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Innovation in aquaculture

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Abstract

This review examines the current status, issues and challenges in aquaculture innovation, and explores likely areas of future innovation. It seeks to identify the engines and incentives that are behind the major areas of aquaculture innovation. The broad categories and sectors where innovation is occurring are described, as are the risks, benefits, and broader impacts – some of which are potentially less desirable. The review also explores policies that individual country governments and regional organizations can adopt to encourage innovations with preferable socio-economic outcomes.

High-profile aquaculture innovations include: large-scale, intensive, land-based RAS systems; highly-automated offshore net pen systems; increasing use of robotics and remote command-and-control; and novel financing tools for larger companies and small start-ups. However, more broadly impactful innovations are often less obvious: improved selective breeding; refinements in feed formulations; expanded use of vaccines; and better extension, outreach, and training for farmers.

Tensions can arise around aquaculture innovations that offer differing costs and benefits to different sectors. For example, offshore operations and intensive onshore RAS systems, in particular, benefit from increasing automation and economies of scale. Greater scale and automation result in expanded production and more efficient yields. This can then move the industry closer to meeting global production goals, increase the availability of healthful aquaculture products to consumers, and lower the production costs and, therefore, possibly, market price. This can then provide broad societal benefits through improved nutrition. However, larger-scale, capital-intensive systems also displace small- or medium-scale producers, and increasing automation reduces the need for less-skilled labor.

By contrast, benefits from applying genetic technologies and bioinformatics tools are more broadly available, with fewer negative impacts. Some genetic technologies have been resisted, or more slowly adopted but could offer significant benefits to industry, genetic diversity, and ecosystem health. CRISPR gene-editing technologies, for example, could produce 100% guaranteed sterile stocks, preventing the interbreeding of farm stock with wild populations. Those countries or certification schemes which apply overly restrictive regulation of gene-editing could also put their producers at a disadvantage. Governments need to be conscious of such dynamics when establishing aquaculture policies.

The review describes a range of government or agency policies that might encourage or constrain aquaculture innovation, such as:

- assertively focusing greater support for aquaculture expansion, to reduce the overall impact of food production systems on the global climate crisis, freshwater use, and land use, with concomitantly less support for more-impactful terrestrial animal proteins;
- expanding the use in aquaculture feeds of agricultural proteins and oils, including both crops and animal by-products, as well as optimizing the use of seafood processing by-products;
- encouraging innovative financial models, particularly for new start-up companies, and offering pre-permitting of areas for aquaculture use;
- balancing the dominance of larger-scale operations by supporting greater co-operative efforts for smaller-scale operators, such as application of the 'nucleus estate' model;
- replicating the broad benefits of collaborative selective breeding programs, such as the GIFT program (Genetically Improved Farmed Tilapia), in other aquaculture species;
- establishing collaborative programs to preserve genetic resources in wild populations, such as for the slower-growing but more salt-tolerant tilapia species in Mozambique (*Oreochromis mossambicus*);
- fostering private sector, pre-competitive collaborations (such as the Global Salmon Initiative) to better address aquaculture's challenges.

Governments should be careful not to inhibit the application of new technologies to protect those producers more dependent on the status quo. Policymakers should remember that seafood is one of the most-traded global commodities. Therefore, direct government involvement in market manipulation or direct investment is unlikely to establish an innovative, beneficial or profitable industry.

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Key Messages

Government or agency policies might encourage or constrain aquaculture innovation, by:

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- fostering private sector, pre-competitive collaborations (such as the Global Salmon Initiative, GSI) to better address aquaculture’s challenges.

Governments should be careful not to inhibit the application of new technologies in an effort to protect those producers more dependent on the status quo. Policymakers should remember that seafood is one of the most-traded global commodities. Direct government involvement in market manipulation or direct investment is therefore unlikely to establish an innovative, beneficial or profitable industry.

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1. Introduction: Innovation as a theme

Any discussion of innovations in global aquaculture industry needs to be rooted in the overarching context that the vast majority of production - 91.7% of total global aquaculture (FAO, 2020 a) - is produced in the Asian region, primarily by small-scale farmers. This review of the theme of global aquaculture innovation seeks to address *all* innovations: those that are being applied on a large-scale, through capital-intensive production in enclosed land-based systems or massive offshore operations, through small- to medium-scale enterprises for freshwater operations, and on the artisanal and subsistence scales.

Innovation can drive increasingly rapid expansion of aquaculture to meet the burgeoning demand for nutritious animal protein and to ensure the continued sustainable development and profitability of the aquaculture sector (on the basis of the three pillars of sustainable development, namely environmental, economic, and social sustainability (Godfray, et al., 2010; Nature, 2010)).

This review examines the current status, issues and challenges, and future developments in aquaculture innovation. Some of the innovations covered include: application of precision or smart technologies, geographic information systems (GIS), sensors, robotics, and bioinformatics. It explores ways that aquaculture is benefiting from smarter technology in data rich environments, and highlights those trends or technologies that will be the primary drivers of future growth in the industry (Bizri, 2018). Big data and artificial intelligence (AI) are not specifically addressed, as, while there is much enthusiasm around their early adoption, there is not yet any realistic, significant utility in aquaculture.

The review seeks to identify the engines and incentives that are behind the major areas of aquaculture innovation. The broad categories and sectors where innovation is occurring are described, as are the risks, benefits, and broader impacts – some of which are potentially less desirable. The review also explores policies that individual country governments and regional organizations can adopt to encourage innovations with preferable socio-economic outcomes.

It is first imperative to re-emphasize the critical need for expanded growth in aquaculture. This is no longer just an issue of food security. More importantly, aquaculture needs to increase the global availability of seafood, to begin to help address the global climate crisis. For this to happen, seafood consumption per capita must be increased in a sustainable manner to alleviate pressures on land and freshwater resources from terrestrial livestock (Hall, et al., 2011; Bohnes and Laurent, 2021). According to the UN High Level Panel on the Oceans and Climate Change (Hoegh-Guldberg, et al., 2019), it is imperative that humanity begin to transition from more terrestrially-sourced foods to more marine-sourced foods.

There is therefore not one single goal for aquaculture innovation. Innovation in the industry, as viewed in this review, should have the goals of:

1. Nourishing humanity. Aquaculture needs to increase food security at the national levels, and improve consumer nutrition, on the individual level;

2. Providing gainful employment by expanding opportunities, particularly for minorities who may have been underrepresented in the industry;

3. Reducing the impacts of humanity on finite global resources, and the environmental impacts of aquaculture operations;

4. Improving the workplace safety of aquaculture employees;

5. Expanding production to enable mitigation of the global climate crisis, and building resiliency so that the industry can better withstand the impending changes from the global climate crisis.

