricultural farms. Aquaculture standards were subsequently added. While its aims include both "safeguarding the environment and the welfare of farming communities", its standards are primarily concerned with food quality (safety and hygiene). Environmental standards were subsequently included owing to public demand (Bush and Duijf, 2011). GlobalGAP requires traceability up to the farm gate (i.e., traceability for inputs but not for processing). Its environmental standards include targets for: water usage and disposal, biodiversity, high conservation value areas, genetic engineering, escapees, predator control, feed, and veterinary medicine/chemical storage and use (Kalfagianni and Pattberg, 2013). Its managerial standards include targets for: compliance with relevant legal frameworks and hatchery management (ibid). GlobalGAP also has a compound feed manufacturing standard that also applies to the production of aquafeed. One challenge with the GlobalGAP is that its standards are set against market norms, resulting in different levels of stringency for different producers (ibid), such that transnational comparisons between companies is difficult.

- **ASC** was established in 2010, as an outcome of the 'Aquaculture Dialogues' stakeholder discussion led by WWF and the Sustainable Trade Initiative. ASC has different standards for the production of different aquatic species and ensures traceability throughout the value chain. It aims to "minimise the key environmental and social impacts of aquaculture" (ASC 2010). Its environmental standards include targets for: water and land resources, energy consumption, biosecurity, genetic integrity of local populations, genetic diversity, genetic engineering, escapees, predator control, feed, and veterinary medicine/chemical storage and use (Kalfagianni and Pattberg 2013). Its managerial standards include targets for compliance with relevant legal frameworks and farm management plan (ibid). LCA analysis showed that farms with ASC certification, compared to non-certified farms, have lower impacts on resource use, global warming, acidification, and eutrophication. However, ASC certification has no impact on water resource use or freshwater eutrophication (Nhu et al, 2016). The ASC is currently working on increasing the number of animal welfare indicators for accreditation.

- **Global Seafood Alliance (formerly Global Aquaculture Alliance) BAP** certifies all stages of the value chain (e.g. separate certifications for hatcheries versus processing plants, and also for feed). This scheme aims to ensure that environmental, animal welfare, food safety, and social standards are met. Its environmental standards include targets against: wetland and biodiversity conservation, sediment and water quality, fishmeal/oil conservation, escapees, genetic engineering, predator and wildlife interactions, and storage and disposal of farm supplies (Kalfagianni and Pattberg, 2013). Its managerial standards include targets for compliance with relevant legal frameworks and the development of area management agreements with local communities (ibid).

Certification bodies specific to upstream and downstream activities in the value chain include marine ingredient certification (MarinTrust), responsible soy production (USSEC, ProTerra, RTRS), decent working conditions (FairTrade), among others. A complete list of food certification programmes can be found at EcoLabelIndex.com, but no complete list specific for aquaculture is currently available. Many certification schemes also have their own Chain of Custody standards, that help to secure product verification through lengthy and sometimes complex supply chains.

Some retailers have their own regulatory schemes to protect their own reputation and brand quality (e.g. Marks & Spencer Select Farms, or Young's Bluecrest Fish for Life), but some have been criticized for causing customer confusion and creating additional costs for suppliers (Little et al, 2018). Other rating systems exist, such as the Monterey Bay Aquariums' SeaFood Watch programme, which has rated over 2,000 aquatic food products. The Certification and Rating Collaboration (CRC) dataset collates data from six global certification and ratings programmes to provide updated statistics by country, species, and other factors. The CRC data tool available online is estimated to cover 2.1 million tonnes of aquaculture production, globally. Data tools are interesting in the context of this work because they have the capability to link systems, collate data and information, and assist in reporting, all of which are fundamental to understanding current production systems, and monitoring change over time.

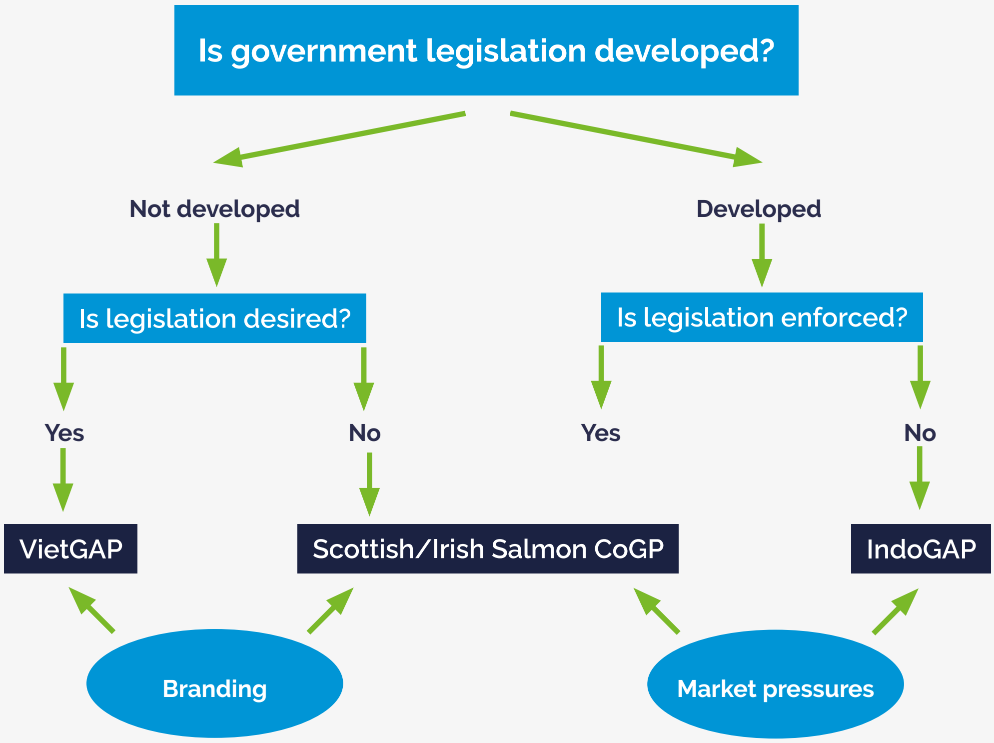
4.2.10. ALTERNATIVE GOVERNANCE STRUCTURES: INDUSTRY-LED STANDARDS

Codes of Practice/Good Practice (CoP/GP) are industry-led standards to avoid the development of complicated legislation. In some contexts, CoP/GP are generated by private industry in an attempt to demonstrate sustainable practices and avoid government interference (e.g. Scottish Salmon CoGP; Salin & Ataguba 2018). In other contexts, CoP/GPs aim to improve sustainability, quality, and international branding within the industry in the absence of (e.g. VietGAP) or failure of government legislation (e.g. IndoGAP). Figure 3 visualizes these different pathways to development.

CoP/GP have been shown to minimize disease transmission through improved biosecurity measures (Murray et al, 2010; Yatabe et al, 2018), and encourage industry to go 'beyond compliance', which can have environmental and social benefits (McGhee et al, 2019).

Uptake of industry-led third-party or second-party audited schemes will vary, where the prior is more highly regarded within the value chain. While both are external audits, second-party auditing of the supplier is conducted by the customer or retailer on behalf of the customer (e.g. Marks & Spencer), whereas third-party auditing is performed by an unbiased, specialized auditing organization (e.g. Scottish Salmon CoGP).

Figure 3: The development of CoP/GP can depend on whether government legislation has been developed and to what degree it is enforced and desired by the industry. Market pressures and a collective attempt at national product branding may also impact on its development



4.2.11. ALTERNATIVE GOVERNANCE STRUCTURES: COMMUNITY-BASED GOVERNANCE

Community-based aquaculture may be another option in rural contexts, where production is destined for local consumption and regulatory bodies are inefficient. For examples:

- Community-based fisheries management in Bangladesh was a response to ineffective governance (Khan et al, 2012), resulting in better biodiversity and improved livelihoods for fishers (Islam et al, 2014).
- Successful community-based aquaculture in Bangladesh benefited all stakeholders (Haque et al, 2012), including improved livelihoods and reduced economic inequalities (Haque et al, 2017).
- Trials of community-based rice-fish culture in Vietnam and Bangladesh were also shown to be profitable and beneficial for farmers, with some evidence of wider early adoption (Dey et al, 2007).
- Community-based aquaculture in Vietnam showed promise as an alternative livelihood strategy for resilience against environmental and economic change (Joffre et al, 2011).

Literature and/or evidence concerning the longer-term impacts of community-based aquaculture is generally lacking. However, ongoing institutional and managerial support for these systems may be critical to their success, as many community-based aquaculture projects have failed due to a lack of either long-term support or clear strategy for sustainability (Ateweberhan et al, 2018).

A key element of sustainable community-based aquaculture is access to consistent and biosecure seed supply. With the exception of rice-fish culture, where seed can be supplied by brooders within the pond, most community-based aquaculture will require access to hatcheries. For example, hatchery infrastructure and human resource capacity development was required for the successful implementation of community-based aquaculture in Zanzibar (Ateweberhan et al, 2014).

4.3. Other considerations in support of aquaculture governance

Some non-government organizations (NGOs) are directly linked with certifications or ratings, for example, the Global Seafood Alliance (previously known as the Global Aquaculture Alliance) with Best Aquaculture Practices (BAP) standards and Monterey Bay Aquarium with the Seafood Watch assessments. These organizations span market and regulatory governance arenas and are often in direct communication with farmers, government ministries, and international buyers and consumers. This global reach and engagement across the value chain can have positive benefits to support the trajectory towards sustainability. For example, WWF was the lead organization in the development of the ASC standards. Although these were devolved to a separate organization after creation, WWF offices continue to engage national governments and industries to encourage them to utilize ASC as the foundational requirement for entry into markets – moving beyond the realm of voluntary market-based governance into involuntary regulatory stipulation based on specific standards.

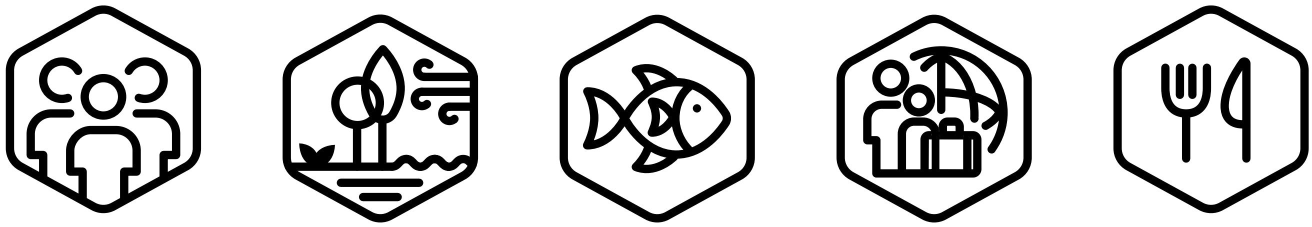
NGOs not directly linked to certification schemes can still play a role in governance and are linked to improvements in sustainability. NGO development agencies have a role in growing the aquaculture industry in line with government regulations or promoting specific voluntary standards. Development NGOs in particular may be involved in communication between national-level and industry practice through aquaculture improvement projects, extension projects, and government collaborations (Bottema 2019). They may also provide guidance on the practical implementation of regulations. As development NGOs are often socially focused, this may complement environmentally focused certification and government policies.

NGOs may also launch campaigns to change industry practice directly. For example, Seafood Watch has been working with Chilean salmon producers, who, as a result, have pledged to reduce the use of antibiotics (White 2019). Other NGOs may campaign directly with the government. For example, SustainAqua Indonesia has participated in virtual meetings with both industry and government to increase the sustainability of the Indonesian shrimp sector. NGO leverage is also often through retailers (e.g. the partnership between Walmart and the Sustainable Fisheries Partnership).

4.4. Resources and databases for information on regulations

The following list contains resources and databases with information relevant to the regulation of aquaculture, including governance, certification, and others. These sources are from academic institutions, governmental organizations and NGOs. The icons next to each resource indicate what types of governance topics the repository includes.

Legend:

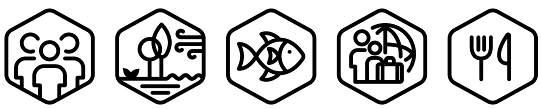


Social issues | Environment | Animal Health and Welfare | Inclusive Markets | Food Safety

*All icons are from TheLexicon Foodicons

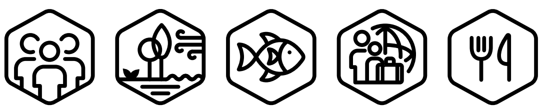
4.4.1. AQUACULTURE-SPECIFIC RESOURCES

AquacultureGovernance.org



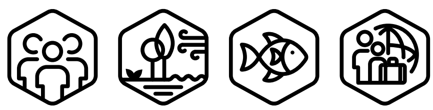
Developed through a collaboration between Monterey Bay Aquarium and Wageningen University, the Aquaculture Governance Indicators (AGIs) aim to provide insight into areas of aquaculture governance that could be improved. These indicators are specific to each country and sector (e.g. Thai shrimp or Chilean salmon) and are based on four categories: legislation, voluntary codes and standards, collaborative arrangements, and capabilities. The major limitation of this resource is that it is still under development, currently only providing assessments for nine countries and four species.

FAO National Aquaculture Sector Overviews



The FAO database of National Aquaculture Sector Overviews provides a useful summary of the country's aquaculture sector (main species, systems, production performance, etc.) and includes a section detailing institutional frameworks and governing regulations. This section outlines which governmental departments are responsible for governance, legislation specific to aquaculture, and any research policies. These overviews are often available in several languages. This overview also includes a section on 'trends, issues, and development'; however, it is not updated regularly and many are outdated. Furthermore, it is not possible to easily compare legislation and governance between countries without manual extraction of information.

FAOLEX Database and National Aquaculture Legislation Overviews



The FAO FAOLEX database includes a list of relevant legislation and policies that are directly related to aquaculture production and operation for each country. This database also provides a description and context for each listed policy, and a link to the relevant document. This database is useful for detailed investigation of a country's legislation and comparing legislation between countries. As with the FAO National Aquaculture Sector Overviews, the FAOLEX database/ National Aquaculture Legislation Overviews are not always updated with the most recent policies and some of the links are broken or merely linked to the country's general government website rather than the actual policy. FAO has also been developing ALART (Aquaculture Legislation Assessment and Revision Tool) and has recently piloted this in several countries.

WorldFish Database

The FAO database of National Aquaculture Sector Overviews provides a useful summary of the country's aquaculture sector (main species, systems, production performance, etc.) and includes a section detailing institutional frameworks and governing regulations. This section outlines which governmental departments are responsible for governance, legislation specific to aquaculture, and any research policies. These overviews are often available in several languages. This overview also includes a section on 'trends, issues, and development'; however, it is not updated regularly and many are outdated. Furthermore, it is not possible to easily compare legislation and governance between countries without manual extraction of information.

European Food Safety Authority (EFSA)

The EFSA provides links to specific EU regulations on animal welfare in aquaculture. It has specific sections on handling, harvesting, and slaughtering and links to relevant publications on aquatic animal welfare. It is the European Commission's scientific advisor on food safety, providing evidence-based opinions on topics including contaminants (e.g. PCBs, PCDDs, heavy metals) and feed additives (e.g. pigments, synthetic antioxidants).

European Legislation on Aquaculture Production

This website provides an overview of aquaculture in Europe, and relevant links to policy and legislation concerning the various facets of production. These are focused on social, environmental, animal welfare, competitive markets, and food safety topics. This site is useful to understand policy concerning aquaculture production in the EU.

Scottish Environmental Protection Agency (SEPA)

SEPA's website has links to relevant UK and Scottish legislation concerning aquaculture production. It is useful for accessing up-to-date information and any recent changes or updates to legislation. It also provides information on accessing new site permits. SEPA is mainly concerned with animal welfare and environmental governance. This site is useful to understand policy concerning salmon production in Scotland.

National Oceanic and Atmospheric Association (NOAA)

NOAA's website has a page dedicated to explaining its role in the governance of aquaculture in the United States. It references the various acts and policies relevant to the industry with factsheets on each. This site is useful to understand environmental policy concerning aquaculture production in the United States.

United States Food and Drug Agency (FDA)

The FDA website provides a list of policies and legislation relevant to food safety topics on aquaculture products. These include policies around antibiotic and other veterinarian medicine and chemical use. Links are provided for each policy. This site is useful for understanding food safety requirements for aquaculture for consumption in the United States.

4.4.2. GENERAL GOVERNANCE RESOURCES RELEVANT FOR AQUACULTURE

Worldwide Governance Indicators (WGI)

Developed by the World Bank and the Natural Resource Governance Institute, WGI scores a country's governance on a scale from -2.5 (poor) to 2.5 (good), by combining the views of 32 different sources, including industry, citizens, and experts (from survey responses) for six dimensions of governance: accountability, political stability and absense of terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. Covering over 200 countries from 1996 onwards, these indicators are updated yearly and are useful for identifying trends over time and for comparing countries. While not specific to aquaculture, countries with higher WGI scores had regulations and implementation mechanisms that are necessary for sustainable aquaculture, such that WGI scores have been strongly associated with better marine governance policies (Davies et al, 2019); however, WGI scores are not correlated with aquaculture growth rates (Nadarajah and Flaaten 2017).

World Bank's 'Ease of Doing Business' Ranking

The World Bank has ranked approximately 190 economies in terms of how conducive their business regulations are for local industries. While we are unaware of any literature that has explored correlations between these rankings and aquaculture growth or productivity, ease-of-doing-business coefficients have been correlated with foreign direct investment generally, for example in Sub-Saharan Africa (Nketiah-Amponsah and Sarpong, 2020). Countries with a low ease-of-doing-business rating may require larger agricultural investments to stimulate agricultural growth (Thapa et al, 2019), while increasing the ease-of-doing business may support agribusiness competitiveness (Shrestha and Cauchan, 2020).

EU Inform Risk Portal

The EU Inform Risk Portal aims to collect recent information on current humanitarian crises to inform risk response. This group aims to support decisions around risk preparation, preparedness, and response, including early action. It aims to measure the level of support required for each crisis, so that humanitarian interventions and support efforts are appropriate. As many aquaculture facilities are in flood-prone river deltas, coastlines, and other areas prone to natural disasters, this portal could be an important resource for managing aquaculture operations in areas of crisis, or for the spatial planning of aquaculture expansion.

