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# Ocean/aquatic food systems: Interactions with ecosystems, fisheries, aquaculture, and people

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and Åsa Strand

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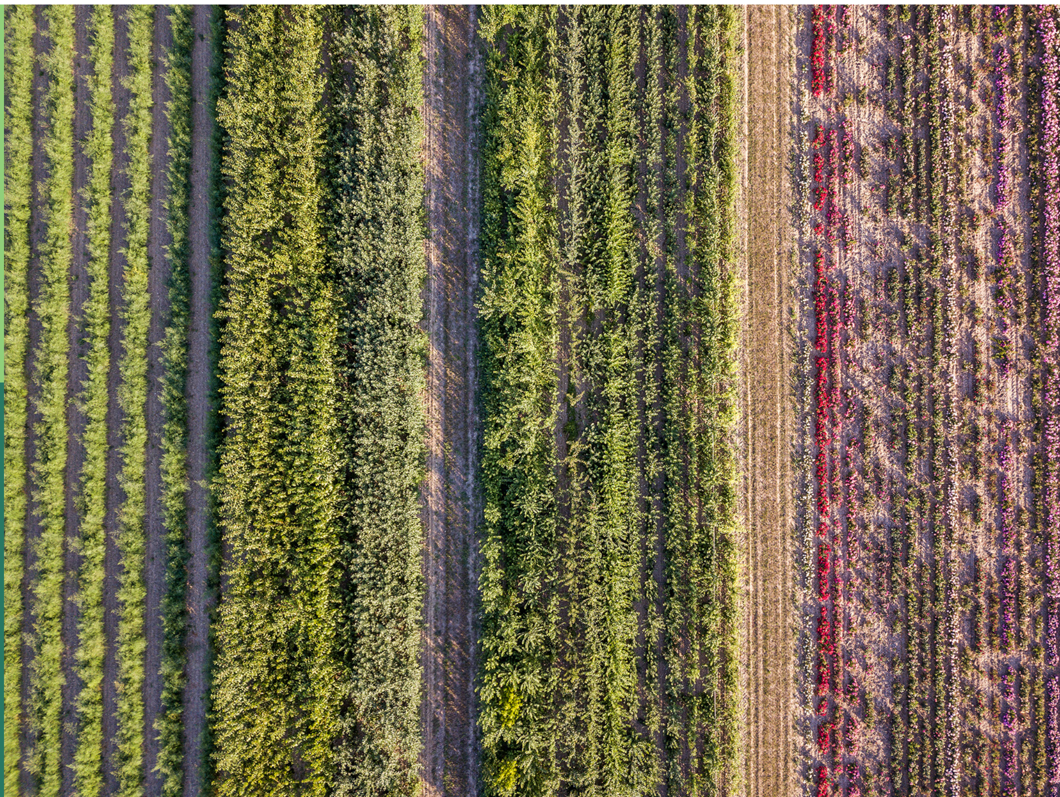

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# Ocean/aquatic food systems: Interactions with ecosystems, fisheries, aquaculture, and people

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# Editorial: Ocean/aquatic food systems: Interactions with ecosystems, fisheries, aquaculture, and people

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Editorial on the Research Topic
Ocean/aquatic food systems: Interactions with ecosystems, fisheries, aquaculture, and people

World population is predicted to reach 9.6–12.3 billion this century with most new growth in Africa and Asia. Humanity has moved past planetary boundaries. The ocean is 71% of Earth but provides only 4–8% of human foods. Continued expansion of agriculture is threatening survival of the world's remaining natural areas and biodiversity strongholds. Sustainable intensification of agriculture and large-scale dietary shifts away from terrestrial animal proteins as sole solutions to the agriculture/biodiversity crisis are unreasonable, as they would have to be adopted and implemented nearly universally. To avoid this looming environmental-food calamity, humanity must develop new frameworks and action plans that emphasize the integrated sustainable development of ocean/aquatic food systems (Figure 1).

Marine and freshwater food systems in capture fisheries and aquaculture are managed as if they are independent entities separate from markets. FAO has stated that "Fisheries and aquaculture interact with increasing intensity as fishers shift from fishing to aquaculture and by competing in the same markets with similar products. The need to integrate planning and management of the two sectors seems vital to their future development and sustainability." In this Research Topic, analyses of ocean/aquatic foods were investigated by 82 authors in 10 articles: four original research, two reviews, two perspectives, one policy, and one hypothesis/theory. Articles covered the historical, present status, and policies necessary to increase the production of ocean/aquatic foods in the context of sustainable development goals. Together these studies give insights into the development of this vitally important sector that will be a critical source of food and income into the future.