Private sector innovations have the primary goal of higher profits, which can be achieved by increased production efficiency, and /or reducing costs and/or increasing the price. At the same time, however, increased awareness of aquaculture impacts – particularly among consumers - and increasing transparency and accountability of the industry, have also elevated broader environmental, social, and governance goals amongst corporate producers. This is driven by either desire for specific market access (through a range of novel certification schemes and standards, connected with buyers and retailers), or the desires of companies for access to sites, by earning greater social license (both of which are ultimately linked to the market share and profitability of the company).

Private sector innovation can be useful as a tool to achieve the above goals, but may also establish incentives that run counter to them. For example, increased automation may enable greater scale of operations, and more operational efficiency, and might also increase workplace safety (e.g. net-cleaning robots for net pen operations removes the need for SCUBA-diving for cleaning). At the same time, however, such developments could reduce the overall number of employees on a farm, and ultimately reduce the employment in the industry, and increase the reliance of operations on technology and infrastructure (e.g. access the electrical grid and the cloud). This review seeks to highlight such tensions, but it is beyond the scope to provide remedies, or recommendations. That must ultimately be the responsibility of the policy-makers for whom this review is intended.

2. The Current Status of Aquaculture Innovation

The status of aquaculture innovation has been thoroughly reviewed elsewhere (FAO, 2019; COFI, 2019). The most dramatic innovations in aquaculture – to the casual observer - include large-scale, intensive, land-based RAS systems, highly-automated offshore net pen systems designed along the principles and scale of offshore oil rigs, increasing robotics and remote command-and-control, and novel financing tools for larger companies or small start-ups. The most impactful innovations in the industry are, however, often of a far lower profile: improved selective breeding for better growth, feed conversion efficiency, and environmental stressor and disease tolerance (resistance), refinements in feed formulations to reduce the reliance on forage-fish resources for fishmeal and fish oil in aquaculture diets, expanded use of vaccines to improve animal health, and better extension, outreach and training for farmers.

The last decade has seen spectacular advances in all these areas. For example, the average fishmeal and fish oil content of Norwegian salmon feeds have fallen over a 30-year period from a high of 65% and 24% in 1990, to a low of 13% and 11% in 2019, respectively (Naylor, et al., 2021). The increase in production for the main fed finfish and crustacean aquaculture species has been dramatic over the past several decades, with global production increasing at an average annual rate of 14.2% per year for catfish (5.78 million tonnes in 2018), 9.6% per year for marine shrimp (6.0 million tonnes in 2018), 9.4% per year for Tilapia (6.03 million tonnes in 2018), 6.4% per year for marine fish species (3.0 million tonnes in 2018), 5.4% per year for salmon (2.64 million tonnes in 2018), and Chinese fed carp species (14.14 million tonnes in 2018 (FAO, 2020a).

2.1 Genetics and breeding

The rapid expansion of tilapia farming through the GIFT program (Genetically Improved Farmed Tilapia), and other selective breeding work (the Chitralada Bouaké strains) is exemplary. The GIFT program was established by WorldFish Center in 1988, in cooperation with the Rockefeller Foundation and in collaboration with national partner institutions in the Philippines and China (Ponzoni et al., 2010). GIFT strains of Nile tilapia (*Oreochromis niloticus*) were developed to be fast growing, and adaptable to a wide range of environments, and are now the primary strain for commercial culture of the species worldwide. Nile tilapia ranks third among the major species produced in world aquaculture (FAO, 2020 b).

Similarly, selective breeding and hybridization have produced disease-resistant and fast-growing strains of bivalves, and varieties with unique shell colours (Guo, 2021). In China and elsewhere, over 30 molluscan species have been subjected to some genetic improvement. Sterile triploid oysters (i.e. with three sets of chromosomes, instead of the normal two) grow faster and maintain meat quality during their spawning season. These are often produced by crossing tetraploid oysters with diploids for more consistent triploidy production (i. e. 4N x 2N = 100% 3N).

Genomic selection (i.e. the use of genetic markers to drive breeding programs) is particularly effective, eliminating the need for expensive phenotyping programs (i.e. there is no need for grow-out of individuals to prove their improved fitness). Genomes have been sequenced for many cultured species, and high-throughput genotyping platforms, such as single-nucleotide polymorphism (SNP) chips, are now more widely used. This further ‘democratizes’ the application of genetic tools in aquaculture. There is much more that still needs to be accomplished, however. Gjedrem et al. (2012) estimated that less than 5% of world aquaculture production was derived from seeds produced in family-based breeding programs. This demonstrates that although the technology exists, it is not yet being applied fully or at scale.

Some genetic innovations, however, have not been widely adopted. For example, supermale technology for tilapia (producing all male YY fish) can now be accomplished without any hormonal treatment, allowing 100% male stocks, resulting in faster growth rates and better feed conversion efficiencies (Kaneko et al., 2015; Li et al., 2015). The industry, however, still relies almost universally upon methyl-testosterone (MTT) treatments, despite the apparent benefits of supermales, and significant reduction in risks to hatchery workers from potential MTT exposure. By the time of harvest (usually around 9 – 12 months), all traces of MTT are gone, and so consumer interest groups and public health officials are more accepting of the status quo.

2.2 Operational innovations

The aquaculture industry, as a whole, has made phenomenal advancements over the last decade in reducing the reliance on wild-caught forage fish fisheries, to provide the fishmeal and fish oil ingredients. For example, the decreased dependency of the aquafeed manufacturing sector upon fishmeal and fish oil has been due to the increased use of terrestrial vegetable and animal protein and lipid sources, and dietary supplementation with limiting essential amino acids, fatty acids, and trace minerals (Naylor, et al., 2021; MOWI, 2020). Better feed formulations have also increased overall feed efficiencies and resulted in improved animal health, survival, and growth rates, through inclusion of probiotics and prebiotics (Romano, 2020). Similarly, selective breeding has improved feed efficiencies, in some cases for specific feedstuffs, e.g. Overturf, et al., (2013), who demonstrated selective breeding of rainbow trout for increased tolerance of soy products in the diet).

Aquatic animal health management has improved dramatically, with innovations in early warning, diagnostics, treatment and prevention, through use of vaccines, monitoring of environmental DNA, prebiotics and probiotics, and other non-antibiotic treatments. Biological controls are now increasingly common, such as sea-lice treatment in Norwegian salmon net pens using lump fish (*Cyclopterus lumpus*) and other wrasse species.

The expansion of computing power and portability and greater accessibility and affordability of cloud-based data systems has allowed more on-farm application of these technologies. On-farm data collection and management systems are now widely used in larger commercial operations, including sophisticated tools for biomass assessment and monitoring of animal behaviors, feed management (rapid data collection and analysis to improve feed efficiencies), water management and pollution control, monitoring fish health and/or fish escapes and biosecurity.