IndexMundi

IndexMundi compiles reports, charts and maps at the country-level on national statistics, including economic (e.g. GDP, agriculture products), social (e.g. poverty, household income/consumption), and political (e.g. administrative divisions, legal structure). This resource is available in multiple languages and may be useful for understanding the general governance of countries in which aquaculture is produced.

U.S. Department of State - Trafficking in Persons report

Trafficking in Persons reports have been released annually from 2017 to 2021. These reports focus exclusively on human trafficking and slavery, which are unfortunately still issues in certain seafood value chains (Nakamura et al, 2018). These reports have particular detail surrounding slavery and trafficking in agriculture at the country level.

The Rapid Alert System for Food and Feed (RASFF) web portal

The RASFF portal is an alert system for food safety and contamination events. This tool is used to quickly confer and distribute alerts between EU members. They produce annual reports that summarize events by country, type of food, and type of hazard. They have two portals: one allowing search functions and another browsing-friendly version for consumers. The consumer portal provides country-level listings on food recalls and hazards. This website is useful for its up-to-date information, but is limited to EU countries.

EcoLex.Org

Developed by FAO, IUCN, and UNEP, Ecolex is a database containing details on environmental law across the world. Ecolex is not specific to aquaculture, but contains environmental law that is applicable to the aquaculture industry. It is primarily a repository, where content is accessed via search functions. Some documents are available in multiple languages.

4.4.3. CERTIFICATION

Aquaculture Stewardship Council (ASC)

The ASC website provides documentation on its certification, metrics and standards, audit requirements, and other educational materials. The documents are often available in multiple languages and are species-specific. It also has a search function, where it lists certified farms by name, species, and location, including details on certification completion and expiration dates.

Global Seafood Alliance's Best Aquaculture Practices (BAP)

The BAP website provides detailed information on its standards, the auditing and certification processes, sampling and testing requirements, news, and other educational materials. Standards are listed by species. Similar to the other certification websites, it includes a list of companies which have achieved certification. It also includes a list of companies striving to achieve certification and those up for renewal. Conveniently, company locations are shown on a map, demonstrating coverage of BAP standards.

GlobalGAP

The GlobalGAP certification website provides documentation describing the certification requirements, audit benchmarks, a list of approved auditors, guidance on passing audits, and other educational materials. Their search function provides a list of companies that are certified by GlobalGap, filtered by country, product type (fish species or other crop), company type (individual producer or producer group), and particular scheme type. The certification number and address is provided for each company. This could be used, for example, to generate maps understanding where this certification body is operating. The GlobalGAP also has a documentation centre, listing their governance guidelines and standards against which farms are audited. This list must be filtered for aquaculture. Documents are often available in multiple languages.

IndoGAP

IndoGAP's website provides certification requirement documents available for download. It also has a public 'self-check' function, allowing the user to inquire if a particular farm is certified, but does not provide lists of companies (i.e. the user must know the company name). This website's content is not available in English.

VietGAP

The VietGAP website provides documents and other information about certification, including news updates. It also provides a list of certified companies with their product, owner name, certification date, expiration date, and addresses that may be used to compile maps that describe coverage. This website's content is not available in English.

ThaiGAP

Similar to the VietGAP website, the ThaiGAP website provides documentation for download concerning certification standards and the application process. It also has a blog and contact information. This website's content is not available in English.

Organic Labels

Several organic certification schemes exist and are particular to the country in which they operate. All are primarily concerned with environmental management. Government legislation must approve the organic certification scheme. Information and legislation regarding organic certification is available for several countries, including, the United Kingdom, the United States, France, Chile, China, and India.

RSPCA Assured

This certification from the RSPCA is focused on assuring that the farm has met animal welfare standards. Currently, these standards are only available for salmon and trout. Their standards are available for download via the website. Their website is geared towards consumers and supporting purchasing choices that drive a demand for animal welfare.

Friend of the Sea

This certification was made famous by its campaign to certify 'dolphin-safe tuna'. Its aims are mainly environmental, with additional animal welfare considerations. Although better known for its fisheries certification, it also certifies aquaculture. Its benchmarks for aquaculture, specific to each species, are available for download through their website.

Label Rouge - AquaLabel

The Label Rouge certification originates in France and is concerned with the final quality of the product for the consumer. Their standards are set based on the taste and sensory experience of the final product. Like other certification schemes, traceability is also a key component. This certification is less concerned with environmental impact, animal welfare, or other areas. Its standards are specific to each species and food type (e.g. smoked salmon), and are available for download via their website.

International Featured Standards (IFS)

The IFS provide general standards for food safety, packaging, and quality. They include specific standards for smallholders for inclusivity purposes. These standards are for food generally rather than specific to aquaculture. Guidance documents can be downloaded from their website.

BRC Global Standards

These standards are focused on food safety and quality, ensuring traceability throughout the value chain. The certification is for food generally, and not specific to aquaculture. Their website provides details on their benchmarks, the application process, and other educational materials.

FAO Qualitative Assessment of Aquaculture Certification Schemes (Asia-Pacific region)

This qualitative assessment provides a comprehensive report of certification schemes and their aims and roles within governance. It compares government-led schemes, industry-led schemes, retailer-driven schemes, organic schemes, and NGO-led schemes. It also provides a list of legislation from the Asia-Pacific region that is relevant to certification of aquaculture. This report provides an excellent overview of the topic. However, it is now outdated as it was published in 2007. Furthermore, it is limited to the Asia-Pacific region, although many of the schemes discussed are prevalent internationally.

4.4.4. CODES OF GOOD PRACTICE

Scottish Salmon Producers Organisation's (SSPO) Code of Good Practice

The SSPO's website has downloadable chapters of their code of good practice, to which all finfish producers (salmon, trout, finfish) in Scotland subscribe. Each chapter describes best practices for each type of production (e.g. production of fish in raceways versus cages). The code mainly covers topics concerning fish welfare, environment, and food quality and safety. Some of their news articles also cover worker safety and career highlights. This website also provides information on how to become certified. This information is in English only.

Global Food Safety Initiative (GFSI)

The GFSI organization is mainly geared towards ensuring food safety and biosecurity transnationally. They offer certification. The benchmarking documents are available for download through the website. They also provide supporting documents, news articles and blogs, publications, videos, and podcasts. This information is only provided in English.

Sustainable Shrimp Partnership

Led by the Ecuadorian shrimp industry, the Sustainable Shrimp Standards are a CoGP that have been ASC certified. A main goal of their standards is reducing the use of antibiotics, largely driven by customer concerns. Their code focuses on environmental, social, and quality standards. Their website has the standards available for download, as well as their criteria, and news articles.

5 Opportunities for aquaculture in integrated food production systems

In this section, we introduce promising integrated production systems that have the potential to optimize production efficiency and avoid the loss of nutrients to the biosphere, namely, aquaponics, integrated multi-trophic aquaculture (IMTA), mangrove-shrimp systems, and rice-fish systems. Nutrients contained in animal feeds, including those for aquaculture, constitute a valuable resource. Integrated systems, such as those where aquaculture and agriculture operate in combination, have the potential to increase food yield from the same land area. However, WorldFish have noted that, in order to avoid a repeat of the unintended negative consequences of the 'Green Revolution' in agriculture: "the next great transformation must involve a transition toward food, land and water systems that are equitable and inclusive, as well as healthy, resilient and sustainable" (WorldFish, 2020). A major challenge with some of these extensive or semi-intensive systems is that much of the production goes unrecorded.

5.1 Regenerative agriculture principles for sustainable aquaculture development

Evidence suggests that some principles underlying traditional aquaculture systems could help contemporary practices become more sustainable. The concept of regenerative agriculture utilizes these principals to promote practices that rehabilitate and enhance the entire ecosystem of the farm, with neutral or net positive effects on the surrounding environment. Regenerative agriculture is principally concerned with ensuring farming practices are productive, environmentally sensitive and contribute to maintaining social cohesion (Pretty, 1995). Potential benefits for producers include:

Potential benefits for producers include:

- increased yields with lower levels of inputs
- enhanced water conservation and harvesting avoidance of erosion and associated nutrient and soil loss
- reduced fertilizer and pesticide use, with significant cost savings

Recognition of the broader benefits of carbon capture and storage, enhanced biodiversity conservation and improved soil structure associated with regenerative agriculture and aquaculture is growing strongly (Bunting and Pretty, 2007; Regeneration International, 2022).

Regenerative agriculture has potential to inform sustainable aquaculture development. Fundamental to achieving this are the development and application of appropriate resource-conserving technologies and processes by producers and local institutions and groups, supported by external institutions concerned with research, development and extension (Bunting, 2007). To be successful and spread further afield, there must be an enabling 'policy environment' (Pretty, 1995) and investments by a range of funds are set to support the uptake of regenerative food production practices globally (Investing in Regenerative Agriculture and Food, 2022).

5.2. Integrated production to enhance nutrient use efficiency

Nutrients entrained in waste streams are a major resource that is lost to the biosphere that could potentially be used productively to enhance diets around the world (Willett et al, 2019). It has been suggested that selected wastewater-fed aquaculture practices involving intermediate products and appropriate biorefinery technologies could be used to retain and productively reuse these resources to produce nutrient-rich and economically valuable products (Bunting and Edwards, 2018). For example, algae, aquatic plants, bivalve molluscs, crustaceans, phytoplankton, and zooplankton can all be used as feedstock for emerging biorefinery industries. Intermediaries such as duckweed, small carp, and tilapia could be grown using wastewater and used in the formulation of animal feed, including aquaculture feeds. The World Health Organization (WHO, 2006) publishes guidelines on appropriate monitoring and control measures to guarantee food safety of produce from these locations. Alternative strategies for reusing nutrients across aquaculture value chains are summarized in Table 9.

Table 9: Opportunities to reuse nutrients that are not assimilated in primary aquatic foods

Nutrient source	Reuse strategy	Contextual issues
Process water (in situ)	Integration of other aquatic animals and rice can maximize the capacity of ponds and flooded fields to convert available nutrients to harvestable biomass.	Successful integrated production depends on the availability of suitable species with a value in accessible markets to fill available feeding niches .
Process water recirculated or discharged	In land-based units, nutrients entrained in process water can be used to culture other aquatic species in IMTA systems (Shpigel et al, 1993; Bunting and Shpigel, 2009) or to grow plant crops in aquaponic systems (Love et al, 2015).	Achieving the movement of water either depends on access to a suitable site and source of water or entails significant costs. IMTA and aquaponics require significant technical, managerial and financial skill.
Treatment effluents	Concentrated nutrients in effluent streams from treatment units can be used as feedstock for biorefinery processes (Aqua Spark, 2022) or to fertilize terrestrial crops.	Effluent streams may require additional conditioning prior to on-site use in biorefinery processes, or transport and application to farmland at specific points in the growing season.
Pond sediments	Pond bottoms are routinely dried and dosed with lime to regulate pH and hardness levels and optimize primary production (Pillay and Kutty, 2005). Forage crops might potentially be grown on pond bottoms and embankments to increase food availability for newly stocked aquatic animals or livestock (Shaalan et al, 2018).	Mechanical draining and drying of ponds can be costly and difficult to achieve when weather patterns are unpredictable. Forage crops might yield a harvest for human nutrition and could potentially fix atmospheric nitrogen in soils to further enhance productivity.
Removed pond & settlement tank sediments	Accumulated pond and settlement tank sediments may require intermittent removal to maintain production system performance. Nutrient-rich sediments can be used as a soil conditioner and to fertilize dike-crops, orchards, forage crops, or farmland (Korn, 1996).	Draining ponds, excavating sediments, and transporting them to cropped areas can be labour intensive and costly. Pumps can be used to remove sediments from full ponds but they may need to be dewatered to make them manageable prior to use as fertilizers.

Co-location of fish production and the farming of terrestrial animals used to be common in Asia, but these practices are in decline owing to the expansion of specialist producers and concerns over the transfer of pathogens and diseases. The utilization of livestock waste to fertilize ponds is still widespread in extensive and semi-intensively managed pond-based systems in Asia (Wahab et al, 2003; Nhan et al, 2007; Karim et al, 2011). Production of maggots as an intermediate stage in utilizing livestock waste has been noted (Little and Edwards, 1999). There may be scope to use other non-agriculture and food processing waste resources as fertilizers, or as substrates for insect production as alternative feed ingredients, although consideration must be given to possible contamination with chemicals, pathogens, and non-organic materials.

Dike-cropping systems integrated with freshwater and brackish water pond culture have been demonstrated to have potential at small- and medium-scales (Rothuis et al, 1998; Faruque et al, 2017). However, the production of dike crops in high salinity situations is not generally possible, which is an additional argument for not promoting saline water intrusion for the culture of marine and brackish aquatic animal species. As a result of adopting integrated farming, including dike-cropping, households in southwest Bangladesh saw incomes increase, cash flows improve, and risks of crop damage reduce (Ahmed, 2013). In Mymensingh District, Bangladesh, dike-cropping around freshwater ponds yielded additional food for households (Karim et al, 2011). These significant gains were achieved without genetic improvement of the fish stocked or value addition (p.233). If managed correctly, integrated aquaculture systems can also sequester carbon and potentially contribute to climate change mitigation and adaptation (Ahmed et al, 2014, 2017).

5.3. Aquaponics principles and commercial operation

Aquaponics is an integrated closed-loop multi-trophic food production system, where waste produced by farmed fish or other aquatic species supplies nutrients for plants grown hydroponically (i.e. in the absence of soil), which in turn purifies the water (Delaide et al, 2016, Turnšek et al, 2019).

Recent interest in engineered closed aquaponic systems stems back to the late 1970s, with research into ‘sustainable’ (water, land and nutrient efficient) low investment systems, particularly in the US Virgin Islands (Bailey and Ferrarezi, 2017), fuelling initial enthusiasm. However, the industry has developed slowly since then, due to the fundamental commercial challenges outlined below. There remains a deficit of economic data on the production performance and diversification possibilities of aquaponics in a commercial setting, and many popular claims remain predicated on model research cases.

The degree of coupling between the recirculating aquaculture system (RAS) and hydroponic elements is a critical economic design consideration. Commercial attention has shifted from an early focus on fully coupled single recirculating aquaponic (SRAP) systems to more decoupled double recirculating aquaponic (DRAP) systems. The latter approach permits more autonomous operation of the two elements, whereby effluent from the fish (aquaculture) system supplies plant nutrients but there is total/greater reliance on RAS mechanical and biofiltration components to treat the aquaculture water. This approach also addresses a fundamental ‘gearing’ challenge, whereby the ratio of aquatic species to plant output is highly skewed toward the latter in fully coupled systems (i.e. fundamentally positioning them as horticultural systems with relatively low yield and output of aquaculture by-product).

The build ratios of fully decoupled SRAP systems range from 0.2-0.4m2 of growing space per m3 of deep-water culture volume, and have a stocking density of 1-2kg/m3 of fish production in systems attempting to balance fish and plant production (Purdue University, 2011; Rackocy et al, 2010). SRAP fish yields can be progressively enhanced through the addition of further aeration and filtration capacity, moving yields towards levels exceeding the 50kg/m3 routinely achieved in fully decoupled RAS systems. The important point is that the vegetable crop is usually the major product and the fish is minor under current technology. Table 1 shows a SWOT analysis of the different types of configurations for SRAP systems, considering various attributes, such as labour requirements, capital costs, and accessibility.

These observations point to a spectrum of hybrid operating conditions between SRAP and DRAP configurations, based on the type and degree of system coupling. Baganz et al, (2021) eschew the term ‘decoupled’ in favour of a more nuanced ‘on-demand coupled system’, with an on-demand nutrient water supply for the independent operating plant cultivation component. The optimal coupling configuration for commercially viable models requires consideration of production efficiency factors and strategic market requirements.

The various configurations include:

- **Nutrient film techniques** that create a shallow stream of nutrient-rich water that runs through the roots of the plant.
- **Media beds** that involve growing plants in a bed with gravel or clay then flooding the beds with nutrient-rich water
- **Deep water culture** that completely submerges the plant roots in the nutrient-rich water.