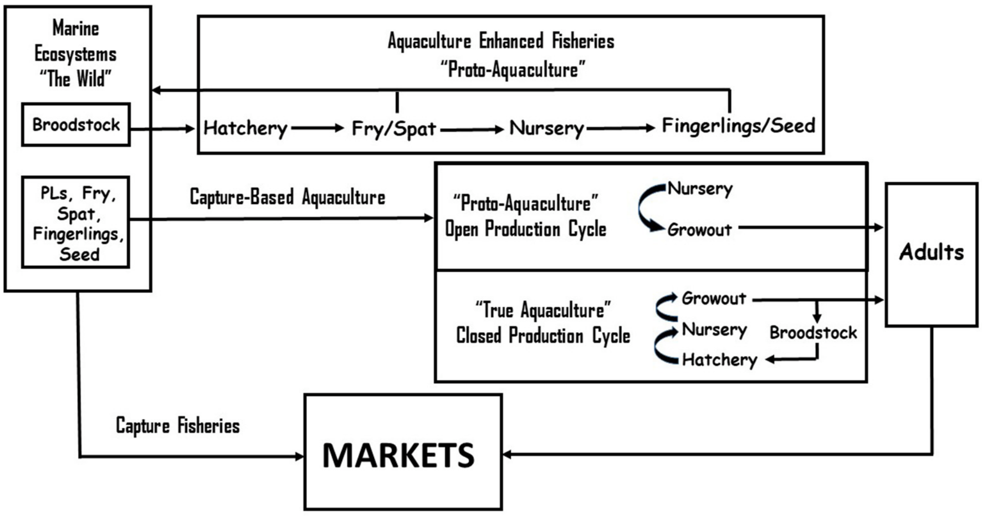


FIGURE 1
System connections between marine ecosystems ("the wild"), capture fisheries, capture-based aquaculture, aquaculture-enhanced fisheries, and aquaculture that together enter a common marketplace. "True" full cycle aquaculture is a closed production network where domestication of an aquatic species is underway. Broodstock are selected from species in captivity and selective breeding occurs via genetic improvement with occassional replenishment of broodstock from the wild, but not at the massive scale or dependancy on the wild as practiced in aquaculture-enhanced fisheries. There are scientific, educational, and governance shortcomings ocean/aquatic ecosystems due to poor, duplicative, or incomplete data that have led to artificial policy,management, and institutional barriers that need to be resolved to accelate food production from the waters of the world.

A recurring theme in this Research Topic was that ocean/aquatic and terrestrial food production systems "remain siloed from each other with few studies addressing their combined contributions." In *Fad, food, or feed: alternative seafood and its contribution to food systems* (Marwaha et al.) key economic, social, and environmental implications associated with production, distribution, and consumption of ocean/aquatic foods, and their interactions with fisheries and aquaculture were explored. Knowledge gaps were identified to inform inclusive, equitable, and sustainable development and governance. Transdisciplinary research in aquaculture has the potential to enhance the resilience of global food systems through diversification and improved efficiencies. Authors of *Seafood in food security: a call for bridging the terrestrial-aquatic divide* (Stetkiewicz et al.) demonstrated that the aquaculture literature is dominated by research in single disciplines, and that ocean/aquatic food systems were under-researched compared to terrestrial animal and plant systems in discussions of food security. Researchers in *Prospects of low trophic marine aquaculture contributing to food security in a net zero-carbon world* (Krause et al.) called for moving aquaculture toward production of low trophic marine (LTM) species to "enable a blue transformation to support a more sustainable blue economy. Transdisciplinary research approaches co-produced with consumers and the wider public will be required for such a blue transformation." In *Making a web-portal with aquaculture sustainability indicators for the general public* (Mikkelsen et al.) progress was made toward assisting society in providing or denying a "social license to operate" for the Norwegian aquaculture industry. Researchers developed a continuously updated web-portal with sustainability indicators covering 22 themes having spatial and temporal resolution from publicly available sources produced by Norwegian authorities or research institutions.