Remote sensing tools and integrated GIS systems are now also widely used for more efficient site selection, to map and analyze oceanographic conditions (e.g. currents, waves, temperature), bathymetry, multiple users of the area (e.g. shipping, recreation), and other factors to support evidence-based decision making for site selection (e.g. NOAA AquaMapper; http://www.shellsim.com/ and ShellGIS; Silva, et al, 2011). The increasing use of real-time remote sensing and improved sensor development has opened opportunities for predictive (instead of reactive) evaluation of threats such as oceanographic phenomena (anoxic upwelling) and harmful algal blooms. Carrying capacity models are also of increasing utility, particularly for bivalves, when relatively simple inputs such as flushing rates, chlorophyll measurements, stocking density, and oceanographic conditions are paired with GIS and remote sensing tools.

2.3 Aquaculture financing

Innovative aquaculture is a high-risk endeavor, and has frequently faced challenges in obtaining financing through traditional avenues (e.g. bank loans, project financing collateralized through offtakes or stock insurance policies, and strategic partnerships between producers and retailers). More recently, however, new financing tools, strategies, and programs have evolved for supporting innovative aquaculture. The last decade has seen a number of innovative mechanisms for start-up aquaculture companies to obtain financing or other support to increase their likelihood of success. This represents innovation in support of innovation: new financing tools to foster new technologies and species development.

The major mechanisms supporting innovative aquaculture research are public sector financing. Traditional public sector financing is directed through universities and research institutions, but these have generally proven less adept at bringing innovations into the marketplace. More astute use of public financing for innovative research now focuses specifically on fomenting developments in the private sector, and particularly small business start-ups. Brazil, for example, operates an Innovative Research in Small Business (PIPE) program that supports many aquaculture start-up projects that have since become successful companies[1]. In the United States, 2% of all Federal research dollars are, by law, directed through the Small Business Innovative Research program. In Australia, a significant portion of government funding for aquaculture R&D is directed through Co-operative Research Centers, which are collaborations between public universities and research institutions and private sector partners which require financial contributions from each of the participants.

Increasingly, governments are also directing public financing through autonomous or semi-autonomous investment funds, or public-private partnership funds. One advantage of this dual approach is that private sector investing partners then have greater confidence in government support for the industry. This greater certainty around government policies then increases the amount of private financing, and reduces the risk profile for investment, thereby amplifying the benefits of the public financing.

There has recently been a notable increase in the number of aquaculture-focused investment funds, or impact investors with seafood or aquaculture focus. This has largely been catalyzed by two developments: broader recognition among environmental NGO, academia, and science communities of the potential environmental benefits of expansion of aquaculture, and a greater recognition in the financing community of the potential profits that can be generated from aquaculture.

A number of small-business incubators and accelerators have recognized the opportunities and have begun supporting aquaculture start-ups. Some accelerators, such as Hatch, are specifically focused on aquaculture. Others, such as Pearse Lyons Cultivator (https://www.pearselyonscultivator.com/) are more broadly focused on agriculture, but recognize the greater growth potential in aquaculture.

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[1] https://fapesp.br/en or https://fapesp.br/pipe/pappe_pipe/4/

Fish 2.0 – a seafood business and investment platform and competition – initially excluded applicants from net pen operations. It is supported by government agencies, individuals, and foundations. Fish 2.0 has expanded from originally California to include participation by entrepreneurs from Latin America, Europe, the Pacific Islands, and South-East Asia. The program offers online support for entrepreneurs and an avenue for investors seeking access to new opportunities.

Hatch is a private investment fund that has developed the first global aquaculture and alternative seafood accelerator program. Hatch provides seed capital to selected startups, and offers access to global subject matter experts and other mentors from the industry over an intensive coaching program in Norway, Singapore, and Hawaii.

Other Accelerators such as Trendlines and Yield Lab have taken strong interest in aquaculture, particularly in countries which offer additional financial support by the government for local enterprises.

Impact investing has also found traction in aquaculture, given the greater scalability and lower overall global impact from farmed seafood (c.f. wild-caught, or terrestrial livestock production). Several funds are now operating in the seafood space, or are exclusively focused on aquaculture (Aquacopia, Pontus Aquaculture, Aqua-Spark, Varuna Fund). Other funds are more broadly divested, but have keen interest in the space (e.g. Google Ventures, Tyson Ventures, Rabo Ventures, Kawasaki Ventures, Chevron Ventures, BP Ventures).

Financing of aquaculture projects by foundations, environmental NGO and angels (individual investors) has also become more widespread. The Nature Conservancy and Conservation International have both established funds for investment in innovative aquaculture projects, particularly focused on restorative aquaculture (i.e., environmentally beneficial forms or aquaculture, such as seaweed and bivalve farming). The WWF has also set up a fund to support seaweed research and development, with additional capital reserves for deployment into companies and concepts that offer the possibilities of broadly beneficial industry growth.

Some governments have used regulatory incentives to encourage increased production. The Singapore Food Agency (SFA), for example, has established six agrotechnology parks to increase mainly local agri-food production. The SFA dispenses with licensing fees if farms in their system meet a production goal, defined as a minimum tonnage per hectare per year. The Natural Energy Laboratory of Hawaii Authority offers test-bed facilities for aquaculture start-ups, complete with pre-permitting, land preparation, and infrastructure (electricity and reticulation for fresh water, surface seawater and deep seawater). Originally designed for ocean energy research, NELHA now hosts over 20 aquaculture companies in various stages from early start-up to publicly traded corporations. The NELHA required significant capital investment from government, but it now operates at approximately break-even (covering administrative and maintenance costs for shared infrastructure), with additional benefits to government from corporate excise taxes and income taxes on employees.

A number of environmental NGO have now begun to be actively involved in innovative aquaculture, through farmer training and extension work, field science, and policy engagement (e.g. O'Shea, et al., 2019). The WWF, The Nature Conservancy, and Conservation International are all now involved in innovative small-scale macroalgae and bivalve culture in Belize, China, Faroe Islands, Indonesia, Palau, New Zealand, Tanzania, and the U.S.A. (Waters, et al., 2019).

Together, these advances over the last decade and more have contributed to aquaculture as the most rapidly growing food production system on the planet. Yet still, it is not enough. To meet the supply/demand gap for aquatic food products, aquaculture does not merely need to continue to expand, it needs to increase the rate of expansion dramatically. The following section reviews some of the areas where further innovations would have greatest impact, enabling expansion and intensification of aquaculture, while minimizing detrimental consequences of rapid growth.

3. Issues and challenges

Almost inevitably, innovation is disruptive. Any new tool, system, or policy is going to impact the *status quo*, and the change will disadvantage some companies, individuals, or consumers. For each of the major areas of innovation, itemized below, some of the attendant impacts, both current and future, real, and perceived are discussed.