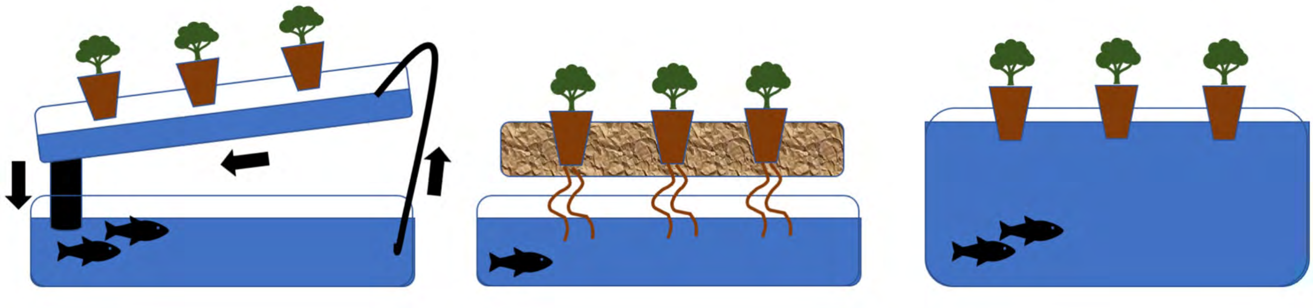


Image by: Alexandra Pounds

Table 10. SWOT analysis of three main hydroponic configurations in aquaponic systems (efficiency comparisons per unit of plant production)

Attributes	Nutrient film technique (NFT)	Media Beds	Deep Water Culture (DWC)
Labour input	Low	Higher	Intermediate
Space efficiency	High	Lower	Lowest
Accessibility	High	Intermediate	Intermediate
Biofouling risk	Higher	Intermediate	Lower
Water volume	Lowest	Intermediate	Highest
WQ homeostasis	Lower stability	Intermediate	Higher
Nutrient uptake	Lower (smaller root contact area)	High	High
Biofiltration	Lower	Highest	Lower
Scalability	Highest	Intermediate with flood & drain method	Lower
Management	Low constant water flow	Highest cleaning load	Constant water flow
Capital cost	Lower	Intermediate	Higher
Other	Unsuited flowering plants Good for vertical (stacked) farming Low flow suited to DRAP	Media bed micro-flora root & nutrient mineralization synergies Good for vertical crops	Supplementary root aeration required

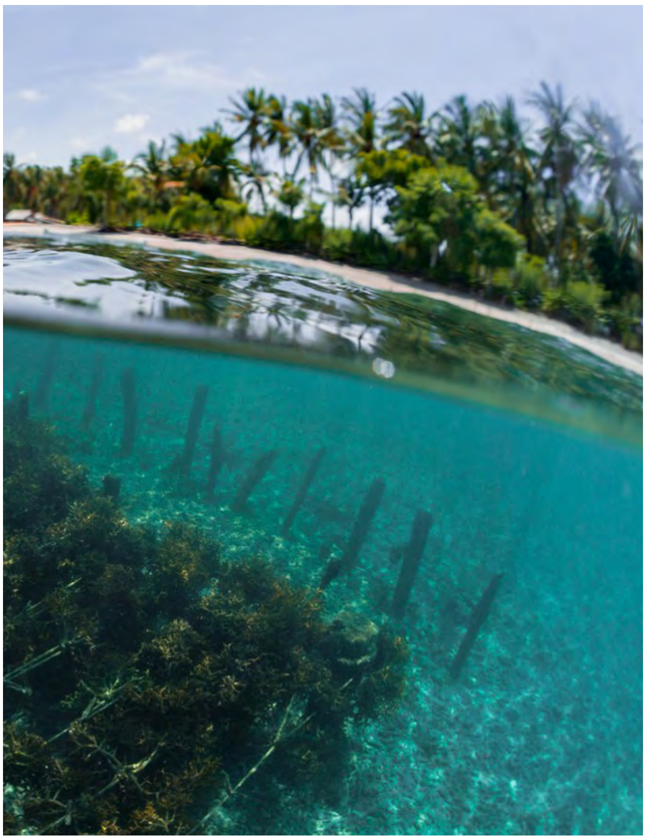
Aquatic animal production: SRAP also imposes greater management complexity in meeting the culture water quality requirements for the aquatic species (e.g. water temperature, pH and waste metabolite/nutrient concentrations).

Most aquaponic focus has been on short-cycle freshwater species, including rainbow trout, Nile tilapia, African catfish, and major carp species, which have relatively simple culture requirements. Efforts to integrate brackish water species, including shrimp and marine bivalves, are limited by the relatively small number of commercially viable salt-water tolerant halophytes (e.g. Salicornia, Sarcocornia, Halimione species – all relatively low yielding plants), more complex nutrient and water quality interactions, water sourcing and remediation requirements for effluent treatment and solids waste disposal, and contingent siting limitations (Marques et al, 2021; Sontakke and Haridas, 2020; Campbell, 2021; Gunning et al, 2016).

Plant production: A diverse range of vegetables, herbs, flowers and aquatic plants can be cultivated in aquaponic/hydroponic systems as an alternative approach to horticultural (glass-house) production. Herbs, lettuce, and specialty greens, such as basil or spinach, are especially well suited for SRAP systems based on their lower/less-complex nutritional needs for micro- and macro-nutrients. The focus will usually be on higher value crops, such as herbs. DRAP growers can also add synthetic fertilizers to meet the nutritional needs of more demanding high-value horticulture crops, including tomatoes, peppers and cucumbers, and increase yields without harming the aquatic species. Suhl et al, (2016) determined that synthetic fertilizer use for tomato production in DRAP can be reduced by up to 24% compared to conventional horticulture. SRAP can further reduce fertilizer dependence (by an additional 14% according to the above-mentioned study), but the gearing and plant compatibility factors mentioned earlier in this section are likely to make this an economically unviable means to fertilize plants at commercial scale in the absence of a sufficient market premium. Other non-system challenges include the high degree of interdisciplinary knowledge required to operate the integrated systems. However, these complexities also underpin the holistic science, technology, and engineering (STEM) learning objectives of many small-scale aquaponic applications predicated on a social business model.

Commercial application: A study of 208 aquaponic businesses in the United States, which has one of the highest adoption rates to date (Love et al, 2015), found an average investment cost of $5,000 - $10,000, with only 10% of businesses reporting more than $50,000 annual revenue due to some of larger operations also servicing a back-yard 'hobby' industry. The highly localized nature of supply chains for perishable horticultural outputs are also likely to be the limiting determinant for site location of aquaponic systems.

Marketing: Successful commercialization of aquaponics is likely to require additional investment in branding strategies to secure a market premium. This reflects the currently relatively poor consumer understanding and acceptance of the technology compared to stand alone hydroponics, as well as additional CAPEX and OPEX costs due to smaller production scales. A recent US start-up (Superior Fresh, 2022) uses effluents from small freshwater salmon RAS (70 tonnes/year capacity) to produce five times the volume of (USAID) organically certified leafy greens in a separate hydroponic system. However, the ideological grounding of organic certification in soil health has resulted in inconsistencies in eligibility for organic certification of plant and animal components under different regulatory regimes. There is a need for harmonized regional standards for integrated aquaculture production systems. Applied research on the economic viability of aquaponic systems today remains very limited compared to conventional hydroponic systems.



5.4. Prospects for optimizing nutrient use efficiency with integrated multi-trophic aquaculture

Combining fed and extractive aquatic species (e.g. fed finfish with filter feeders like mussels) has been termed 'integrated multi-trophic aquaculture' (IMTA). Field trials and pilot-scale systems have indicated that this strategy holds promise in selected open-water and land-based situations (Troell et al, 2009; Bunting and Shpigel, 2009). Benefits associated with IMTA include:

- Sequestration of nutrients by extractive species to help avoid adverse environmental impacts.
- Increased revenues and enhanced cash-flows to bolster the financial resilience of firms.
- Production of novel sources of food, feed ingredients or feedstock for biorefinery processes.

Outside of China, however, commercial-scale development has been limited. Combining fed and extractive species within individual firms currently has limited potential given the prevailing economic and socio-political context and established regulatory regimes. Priority research and development issues demanding attention have been identified (Bunting, 2008, 2010), and calls have been made for further analysis of the potential role of IMTA for "improved environmental, economic, and social acceptability" (Troell et al, 2003; p.70). If adopting IMTA strategies could make site licenses easier to obtain in a particular location, it may promote adoption of such practices and shift decision-making around aquaculture development toward a more holistic approach.

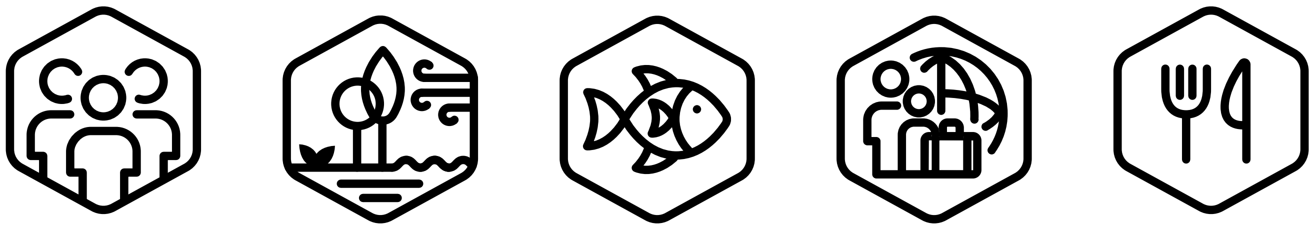
Extensive co-location of fed and extractive production units in open-water settings is occurring in China (Ferreira et al, 2008). However, the primary motivations of producers, and whether these arrangements were conceived as integrated systems or have developed in parallel, remains unclear. The density of production systems witnessed in some bays can be high and such developments are unlikely to be acceptable in other jurisdictions where aesthetic, fishing, navigation, recreation, and wildlife interests must be carefully considered in planning processes and site licensing (see Section 6.6.1 for further details).

6 Case studies demonstrating lessons for aquaculture growth

About the case studies

In this section of the report, we use case studies and contemporary accounts to contextualize concepts in global aquaculture development. These studies were selected to provide real world context (across geographies, species, and value chains) for some of the concepts outlined in earlier sections. Icons accompany each case study to highlight key areas where benefits could potentially be realized. These icons and the issues they deal with across food systems are presented in the legend below.

Legend:



Social issues | **Environment** | **Animal Health and Welfare** | **Inclusive Markets** | **Food Safety**

For each concept, we explain how the chosen case studies are exemplary of the concept. We then present an overview and outcomes of each case study, including a 'further reading' section that provides hyperlinks to earlier sections of this document with more information about the mechanisms mentioned in the case study.

6.1. Critical roles for regulation and good governance

The role of regulation and governance for environmentally sustainable development and quality assurance

A critical role for regulation and governance is ensuring that aquaculture development remains within local carrying capacities and provides oversight of quality-assurance. Governance and national regulations are an important basis for environmentally sustainable development.

Our first example considers the potential for cage culture growth across the African Great Lakes region. Aquaculture looks set to expand in many regions in Africa and potential opportunities and constraints are considered in this case study. These lakes include areas with both over- and under-development of cage culture; valuable lessons can be learned from over-developed areas about the need for appropriate government policies that prevent the environmental impact of development that exceeds the carrying capacity of the local ecosystem.

In the subsequent examples, we consider national standards to reassure consumers and partnerships as well as networks that could lead to transformative aquaculture sector growth. To demonstrate the quality of aquatic foods being produced in Saudi Arabia, a national standard has been developed that draws strongly on established international standards, and this is being used for marketing homegrown produce to consumers nationally. Ecuador's national standard similarly aims to improve the national quality and branding of shrimp production, but is targeting international markets.

As described in earlier sections, governance is not only driven at the national policy level, but also by the industry. As an example of industry-driven governance, we look at two examples of industry collaboration – in the tilapia industry in Hainan, China, and the farmed shrimp supply chain in Thailand – as examples of multistakeholder processes that have enabled improved dialogue both between different nodes of the supply chain and between the supply chain and regulators.

6.1.1. Development and potential of sustainable and financially viable commercial cage culture in the African Great Lakes

Summary:
This case study is an example of:

- An area with large aquaculture potential that is both under- and over-developed, with environmental and food security implications.

The learnings from this case study are:

- Aquaculture development of inland water bodies requires appropriate zoning and regulation, often across national boundaries, to sustainably stay within carrying capacity.

The Great Lakes span ten riparian countries, collectively containing over 31,000 km2 of water and contributing approximately 25% of the world's unfrozen surface fresh water. An estimated 107 million people live in the region, with the area described as one of the most

Emergent aquaculture and declining fisheries: In the last 20 years, production from the region's wild-caught fisheries has significantly decreased, in spite of efforts nationally and internationally to prevent decline. Simultaneously, commercial cage culture of tilapias has started to develop, primarily in Lakes Victoria, Malawi, Kivu and Tanganyika. Commercial cage culture at different scales in Lake Victoria contributes the vast majority of Uganda, Kenya, and Tanzania's annual aquaculture production. Lakes Kivu, Albert and Tanganyika primarily have small-scale production units, although this is changing. Early signs of cage culture were identified in 2016 in Lake Kivu, and other lakes in Rwanda. A total of 656 cages were recorded, but only 19.5% of these were stocked and operational.

By 2021, the Kenyan Fisheries Services estimated there were over 3,500 cages in Kenya's Lake Victoria waters, spanning just 7-8% of the shoreline of this huge lake. These are mostly smaller, locally manufactured cages producing 1-10 tonnes of tilapia annually. An additional 15 to 20 mid-level entrepreneurs have sites with 20 to 30 cages and their own associated hatcheries, producing between 50 – 500 tonnes annually and employing up to 30 local staff. Victory Farms is the largest operation, employing over 450 staff and producing over 7,000 tonnes of tilapia annually, which is sold nationally through a chain of branded retail outlets.

Unmet aquaculture potential: There is undoubted potential for the further growth of tilapia cage culture as a sustainable food production system across the Great Lakes region. This can be seen most clearly across the more densely populated areas of the East African Community (EAC), where increasing peri-urban populations fuel demand for fresh fish at competitive prices. Currently, when comparing start-up capital costs of such lake-based cage farms to land-based ponds or more intensive tank base RAS technologies, lower- to mid-scale (1- 250 tonnes of tilapia per year) cage farms appear to be a competitive proposition.

Environmental and economic costs of unplanned growth: There are already warning signs emanating from across Africa, where unmanaged expansion of aquaculture cages in some large inland lakes has led to significant environmental and socio-economic concerns. The success story of Ghana's commercial tilapia cage industry in Lake Volta from the early 2000s came to a shuddering halt in 2015-16 when a series of fish diseases swept through the lake. This caused severe financial losses for cage farmers, with costs to the industry estimated at over $70 million.

How can we ensure sustainable and longer lasting aquaculture in Africa's Great Lakes to feed growing populations? Lessons must be learnt from the poorly regulated and unmonitored aquaculture development that is already in some of Africa's large (manmade) lakes – particularly for Lake Volta and Lake Kariba, where tilapia cage culture is now growing rapidly. Although Lake Victoria is the third largest freshwater lake in the world by area, it is already facing pressures from the build-up of cages and other industrial activities, particularly along its north-eastern Kenyan and Ugandan shores.

It is hoped that stakeholders from across the region can identify and address the issues arising from of the development of the Great Lakes. With effective governance, aquaculture in the Great Lakes can be environmentally sustainable and financially viable in producing fresh food and employment for the growing populations. (Summarized and expanded from Obiero et al, 2020).

Further reading:

- 2.2.1. Aquaculture's links with capture fisheries: opportunities and challenges
- 2.2.3. Local environmental interactions
- 2.2.6. Investment opportunities contributing to the SDGs
- 2.2.11. Critical roles for regulation and good governance
- 2.4.1. Semi-intensive production modes
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.6. Low-capital expenditure systems
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.10. Alternative governance structures: industry-led standards
- 4.2.11. Alternative governance structures: community-based governance

6.1.2. SAMAQ: A label validating compliance with national regulations and international certification

The SAMAQ logo (left) and a display of SAMAQ certified products in the market (right).

Summary:
This case study is an example of:

- A government-led certification scheme to improve quality-assurance of national aquaculture products and increase consumer awareness of responsible seafood consumption.

The learnings from this case study are:

- Consumer demand for certification encourages producers to have responsible practices.
- Resources for effective compliance are critical.

The shrimp industry in Saudi Arabia suffered catastrophic impacts from white spot syndrome virus in 2010. By 2016, owing largely to the implementation of a robust national strategy for biosecurity monitoring and control (see Section 5.5.2), the aquaculture sector in Saudi Arabia had recovered and it continues to grow.

Developing a blended approach: Compliance with regulations was a challenge because local authorities lacked the capacity to properly monitor aquaculture operations and, since local markets did not differentiate between certified and non-certified products, there was no financial incentive for producers to obtain certification. Certified products were often mixed with lower-quality or less-responsibly grown products of the same species, without discernment from consumers.

To address these issues, the Saudi Arabian government establish SAMAQ[16], a national certification scheme. Eligible producers must comply with the Saudi Arabian Code for Responsible Aquaculture Practices and hold the international Best Aquaculture Practices (BAP) certification. In addition to the BAP criteria, additional ones have been included to ensure the Halal nature of the products, in accordance with the religious and social norms of the domestic market.

Government-led consumer and industry awareness campaigns increased the demand for certified products, using the SAMAQ label as the basis for generic product marketing. With increased demand for SAMAQ labeling, domestic aquaculture producers have been incentivized to upgrade their operations and practices, eventually qualifying for international, third-party certification. In this way, SAMAQ is an interesting example of the merging of state regulation with independent, third-party audited certification standards, with compliance inspected through a second-party, government-linked scheme.

The reception of SAMAQ certified and labeled products by consumers in the market has been positive. Today, more than 95% of the aquaculture production facilities operating in Saudi Arabia are SAMAQ/BAP-certified, which allows for almost all products of the domestic aquaculture industry to be eligible for the SAMAQ label. In the light of this, BAP or SAMAQ certification is now a prerequisite for license renewal of all aquaculture on-growing facilities operating in Saudi Arabia.

Further reading:

- 2.2.11. Critical roles for regulation and good governance
- 2.4.4. Opportunities and constraints associated with responsible development
- 3.2. Evidence programmes globally
- 4.1. The role of governance in aquaculture
- 4.2. Considerations on governance

6.1.3. The Sustainable Shrimp Partnership: an industry-led initiative to improve shrimp farming standards

Summary:
This case study is an example of:

- An industry-led certification scheme to improve quality-assurance and branding of shrimp related to sustainable practices.

The learnings from this case study are:

- Traceability, transparency, and compliance are key components of establishing consumer trust and brand reputation.
- Industry-led initiatives can help increase sustainable practices and food safety, such as reduced antibiotic use in shrimp culture.

The Sustainable Shrimp Partnership (SSP) is an industry-led certification scheme that aims to:

- Increase the use of best practices within the shrimp farming industry
- Improve traceability
- Eliminate antibiotic use
- Demonstrate compliance with best production and management practices

The SSP was started in 2018 by producers in Ecuador and uses the Aquaculture Stewardship Council (ASC) standards as best production and management practices, and helps farms to reach these standards.

Inclusivity and market access for smallholders: SSP and its Advisory Board implemented a farm improvement programme aimed at helping small- and mid-sized farms to work towards the SSP standards. First, farmers were benchmarked against several environmental and social indicators to establish their current performance and identify opportunities for improvements. Aiming for certification, farmers were then trained in environmental and legal requirements, good aquaculture practices, and the requirements for ASC certification.

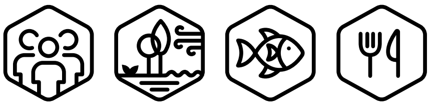
Traceability and transparency were critical components of establishing the brand: SSP joined the IBM Food Trust ecosystem, a platform that uses blockchain technology. Together, they developed a traceability application that is intuitively designed for consumers. By scanning a QR code, consumers can access product information, including its journey to their plate. Sharing key information with customers and consumers is critical to empowering them to make informed choices and drive market demand for more sustainable practices.