The Chinese market for aquatic products is the largest in the world; however, little has been published on its freshwater fish market. In *Characteristics and dynamics of the freshwater fish market in Chengdu, China* key (Fang and Fabinyi) informants were interviewed at a freshwater fish market. They indicated that price, food safety and quality, freshness and local culinary traditions were the most important influences on freshwater fish consumption. Imported species such as pangasius have increased in popularity, indicative of changes in Chinese markets due to globalization. Markets for wild and farmed Arctic Charr were reviewed in *Wild and farmed Arctic Charr as a tourism product in an era of climate change* (Helgadóttir et al.). Arctic Charr are a traditional food in the Nordic, Arctic, and Subarctic regions. Researchers considered innovative connections between culinary, heritage-based, and nature-based tourism and the Arctic Charr aquatic food system.

"Research and practice will require a closer collaboration between tourism researchers and natural scientists to explore what climate change might mean for Arctic Charr fisheries, aquaculture, and tourism."

In *Farm production diversity in aquaculture has been overlooked as a contributor to sustainability* (Johnson) issues of scale and production diversity were addressed. Promotion of diverse aquaculture scales may allow development of "new ecological and social synergies for smaller farms to achieve economic viability at regional scales. Cost, price and/or regulatory incentives will be needed." Seaweed aquaculture is a good example of this diversity of scales as it is developing rapidly outside of its traditional areas in Asia. In *Commercial seaweed cultivation in Scotland and the social pillar of sustainability: A Q-method approach to characterizing key stakeholder perspectives* (Bjørkan and Billing) responses of stakeholders on how commercial seaweed cultivation in Scotland should develop were summarized. Results indicated that stakeholders thought large-scale and multi-national owned farms were not the ideal model for seaweed aquaculture development. An example of an economically viable alternative for the sustainable development of small scale seaweed aquaculture by fishing families was described in *Engineering a low-cost kelp aquaculture system for community-scale seaweed farming at nearshore exposed sites via user-focused design process* (St-Gelais et al.). Researchers developed and tested an inexpensive, lightweight, and highly mobile gear and completed an economic assessment that showed the "low-cost seaweed farming system could increase incomes when compared to non-farming off season jobs."

Lastly, in *The anthropology of aquaculture* (Costa-Pierce) the cultural/environmental history of aquaculture in seven diverse parts of the world was reviewed. Analysis supported a structural anthropological theory that "whenever the demands of ocean/aquatic food-eating peoples exceeded the abilities of their indigenous fishery ecosystems to provide for them, they developed aquaculture".

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

## Conflict of interest

Author BC-P was employed by the Ecological Aquaculture Foundation LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

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# Making a Web-Portal With Aquaculture Sustainability Indicators for the General Public

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The sustainability of aquaculture is a complex issue that can be hard to assess and communicate. Communicating it to the general public is in many ways an even bigger challenge than communicating to experts on sustainability or aquaculture. The general public's perception of the status and challenges for sustainability is important for the development of the aquaculture industry and for society at large, through its roles both as consumers and electorate, and generally in providing or denying a "social license to operate" for the industry. This paper presents the process and challenges involved in choosing and quality assuring sustainability indicators for Norwegian aquaculture, covering environmental, economic, and social dimensions. It involved a team of researchers, a quality assurance group, IT developers and designers, a literature review, a national survey, and user-testing, all to establish criteria for selecting data and indicators and how to present them, and to do the actual production. The endpoint is a web-portal with indicators currently covering 22 themes, aimed at anyone interested in the sustainability of Norwegian fish farming. The portal does not conclude if or to what degree Norwegian fish farming is sustainable, as that would require making valuation and trade-offs among different sustainability objectives. Many indicators are automatically updated, and data are only from publicly available sources and produced by the authorities or research institutions. The portal is under continuous development, with new themes and indicators, and improving spatial and temporal resolution.

**Keywords: sustainability indicators, aquaculture, web portal, Norway, salmon**

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## INTRODUCTION

Global aquaculture production has grown tremendously over the last 6–7 decades (FAO, 2020) and is affecting economic and social conditions and the environment in many places (Gephart et al., 2020). In Norway, the aquaculture business had gross value added of more than 40 billion NOK (4 billion €) in 2019, with a production of around 1.4 million tons (Fisheries Directorate, 2021). The export value was 74 billion NOK (7.4 billion €) in 2020 (NSC, 2021). The distribution of the economic benefits has however been a much debated issue the latter years (Hersoug et al., 2021). The industry also has a number of environmental challenges (Olaussen, 2018), in particular salmon lice from fish farms affecting wild salmon stocks (Overton et al., 2019), and which also creates significant costs and losses for the farmers (Iversen et al., 2020b).