3.1 Scale:

The fundamentals of economics deign that aquaculture operations, as for almost any commercial business, are incentivized to increase their scale. The primary drivers behind this propensity are greater profitability with more economies of scale, greater market share, or (even if profits per unit production are unchanged), simply more profits from expanded volume. This has most clearly been demonstrated over the last decade in the scale and intensity of operations of shrimp farms, land-based RAS systems, and net pen culture of salmon, sea bass, or sea bream. For marine shrimp, *Litopenaeus vannamei* (white shrimp), the grow-out methods are evolving away from extensive pond systems (usually 5–10 ha, but up to 30 ha per pond) towards more intensive, smaller ponds (0.1–1.0 ha), or highly-intensive raceways (from 50 to 2,000 m^2) in greenhouses, supported by bioflocs with nanobubble and diffuser aerators (FAO, 2021; Rahmawati, et al., 2021). Land-based RAS systems for salmon are now being built that are designed to produce up to 220,000 T/year[2]. Offshore net pen arrays frequently use cages of up to 50 m in diameter, up to 20 m deep. At Salmar Fish Farm 1, one offshore net pen (Figure 1) has twice been stocked with 1.5 million smolts per cohort. Salmar is currently constructing a larger Fish Farm 2, and has plans to deploy up to 10 units, each of which will accept 3 million smolts per cohort[3].

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[2] Atlantic Sapphire Investor Day - May 9, 2019, from www.atlanticsapphire.com

[3] https://salmonbusiness.com/salmar-expects-serial-production-of-offshore-fish-farming-ocean-rigs-five-to-ten-units-in-the-first-phase/

There are broad benefits to society from such expansion. In general, more aquaculture production meets the goals of nourishing humanity and mitigating the global climate crisis, by supplanting terrestrial animal proteins with their attendant land-use, fresh-water use, and greenhouse gas emission impacts. Greater efficiency increases corporate profits, incentivizing even further expansion, but also provides products to consumers at a lower price, making nutritious seafood available to more people, particularly those of lower socio-economic strata. Larger, more capital-intensive systems are generally more rigorously managed, and are designed and operated to have less overall environmental footprint, on a basis of per ton produced (Bohnes and Laurent, 2021).

By driving down the price of aquaculture products, however, larger-scale, capital-intensive systems also displace small- or medium-scale producers, who are unable to match the production efficiencies and the market prices of the corporate entities. This can result in less socio-economically diverse development, less geographical dispersion of production (concentration by a few large companies in selected regions), and less overall employment in the industry.

3.2 Automation, remote command-and-control and precision aquaculture:

Similarly, emerging technologies and tools such as precision aquaculture or smart aquaculture, GIS systems, remote sensors, machine learning, and robotics all offer great potential for increased production, reduced labor requirements, increased production efficiencies, and greater profitability for corporations. The corollary of these developments is more aquaculture product for consumers, often at a lower price, and frequently with less inputs and lower environmental externalities.

As in other industries, however, the development and application of such sophisticated tools limits their utility to those companies that have both access to capital, and the strength in human resources to install and maintain these systems. Again, this frequently disadvantages small- and medium-scale producers.

3.3 Selective breeding and genetic tools:

By contrast, the benefits of the powerful new genetics and bioinformatics tools are more broadly available, as most commercial aquaculture industries now support independent companies whose core business is running selective breeding programs and commercial hatcheries, and making improved progeny available on the open market (Gjedrem, et al., 2012). Small-scale or subsistence producers who do not have access to capital for purchase of improved seed stock may still be disadvantaged, but only to some lesser degree.

Larger, better-capitalized companies may support their own selective breeding programs, or have exclusive relationships with hatcheries or genetics companies that allow them to develop their own exclusive strains. Seed stock with more advanced traits are generally not available to smaller-scale producers. Governments should therefore consider providing assistance for breeding programs that specifically extend selective breeding benefits to smaller-scale producers. The larger companies will also benefit from government support for building more extensive genetic databases, and more family lines.

To date, in aquaculture, there has been no effective exertion of control of genetic resources by larger corporations[4], such as has resulted in conflicts in terrestrial agronomy over patented seed technology.

There is ongoing consolidation of hatcheries by multinationals, and integration of farm companies and feed companies. Generally, however, genetic gains in aquaculture are dispersed in a more egalitarian manner than other technological innovations. The commercial benefits of improved strains, that might offer greater production volume, improved feed conversion efficiencies, better survival, and better product quality can be – and usually are - shared more diversely, with consequent advantages for producers in rural areas, as well as for consumers in metropolitan centers. Overall improvements in production from better strains then results in more profitable operations for small-scale, rural producers, and this then also encourages greater participation in the industry, and even more expansion of production.

There are some concerns with the application of novel genetic tools. Sophisticated breeding programs – those which result in the greatest production gains - mostly focus on just a few species. For instance, only two species of shrimp, *Penaeus vannamei* and *P. monodon,* constitute about 80% of farmed shrimp production, and thus almost the entire global selective breeding is directed towards these two species. This may have long-term consequences for industry equitability, resilience, and biosecurity. Those countries where *P. vannamei* and *P. monodon* are not native, or where their culture is limited by other factors, could therefore be excluded from participation in this industry. Further, a single pathogen that afflicts the dominant species could then more greatly impact global production and supply chains. Perhaps terrestrial agriculture will provide the model for eventual evolution of aquaculture, i.e. fewer and fewer species cultured globally, with broad industry consolidation driven by control of genetic attributes. Although this end result is considered to be less desirable, there are few alternatives that can be recommended, and no obvious policy initiatives that might divert this species trend.

Genetic selection can also be problematic if escapes or on-farm spawning allow genetic introgression (intermingling between farmed stock and wild populations). This is generally perceived as lowering the overall fitness of wild populations, e.g. hatchery-raised salmon blurring the genetic integrity of wild salmon stocks in discrete watersheds, or Pacific oysters selected for resistance to herpesvirus (Dégremont, et al., 2015) potentially intermixing with wild populations, and hence increasing the invasiveness of the species. Sometimes, however, introgression may result in benefits as in the case of intermixed strains of *Ostrea edulis* selected for higher resistance to *Bonamia* with wild *Ostrea* populations. Holmenkollen (Holmenkollen Guidelines. 1999) advises a precautionary approach; however, an overly precautionary stance may incur real costs for industry and for consumers, as lost aquaculture opportunities, i.e., where industry is forced to forego the advantages of selectively bred stocks, reduce the overall seafood availability, and increase its price. An overly cautious approach in one country may also put its producers at a disadvantage in the global seafood marketplace.

Farming of sterile stocks is often pursued to improve growth performance beyond the age at maturation (as the animal then should direct more resources towards somatic growth, rather than reproduction), and for a superior product (e.g., to overcome milt or roe in farmed bivalves).