SSP aims to improve the overall impacts of the shrimp farming industry globally.

Further reading:

- 2.2.3. Local environmental interactions
- 3.2.5. Coverage of certification schemes
- 4.2.3. The role of certification schemes
- 4.2.4. Certification schemes' Theory of Change
- 4.2.6. Limitations of certification schemes
- 4.2.7. Coordination between governance and certification
- 4.2.9. Types of certification schemes
- 4.2.10. Alternative governance structures: industry-led standards
- 4.4.3. Certification
- 4.4.4. Codes of good practice

6.1.4. Hainan Tilapia Sustainability Alliance: industry-led transference and adoption of CoGP across regions



Summary:
This case study is an example of:
- An industry-led, multistakeholder code of good practice (CoGP) that aims to improve sustainable seafood production in China.

The learnings from this case study are:
- New CoGP can be modelled after CoGP from other industries.
- Multistakeholder engagement is important to gain cooperation and adherence.

The Hainan Tilapia Sustainability Alliance is the first independent, industry-led, multistakeholder association to promote sustainable seafood production in China. The Alliance works closely with industry leaders, farmers, research institutes, foreign buyers, and retailers, as well as third-party organizations.

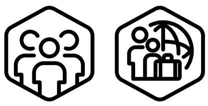
Modelling the Scottish salmon CoGP: The idea for the Alliance came following a visit to Scotland and understanding the structure and aims of the Scottish Salmon Producers Organization and its adoption of the Code of Good Practice for Scottish Finfish Aquaculture (developed by industry with other stakeholders and now enshrined in legislation[17]) - both in terms of promoting best practice and supporting branding. The Alliance has seen interest from producers in other areas of China who are interested in copying the model.

The core objectives of the Alliance are:

1. To minimize negative environmental impacts caused by tilapia aquaculture in Hainan, to reduce regional risks of disease outbreaks, hence strengthening its food safety management through zonal management and compliance with the Code of Good Practice.
2. To enhance transparency, traceability, and production efficiency across the supply-chain in Hainan through information sharing platforms, traceability systems, and long-term development planning.
3. To build up buyer and customer recognition and trust of 'Hainan Tilapia' through improved communication of science and effective marketing campaigns.
4. To obtain governmental support on sustainable development for the Hainan tilapia industry by engaging with policy-makers and defending the industry's interest in resource allocation (e.g. water and land use) when competing with other industries.

Further reading:
- 2.2.3. Local environmental interactions
- 3.2.5 Coverage of certification schemes
- 3.2.7 Zoning and policy development
- 4.2.3. The role of certification schemes
- 4.2.6. Limitations of certification schemes
- 4.2.7. Coordination between governance and certification
- 4.2.9. Types of certification schemes
- 4.2.10. Alternative governance structures: industry-led standards
- 4.4.3. Certification
- 4.4.4. Codes of good practice

6.1.5. Seafood Task Force: an industry-led coalition to eliminate forced labour in seafood supply chains



Summary:
This case study is an example of:
- An industry-led coalition that aims to increase transparency to reduce illegal fishing and poor labour conditions in seafood supply chains in South-East Asia (with more recent interests in India).

The learnings from this case study are:
- Demanding traceability is one way to ensure adherence to laws and regulations in the absence of appropriate local enforcement capabilities.

The Seafood Task Force (STF) is a global industry coalition with the goal of eliminating forced labour and illegal fishing in shrimp and tuna seafood supply chains by assisting the industries and governments to increase transparency and oversight. It was formed to address the credible allegations of slave labour in the supply chain of shrimp for supermarkets in the US and the UK. The focus is on illegal, unreported, and unregulated (IUU) fishing, as social and environmental issues are closely linked to IUU fishing.

STF focuses on strategies to eliminate forced labour through:

- Improved traceability using audits and digital/electronic solutions
- Responsible recruitment by agencies across multiple countries
- Increased accountability through audits and other methods (e.g. remote vessel behaviour monitoring)
- Capacity building and training
- Raising awareness and working with government agencies and NGOs to:
  - Highlight forced labour issues
  - Provide appropriate standards, tools, and direct training to supply chain members

The organization's work to date has promoted dignified work for workers who fish, farm, process and produce seafood. This has been achieved through the STF-developed codes and guidance documents, which form a blueprint for members and key stakeholders to implement change for both land-based and at-sea workers. This work aligns closely with the United Nations Guiding Principles on Business and Human Rights and the International Labour Organization C188 Work in Fishing Convention.

Further reading:

- 2.2.11. Critical roles for regulation and good governance
- 4.1. The role of governance in aquaculture
- 4.2. Considerations on governance

6.2. The role of regulations and governance for good social relations

An emerging issue across the aquaculture sector globally is securing a social license to operate (SLO), as described earlier in this document. Our first example, Atlantic salmon culture in marine waters around Scotland, is perceived as a large-scale and efficient industry that has developed over a 50-year period; however, regulatory frameworks must continue to evolve to meet the changing needs of industry and other stakeholders.

While a SLO can be driven through higher-level governance and regulations, as in Scotland, it can also be achieved through community-based governance and corporate ethos. This alternative approach is described using a case study of Victory Farms, Kenya.

6.2.1. Opportunities to enhance governance for renewed Scottish aquaculture growth

Loch Ainort fish farm. The salmon farm is operated by Marine Harvest. On the far shore of the loch, the community of Luib nestles beneath Glas Bheinn Mhòr (on the right), Beinn na Crò, Beinn Dearg Mhòr and Beinn na Caillich (on the left). Photo by Richard' Dorrell

Summary:
This case study is an example of:

- The importance of SLO in developing the aquaculture sector.
- The role of regulation in supporting positive community relations.
- Challenges of regulating a sector that consists of a variety of species and production systems.

The learnings from this case study are:

- Appropriate communication of aquaculture science and practice from a single authority is important for establishing trust between stakeholders.
- Aquaculture governance in Scotland is developing to be specific to each industry (e.g. shellfish versus finfish).

Reactive regulation strategies limit Scottish aquaculture:
In its infancy, Scottish aquaculture was not subject to many regulations, as little knowledge existed about aquaculture and farms were generally adjunct to small rural businesses. As the sector expanded, ad-hoc regulations were added reactively as issues arose. Even now, Scottish aquaculture is a dynamically developing sector. It produced 192,000 tonnes valued at £932 million in 2020, yet the sector is still governed by disjointed regulations. In a recent study on perceptions of the aquaculture sector in Scotland (Griggs, 2022), stakeholders believed that the current regulatory process for aquaculture is not fit for purpose.

Scotland aims to centralize regulation through multilateral decision making: Griggs (2022) recommends a centralized approach to developing, streamlining, and communicating appropriate legislation (separate and specific legislation for finfish, shellfish, and seaweed), with national and local bodies acting as implementers only. Legislation should frame compliance policies around key principles rather than 'ticking boxes', as the latter may encourage satisficing rather than ownership and long-term improvement. Furthermore, development of legislation should be multilateral, where stakeholders are included in decision-making.

Trust through effective communication of policies and science is critical for SLO: Currently, developing multilateral agreements and working relationships between stakeholders is difficult due to an intense degree of mistrust between the different stakeholders. These sentiments are strongest in the finfish industry but also exist to a lesser extent in the shellfish and seaweed industries. Public comments on aquaculture development are overwhelmingly negative (Billing, 2018), although it is unclear how prevalent these perceptions are in the broader Scottish population. Negative consumer perceptions are driven by negative media coverage, whereas the industry feels that they strive for continual improvement and that the public should trust their efforts (McGhee et al, 2019). In contrast to most of Scotland, the Shetland community are supportive of aquaculture, as it is perceived as an economic driver, and most issues are resolved through multilateral consultation (Griggs, 2022). Going 'beyond compliance' has been shown to increase public support for Scottish finfish production (McGhee et al, 2019).

Trialling this new approach: Scotland's upcoming aquaculture development roadmap aims to address these issues, using Shetland as a model. Producers will be expected to increase their support to and engagement with local communities, including community benefits and the support of innovation and enterprise. It also recommends a Norwegian-style auction system for new farm developments, that will help to drive innovation and provide income to the government to cover the costs of inspection and enforcement. Information on Scottish aquaculture will also be made publicly available through a single, user-intuitive friendly website (Griggs, 2022). Increasing consumers' access to scientific information – either online or on paper – can improve the public perception of aquaculture generally (Carrassón et al, 2021).

Further reading:

- 2.2.10. Achieving and maintaining good sector and social relations
- 2.2.11. Critical roles for regulation and good governance
- 2.4.5. Development opportunities associated with marine finfish aquaculture
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 3.2.7. Zoning and policy development
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.5. Social license to operate
- 4.2.10. Alternative governance structures: industry-led standards

6.2.2. Victory Farms gains license to operate through social engagement

Fishers in Roo Village, Kenya, park their boats near shore to offload their catch to women, who process the fish for drying and processing. Photo by: Alexandra Pounds

Summary:
This case study is an example of:

- A commercial scale farm that has achieved SLO and is intensifying in alignment with the UN SDGs.

The learnings from this case study are:

- Sustainable intensification that provides benefits to local communities is enabled through community-based management structures.

Community approval for legal permission: In 2015, the founders of Victory Farms scouted Lake Victoria, Kenya for the best location to set up an intensive commercial tilapia farm. Part of this process involved meeting the numerous stakeholders and gauging local community interest in hosting the farm. Local support was critical, as part of the licensing process to operate in Lake Victoria requires getting authorization from local Beach Management Units (BMUs), who are responsible for the enforcement of policies and regulations concerning common water resource use of the Lake. For both logistical and legal reasons, the success of the company relies on continued BMU and community support.

Tactics for achieving SLO: For Victory Farms, regulatory processes overlap with SLO: providing benefits to the community and the BMUs encourages positive licensing decisions. For example, communities have access to fish discounts and donations, Victory Farms sponsors scholarships and graduate training programmes, and equipment (e.g. boats, lights) is donated to local BMUs. Victory Farms' labour and employment candidates are primarily sought via local communities where possible, and 65% of their farm employees are youth. Most importantly, Victory Farms meets with stakeholders on a weekly basis to give them opportunities to air grievances and brainstorm solutions and other community projects. In this way, governance and social considerations overlap.

Sustainable development and the SDGs: Victory Farms' mission is to develop sustainably raised, affordable tilapia without antibiotics that will nourish millions of Kenyans, operating in alignment with the UN SDGs. It is on track to become the worlds' first carbon-negative tilapia farm, through approaches like harnessing solar energy, reforestation projects, and using locally made feed. Currently, Victory Farms sells over 30 tonnes of sustainable tilapia to low-income consumers daily.

Further reading:

- 2.1. Potential contributions of sustainable aquaculture to the SDGs
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 3.2.7. Zoning and policy development
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.5. Social license to operate
- 4.2.10. Alternative governance structures: industry-led standards
- 4.2.11. Alternative governance structures: community-based governance

6.3. Technology for growth

National aquaculture industries and supporting infrastructure, institutional arrangements, and associated research and innovation systems are at markedly different stages of development and sophistication throughout the world. Identifying promising technologies for transfer to new regions could help stimulate growth.

It is important to impart a note of caution regarding technology transfer as often the technologies in question fail to match the needs of operators in different physical, environmental and socio-political settings. Technology transfer can also be constrained in some cases by confidentiality arrangements and the need to protect intellectual property rights. On the other hand, these transfers can benefit producers and other value chain actors. Appropriate better management practice (BMP) guidelines have been developed to promote this in certain situations.

In this section, we highlight promising opportunities to share and extend the adoption of best practice across value chains, including feed and seed value chains. We do this through a case study illustrating how the establishment and sustained growth of freshwater fish production in Andhra Pradesh, eastern India, was possible owing to the transfer of hatchery techniques originating in China. This growth, in combination with more recent technology transfer from the shrimp processing and distribution industries, has made freshwater fish more accessible to poorer consumers across India.

Secondly, we discuss the potential benefits of transferring production systems technologies between regions. In a case study from the Philippines, we describe key aspects of local innovation and the transfer of green-water technologies to shrimp farmers in the Philippines, that have both enhanced animal welfare and reduced production costs. In another, we summarize the case for adopting offshore, continuous longline mussel cultivation technologies in the UK, based on the potential these have demonstrated at scale in New Zealand.

Finally, we discuss the emergent opportunities of digital technologies, such as cloud computing, the 'internet of things' (IoT), artificial intelligence (AI), and machine learning. These technologies are resulting in increased productivity and efficiencies for particular industries; however, we also describe why their transferability may be limited.

6.3.1. Technology transfer to enhance production in Andhra Pradesh, India

Farmer feeding carp with feed formulated in the village. Photo by: Arabinda Mahapatra

Summary:
This case study is an example of:
- Technologies and strategies for increasing production in semi-intensive farming systems

The learnings from this case study are:
- Key enabling conditions for intensification and large-scale grow-out of multiple fish species are:
  - Investments by entrepreneurs and knowledgeable individuals
  - The establishment of functioning and transparent leasehold markets
  - The availability of bank loans and the ease of doing business in the state

History of carp farming in Andhra Pradesh: Carp farming in Andhra Pradesh boomed and production reached over one million tonnes per year in 2012 (Belton et al, 2017). Extensive areas of low-lying land adjacent to Lake Kolleru and favourable climatic conditions encouraged operators to establish many hundreds of fish farms with an average size of a couple of hectares, as well as some that were up to one thousand hectares. Early growth was facilitated by the availability of dependable seed supplies from West Bengal, India, which were possible owing to the earlier transfer of Chinese carp rearing and nursing technologies to the state.

Rohu and Catla came to dominate production: Gradually, two indigenous carp species (rohu and catla) came to dominate production in Andhra Pradesh at the turn of the millennium. These species were favoured as they grow well in large ponds and there is good market demand. Other techniques and strategies adopted to sustain and increase production included:
- Producing advanced fingerlings and stunted yearlings to maximize growth rates and help avoid mortalities associated with stocking smaller fish.
- Utilizing plastic holding tanks, with aeration facilities, to enable larger fish for broodstock and stocking to be transported effectively.
- Developing hatcheries and nurseries locally so that the state became self-sufficient in carp seed.
- Stocking simple species combinations to optimize production based on supplementary feeding of de-oiled rice bran and natural foods found in ponds.
- Deepening ponds, using mechanical diggers, to provide a greater volume for production and widening bunds to permit access by tractors.

Efficiencies across the value chain: Some other key developments across value chains enabled more efficient production, distribution and marketing. Local manufacture of floating feeds enabled the pangasius farming industry to develop quickly and efficiently, with production increasing to over half a million tonnes per year in 2010. Utilizing plastic trays in the state's shrimp processing industry has helped to avoid physical damage to the product during transportation and food losses. As large whole fish are more difficult to transport than filets, processing pangasius into filets and preserving them, by chilling or freezing, has enabled value chains to be lengthened and products to be distributed to cities across India.

Key factors for successful development: It is interesting to reflect on why large-scale grow-out of multiple fish species has occurred in Andhra Pradesh, as compared to West Bengal where most of the fish seed produced in India centred and demand for fish among consumers is strong. Factors attributed to Andhra Pradesh success include: investments by entrepreneurs and knowledgeable individuals, the establishment of functioning and transparent leasehold markets, the availability of bank loans and the ease of doing business in the state.

Further reading:

- 2.2.11. Critical roles for regulation and good governance
  2.2.2. Optimizing feed utilization and ingredients supply
- 2.2.4. Seed supply
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.6. Low-capital expenditure systems
- 2.4.1. Semi-intensive production modes
- 3.2.7. Zoning and policy development
- 4.1.1. The aims of governance
- 4.1.3. Social impacts of insufficient governance
- 4.1.4. Excessive governance limits development
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations

6.3.2. Green-water technologies for more productive aquaculture

Tilapia coming to the surface in anticipation of feed in a green water system

Summary:
This case study is an example of:
- Integrated aquaculture technologies that improve animal welfare conditions for better productivity and lower costs.

The learnings from this case study are:
- Green water technology can improve the health and productivity of integrated shrimp and fish systems.

Phytoplankton as supplementary feed and contributor to water quality management: Harnessing the natural productivity of phytoplankton in extensive and semi-intensive aquatic farming systems is often deemed essential for sustainable production (Edwards, 2009). The inclusion of phytoplankton in aquaculture systems has been termed 'green-water technology'. The process of photosynthesis leads to oxygenation of the culture water and it routinely provides an important source of nutrition for the cultured animals or the organisms that they feed on.

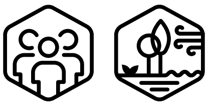
What is green-water technology? In the Philippines, producers have devised a more sophisticated green-water technology system to capitalize on the natural productivity of fertilized systems and the synergistic effects of stocking fish species (Asian seabass and Nile tilapia) that can protect the health of shrimp cultured in the same system (Bosma and Tendencia, 2014). Prior to use in shrimp culture, water may first be conditioned in a separate pond stocked with fish or the fish can be stocked in net pens in the shrimp ponds.

The presence of Nile tilapia enhances nutrient cycling and helps a complex microbiome develop that can inhibit the development of pathogens (e.g. white spot syndrome virus). Tilapia are also phytoplankton grazers, so green-water systems also supply endogenous feed for growth and can improve tilapia feed conversion ratios (FCRs) even further. When Asian seabass are stocked they predate on aquatic animals that may harbour pathogens. Where Nile tilapia is non-native, caution is required and the identification of an alternative local species that induces the same effects is suggested.

Green-water results in lower costs: Considering the financial returns from such systems, production costs for shrimp cultured using green-water technologies were lower than in comparable non- green-water systems in Indonesia and Vietnam. Shrimp cultured using green-water technology survived better and had higher individual weights at the end of the grow-out period.

Further reading:
- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 3.2.6. Animal welfare considerations

6.3.3. Addressing spatial constraints: opportunities from offshore longline mussel culture in New Zealand



A New Zealand Green Lipped Mussel Farm near Havelock, South Island, New Zealand. Photo by: QFSE Media

Summary:
This case study is an example of:
- An aquaculture system that is limited by space and its opportunities for expansion using current technology.