In line with this, the issue of the sustainability of aquaculture has become increasingly prominent both in academia, politics and in media, both in Norway and globally. But sustainability is not a straight-forward concept to work with, for many reasons. It has no universally agreed definition beyond the broad concept in the Brundtland report (WCED, 1997), and many have tried to shape the content of the term to fit their purposes and objectives. Many aspects of sustainability, even if agreed upon, are difficult to measure, and in addition, sustainability is an integrated concept where the different aspects may impact each other, and be weighted differently over time, across geographies, and groups/individuals. Is it then at all possible to present indicators on the sustainability of industrial activities that are seen as undisputed facts and are relevant?

Is it also possible to choose and present indicators so that they inform the general public in a way that promotes a more knowledge-based public debate on the sustainability of aquaculture? The general public's knowledge and perceptions on sustainability of the aquaculture industry are important for the industry, but also the public policy and society at large. As consumers and as electorate for the politicians determining public policies, the general public is important for aquaculture's social license to operate (Kelly et al., 2017).

Aquaculture is a diverse activity, that can be in different water environments and locations, with various species, technologies, and industrial organizations, and then also with a big Specter of environmental risks and impacts, and economic and social consequences (FAO, 2020). Some sets of (potential) indicators aim to be rather generic and cover many different types of aquaculture and contexts (e.g., Valenti et al., 2018), while others target more narrow, like the set collected by Amundsen and Osmundsen (2018) based on eight certification schemes for salmon aquaculture.

In this paper we discuss the challenges involved in selecting, collating, and presenting data on the sustainability of aquaculture in Norway, which is mainly salmon and trout farming, and present our final criteria and indicators. Our process and findings should be interesting for those striving to choose, collect, and establish sustainability indicators, especially when presenting them for a non-specialist audience, and on aquaculture.

The research questions that have guided the work with the paper are: (1) Which themes and indicators are especially relevant for considering the sustainability of Norwegian fish farming? (2) What makes indicators and a web portal on the sustainability of aquaculture trustworthy? (3) What are important process elements and issues for establishing relevant and trustworthy indicators and a web portal on the sustainability of aquaculture? (4) What are good criteria for selecting such indicators?

The paper is organized as follows: The next section gives a background on sustainability indicators and their design, existing indicator-sets on the sustainability of aquaculture, and on aquaculture in Norway. The Methods section describes how we approached the process to make the content for and design of the web-portal. The Results section describes the resulting workflow, results of a survey to the general public, the concluding set of criteria for the indicators, and the actual set of indicators in the published version of the web portal. The Discussion and Conclusion section considers challenges and dilemmas in designing such a web portal, as well as future directions for the work with the portal.

# BACKGROUND

## Sustainability and Indicators

Since sustainability was introduced as a term at the global high level by WCED (1997), it has become a widely used objective guiding the actions of both governments, industries, and consumers (Portney, 2015; UN, 2015), although also being contested and problematized (Aarset et al., 2020). Most common frameworks of sustainability identify three sustainability dimensions: economic, environmental, and social (e.g., Bracco et al., 2019; Eustachio et al., 2019). Many frameworks also include a governance dimension covering institutional sustainability. Sustainability is a complex phenomenon that is difficult to observe directly (FAO, 1999; UNDESA, 2007), and many indicator-sets and abstract indicators have been constructed to capture it (Singh et al., 2012). Such indicator-sets can contain many indicators, like those suggested for fisheries (FAO, 1999; Anderson et al., 2015) or for aquaculture (Valenti et al., 2018). Certification schemes for sustainable aquaculture can be seen as a type of abstract indicator, based on several indirect sub-indicators (Osmundsen et al., 2020a). It seems that the social dimension of sustainability has been the hardest to grasp (Vifell and Soneryd, 2012; Hicks et al., 2016; Alexander et al., 2020).