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[4] http://www.fao.org/cgrfa/meetings/ttle-abs/en/

Sterility is also posited as a solution to introgression, but the most widely applied technologies (e.g. triploidy) are rarely 100% reliable (Guo and Allen, 1994), and often bring attendant issues (e.g. spinal deformities in triploid salmon (Fjelldal and Hansen, 2010)).

Gene-editing through CRISPR/cas9 offers the opportunity of modifying the entire suite of a genome in a way that mimics natural mutation. This approach is therefore fundamentally different from the introduction of foreign genes, i.e. transgenics, or so-called "Frankenfish". Three countries already allow use of CRISPR in aquacultured animals (Japan, Australia and Brazil). These new genomic tools need to be rigorously evaluated, to ensure there are no significant unintended consequences (either consumer health or ecosystem health), and to build consumer acceptance and political support. Any overly restrictive regulation in this area could, however, be detrimental to overall aquaculture production, and to the industries in individual countries which more rigorously apply such restrictions. The potential for applying genetic tools (such as gene editing) to produce sterile stocks is particularly appealing, because it offers guarantees of 100% sterility. This would then, *ipso facto*, negate any concerns about potential introgression of genetically modified strains.

3.4 Alternative feedstuffs:

As with most innovations, the use of alternative feedstuffs often brings attendant concerns. For example, the use of fish processing by-products, or trimmings, to provide fishmeal or fish oil in aquaculture diets has increased dramatically. Biosecurity concerns, however, mandate that such fish processing by-products are not used in diets for closely related farmed species[5].

Many of these alternative feedstuff products are also used in the wider terrestrial animal nutrition markets (mainly poultry and pigs), and so aquaculture competes for these feedstuffs; however, alternative protein and lipid sources are more prominent in aquaculture because of the rapid industry growth, and because the fastidiousness of many fish species limits the utility of many products (compared to chickens and pigs). Aquaculture also represents, on a global level, the best and highest use of many of these products (most specifically EPA and DHA), because of the efficiencies of trophic transfer in cold-blooded aquatic animals, compared to warm-blooded terrestrial animals.

Traditional agricultural proteins that are now in wider use in aquaculture diets include soy protein isolates or soy concentrates, barley, wheat, and corn proteins, and animal processing by-products (bloodmeal, poultry meal, feather meal). Each alternative feedstuff presents its own array of opportunities and challenges. For example, concerns around mammalian land animal by-products (pork and beef) associated with prion infections (the causative agent in "mad-cow disease") prohibit their use in some jurisdictions. The best available science, however, is clear that prions cannot be transferred between the different classes of vertebrates (e.g. from mammals to fish), or from vertebrates to invertebrates (e.g. mammals to crustaceans such as shrimp). Wider use of land animal proteins and fats in aquaculture could alleviate pressure on wild fish resources (Pelletier, et al., 2018).

Agricultural grains and animal processing by-products have also provided an increasing amount of the lipids in aquaculture diets. Many of these more conventional sources, such as canola or soy oil, can now also provide selected or modified strains that include specific lipid fractions, such as EPA or DHA.

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[5] E.g. Aquaculture Stewardship Council standards for Salmon, Seriola, and Cobia, and others.

These strains are often genetically modified, but as the purified lipids carry no DNA material, there is no scientific basis for restricting their use, even in jurisdictions which normally prohibit use of GMO products. Again, such a science-driven approach to policy offers great potential benefits for aquaculture, and for minimizing the ecological footprint of nutritious food production.

Innovative proteins and oils are also becoming more widely available, as their utility is further demonstrated, and as investors and larger agribusinesses begin to align around their production. New protein sources include single-cell proteins (Calysta, KnipBio), and insect meals (e.g. black soldier fly larvae). Novel sources of oils include yeasts (e.g. Verlasso salmon), and microalgae that are grown in heterotrophic conditions, such as *Schizochytrium* and Veramaris oils, rich in EPA and DHA, that are produced in converted bioreactors at old ethanol plants in the mid-Western U.S.A. (Lane, 2018). Automated, large-scale photobioreactors for phototrophic microalgae (e.g. Erbland et al., 2020; Barcenas-Perez et al., 2021) still have yet to prove cost-effective as a means of producing feedstuffs for aquaculture.

Alternative feedstuffs also offer great potential to reduce the overall ecological footprint of fed-aquaculture dramatically. There is now much greater awareness of, and better accounting practices to evaluate, the carbon and energy inputs and other ecological footprint metrics for various feedstuffs (e.g. Pelletier, et al., 2018).

3.6 Certification schemes:

The past decade has also seen a proliferation of aquaculture certification schemes focusing on metrics for environmental and social impacts, and overall corporate governance. The formation of these organizations grew out of concerns amongst retailers that their customers were increasingly interested in the provenance of the foods they were purchasing, and retailer apprehension over reputational risk of carrying products that might be associated with environmental or social detriments (Eco-labeling; Chikudza et al., 2020).

These concerns were – and still are - largely confined to seafood retailers in more economically developed countries, where consumers and media are more focused on such issues. Certification schemes have therefore engaged mostly with highly traded products, such as shrimp, salmon, and catfish. Certification tools have been less impactful in aquaculture industries that provide product into domestic markets, or that sell into economically less developed countries, where retailers and consumers may have less access to information, or less market choice.

Recognizing these concerns, some certification schemes have worked to offer processes that are more inclusive of small- or medium-scale farm operators. Group certification schemes have begun to address these issues, but the mechanisms for certifying neighboring farms who share the benefits, risks and responsibilities are complicated. The evolution of aquaculture improvement programs (i.e. providing producers with provisional access to markets, so long as they adhere to a defined trajectory for eventual certification) has also broadened the potential outreach and impacts of certification schemes. Some initiatives in this area include incorporation of FAO's Ecosystem Approach to Aquaculture (FAO, 2010) into market-based incentive schemes.

Conservation International and partners are developing a 'jurisdictional approach' to aquaculture improvement projects, focused on aligning incentives to improve sustainability outcomes across a whole jurisdiction, rather than just farm by farm (Bone, et al., 2018; Kittinger, et al., 2021).

Clearer demonstration of the actual beneficial impacts of certification schemes would also improve their uptake. More rigorous monitoring and evaluation programs are therefore needed.

4. Future Developments

Prognostication on future innovation is fraught. The beauty of disruptive ideas is that they are often previously unforeseen. Nevertheless, this study's authors believe that aquaculture will continue to see innovation in the following areas. We also wish to highlight a number of areas of future concern.

4.1 Scale:

The size of aquaculture operations will, overall, continue to increase, driven by the inexorable trend towards economies of scale, consolidation in the marketplace, and higher profits. This will most notably impact shrimp (both extensive farming and RAS systems), offshore salmon and marine finfish culture, and intensive, land-based RAS systems fish and crustaceans.