The learnings from this case study are:
- Offshore aquaculture can provide a solution to aquaculture operations limited by space or curtailed by competition with other waterbody users.

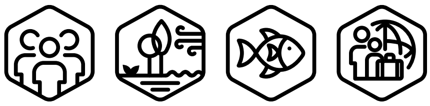
Demand for blue mussels across Europe is strong, but supply from established culture systems and centres of production has reached capacity, leading to higher prices for consumers. Further growth in blue mussel culture in inshore areas in Europe is limited because:

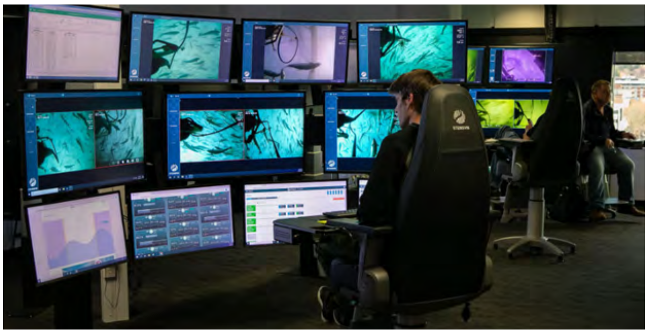
- Many suitable inshore areas are already in use for mussel production.
- There is competition for sites with other users.
- Excess turbidity and variable water quality in shallow and inshore areas limit feasibility.
- Availability of natural seed supplies are unpredictable.
- Small-scale and dispersed nature of business in some countries makes mechanization and associated cost sharing impossible.

Against this backdrop, producers have looked to move offshore and to scale-up activities to make operations more efficient and reduce per unit costs of production (Holmyard, 2008). Traditional mussel harvesting requires intensive manual labour that can be slow and require many workers. By contrast, production in New Zealand using efficient continuous longline technologies and appropriate on-vessel harvesting machines shows that a crew of four people operating offshore can harvest, clean and grade between 50 and 100 tonnes of mussels per day. Site selection is important for mussel production offshore, to ensure good phytoplankton availability (which mussels feed on), adequate spat supplies, acceptable levels of predator and fouling organisms, and appropriate depths. Typical weather and sea conditions throughout the year should also permit sufficient days at sea for the management tasks required.

Further reading:
- 2.2.3. Local environmental interactions
- 2.2.4. Seed supply

6.3.4. The digital blue revolution





Digital salmon feeding control centre in Australia. Photo by: Tassal Group

Summary:
This case study is an example of:
- 'Precision aquaculture': How cloud computing, the internet of things (IoT), AI, and machine learning are used in the salmon aquaculture industry.

The learnings from this case study are:
- Digital technology can enhance the productivity of aquaculture systems through better feed, health, and welfare management.
- The sustainability of these systems can also be improved through digital solutions that increase feeding efficiency.
- These technologies may only be useful for large-scale, high-capital expenditure systems, as the costs may be insurmountable for smallholders.

Digital technologies – including cloud computing, IoT, AI and machine learning – are facilitating the sustainable growth of aquaculture production. These types of technologies applied to aquaculture are called 'precision aquaculture techniques'. Broadly speaking, there are three types of digital solutions for aquaculture: digital sensors and (intelligent) hardware; digital platforms; and trading and financing platforms. These can be integrated to provide end-to-end services that increase efficiency. For example, some IT-engaged companies report FCR reductions that range between 5% and 28%in 2020 (Aqua Spark, 2020).

Digital sensors allow the automatic digital collection of data, such as water quality sensors (measuring factors like temperature and oxygen). In addition, high-definition cameras monitor feeding, fish weight, and stock health, as well as undertaking net pen inspections. However, since most aquaculture production – particularly in tropical inland ponds – takes place in opaque water systems, where cameras are ineffective, passive hydroacoustics ('listening' within ponds) are used instead for successfully controlling feeding, and active hydroacoustics (sonar systems, similar to fish finders) have emerged for monitoring fish and shrimp behaviour.

Intelligent hardware capable of forecasting fish appetite and behaviour (based on sensor data) and distributing feed in response to the data collected can also be part of the digital suite.

Digital platforms allow the collection and storage of data from different sources – such as publicly available databases, as well as sensors, video cameras, and manual collection. Data are then analyzed (often using AI, but increasingly big data, machine learning, and even deep learning approaches) to provide recommendations to farmers on factors such as farming practices and inputs.

Trading and financing platforms use data on feeding and growth to provide a track record for financial institutions that finance feed purchase, provide insurance, and provide faster payment services, which shortens the time between crops and allows forecasting of harvest times, sizes and volumes needed to fulfill trading contracts.

Impacts of digital technologies include that monitoring systems support better animal welfare, reduce mortalities or poor growth, and improve cost-effectiveness. For example, feeding behaviour identifying pancreas disease – a major issue in European salmon farms – could be diagnosed a month earlier using AI than through conventional methods (Måløy, 2020). An early diagnosis system can provide earlier alarms – and across many farms at once – by developing a dedicated algorithm. This will allow fish health efforts to be more efficiently directed at sites which need attention, rather than regularly screening all farms, and usually only catching the problem at the 'firefighting stage'.

Examples of successful applications include Norwegian salmon farming companies that have been using feed control centres for a number of years now, with those in Scotland, Canada, Chile and Australia now following suit. Costing up to $14.6 million each, these centres can be connected to hundreds of underwater cameras and sensors at different depths within the cages, allowing one operator to distribute feed pellets to 15 million salmon. Through automation, these centres reduce the responsibility placed on a single human operator, guiding and allowing the operator to focus on the cages that most need their attention. The system also keeps the operator informed of the biomass of salmon in each cage and their growth rates, as well as forecasting harvest dates.

Accessibility of digital solutions of this scale are beyond the grasp of all but the largest farming companies. Currently, less than 100,000 farmers use the full-suite of digital solutions, with the largest proportion in Asia, although the most advanced solutions (including integrated hardware) are most common in North America and Europe. The other downside of the digital revolution and the use of AI is that automation can result in a reduction in lower skill level job opportunities, while the upside is greater job opportunities for staff operating digital systems.

As well as helping to guide farmers in their decision-making and alerting them to possible dangers to their crops, digital solutions are making aquaculture more efficient and precise – reducing wasted feed, improving the welfare of farmed aquatic animals, and reducing environmental impact. They open up new opportunities for farmers wishing to comply with aquaculture standards that can lead to new market opportunities.

Further reading:

- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 3.2.6. Animal welfare considerations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.9. Types of certification schemes

6.4. Optimizing Feed

Feed is often the most costly input for semi-intensive and intensively managed farms, so innovation to make feed use more efficient is often the key to sustained aquaculture sector growth. Commercial feed companies have to balance the inclusion of specific nutritious ingredients with cost and trade-offs in production performance. Feed formulation is critical to meeting the nutritional needs of the cultured animal (see Section 5.5), ensuring that nutrients are readily assimilated and do not result in waste or loss of nutrients to the biosphere, and that the final product meets the nutrition requirements of consumers.

In the first case study, we examine the potential for reducing pressures on wild fisheries and improving the environmental sustainability of feed through alternatives to fish-derived ingredients. Wild fish are a valuable resource for human nutrition as well as cultured fish species, and we describe opportunities for better management to maximize this resource. Effective traceability systems to assure the sustainable provenance of marine and terrestrial (plant) ingredients is important for monitoring, evaluation, and evidence-based policy design.

In the second case study, we present a case study from Sub-Saharan Africa showing that, beyond effective feed formulation, it is crucial to consider how feed quality can be maintained and assured across value chains and how the transfer of locally appropriate technologies might help in this regard. On-farm handling, feeding regimes, and delivery mechanisms can also be instrumental in governing the rate of feed conversion (also see Section 5.3.2 and 5.3.4). BMP guidelines have been proposed globally for several production systems to help enhance the efficiency and cost-effectiveness of feed use. For example, WorldFish's digital vocational training repository hosts a wide range of general as well as country-specific BMPs for various species. Potential roles for value chain intermediaries, and notably technicians from feed companies, have been identified on farms to facilitate knowledge sharing and finance provision.

6.4.1. Securing alternatives to fish-derived ingredients for aquaculture feeds

Small fried fish, often eaten in stews and curries, are sold in the markets of Bangladesh. Photo by: Alexandra Pounds

Summary:
This case study is an example of:
- The implications and opportunities related to the use of wild fisheries for aquaculture feeds.

The learnings from this case study are:
- Wild fisheries fit for human consumption should not be used in aquafeeds.
- Wild fisheries unfit for human consumption can continue to be used in aquafeeds.
- Some inclusion of fish in aquafeeds may be more sustainable than relying on terrestrial crops alone.

Fish as food instead of feed: It has been recommended to avoid using freshwater and marine small pelagic fish species (SPFS) as feed ingredients for aquaculture when people suffering from nutrient deficiencies and malnourishment (especially young children and breastfeeding women in low- and middle-income countries) could benefit from the direct consumption of this nutritious source of food (Thiao and Bunting, 2022).

The divergence of SPFS from poor consumers for aquafeeds and IUU fishing[18] is particularly problematic in Sub-Saharan Africa. To address this issue, a multistakeholder review covering eight key countries (Congo, Gambia, Ghana, Malawi, Mauritania, Senegal, Sierra Leone, and Uganda) generated 15 recommendations for decision-makers, researchers, and development investors (Thiao and Bunting, 2022; Bunting et al, in preparation).

Ten recommendations for decision-makers were to:

1. Promote plant- and insect-based protein sources for feed use.
2. Build capacity of farmers to formulate and produce efficient-to-use feeds incorporating alternatives to fish derived ingredients.
3. Regulate fish-based feed (FBF) production according to fish stock status and the need for fish for direct human consumption.
4. Promote practices to reduce bycatch and food losses.
5. Purposely regulate the price for edible fish making it less desirable for FBF production and affordable for local processors and consumers.
6. Implement environmental audits of FBF producers.
7. Promote health and safety at work and environmentally sound practices.
8. Prohibit dumping of toxic waste in inland and marine waters.
9. Avoid building fishmeal and fish oil factories in residential areas.
10. Implement and enforce policies for the FBF industry.

Five recommendations for future research were to:

11. Regularly assess key SPFS and harvest and post-harvest activities.
12. Assess fish consumption, including affordability and importance for food and nutrition security.
13. Assess national and regional demand/need and affordability of FBF for the aquaculture and livestock sectors.
14. Assess chemical composition of wastes from fish-derived ingredient factories and associated environmental and health impacts.
15. Promote research to identify alternatives to FBF and assess their efficiency, feasibility, profitability and viability.

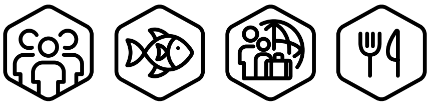
These recommendations from the people most affected by this dynamic can help increase food security in Sub-Saharan Africa. Aquafeed certification can play a role in assuring that food security in these areas is not threatened.

Yet, complete removal of fish from feed in this region may be inappropriate for two main reasons. Firstly, not all SPFS is of high-enough quality or geographically positioned to supply human consumers (i.e. is too far away from or not easily transported to demanding markets, and local market demand for SPFS may be weak). Rather than wasting lower-quality fish and fisheries by-products, these materials can be used for generating fishmeal and fish oil. Secondly, the complete replacement of marine-derived ingredients with terrestrial alternatives may result in other negative outcomes (Malcorps et al, 2019). For a more in-depth discussion on fishmeal and fish oil use in aquafeeds, please read Section 2.2.2.

Further reading:

- 2.2.1. Aquaculture's links with capture fisheries: opportunities and challenges
- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.3. Alignment with the FAO Code of Conduct for Responsible Fisheries
- 2.4.2. Integrated farming systems
- 4.1.5 Concern over local impacts shifts them elsewhere

6.4.2. Quality assurance of aquaculture feeds and associated value chains in Sub-Saharan Africa



Varying qualities of fish feed from the same source are shown side by side in a fish feeder's hands. Photo By: Alexandra Pounds

Summary:

This case study is an example of:

- How issues in upstream value chains can have impacts on quality of feed.
- Using fish in aquafeeds may divert fish from being consumed by humans.

The learnings from this case study are:

- Quality-assurance throughout the value chain, including feed production, is critical for supporting the needs of a growing aquaculture sector.

Feed value chain issues: Commercial aquaculture development across Sub-Saharan Africa appears to be gathering momentum and could soon make a substantial contribution to aquatic food supplies. Issues with feed value chains (both upstream and downstream) have been noted, however, that could undermine growth of the sector, and limited feed production capacity and delivery to farming sites may constitute key constraints. Concerns have been expressed about diverting fish away from direct human consumption and into animal feeds, especially in this region of Africa, and authorities could draw on published recommendations to help address this important issue (for details see Section 5.4.1 and Thiao and Bunting, 2022).

Barriers and opportunities in ingredient processing: Artisanal processing and storage of fish-derived ingredients (FDI) are often sub-optimal, resulting in physical losses and declines in nutritional quality (Wesana et al, in preparation). Adoption of locally appropriate techniques and better management practices could help improve this situation (Bunting et al, in review). The weather and climate change impacts can affect processing outcomes. Identification of affordable technologies and materials for improved fish drying (e.g. corrugated plastic and polythene sheets) could also help enhance the efficiency of operations, increase the number of processing days, and extend the shelf-life of FDIs to match the demand.

Contamination and quality-assurance: Problems with contamination (e.g. dirt, fecal matter, toxins, pests, sand and shells) and adulteration of FDIs produced by artisanal processors and across associated value chains have been highlighted in Kenya and Uganda (Nalwanga et al, 2009; Kigozi et al, 2020). FDIs, other non-fish ingredients, and finished feeds in the region have been found to be susceptible to aflatoxin contamination. Reviewing the quality of formulated feeds being produced by local firms in Uganda, it was noted that the stated levels for crude protein listed on labels did not match with the laboratory analysis of samples and routinely overstated the quality (Nalwanga et al, 2009).

The need for quality-assurance measures: It is apparent that the FDI processing and feed manufacturing industries, and their associated value chains (upstream and downstream) demand attention. Quality assurance measures can ensure that the quality of feeds:

- Matches the requirements of cultured animals and producers.
- Standardizes the composition of fishmeal, which can be highly variable resulting from different raw materials and processes.
- Reduces contamination and adulteration in the supply chain.

These actions are required to safeguard feed and food safety and to bolster confidence in the industry as well as its financial returns.

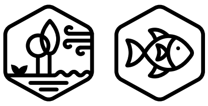
Further reading:

- 2.2.1. Aquaculture's links with capture fisheries: opportunities and challenges
- 2.2.11. Critical roles for regulation and good governance
- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.4.3. Resilience through diversity of producers and production systems
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.3. The role of certification schemes
- 4.2.6. Limitations of certification schemes
- 4.2.8. Certification and market access

6.5. Animal health and welfare

In the following case studies, examples of initiatives to enhance animal health and welfare are described, including a focus on biosecurity that is essential at all production phases.

6.5.1. Biosecurity enhancements support salmon farming recovery in the Faroe Islands



Akrar is a village in Suðuroy, Faroe Islands. The fjords near Akrar are called Vágsfjørður and Lopransfjørður. There are salmon farm rings in the sea near Akrar. Photo by: Eileen Sanda

Summary:
This case study is an example of:

- Successful containment and management of outbreaks of infectious salmon anemia (ISA) in salmon.

The learnings from this case study are:

- Biosecurity plans, vaccination programmes, reducing transmission, and careful monitoring of stocks can help prevent disease outbreaks and aid management of other health issues such as sea lice.

The impact of disease: Outbreaks of ISA have seriously affected the production and economic returns generated by the aquaculture industry in several countries, including the Faroe Islands (Falk and Aamelfot, 2017). To counter this, the industry now routinely administers vaccinations and has implemented tighter biosecurity arrangements.

Lillehaug et al (2015) noted that biosecurity consists of preventative measures to reduce the risks of transmission of disease agents and pests that in practice may include:

- Establishing a biosecurity plan to ensure actions are comprehensive and coordinated.
- Recording progress with implementing the biosecurity plan, including certificates for vaccinations.
- Identifying possible routes for transmission of infectious agents and implementing targeted mitigation actions.
- Adopting standard operating procedures for disinfection.
- Instigating measures to reduce horizontal and vertical transmission on farms.
- Monitoring stocks closely for cases of infection and slaughter and disposing of infected animals in a timely and appropriate way.

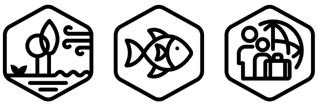
Use of waste products: Special attention was given in the case of the Faroe Islands to the hygienic disposal of mortalities and the safe recycling of this material in Norway, either through biogas production or as an ingredient in terrestrial animal feeds or pet food (Fish Focus, 2022).

Other relevant points: Despite improvements in the biosecurity measures and associated farmed animal welfare, however, concerns over whaling in the Faroe Islands constrain sales in countries where this is regarded negatively by seafood buyers and consumers.

Further reading:

- 2.2.1. Aquaculture's links with capture fisheries: opportunities and challenges
- 2.2.3. Local environmental interactions
- 2.2.11. Critical roles for regulation and good governance
- 2.4.5. Development opportunities associated with marine finfish aquaculture
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 4.1.1. The aims of governance
- 4.1.2. Environmental (and market) impacts of insufficient governance
- 4.1.4. Excessive governance limits development
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.3. The role of certification schemes
- 4.2.5. Social license to operate
- 4.2.6. Limitations of certification schemes
- 4.2.10. Alternative governance structures: industry-led standards
- 4.4.4. Codes of good practice

6.5.2. Application of a national biosecurity monitoring and control programme in Saudi Arabia



Whiteleg shrimp (Litopenaeus vannamei), normally a pale grey colour, turn pink when cooked

Summary:
This case study is an example of:
- An entire industry that was threatened with collapse due to disease.

The learnings from this case study are:
- Coordination of industry through government-supported and improved industry-wide biosecurity standards.
- Prompt response to biosecurity threats, surveillance, and biosecurity measures are critical for maintaining good production.

Disease outbreaks halted Saudi Arabia's aquaculture growth: While some Nile tilapia culture began in the 1980s, Saudi Arabia's aquaculture sector really expanded in the mid-1990s with the commercialization of semi-intensive giant tiger prawn production. However, during 2010 and 2011, the global White Spot Syndrome virus pandemic resulted in huge losses.

Government-led disease containment efforts: In response, the Ministry of Environment, Water and Agriculture implemented a recovery strategy that would also safeguard the industry from future biosecurity threats. The strategy was successful: production reached pre-pandemic rates within two years and continued to grow thereafter. By 2018, production was more than double pre-pandemic levels.

Tactics for recovery:
- Production switched from giant tiger prawn to the more robust and disease-resilient whiteleg shrimp.
- The initial batches were checked for all pathogens listed by the World Organization for Animal Health for shrimps and subsequently only specific pathogen-free (SPF), specific pathogen-tolerant (SPT), and specific pathogen-resistant (SPR) shrimp were allowed for stocking in on-growing ponds.
- Regulators rolled out a strict national biosecurity monitoring and control programme that included all national aquaculture industries.

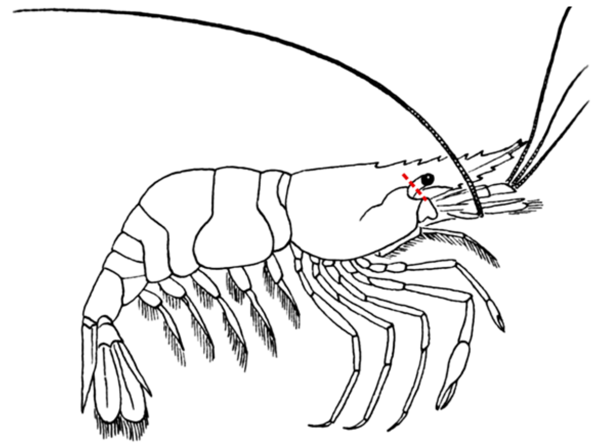
Strategies for ongoing surveillance:
- Promptly detect harmful pathogens that could adversely affect the industry and the local environment.
- Ensure the application of approved Standard Operating Procedures (SOPs) for aquaculture practices that prevent transmission of pathogens.
- Develop rapid alert systems and contingency plans in the event of detection of any such pathogen/disease.
- Provide relevant support to industry stakeholders through capacity building and access to relevant knowledge and information.
- Maintain a database for the most efficient and effective way of using national (and company-based) biosecurity data and information.

Surveillance: A surveillance plan was also implemented, where sampling for disease screening occurred every 14-30 days across all aquaculture units, their surrounding environments, and market points. On average, 2,000 animals (specimens) are collected per month from all the sampling points.

The programme has been running successfully since 2016, and any biosecurity related issues that have appeared during these years have been promptly and effectively dealt with, ensuring the protection of the industry and its subsequent growth.

Further reading:
- 2.2.11. Critical roles for regulation and good governance
- 2.2.3. Local environmental interactions
- 2.2.4. Seed supply
- 3.2.7. Zoning and policy development
- 4.1.1. The aims of governance
- 4.1.2. Environmental (and market) impacts of insufficient governance
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations

6.5.3. The end of eyestalk ablation: better shrimp welfare supports disease resilience



Line drawing of a shrimp with red dotted line indicating the location to cut for eyestalk ablation. Drawing by: Pearson Foreman

Summary:
This case study is an example of:

- Addressing the application of poor animal welfare practices in crustacean aquaculture through the use of alternative management practices.

The learnings from this case study are:

- Innovations in management practices can improve animal welfare and disease resistance.

What is eyestalk ablation and why is it used? Spawning in female shrimps is controlled by hormones produced in their eyestalks. To induce spawning in shrimp aquaculture, eyestalk ablation (removal or constriction through cutting, cauterizing or tying) is common practice, because it has helped hatcheries ensure a regular and consistent supply of eggs for production. However, this practice has negative animal welfare and health implications (Zacarias, 2020). A summary of the effects of eyestalk ablation on female shrimp and their offspring is presented in the following diagram:

Eyestalk ablation effect

Welfare

- Physiological imbalance
- Reproductive exhaustion
- Physical trauma and stress
- High energy demand
- Alteration of biochemical pathways
- High broodstock mortality

Health

- Activation / reduction of immune related genes
- Decrease shrimp broodstock offspring robustness to disease

Ablation decreases disease immunity in offspring: Recent research has discovered another negative side effect of ablation. Offspring of ablated females are more susceptible to some of the main shrimp diseases, such as acute hepatopancreatic necrosis disease and white spot syndrome virus (Zacarias et al, 2021).

Alternatives to ablation: Spawning can be controlled through a variety of other management practices, such as:

- increasing the stocking density
- changing the ratio of males to females
- using domesticated families of shrimp that breed more easily without ablation
- supplementing females with fresh-frozen natural feeds, like mussels and squid

These approaches are important in light of consumer demand and increasing certification requirements for improved animal welfare. Cultured shrimp producers in Brazil, Colombia, Ecuador, Mexico, and Thailand have successfully abandoned eyestalk ablation.

Further reading:

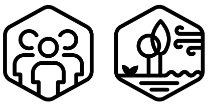
- 2.2.11. Critical roles for regulation and good governance
- 2.2.4. Seed supply
- 2.4.4. Opportunities and constraints associated with responsible development
- 3.2.6. Animal welfare considerations
- 4.2.3. The role of certification schemes
- 4.2.9. Types of certification schemes

6.6. Opportunities for aquaculture in integrated food production systems

In this section, we review some of the key features of integrated farming systems that apparently make them more sustainable and resilient to adverse drivers of change. Prospects for extending the benefits of such approaches to other geographical areas are then considered.

In the following case studies, we describe an example of IMTA in China that could be scaled to other intensively cultivated areas of the ocean. We then show an example of a regenerative aquaculture system in Indonesia involving the rehabilitation of mangrove forests in conjunction with shrimp production. Not only does this system provide ecosystem benefits, but also provides benefits to the shrimp farmer. Subsequently, we present a description of rice-fish farming, as an integrated, regenerative aquaculture system. In particular, we provide a case study of rice-fish farming in Bangladesh that stems from local indigenous practices.

6.6.1. Integrated multi-trophic aquaculture in Sanggou Bay, Shandong, China



Kelp culture on ropes in a marine environment. Photo by: Prof. Joao Ferreira

Summary:
This case study is an example of:

- A commercially successful IMTA industry that has positive environmental impacts.

The learnings from this case study are:

- IMTA has the potential to improve the environmental impact of aquaculture; however, it may not be appropriate in all contexts due to technical challenges.

Pioneers in IMTA: Sanggou Bay, located in the eastern part of Shandong Province, China, was one of the first areas in China to start IMTA mariculture (Mao et al, 2018). Seaweed farming became popular in Sanggou Bay in the 1960s. Since then, the mariculture industry in Sanggou Bay has expanded considerably, benefiting from the successful development of breeding and farming technology. Moreover, there are multiple farmed species of seaweed, shellfish, and fish, which form a large coastal water ecosystem of IMTA.

- Sea area: 144 km2
- Total farming area: 100 km2 (70% of total bay area; Fang et al, 2016)
- 30 species produced (mainly low trophic level)
- 240,000 tonnes of annual production (Fang et al, 2016)
- Algae and shellfish account for 80% and 15% of the total biomass respectively (Sun et al, 2020)

IMTA addressed growing environmental problems: Like many other areas in China, Sanggou Bay faced many problems in the early stages of mariculture development. The blind pursuit of seafood production and the uncontrolled expansion of farming activities resulted in many negative impacts. Eutrophication destroyed the balance of the ecosystem and eventually led to a decline in the quality of farmed aquatic products. To resolve these problems, a new aquaculture model of IMTA was applied in Sanggou Bay in the 1990s (Yang, 2018). Farmers adjusted the ratio of farmed seaweed, shellfish, and fish, to ensure the complementary development of aquaculture with ecosystem conservation.

The chemistry behind IMTA: Seaweed can effectively absorb the nitrogen and phosphorus produced by fish and shellfish farming. In addition, seaweed detritus provides a food source for some shellfish, which may also potentially filter phytoplankton that have grown due to the nutrients (nitrogen and phosphorus) provided by finfish farming.

IMTA provides environmental benefits: The Sanggou Bay ecosystem is stable and the water quality is excellent, though there are substantial farming activities (Mao et al, 2018). In addition, aquaculture in Sanggou Bay contributed to considerable carbon sequestration. The model of IMTA in Sanggou Bay avoids the degradation of ecosystems and ensures the production of diverse and good quality aquatic products. The net dissolved inorganic carbon sink in Sanggou Bay is estimated at 139,000 tonnes per year (Jiang et al, 2015).

A model of excellence: As an excellent example of nature-based solutions for synergizing ecological protection and the aquaculture industry, Sanggou Bay was declared a national sea ranching demonstration area in 2016, serving as a model for the reform and optimization of China's mariculture industry.

Can the success of Sanggou Bay be recreated elsewhere? Reflecting on the success of aquaculture in Sanggou Bay, it may be questionable whether this degree of coverage would be acceptable in other locations as it could interfere with fishing, navigation and recreation, and has an ecological and visual impact. Production of marine algae in China has grown significantly to meet demand for direct human consumption, processed foods and beverages, agar extraction, animal feed ingredients, fertilizers and soil conditioners, and cosmetics. Where markets for marine algae are not well established, it has been proposed that the biomass produced could be utilized for renewable energy production, but the practical and economic viability of this demands further analysis. Seaweed producers must also be wary of biofouling and self-shading problems that can constrain production. Seaweed culture is generally perceived as relatively benign in terms of environmental and social impacts, but it needs to be considered in the context of Integrated Coastal Zone Management principles when planning and managing large-scale commercial scale production systems (Ferreira et al, 2008).

Further reading:

- 2.2.11. Critical roles for regulation and good governance
- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.2.3. Local environmental interactions
- 2.4.2. Integrated farming systems
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 3.2.7. Zoning and policy development
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations

6.6.2. Mangrove-shrimp culture systems in Indonesia

Mangrove trees planted within ponds used to culture shrimp in the Mahakam Delta, East Kalimantan, Indonesia. Photo by: Stuart Bunting

Summary:
This case study is an example of:

- The integrative approach of reintroducing mangroves to shrimp ponds, which provided the local ecosystem with the benefits of mangrove forests while improving the productivity of shrimp.

The learnings from this case study are:

- Improved environmental management can enhance aquatic and terrestrial biodiversity and deliver a host of ecosystem services to benefit local communities and aquaculture production.

Mangrove-shrimp culture originally had mixed results: Over the past 30 years, stakeholders in the shrimp industry throughout Indonesia (e.g. farmers, local and national government departments, and universities) have been working to develop innovative production strategies that integrate shrimp culture with mangroves (Fitzgerald, 2007). Initially, farmers found that clearing mangroves for shrimp culture was financially viable, but after a few years, problems with declining water quality and shrimp health were noted and many producers went out of business. This led to calls for a more balanced approach to the restoration of mangroves, taking advantage of their potential to:

- Provide a source of detritus within ponds to stimulate associated food webs and enhance shrimp production.
- Facilitate water conditioning that can help enhance shrimp health and counter disease problems.

Issues and solutions for co-culture: Restoring mangrove trees within shrimp ponds can cause issues, however, as excessive leaf fall of certain mangrove species can lead to unwanted acidification of pond sediments. It was therefore suggested that shrimp ponds with separate mangrove forest areas alongside shrimp culture areas could constitute a more manageable and reliable strategy. Evaluating the potential of such an integrated system in Indonesia, it was noted that predicted financial returns from an 11-hectare farm were better than those from traditional, extensive and semi-intensive pond-based production (Bunting et al, 2013). Estimated profits (excluding depreciation) were $68,923 per year, and with a pay-back period of 1.3 years this strategy appeared commercially viable. Other benefits associated with integrated mangrove-shrimp production include:

- Semi-intensive shrimp culture as part of the integrated production strategy resulted in the lowest ecological footprint for land-use (35m²/kg).
- Ecosystem services delivered by the mangrove stand could provide food and medicinal plants for local communities and protection against storms and tidal surges.
- Mangrove stands provide a valuable habitat for both marine and terrestrial wildlife.

Current status, benefits, and drawbacks: Following a government programme to promote integrated mangrove-shrimp culture the practice has become established in East Kalimantan (The Big Prawn, 2022). Compared to conventional semi-intensive production, the presence of mangrove trees in and around shrimp ponds provides a source of leaf litter that can enhance the health and survival of juveniles and increase yields (Alam et al, 2021). Aerial roots provide a safe refuge from predators and shade can help avoid problems with high temperatures in shallow ponds. Mangrove stands can improve water quality and assimilate excess nutrients that might otherwise cause problems in receiving environments. Mangroves within ponds can make aspects of management more difficult or time consuming, but compared with traditional, extensive and semi-intensive management options, financial returns can be significantly higher (Bunting et al, 2013). Operators may be reluctant to switch from other production modes, however, owing to the higher capital costs associated with establishing a mangrove-shrimp system.

Further reading:

- 2.2.6. Investment opportunities contributing to the SDGs
- 2.2.11. Critical roles for regulation and good governance
- 2.2.3. Local environmental interactions
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.1. Semi-intensive production modes
- 3.2.7 Zoning and policy development
- 4.1.1. The aims of governance
- 4.1.2. Environmental (and market) impacts of insufficient governance
- 4.1.4. Excessive governance limits development

6.6.3. Rice-fish culture

Integrated production of fish in flooded rice fields is an excellent example of a regenerative, resource-conserving agricultural system (Pretty, 1995). Rice-fish farming was developed and refined by farmers in countries across South and Southeast Asia, including Bangladesh, China, Indonesia, Malaysia, Myanmar, the Philippines, Thailand, and Vietnam (Little et al, 1996; Rothuis et al, 1998; Halwart and Gupta, 2004).

Rice cultivation is carried out on millions of hectares globally in tropical, sub-tropical and temperate climates. When this involves flooded fields, it presents opportunities for the integrated production of a variety of aquatic animals (e.g. crabs, fish, prawns and shrimp). In Bangladesh, farmers have devised an effective field-pond configuration that permits the integrated production of rice and fish. Both are important crops for food and nutrition security in the country. Additional culture of prawns, which are regarded as a cash-crop, can contribute to further economic development and generate important foreign exchange earnings (Ahmed and Flaherty, 2013). In Bengali, these systems are called ghers, more details on their construction and operation are presented in the next case study.

Other opportunities to capitalize on flooded fields to promote aquaculture sector growth include using hapas (i.e. small open-topped cages constructed from mosquito netting) to nurse juvenile fish until they are large enough for stocking in cages and ponds, or to hold fish at intermediate locations prior to transport to on-growing sites (Barman and Little, 2006, 2011). These activities also provide novel employment and livelihoods options.

Flooded rice fields often constitute an important habitat for a range of aquatic animals and, in some cases, farmers, communities and institutions intervene to encourage and bolster the production of self-recruiting species (Amilhat et al, 2009; Freed et al, 2020). Herbicide and pesticide use in rice fields can, however, make it impossible to culture aquatic animals in such situations. ,

Consequently producers carrying out co-culture in rice fields must adopt appropriate 'integrated pest management' practices. These can potentially eliminate the costs of agrichemical use, increase rice yields, and permit food and income generation from aquatic animal production (Kamp et al, 1993; Berg, 2001).

Outside of Asia, notable examples of integrated rice-fish production involve co-culture in Egypt, with Nile tilapia, carp and catfish stocked simultaneously with rice to enhance economic returns from the accessible freshwater resource (Shaalan et al, 2018). Total production of fish from such systems was reported at 34,537 tonnes per year, with Nile tilapia accounting for half.

Insights concerning the management of rice-fish systems in Myanmar (WorldFish, 2020) and Bangladesh, and knowledge of what works in the commercially orientated production systems in Egypt, has helped to guide development investments of such systems in other areas, such as by FAO in West Africa.

6.6.4. Integrated production of rice and aquatic animals in ghers in Bangladesh

Rice planted on the central platform of a modified paddy field in Bangladesh with open water surrounding to permit effective aquaculture. Photo by: Dr. Nesar Ahmed

Summary:
This case study is an example of:
- Successful and productive integrated rice-fish systems derived from indigenous practices.

The learnings from this case study are:
- Integrated rice-fish systems can increase productivity of rice fields, provide multiple revenue streams, and improve food security for farmers.
- Access to land and water quality issues are limitations to rice-fish systems.

"Rice and fish make a Bengali": In Bangladesh, fish and rice are long-standing staples to the population, tied to culture, literature, and rural lifestyles. In parts of the country, integrated rice-fish farming systems are another manifestation of the old Bengali proverb, Mach-e bhaat-e Bangalee, "Rice and fish make a Bengali".

Rice-fish systems in Bangladesh: Gher farming systems have been developed as an indigenous technique to combine the production of rice and aquatic animals, notably freshwater prawns (Macrobrachium rosenbergii) and fish (e.g. catla, common carp, grass carp, mrigal, rohu and silver carp) in low-lying and flood-prone areas in southwest Bangladesh (Ahmed et al, 2008). The average size of ghers surveyed in Bagerhat District was 0.23 hectares and mean yields of rice, prawns and fish were 2,352kg, 432kg and 395kg per hectare per year, respectively - indicating that rice remains the key product.

What is a Gher? Ghers are characterized by a raised soil platform in the middle that is used to cultivate rice, and a deeper trench surrounding it that provides a refuge for stocked animals. Prawns and fish consume plant pests and eat weeds and their actions help mobilize nutrients to fertilize the rice plants. Integrated production helps enhance and diversify the cash-flow of producers, yields staple- and cash-crops, and sustains a higher level of agrobiodiversity that together contribute to increased socio-ecological resilience (Bunting et al, 2015, 2017).

Several constraints to production have been noted, including: pollution and water quality issues; droughts, floods and excessive rainfall; poisoning and theft; and poor access to affordable and reliable finance arrangements to meet increasing production costs (Ahmed et al, 2008).