Permitting for large-scale aquaculture projects is a purview of public policy. Governments therefore should consider the wide-ranging impacts of such developments on a cost-benefit basis. Costs may include displacement of other small- and medium-scale producers, and consequent reduced employment, consolidation, and less geographical diversification of the industry. Benefits may include wider availability of more affordable seafood products in the local marketplace, and consequent improved consumer nutrition.

Governments may wish to reduce the dominance of larger-scale operations by supporting greater co-operative efforts for smaller-scale operators, such as bulk-purchasing for supplies and joint-marketing initiatives. Rather than government-run co-operatives, more efficient approaches may be found in the 'nucleus estate' model, or other forms of privately-incentivized contract farming (see http://www.fao.org/3/y0937e/y0937e05.htm). There are, as yet, however, few examples of contract farming in aquaculture that can provide models for governments or entrepreneurs to follow.

4.2 Automation, 'smart' aquaculture, and remote command-and-control:

As discussed above, there are similar trade-offs in implementation of greater automation, smart aquaculture, and remote command-and-control systems. These developments can increase production volumes and reduce the cost-of-goods, but also displace those producers with less access to capital or technologies. New technologies may also reduce the need for labor, resulting in reduced employment opportunities, and less demand for semi-skilled or unskilled labor. More efficient operating systems can also contribute to reduced carbon footprint (e.g. more efficient aeration or pumping systems, and greater precision of operations lowering input requirements) (Føre et al., 2018).

The process of creative destruction that attends entry of innovations into the marketplace implies that more traditional producers will be disadvantaged by these technological innovations. Governments should be careful not to inhibit the application of new technologies in an effort to protect those producers more dependent on the status quo, unless there is a clear environmental or social benefit that the established order provides, which could be lost or diminished through disruption. Policymakers should remain cognizant of the global dynamics of the marketplace. If the policy of any one national government strives to limit technological advancements, other countries will still certainly adopt the more efficient methods, and outcompete those who have not embraced the new technologies.

As better-capitalized companies introduce automation and smart aquaculture systems, small- to medium-scale producers could be encouraged to maintain technological parity through training schemes and financing programs that make it possible for them to install and maintain the newer equipment or practices. Government resources or other funding could particularly focus on supporting technologies that improve production per unit of energy, or that enable broader and more rapid adoption of renewable energy systems in aquaculture, such as wind, geothermal or solar. Governments might also support financing mechanisms, research programs or scholarships that integrate engineers, biologists, and entrepreneurs.

4.3 Offshore:

There is tremendous potential for expansion of aquaculture into offshore marine environments – in deeper water, further from shore, with generally stronger currents (Kapetsky, et al., 2013; Gentry, et al., 2017; Kim, et al., 2019). This is beginning to be realized, particularly for marine fish and salmonids, in established aquaculture nations such as Norway, Turkey, and China, as well as in less advanced aquaculture nations such as Panama and the U.S.A. These developments are driven by the growing recognition that offshore culture can avoid some of the challenges that near-shore aquaculture encounters, such as benthic or water quality impacts, wild fish stock health concerns with net pens (especially for migratory species such as salmon), and conflicts over public domain use. Offshore farming systems also offer potential to achieve dramatic improvements in economies of scale (See above, Section 3.1, discussion of Salmar Ocean Farm 1).

Properly sited offshore net pen operations have been shown to have much lower impacts on water quality and benthic substrate (Sims, 2103; Price and Morris, 2013; Rust, et al., 2014; Welch, et al., 2019). Nevertheless, this minimal impact can be affected by the farm scale, density of the net pens, operational experience and site specifics. Continued monitoring of offshore operations is needed to help better understand the interplay of these various factors, and to allow more precise modelling of impacts. Innovative monitoring and modeling are needed to better inform management of the offshore industry, going forward.

Industry and regulatory agencies need to be aware of the potential negative impacts, both environmental and social, from offshore fish farming. Both the cost for capital equipment and costs for feed for the massive cohorts that are grown offshore limit the participation in offshore operations to those with access to capital. The scale of operations means that any escape event, or other negative environmental impact, could be an order of magnitude more impactful than smaller near-shore operations. The increasing role of technology used in offshore pens reduces the labor requirements per tonne of production. Offshore operations at larger scale require both employees, and result in fewer positions for unskilled or semi-skilled workers. This limits the potential for aquaculture growth to provide expanded employment opportunities. The increased scale of production will also, over time, lead to reduced unit costs for marine fish, which could result in small-scale producers from nearshore farms being outcompeted in the marketplace.

The potential for offshore fish farming operations to provide a meaningful benefit to middle- to lower-income countries and consumers has recently been questioned (Belton, et al., 2021). Certainly, the scale of most offshore operations and the capital equipment requirements place constraints on broad participation. Offshore culture of non-fed aquaculture species such as seaweeds and bivalves could be more inclusive of medium- and small-scale operators, because there is no outlay required for feed. To attract more interest in this area of opportunity, there needs to be better definition of the benefits of cultivation of non-fed species through nutrient or particulate uptake, absorption of carbon, or increased biodiversity through the provision of offshore substrates.

4.4 Intensive Onshore systems:

The next decade will probably see further dramatic expansion of intensive onshore systems, such as RAS units for shrimp, marine fish, and freshwater fish. These systems offer advantages in better control of animal health, and improved biosecurity, as well as allowing siting with greater proximity to market. They also can greatly reduce environmental impacts, such as reducing or eliminating nutrient loading in effluent waters.

The scale of such systems, however, burdens them with the same attendant issues discussed above (Offshore, 4.3, and Scale 4.1), around scale-up of operations and impacts on small- to medium-scale producers. Onshore systems are also very energy intensive, and are heavily dependent on capital equipment and sophisticated levels of automation. This means that both construction and operations have greater life-cycle demands than more extensive systems.

Conversely, land-based intensification can reduce the pressure for land-conversion, such as destruction of mangrove swamps for shrimp ponds. Although science can inform on these overall trade-offs between greater volumes of seafood, more broadly available in the market, and the energy and resource requirements of such systems, these questions must ultimately be answered under a policy framework.

Some countries with limited arable land have made advances in super-intensive agri-food production, such as aquaponics. Vertical agri-farming for leafy vegetables and marine foodfish is already established in countries such as Singapore, with high-rise fish production buildings up to 8 stories tall. One such operation is projected to produce 2,700 T/yr of grouper and coral trout by 2023 (Tatum, 2021). These operations are highly dependent on interconnectivity and sensor technology, and rigorous fish health screening, and thus require major investments of capital and expertise. Their primary focus is on high-value species, suggesting that broader applications may be limited. The long-term utility of such operations for improving food security cannot yet be determined. Governments must themselves make a determination as to the desirability of such systems, and apply policy tools to support or constrain growth of large-scale on-shore operations (Shen, et al., 2021).

4.5 Alternative feedstuffs:

The recent advances in reducing the dependence of aquaculture on wild-caught forage fish fisheries should continue, and governments and other entities should expand support in these areas.

While some alternative sources of proteins and oils have received much publicity, they have yet to prove their broad usefulness. For example, *Spirulina* is a good potential source of protein, but on a dollar-per-gram of protein, it is still far more expensive than fishmeal. The microalga *Nannochloropsis* sp is also used widely as a feedstuff in hatcheries (for enriching rotifers or *Artemia*, or for feeding directly to filter-feeding larvae), but is significantly more expensive a source of DHA than fish oil from, e.g., Peruvian anchoveta. While many of these products may be costly today, prices will undoubtedly decrease as producers refine their operations, bring new technologies to bear, and increase their scale. These alternatives may very well end up cost-competitive in the next decade.

A commendable approach for governments and other financing agencies in this field would be to fund long-term programs for feedstuff research and development for the most salient alternatives, and to provide low-cost loans for capital for construction of production or processing facilities. Prospective applicants for loans or other funding should be vetted thoroughly, as many products may initially seem appealing, but are not yet fully proven, or may have constraints to scale-up. Scale-up challenges may include efficient sourcing and aggregation of feed inputs (e.g. for the black soldier-fly larvae), and market resistance to the pricing (for most pond-grown microalgae).

Policies and programs should strive to expand the use of agricultural proteins and oils, including both crops and animal by-products, as well as optimizing use of seafood trimmings. These strategies will then, ideally, reduce pressure on wild fish resources, diversify the supply chains for fed-aquaculture, expand the upscaling of processing by-products, increase profitability of aquaculture operations, and improve food security.

Biosecurity concerns around land-animal by-products used in fish feeds should be addressed through the best-available science. An overly precautionary approach could result in negative impacts by limiting the potential benefits listed above.

Where food security is a compelling concern, government policies and investment programs should consider the more efficient utilization of proteins and oils (c.f. poultry or mammals) in aquaculture, especially when weighing omega-3 fatty acid utilization. Data-based decisions on how best to feed and nourish a growing population should take into account the full cost accounting (cradle to grave) of the different animal protein production sectors, with the most resource efficient sectors receiving more government support. Similarly, the demonstrated lower global impact of aquaculture on greenhouse gas emissions, fresh water and land use (Hall, et al., 2011) should embolden governments to expand support for aquaculture development, with concomitantly lower support for more-impactful terrestrial animal protein products.

4.6 Selective breeding and application of novel genetic tools

Governments and other entities should strive to replicate the spectacular production advances and broad benefits of the GIFT program (Genetically Improved Farmed Tilapia) in other aquaculture species. The GIFT was particularly beneficial for a broad range of producers because of the ease of culturing tilapia in a wide range of environments, from extensive ponds to large-scale net pen culture in lakes, and intensive RAS systems. Long-term commitments are required for selective breeding programs, and governments should support collaborative public-private programs that share the costs and widely disseminate the benefits. This approach should ensure that genetic advances can be made widely available to smaller-scale producers, as well.

Novel genomics tools will be used increasingly to improve growth rates, feed efficiencies, animal health and other production metrics (yield, fillet thickness) (Stokstat, 2020). These advances increase the overall output for aquaculture industries, increase the profitability of individual farms (increasing further investment and employment in the sector), and reduce further the overall ecological footprint of aquaculture.

Governments and other programs are encouraged to support R&D into wider use of gene-editing (i.e. CRISPR/cas9), rather than transgenics, because of the likelihood of wider market acceptance. Regulation of CRISPR gene-editing should be driven by the best available science.

Further development of novel technologies for genetically sterile stocks could be of particular utility. Genetically-guaranteed sterility could be used by regulators as an initial requirement for any other use of transgenic stocks or gene-edited stocks, as a guaranteed means of preventing introgression with wild stocks.

Government action is needed to preserve genetic resources, both separate species or discrete populations that may be under threat. For example, the native tilapia species in Mozambique (*Oreochromis mossambicus*) has advantages in salt tolerance, but a slow growth rate, compared with *O. niloticus*. Niloticus have been introduced into Mozambique, and are now jeopardizing the *mossambicus* wild population through hybridization. A selective breeding program supported by the government could improve *mossambicus* productivity, and spur fish production based on the native species, rather than the introduced fish.

Other attributes that are not directly market-driven need to also be considered during selective breeding, e.g., ethical values of improved animal welfare and environmental services (Olesen et al., 2000).

4.7 New financing opportunities and start-up incentives

As various models for industry-specific investment funds, aquaculture incubators and accelerators, and aquaculture parks are refined and proven profitable, their further expansion should be encouraged. Collaborative public-private research and development programs should be particularly supported.

Governments that wish to encourage more of the 'start-up culture' around aquaculture should look to these models. Not all of them require significant capital. Often, simply undertaking the pre-permitting of an area for aquaculture use, and establishment of basic infrastructure, is sufficient an incentive to start to attract companies to an aquaculture park. The agglomeration of several such companies in one area, although potentially representing some biosecurity risk, will often reach a critical mass, leading to further private sector investment as the start-up 'eco-system' of infrastructure, labor, and regulations grows.

There is also potential for creative financing for aquaculture to start to address some of the global challenges, such as ocean acidification and the Global Climate Crisis. These initiatives could particularly be applied to macroalgae culture, using carbon credits or bonds for achieving environmental goals such as carbon sequestration to the abyssal plain, or other ecosystem benefits (e.g. nutrient removal).

Governments should approach carefully any direct involvement in market manipulation or direct investment in industry. The Chilean government, for example, initially established seaweed incentives as subsidies for seaweed farmers. Although this greatly stimulated production, it did nothing for creating demand for the product. Governments might better assist through public-private fund partnerships, or by broader support of industries that are already established (e.g. improving collaborative marketing, or facilitating supply pipelines for newly cultured species). For example, governments can help establish incubator facilities by providing funding and access to land or water. Providing umbrella permitting for aquaculture start-ups can be especially helpful, such as at NELHA, in Kona, Hawaii.

4.8 Improved biosecurity & disease control

The future of aquaculture is inextricably linked with effective management of plant and animal health. The focus, going forward, should be on prevention, and co-ordination. Most of the challenges can be best addressed through technologies – producing fish offshore with better water exchange, or in tightly controlled land-based RAS environments), or genetic selection of resistant strains, novel vaccines and their wider application, or use of functional foods. Improved government policies are, however, also integral to an overall industry health management strategy, including tighter regional biosecurity measures to lower the risk of pathogen introductions, and establishment of collaborative networks for more efficient sharing of information on emerging diseases.

New private sector, pre-competitive collaborations (such as the Global Salmon Initiative, GSI) should also be established to better address animal and plant health challenges. One of the GSI primary areas of collaboration is sharing information on sea-lice control in salmon net pen culture. This GSI model recognizes the interplay between aquaculture animal health, consumer demand, and social license.