Value-adding by-products (e.g. shrimp heads and tail shells from processing) can add greater value, for example by producing chitosan (a product extracted from shrimp shells for use in health products) for industrial use (Yan and Chen, 2015) and possibly active seafood packaging (de la Caba et al, 2019). Prior to such value-adding production, however, it is recommended that assessments on possible socio-economic impacts should be conducted as by-products (e.g. heads) may already have other local uses that contribute to livelihoods as well as food and nutrition security.

Further reading:
- 2.1. Potential contributions of sustainable aquaculture to the SDGs
- 2.2.3. Local environmental interactions
- 2.4.1. Semi-intensive production modes
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.6. Low-capital expenditure systems
- 4.1.1. The aims of governance
- 4.1.3. Social impacts of insufficient governance
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations

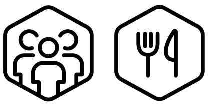
6.7. Aquaculture for food and nutrition security

A more nuanced appreciation of the potential health and nutrition benefits of consuming aquatic foods may favour appropriate technological innovations across value chains. Nutrition-sensitive production strategies have the potential to focus attention on human health and nutrition outcomes. Producing novel products, such as fish powders for mothers and children, could help in the nutrient fortification of foods to tackle malnutrition and support food and nutrition security. Other post-harvest processing and value-added innovations – from fileting fish to producing ready-to-cook products – may also make aquatic foods more accessible and attractive to some consumers.

The case studies below are examples of prospective nutrition-sensitive production strategies that could enhance human nutrition outcomes. In the first case study, we examine the culture of specific species that are rich in particular micronutrients in order to alleviate micronutrient deficiencies in the local communities. Semi-intensive production systems integrating large and small fish species are being promoted in Odisha, India to increase the availability of small, nutritious fish (e.g. mola) to poorer consumers.

The second case study demonstrates broader improvements in food security for developing countries through improved production of species that are affordable, easy-to-farm, and nutritious.

6.7.1. Nutrition security supported through carp-mola polyculture in India and Bangladesh



Fish farmer with mola from his pond, Odisha, India. Photo by: Arabinda Mahapatra

Summary:
This case study is an example of:

- The introduction of an integrated aquaculture system to address nutrition insecurities.

The learnings from this case study are:

- Small nutrient-rich fish can be co-cultured with other species to increase the availability of nutrients for farmers and their local communities.

Odisha State in India has historically high rates of malnutrition. In response, the Government introduced a series of nutrition-sensitive policies in 2006. But, despite massive improvements, malnutrition remained a major problem: as of 2016, over half the women in the state still suffered from anemia and stunting still affected 34% of children under the age of five (Avula et al, 2020). An estimated 94.4% of people in Odisha eat fish, and per capita consumption increased from 7.71kg in 2001 to 16.24kg in 2020 (Padiyar et al, 2021). The Government of Odisha recognized fish as a critical source of nutrition and partnered with WorldFish in order to promote polyculture of small indigenous species for subsistence purposes through a series of interventions.

Co-culture to increase micronutrient production: In backyard ponds, Indian major carp species (Catla catla, Labeo rohita, and Cirrhinus mrigala) were cultured with mola (Amblypharyngodon mola; Kumar Saha and Kumar, 2020). Mola is a small fish typically eaten whole, including its micronutrient-rich bones and organs. Mola contains high levels of vitamin A. When eating larger fish like carp species, people typically consume only the flesh, missing out on the most nutrient-rich parts of the animal. The idea behind the polyculture was to support the production of nutrient-dense mola and dike-vegetables for subsistence purposes alongside market-oriented carp production (Chadag and Ratha, 2020). Interventions also aimed to increase the production of dried fish for making fish-based products that could be consumed by children. Farmers were trained in farming methods, drying methods, sanitation and hygiene, and nutrition.

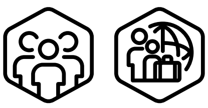
Maximizing water resources with gender-sensitive aquaculture: Another project began in response to the Odisha Fisheries Policy of 2015, which aimed to increase fish production in unused and underused water bodies, such as Gram Panchayat tanks. In 2018, in collaboration with the Government of Odisha, WorldFish launched a nutrition- and gender-sensitive programme, which supported this type of polyculture in Gram Panchyat tanks, managed by women co-operatives (Panemangalor, 2021). Compared to carps-only farming, tanks with carp and mola had an 11-34% larger yield over the two-year project. Furthermore, over 85% of the co-operatives made a profit and 98-100% expressed a willingness to continue farming operations in the tanks after the programme ended.

The impacts of these interventions: Importantly, these projects increased the availability of small nutrient-rich fish for local communities. The Gram Panchyat project also resulted in increased fish consumption for women participating in the co-operatives through retained carps and mola for household consumption (Padiyar et al., 2021). Similar projects and outcomes have also been successfully trialled in Bangladesh (Karim et al., 2021).

Further reading:

- 2.1. Potential contributions of sustainable aquaculture to the SDGs
- 2.2.8. Promoting nutrition-sensitive production practices
- 2.2.11. Critical roles for regulation and good governance
- 2.4.1. Semi-intensive production modes
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.6. Low-capital expenditure systems
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.8. Certification and market access

6.7.2. WorldFish's 'Genetically Improved Farmed Tilapia' has supported food security



Fresh GIFT Tilapia for sale at a market in Dhaka, Bangladesh. Photo by Alexandra Pounds

Summary:
This case study is an example of:

- A genetic selection and improvement programme that has led to significant growth of the tilapia industry globally.

The learnings from this case study are:

- Genetic improvement programmes can increase production.
- Through access to Genetically Improved Farmed Tilapia (GIFT), tilapia farmers are able to achieve profit margins with this low-value product, thereby supporting competitive markets and improving consumer access to affordable fish.

The need for cheap fish: In the 1980s, a rapidly growing global population with high rates of malnutrition led to widespread concerns for food and nutrition security. Fish was identified as a key to addressing this challenge due to its nutrient-rich character and popularity among the most vulnerable communities. Tilapia showed particular potential because:

- It has a low price point.
- It is compatible with a diverse range of conditions (including both fresh and brackish water environments) found in the tropics where food insecurity is rife.
- It has high adaptability, including flexible feed requirements, as an omnivorous species without a need for fishmeal and fish oil.
- It has a short breeding cycle, allowing for rapid improvements in traits.

These traits result in tilapia being a fish that is easy to farm, cheap to produce, and accessible for consumers from a wide range of economic demographics.

The development of GIFT: Yet, at that time, the tilapia industry struggled under inadequate seed supply and poor productivity. WorldFish identified these problems and, with its consortium of partners, began a genetic improvement programme for Nile tilapia in 1988, based on selective breeding technologies from the Norwegian salmon and trout industries. Together, they produced 'Genetically Improved Farmed Tilapia', commonly known as GIFT, and designed with both small and commercial producers in mind. The most distinguishing traits are that its growth rate is 85% faster than non-GIFT varieties and it has high survival rates.

WorldFish has successfully maintained and distributed GIFT to 16 countries in Asia, including the Philippines, Bangladesh, China, Thailand and Vietnam, following the internationally accepted guidelines for introductions and transfers (ICES, 1992). It is now considered an international Public Good and is available to any country that agrees to its responsible use. It is important to note that, as a non-native species, GIFT production must be carefully managed to ensure that adverse effects on local ecosystems are avoided.

The benefits of GIFT:

- GIFT farming accounts for 68% of tilapia production in the Philippines, 46% in Thailand and 17% in Vietnam. In Bangladesh, 75% of mono-sex tilapia hatcheries exclusively used GIFT as their brood stock in 2010.
- GIFT technology has been transferred to other tilapia species in Egypt, Ghana and Malawi.
- The introduction of GIFT is suspected to have led to the growth of the tilapia industry globally. Although it is difficult to quantify the benefits of GIFT (Rossignoli et al, 2021), models estimate that the introduction of GIFT has led to an 8% to 25% increase in production, depending on the country (Dey 2000).
- The boom of the tilapia industry has improved access to fish for poor consumers in the developing world. For example, models estimated that GIFT reduced the price of fish by 11% to 14% in the Philippines and 16% to 18% in Bangladesh, and the consumption of tilapia increased by 16% in the Philippines and 18% in Bangladesh (Dey, 2000). Because prices are low, most of the benefit is for lower-income demographics.

For more information, please visit the WorldFish website.

Further reading:

- 2.1. Potential contributions of sustainable aquaculture to the SDGs
- 2.2.5. Aquatic Health and welfare
- 2.2.8. Promoting nutrition-sensitive production practices
- 2.2.11. Critical roles for regulation and good governance
- 2.2.4. Seed supply
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.6. Low-capital expenditure systems
- 3.3. Research systems in selected countries
- 4.1. The role of governance in aquaculture

6.8. The driving power of market demand

An understanding of market demand is key to realizing the growth of the aquaculture sector. The following case studies are examples of how market demand has driven technologies and growth.

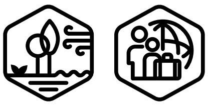
First, we take a brief overview of China's inland aquaculture industry that has been driven by a growing population with increasing affluence, leading to it becoming the world's dominant aquaculture producer. We review some recent trends observed regarding inland finfish aquaculture in the country and note that the sector is still evolving.

Secondly, we compare the examples of the Bangladeshi and Vietnamese pangasius industries that have intensified with different outcomes due to different target markets. Examining the pangasius industries in Bangladesh and Vietnam provides valuable insights as to how production is often linked to prevailing hydrological regimes and market opportunities. The case study presented here suggests that sometimes less regulated, smaller scale, and less intensively managed production, that promotes a circular economy, can have a better overall environmental performance than a more regulated and widely certified production industry.

Thirdly, we examine the rapid development of the Egyptian tilapia and Nigerian catfish industries, which are notable exceptions to the general scale of aquaculture across Africa. Examples of strong industry growth from Africa are apparent now for both Nile tilapia culture in Egypt and African catfish culture in Nigeria and this has been attributed, among other factors, to better connectivity and market access, and associated rises in population density.

Finally, we describe the culturing of mixed-sex stocks of tilapia in cages in Thailand, which may result in a wider variety of harvested sizes of tilapia, where smaller female fish that are harvested early could be a source of food for poorer consumers.

6.8.1. Recent insights concerning inland aquaculture industry growth in China



Marine aquaculture in Luoyuan Bay of Luoyuan, Fuzhou, China. Photo by: Jack Parkinson

Summary:
This overview is an example of:

- A sector with significant production that is contributing to domestic food supply, international trade, and innovation.

The learnings from this case study are:

- Growth is due to increased market demand and innovations in feed.
- Intensification needs can result in technology development to support efficiencies needed to produce a low-cost, export-oriented product (tilapia).

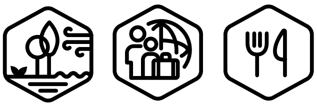
China accounted for 58% of global aquaculture production in 2018 (FAO, 2020). Chinese aquaculture is well developed and productive due to the country's long history and legacy of production. China constitutes an important case study owing to the size of the sector, allowing us to identify enabling conditions that stimulate and promote growth, and to highlight opportunities for technology transfer and effective translation of scientific findings into practice.

- **Historical context:** Growth of inland aquaculture production in China has centred on freshwater fish culture, where government reforms in the 1980s stimulated a rapid increase in production to meet increasing market demand (Naylor et al, 2021).
- **Carp species dominate production:** Carp species continue to dominate production, but traditional polyculture strategies involving eight or nine species have been simplified to include on average three species, often involving a combination of either bighead carp, crucian carp, grass carp, or silver carp (Newton et al, 2021).
- **Innovations in feed:** Farmers involved in carp production have looked to reduce financial costs and associated risks by using less formulated feeds. Instead, some are reverting back to more traditional practices that can involve growing rye grass, soybean and wheat on embankments as feed ingredients to complement the use of smaller amounts of commercial feeds in semi-intensive systems.
- **Innovation in tilapia production:** Farmers who produce Nile tilapia are innovating to enhance their performance by utilizing sensors to continuously monitor water quality, keeping better activity records, and becoming more organized to acquire knowledge on markets and new technologies (CGTN, 2018). Farmers in Hainan Province have started targeting domestic markets, although 95% of their output goes for export (CGTN, 2018).
- **Increased demand from affluent consumers:** The emergence of a growing peri-urban middle class, constituting a large number of more affluent consumers with greater purchasing power, has recently strengthened demand for higher value aquatic species, such as black carp, crawfish, swamp eel, and Wuchang bream (Newton et al, 2021). Consumers frequently prefer to purchase fresh – often live – fish from wet markets, retail outlets, and restaurants. This may limit the degree to which some aquaculture industries can intensify production or streamline associated value chains as the delivery of live fish is highly time sensitive and there is limited scope to hold large stocks at the point of sale. However, an emerging group of consumers is looking for freshness combined with convenience, and this could lead to an increase in online sales.
- **New environmental regulations:** Recent changes in regulations designed to improve water quality and reduce pressure on freshwater resources have resulted in the elimination of fish production in cages and pens in lakes and reservoirs (Newton et al, 2021).

Further reading:

- 2.2.2. Optimizing feed utilization and ingredients supply
- 2.2.3. Local environmental interactions
- 2.2.11. Critical roles for regulation and good governance
- 2.4. The sustainability of different production systems
- 4.1.2. Environmental (and market) impacts of insufficient governance
- 4.1.5. Concern over local impacts shifts them elsewhere
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.8. Certification and market access

6.8.2. Market-driven governance and the environmental impacts of scale: a comparison of pangasius production in Bangladesh and Vietnam



Workers at the Mauktashari hatchery, Jessore, Bangladesh netting pangasius fingerlings for sale. WorldFish provided technical support for brood management at the hatchery as part of the USAID-funded Aquaculture for Income and Nutrition (AIN) project. Photo by: Habibul Haque

Summary:
This case study is an example of:
- Intensification of pangasius (catfish) aquaculture in two contexts, where different target markets have resulted in divergent characteristics and impacts.

The learnings from this case study are:
- Outcomes of aquaculture intensification can vary greatly due to contextual differences in market demand and governance, even for the same species.

Rapid intensification of pangasius production in Bangladesh and Vietnam offers examples of how different market demands impact on governance and sustainable development.

In Vietnam, pangasius production is export-oriented, with international (ASC, BAP) and national (VietGAP) certification schemes helping to maintain food quality and safety assurances to international consumers. While Vietnamese pangasius is produced intensively in both large and small farms across the Mekong Delta, certification standards create economic incentives for larger, vertically integrated farms, which has been suggested to marginalize smallholders (Hansen and Trifkovic, 2014; Trifkovic, 2014). These intensive operations cause large environmental impacts from the land-use for commercial feed ingredients, and carbon emissions from feed production (Huysveld et al, 2013). Large amounts of effluent water are discharged into the Mekong River, although farms have tried to innovate in the use of pond waste as a fertilizer for crops.

Pangasius production in Bangladesh contrasts with that in Vietnam in many ways. Unlike in Vietnam, where high-quality production data is obtained through certification and regulatory monitoring, pangasius production data is often underreported in Bangladesh because its production is dominated by diverse, small-scale actors and is oriented towards local markets (Ali et al, 2013; Hernandez et al, 2018). Pangasius has contributed towards food security in Bangladesh. As a cheap and affordable fish, it has become the most consumed species in rural Bangladesh (Hernandez et al, 2018). Pangasius is often co-produced with carps and tilapia species in extensive polyculture systems, and this minimizes both the impact of market-price fluctuations for the farmers and environmental impact through reduced feed waste that results in better FCRs and water quality (Ali et al, 2013). While Vietnamese production has access to an abundance of fresh water along the Mekong Delta, Bangladesh pangasius production uses fresh water more sparingly due to better water quality from polyculture practices and poorer water accessibility. Wastewater that is produced is retained within the circular economy: pangasius wastewater in Bangladesh is discharged into rice fields, where residual nutrients are used for rice production thus reducing the need for fertilizer by 30% (ibid).

The comparative pangasius stories in Bangladesh and Vietnam highlight how understanding international versus domestic consumer and market demand is critical for governing the sustainable intensification of aquaculture.

Further reading:

- 2.2.11. Critical roles for regulation and good governance
- 2.2.3. Local environmental interactions
- 2.4.1. Semi-intensive production modes
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.6. Low-capital expenditure systems
- 2.4.7. High-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 3.2. Evidence programmes globally
- 4.1. The role of governance in aquaculture
- 4.2. Considerations on governance
- 4.4.3. Certification

6.8.3. Models of aquaculture development for Africa: Egypt and Nigeria

Buying farmed tilapia in a fish market in 2012, Cairo, Egypt. Photo by: Samuel Stacy

Summary:
This case study is an example of:

- The unique contexts of Egypt and Nigeria, where aquaculture has developed much faster than in the rest of Africa. These are two exceptions compared to the rest of Africa, which is the world's slowest developing region in terms of aquaculture.

The learnings from this case study are:

- Population densities in peri-urban areas may reach a critical 'tipping point' where aquaculture industries become financially sustainable, at which point investment into other barriers (such as feed and seed quality and availability) could have a positive impact.

Africa is a net importer of fish, accounting for 19% of animal-source food consumption, but the continent has vast inland waterways that make the potential for aquaculture an obvious way to address food security challenges (Chan et al, 2019). And yet aquaculture development has been slow and is lagging behind the rest of the world.

Low population densities in peri-urban areas restrict growth: While Africa's aquaculture underperformance has been attributed to a variety of causes, in most of Africa aquaculture is restrained by low population density in peri-urban areas. These areas are ideal production sites for aquaculture to access labour and markets as well as affordable land. Low population densities in these areas result in a lack of connectivity and poor access to markets. Without industry development, low competition between input suppliers drives high input prices, further restricting the development or adoption of technology and innovation. With poor access to consumers and the high price of inputs, entrepreneurial ventures are unable to sustain themselves. The financial unsustainability driven by low population densities is one of the primary reasons that massive investments by NGOs and development agencies have largely failed to achieve a long-term impact.

Egypt and Nigeria as positive examples: In contrast to much of the continent, Egypt and Nigeria are examples of countries with population densities high enough to achieve the necessary economies of scale. Tilapia culture in Egypt and African catfish culture in Nigeria experienced rapid growth (25% and 12%, respectively, compared to a world average of 8%, Kaleem and Sabi, 2021). In recent years, growth has slowed due to several factors, including market prices and the rising costs of inputs – especially feed – and, as a result, financial margins.

In Egypt, tilapia production has grown steadily in peri-urban areas since the 1980s, supported by large-scale government investment that transitioned farms from semi-intensive earthen ponds to intensive culture with aeration and formulated feeds (Koge et al, 2018). Much of the land used for aquaculture was government owned and unusable for agriculture (from Burullus Lake down to the city of Kafr El Sheik), and the Egyptian government sold off or leased land specifically for aquaculture development. Egypt produced over 390 thousand tonnes of tilapia in 2009, compared to over 10.5 million tonnes in 2018, and is now the world's largest tilapia producer after China (FAO, 2020). Over 88% of production was in brackish water and producers are predominantly small- to medium-scale (Soliman and Yacout, 2016).

In Nigeria, African catfish dominates production, with over 1.6 million tonnes produced in 2018 (Kaleem and Sabi, 2021). Nigeria is the largest aquaculture producer in Sub-Saharan Africa, where 80% of production is generated from smallholders (Kaleem and Sabi, 2021). Most production is generated by small- and medium-scale private individuals. In a few cases, fish are farmed in RAS-style or concrete tanks using water from boreholes in peri-urban areas and managed through co-operatives of smallholders called 'Fish Farming Estates' (Koge et al, 2018). These estates are owned by a variety of cooperatives, private investors, government, local district councils, and local chieftains.

Key lessons from Egypt and Nigeria: Learnings from these two markets are valuable for other regions of Africa where population densities are high enough for economic sustainability. Firstly, investments into intensifying and modernizing the technology of small- and medium-scale farms may precipitate increases in productivity. Secondly, co-operatives may help farmers secure the necessary start-up capital and source inputs (e.g. feed, juveniles, and packaging materials). Outgrower programmes may provide the impetus around existing large-scale operations seen in many African countries today, with appropriate incentives and management, although the track record of cooperatives in the Nigerian catfish industry has been mixed.

Thirdly, as most fish farming in these examples is still characterized by small- to medium-sized businesses, smallholders should be supported and entrepreneurs encouraged. The diversity of smallholders and their ability to pivot with market demands make them important in emerging economies, yet they are also the most vulnerable. Support can be driven either by the government or by private investors, but must be geared towards businesses with financially sound business models. The developments in both countries examined were effective in stimulating feed and seed industries and developing a stronger value chain to supply the pre-existing large local demand for fish (Koge et al, 2018).

Applications for other African countries? Countries with high population growth, such as Kenya, may reach a 'tipping point' through increased population and increased connectivity in peri-urban areas to enable aquaculture development to become viable. While many factors affect the profitability of aquaculture and development of the sector, understanding the socio-economic factors (e.g. population density, urbanization, infrastructure) that indicate this 'tipping point' would be useful to identify entry points for effective NGO, philanthropic, and government investment in order to have a sustained impact. This will need to be understood in connection with other key factors affecting profitability.

Further reading:

- 2.2.6. Investment opportunities contributing to the SDGs
- 2.2.8. Promoting nutrition-sensitive production practices
- 2.2.11. Critical roles for regulation and good governance
- 2.4.1. Semi-intensive production modes
- 2.4.2. Integrated farming systems
- 2.4.3. Resilience through diversity of producers and production systems
- 2.4.4. Opportunities and constraints associated with responsible development
- 2.4.6. Low-capital expenditure systems
- 2.4.8. Advantages of large-scale production
- 4.1. The role of governance in aquaculture
- 4.2.1. National regulations
- 4.2.2. The importance of aquaculture-specific regulation, and enforcement of regulations
- 4.2.11. Alternative governance structures: community-based governance

6.8.4. Mixed-sex tilapia cage culture: competitive and may deliver added benefits

Nile tilapia displayed in a metal tray by a fish retailer in Aswan, Egypt. Photo taken by Sara Fouad

Summary:
This case study is an example of:

- Traditional technology that reduces the use of chemicals being better suited for local market demands.

The learnings from this case study are:

- Market demand is a key driver of production and the technology used, and understanding consumer behaviours and preferences is critical to sustainable intensification practices.

The global state of tilapia culture: Globally, the culture of all male Nile tilapia stocks has led to huge growth in the industry. Production volumes for this species increased from 1.7 million tonnes in 2006 to 4.6 million tonnes in 2019 (FAO, 2021). All male stocks are preferred as this avoids breeding in semi-intensive systems, leading to a proliferation of small fish. The option to not stock female fish in intensively managed systems may also be preferred as their growth rate tends to be lower than for male fish.

Monosex technologies: Several strategies exist to produce stocks of all male fish, and some hatcheries may opt to treat juvenile fish with 17-methyltestosterone to influence sexual differentiation. When administered carefully and during the early growth phases this should be safe. If poorly carried out, however, this can pose environmental and human health risks and may be regarded negatively by potential buyers and consumers and lead to products being barred products from specific markets (e.g. the EU).

Nascent research explores alternative production methods: Given the potential health hazards and concerns around the perception of tilapia as a healthy aquatic food choice, this raises the question of whether the culture of mixed-sex stocks, under certain circumstances, could be commercially viable and competitive. To address this conundrum, field trials were conducted at a commercial tilapia farm in Central Thailand and results were evaluated from a financial perspective by Bostock et al (in review). Cages located in a river were stocked with either all male or mixed-sex fish at a density of 21 fish per m3 or they were 'over-stocked' with 42 mixed-sex fish per m3 and females were removed at 4- or 8-week intervals.

Alternative economic models to improve returns: Results showed that all strategies resulted in the production of similar, good quality fish, but that mixed-sex culture entailed higher costs and resulted in lower profits. If it were possible, however, to sell some of the harvested females (13%) for broodstock at commercial rates or attain a modest price premium (8%) for the final harvest of non-sex-reversed fish then mixed-sex production could be more profitable than farming all males.

Contribution to food security: In central Thailand, tilapia farming is highly competitive and geared toward producing larger fish (>1kg each) to meet domestic and international demand. It could be interesting to evaluate similar strategies in countries and regions where small fish might be preferred by some consumers. The smaller (~100-200g each) females harvested under those strategies could potentially be an affordable source of nutritious fish for poorer consumers.

Further reading:

- 2.1. Potential contributions of sustainable aquaculture to the SDGs
- 2.2.8. Promoting nutrition-sensitive production practices
- 2.2.4. Seed supply
- 2.4.8. Advantages of large-scale production
- 4.2.8. Certification and market access

7 Priority areas to consider towards the growth of sustainable aquaculture

This final section is a summary of the findings from the preceding six sections of the report, whichprovides a great depth of information on the current context of aquaculture. These findings organized into priority areas will now set the course that will lead to science-based actions and recommendations in a global roadmap towards the growth of sustainable aquaculture. It frames aquaculture's significant role and great potential to contribute to the sustainable development of broader blue food and terrestrial food systems. The priority areas are summarized in Table 11 below.

Table 11: Priority areas towards the responsible growth of aquaculture

Item	Description
Priority areas	**Characteristics and considerations**
Access to markets	• Market demand exists for planned products with successful investments based on credible market assessments (i.e. not production-led). • Products meet market demand through appropriate scheduling of stocking, grading and harvesting and using appropriate techniques and technologies across life-stages, and have advantages in relation to consistency of supply, nutritional profiles and environmental impact credentials. • Infrastructure and logistical capabilities enable cost efficient and timely delivery with assurance of food-safety and organoleptic quality attributes. • Group certification schemes enable producers in emerging economies to access commodity export markets through sharing and reduction of compliance costs. Small traditional producers may have more opportunities in local markets. • More durable opportunities for small-scale participation in trade are associated with higher-unit value commodities, notably shrimp. • Vertically integrated (as well as horizontally expanded) production models often coincide with more consolidated (e.g. salmon) and intensified industries, and are able to control supply chains and increase transparency throughout. [This is particularly important for certified products for international markets.] • Value is created through development of less tangible attributes, such as brand images and narratives designed to attract buyers and consumers in target markets, or branding under an existing certification or labelling system.
Conducive regulatory environment	• Successful, fit-for-purpose, efficient and timely regulatory frameworks are built on transparency, responsibility, accountability and participation, and should also have a good evidence base supporting their aims. • Stakeholder engagement and active participation throughout the regulatory process are critical elements of SLO and effective policies. • Beyond-compliance measures for social, economic and environmental performance support sustainable practices and improve SLO. • Effective policies are developed using best available guidance for the aquaculture sector (e.g. FAO, 2008) and examples of best practices from other jurisdictions. • Aquaculture is a developing industry and regulatory needs should be reviewed regularly in the context of changing practices.

Table 11: Priority areas towards the responsible growth of aquaculture (continued)

Item	Description
Priority areas	**Characteristics and considerations**
Access to finance	• Industry growth is supported by investments, loans, credit, and financial services that match producer needs, timelines, and risk profiles. • Competitive, transparent, secure markets and modes of transaction exist for financial services and associated products. • Investor confidence in the ability of producers and businesses to manage successful business and repay investments and service loans is key, and this is based on accurate data retrieval and reporting. • Industries have better access to finance when businesses commit to adopting better management practices, responsible operations and financial data sharing or join certification and standards schemes that commit producers to industry leading production standards and independent audits. • Investors have more confidence in businesses where knowledge of a diverse range of sector specific risks is reported accurately and clearly. • Financial performance is increasingly linked to environmental, social and governance performance ('Triple Impact' business models), through reputational risks to companies with consumer-facing brands, representing obvious opportunities for producers. • An effective risk management approach is essential for successful investment, and this should be well-informed with a comprehensive overview and understanding of all potential threats and their impacts.
Value chain	• Proximity of primary processing capacity optimizes product quality and ensures opportunities for employment and value addition, and economic and social development both locally and nationally. • Technology transfer between species may assist the pace of sustainable aquaculture development where there are gaps in knowledge. • Production of large volumes of uniform (i.e. commodity) product creates opportunities for mechanization and product development. • Co-products from primary processing are used in value-added items (e.g. feedstock for biorefinery processes). • By-products reuse is an opportunity to ensure nutrients are not lost to the biosphere, but rather, accessible for enhanced human nutrition outcomes.
Disease management	• Movement of stock carries the highest risk of pathogen introduction to a farm, region or country. • Biosecurity measures and plans minimize the risk of transmitting pathogens. • Preventative management measures are effective and successful even when prioritized over therapeutic approaches, which may also reduce additional costs. • Introduction of commercial vaccines supports reduced use of antimicrobials. • Access to diagnostic services and rapid testing and identification of disease are core tenets of disease management. • Area based management (ABM) approaches have demonstrated significant effectiveness in disease management but success is dependent on collaboration and information sharing.
Feed supply	• Access to reliable, nutritionally complete, good quality, and affordable feeds is crucial. • Feeds should be formulated to match the requirements of the species and life-stages being cultured, and the nutritional profile demanded in the consumed end product, at realistic cost. • Environmental impact quantification for feed materials and aquafeed production can be achieved by the use of new approaches, such as life cycle assessment. • Effective traceability systems support the assurance of sustainable provenance of feed ingredients from all sources. • Digital solutions such as video and remote sensing technology have been useful in improving FCRs. • Quality assurance measures during production and use on-farm (e.g. water stability and buoyancy, fines %, digestibility) are key to efficient practices. • The direct feeding of raw fish from fisheries to fish in aquaculture systems carries a high risk of spreading disease.

Table 11: Priority areas towards the responsible growth of aquaculture (continued)

Item	Description
Priority areas	**Characteristics and considerations**
Seed supply	• Dependable and timely supplies of good quality seed that optimize survival and yields are a cornerstone of production. • Good broodstock selection and management programmes can deliver farmed stock with traits desired by producers, buyers and consumers. • Improved strains of selected species maximize the production potential in a specific context. • Juveniles that are certified free, resistant or tolerant to selected pathogens (e.g. SPF, SPR, SPT shrimp) can reduce the risk of disease introduction onto farms. • Risks attached to the use of non-indigenous stocks can be managed via a number of different approaches. Risks include establishment, displacement or hybrid-introgression with wild stocks and adverse ecological impacts. • The use of wild-caught seed in aquaculture production systems creates a risk related to both supply and disease.
Access to technology/ innovation	• Innovative, emerging Tech start-ups (e.g. in precision farming, diagnostics, selective breeding etc.) provide solutions known to improve productivity and efficiency of large-scale farms. • Established technologies and techniques offer high potential in replicating responsible aquaculture growth in new regions. • Public and private sector collaborations typically yield stronger innovations. • New technology solutions are known to improve productivity in other food systems and some are likely to have application in aquaculture assuming incorporation in production systems may be achieved.
Conducive environment/ water quality	• Ecosystem-based management systems taking into account cumulative environmental impacts in site licensing and farm management support better water quality, animal health welfare and site operation longevity. • Assimilative capacity assessments complemented by more precautionary management measures reduce cumulative environmental impacts and ensure growth remains within ecosystem carrying capacities. However, over application of the Precautionary Principle can restrict growth. A balance needs to be found, and this will usually be based on good, robust science. • Protected-area zoning and siting requirements are critical for remaining within ecosystem carrying capacities. Other techniques (e.g. IMTA) can support this goal.
Efficient use of natural resources	• Optimize the use of fish-derived ingredients to ensure most appropriate use in feed because they are a finite resource. • The use of fish as raw material for food or feed is a dynamic that must be continually reviewed from the perspective of how this best supports food and nutrition security. • Water use should be optimized through adoption of technologies and design principles that maximize efficiencies. • When levied at producers, appropriate water use charges and pollution taxes tend to support effective water management strategies. • Certification standards that encourage producers to adopt more efficient practices that use fewer natural resources per unit of production have important roles to play, especially where regulatory frameworks may be incomplete. • Natural phytoplankton production in extensive and semi-intensive systems can maximize yields and encourage culture conditions that inhibit pests and disease (and their potential hosts). • Carbon-sensitive management practices (e.g. that avoid emissions and encourage sequestration) across value chains can collectively help mitigate climate change impacts, and aquaculture has an important position in global food systems. • The adoption of LCA and other techniques for the quantification of aquaculture and aquafeed impacts is not yet standardized.

Table 11: Priority areas towards the responsible growth of aquaculture (continued)

Item	Description
Priority areas	**Characteristics and considerations**
Social factors	• Standards for assurance of responsible interaction with surrounding communities are important to support social sustainability goals, and certification has an increasingly important role to play. • Systematic and regularly updated multi-dimensional national governance indicators, such as those produced by the World Bank (WGI) or Transparency International (CPI) can provide a starting point for risk assessment and calibration of more sector specific due-diligence needs for producers and value chain. • Appropriate safeguards across value chains (both downstream and upstream) ensure human rights are respected and that risk assessments and health and safety measures are in place. • Through mitigation and offsetting measures, for example, in mangrove areas, industry can engage in regenerative aquaculture that ensures the long-term stability of ecosystem services supporting production. These types of aquaculture production strategies can also help communities adapt to worsening climate change impacts. • Through effects in combination with agriculture, aquaculture may support increased yields and additional benefits (e.g. economic and environmental) that maintain associated communities. • Production facilities are better located in areas with access to a labour force that is already skilled or has access to capacity development resources. • To gain SLO, the best advances appear to be where industry respects local use-rights and food supplies. • Through nutrition-sensitive production, industries can improve on the variety and quality of products in local markets, supporting more diversified and nutrition diets that lead to healthier populations. • Engaging neighbouring communities and local stakeholders can increase SLO, supporting licensing and successful operating within the shared environment.
Insurance	• Access to insurance for aquaculture producers trails behind agriculture in its effectiveness.

This report provides an in-depth assessment of relevant knowledge that will be critical in developing a sustainable pathway for the development of aquaculture. Significantly, its exploration of sustainability has gone beyond the conventional review of aquaculture's impacts on the environment and touches on its reverberations in communities, livelihoods and economies. By shedding light on a comprehensive range of dimensions and issues related to aquaculture now, more informed decisions can be made on the levers of change that can bring about a more socially just, economically viable, and environmentally sound future for aquaculture.

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Endnotes

1. https://www.thelexicon.org/foodicons/

2. Key Traceability, 2021. Building a global roadmap for sustainable aquaculture growth to 2030. The Evidence Base: why the development of sustainable aquaculture is essential to a healthy planet, ocean, and food systems. Key Traceability Ltd.

3. https://calysta.com/

4. http://www.ynsect.com/en/

5. https://www.marin-trust.com/

6. https://marineingredientsroundtable.org/

7. The current state of knowledge concerning the efficiency and effectiveness of aquaculture governance and regulation is presented in Section 4 of this report.

8. The content and relative coverage of a comprehensive range of certification schemes is presented in Table 4 in Section 3.

9. The current state of knowledge relating to certification schemes and their role in aquaculture governance and regulation is presented in Section 4.2.2.

10. Responsible aquaculture development is defined here as practices that "contribute to household and community food security and nutrition as well as to livelihoods and income diversification, thus reducing vulnerability and facilitating more efficient water and nutrient management" (Bunting, 2013, p.13).

11. Inclusive business models are defined here as "specific contractual relations and mechanisms that aim to integrate poor people into value chains" (Kaminski et al, 2020, p.1883).

12. Examples of research systems that have developed to support aquaculture sector growth, notably in Norway and Scotland where marine finfish production dominates, are presented in Section 3.2.

13. BMPs are typically guidance documents on standardized good practice for producers.

14. The key aspects identified in this table are the most frequently encountered aspects of seafood sustainability used by the programmes, and suggest that use of the term 'sustainability' is coalescing around several key and recurring themes, including those related to climate change, animal welfare, and social well-being.

15. While offering greater specificity, the OECD 'Governance of sector' and 'Product market regulation' indicators are limited to just 38 (wealthier) OECD countries.

16. SAMAQ stands for 'Saudi Arabian Mark of Aquaculture Quality' (pronounced as 'samak', meaning fish in Arabic).

17. https://www.legislation.gov.uk/asp/2013/7/section/1

18. Illegal, unreported, and unregulated

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The contents of this report are intended to offer a broad understanding of the key considerations related to aquaculture production. They do not represent the entirety of issues for consideration. The selected case studies are included as examples of practice, although we understand that other examples exist.

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