4.9 Expanding macroalgae farming

The current trend of expansion of macroalgae farming beyond East Asia should be encouraged because of the diverse ecological services that macroalgae culture offers (nutrient removal, potential carbon sequestration, increased primary productivity and biodiversity); however, there will be challenges in sustaining this growth unless and until markets for seaweed products grow with the industry. Carbon tax credits (for carbon capture and storage) and nutrient tax credits are theoretically appealing, but have not yet become tangible (and fungible) in any meaningful way.

Governments and other entities that want to promote seaweed production may wish to establish additional incentives for commercial applications of macroalgae products, such as human food and animal feed (especially for pigs or cattle, to reduce methane production, or for herbivorous fish). Macroalgal use for fertilizers is especially appealing because of the current heavy demand for energy in artificial nitrogen fertilizer production, using the Haber-Bosch process. Use of seaweed fertilizers could be incentivized through farmer subsidies, or alternatively be exempt from carbon taxes applied to energy intense fertilizer production.

Research into bioconversion of seaweed for biofuels is more challenging, because of the complex polysaccharides that bind up most carbon in macroalgae (e.g. agar, carrageenan, fucoidan, laminaria).

The "Seaweed Manifesto" (http://www.seaweedmanifesto.com) is a novel example of a collaborative private sector, government and foundation initiative, launched for promoting production and consumption of seaweeds.

4.10 Integrated Multi-Trophic Aquaculture (IMTA)

IMTA in marine ecosystems will remain of academic interest until large-scale projects can demonstrate clear commercial drivers, or until social license concerns justify expanded use of filter feeders and macroalgae to remove particulates and nutrients around fed aquaculture systems.

Interest in freshwater IMTA systems will grow with further developments of urban aquaculture, where effluent water or heat from other systems, or multiple uses of space can be used to reduce input costs for aquaculture. The actual impact on food production will probably be small in the near-term, but further development will benefit from growing consumer interest in circular economy perspectives, and reduction in food miles or 'local' production systems.

4.11 Increased diversification & reduced risks

The consolidation of aquaculture production globally on fewer species is being driven by market forces, but may be less desirable for the reasons discussed above. There may therefore be additional motivations for governments to encourage species diversification in aquaculture (or, perhaps more correctly, to encourage preservation of the diversity of species in aquaculture; there are currently around 600 marine or aquatic species cultured globally (FAO, 2020).

Investment of public or private funds into species diversification *per se*, without clear market drivers, will have a reduced likelihood of success. Where fiscal resources are limited, funds may be better spent on industry development for more established, cosmopolitan species (such as vannamei, salmon, or tilapia), thereby addressing more pressing needs of food security and employment.

4.12 Animal welfare

There will be increased need for commercial companies and supply chains to focus on animal welfare in aquaculture. This can be best addressed through certification programs, and technological improvements that reduce animal stress and pain during handling and slaughter.

4.13 IMTA and Restorative Aquaculture

The concept of Integrated Multi-Trophic Aquaculture (IMTA) has been developed as a strategy to reduce the negative externalities of fed aquaculture; i.e. lessen the input of metabolic wastes produced by marine fish or shrimp, for example, by co-cultivation of extractive species. During the past 20 years, a number of small-scale studies have established the capacity of filter-feeders and seaweed to capture particulates and nitrogen in marine coastal systems (Neori, et al., 2007; Alleway, et al., 2019; Kotta, et al., 2020; Holbach, et al., 2020). There is abundant beneficial environmental impact of seaweed farming on eutrophication and red tides in discrete bodies of water, and macroalgal culture thrives in these areas (Camu, et al., 2020). Some companies do use effluents from fed organisms to increase macroalgal growth rates, and there is potential for nutrient tax credits or carbon tax credits to promote this further. There has, however, to date, been no accurate determination of the utility or implementation of IMTA at commercial scale.

The potential for expanded use of macroalgae is especially appealing from a Life-Cycle Analysis perspective because their culture requires no land conversion, fresh water, or exogenous nutrients, and can absorb nitrogen (potentially reducing eutrophication concerns) and carbon (offering opportunities for carbon capture).

There is similarly increasing interest in so-called Blue Carbon (using marine ecosystems to sequester carbon) and "restorative aquaculture" (i.e. using aquaculture to help remediate stressed marine environments - mainly kelp forests, invertebrate populations and seagrass stands: Brumbaugh, et al., 2000; European Commission, 2012; Han, et al., 2016; Mascorda Cabre, et al., 2021). Restorative aquaculture initiatives have been supported by programs such as the European Community (Horizon 2020), 'Seaforestation' in Vancouver, Canada (OceanWise, 2021) and the Solent project[6]. Such projects currently rely on public or foundation support, and look to nutrient tax credits or carbon tax credits to become financially appealing. A more compelling commercial case needs to be made before such efforts can grow to have any significant scale and impact.

4.14 Resource efficiency

Market-driven concerns with food waste, combined with economic drivers for optimizing production efficiencies, should see increasing focus on better slaughter processes, improved post-harvest handling and processing, and shorter, more rigorously managed supply chains. Blockchain and other tools for improving traceability will become increasingly prominent.

Producers that are unable to engage with these developments may be disadvantaged in the global market. (see above – technological innovations). Governments and other agencies might therefore have a useful role in facilitating access by small- and medium-scale producers.

4.15 Collaborative research and development

There are numerous constraints to bringing innovations to bear in the aquaculture marketplace. Aquaculture research is often disconnected between the research groups and the private sector. For example, multi-national feed companies are not incentivized to engage more closely, or to offer any transparency in development of alternative feedstuffs and feed formulations. Governments and intergovernmental entities should redouble their efforts to expand opportunities for collaborative research and development. Inclusion of the private sector, from the outset, in such collaborative R&D programs should maximize the uptake of research results, and increase the breadth of the benefits.

The Network of Aquaculture Centers in Asia-Pacific (NACA; https://enaca.org/), based in Thailand, offers a good example of regional collaboration in aquaculture. NACA is largely funded by the participating governments, and is now supporting development of a similar entity in the Africa region. In the past, however, similar efforts in Africa (ARAC) and South America were less successful, and essentially folded.

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[6] https://www.bluemarinefoundation.com/projects/solent/

A comparative analysis is needed to elucidate the reasons for success of some regional collaborations, and then to incorporate these lessons into future efforts.

The future of aquaculture – its total production, its efficiency, and its role in helping humanity achieve the U.N.'s Sustainable Development Goals – all depends upon continued innovation, at both small- and large-scales. All innovations will initially be met by some with resistance from entrenched interests. However, the status quo in aquaculture is clearly not desirable. We need to grow more seafood, with less impact. Governments should therefore establish broad policies that encourage innovation in aquaculture production, while simultaneously fostering the broader distribution of benefits, and reductions in overall environmental impacts.

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