Indicators in general provide information on the status or development of a phenomenon, usually one that is difficult or impractical to observe directly (Bracco et al., 2019). Some indicators give precise information on the phenomenon in question, like an indicator light telling that the temperature in a freezer is above a chosen threshold. For more complex phenomena, an indicator may only be able to *indicate* the status or development. Indicators can be qualitative or quantitative, and they can indicate a change, a trend, or status (Bracco et al., 2019). For an indicator to be able to say something on status, reference values for the indicator must be defined. For sustainability indicators, both the choice of reference values for indicators and the selection of indicators *per se* are inherently normative and political choices (Levett, 1998).

Bracco et al. (2019) distinguishes between direct, indirect, and proxy indicators, depending on how precisely an indicator relates to the underlying phenomena of interest. Direct indicators can be used when the phenomenon of interest is rather straightforward. Indirect or proxy indicators are useful when the phenomenon is abstract and cannot be measured directly or it would require complex and resource demanding efforts to measure it well. An indirect indicator does not directly represent the actual phenomenon of interest, but other phenomena related to it. If the phenomenon is escaped salmon from salmon farming, the estimated number of escaped salmon may be adequate as an indicator. If the phenomenon is the quality of aquaculture governance, indirect, or abstract indicators is required. Often a set of indirect indicators is deemed necessary to sufficiently illuminate the actual phenomenon of interest. Abstract indicators are typically constructed from a set of indirect indicators, calculating weighted or unweighted averages or similar, and mathematically normalizing to end up with values for the abstract indicator between 0 and 1 or 0 and 100, like for example in the Ocean Health Index (Halpern et al., 2012).

Choosing which sustainability themes and indicators to present is to some extent a value-laden and political choice (Levett, 1998), even though science can provide guidance, not least on the relevance and validity of specific indicators for various themes. Issues and themes that are used in actual regulation will obviously be relevant. But also themes that come up in public discourses and political discussions must be considered, as well as indicators identified from scientific work. What is considered important and relevant themes will always be constant developing, driven by changes in production technology and industry structure, culture, demography, and general economic activities in society, and also in climate, biology, and ecology. Hence, a set of indicators must also evolve to remain relevant. Another aspect is the balance of indicators between the major sustainability dimensions. Major aquaculture sustainability certification schemes have many indicators for environmental aspects, while social and economic aspects are less covered (Osmundsen et al., 2020a, Alexander et al., 2020). Many sustainability themes are however connected across the main sustainability dimensions, so individual indicators can be relevant for several dimensions.

Given the variation and complexity of choosing and creating indicators, criteria to guide the selection of indicators have been proposed, including for sustainability indicators (e.g., FAO, 1999; UNDESA, 2007; Brown, 2009). Central general criteria for indicators include scientific validity, data availability, robustness, precision, practical feasibility, cost efficiency, ability to communicate information, understandable, acceptance by stakeholders, and relevance for policy priorities.

The selection of themes and indicators can benefit from the involvement of relevant stakeholders (FAO, 1999; Consensus, 2006; Brown, 2009). Their first-hand knowledge can help in achieving scientific validity, robustness and precision as well as general acceptance of indicators. The general public, which can be seen as people without or with limited statistical knowledge, can further contribute to assessing how understandable the indicators are and how they are communicated (Eurostat, 2017, p. 22) Given that aquaculture can be a contentious issue, where available information can shape decisions and affect stakeholders, having an expert-led process can contribute to the trustworthiness of information and assessments (Servaes et al., 2012).

The different types of indicators can have different purposes. Fundamentally, indicators allow for comparisons, either across geography, time, units (companies, activities, etc.), or with reference values. Direct indicators can lead to immediate action, especially if clear reference values have been defined. Indirect indicators will inform on different aspects of a phenomenon of interest and can thus help guide the selection and priority of actions. Abstract indicators can be used to qualify or rank actors and may thus guide the selection among a set of actors. This could be the authorities deciding who should get an aquaculture license or consumers deciding who to buy from. It can also motivate those that score poorly to do something about the situation. But unlike the direct and indirect indicators, the abstract indicators themselves cannot guide *what* to do if the indicator score is too low. For that, one needs to analyse the underlying data and indirect indicators.

When choosing reference values for indicators there are several principal options (UNAIDS, 2010). One option is to choose a historical situation, a baseline value, as the reference point. This will show historical development. Historical trends could also be used as reference, or some measure of stakeholders' expectations. Comparison with similar activities elsewhere and how they develop, or using expert opinions and research findings are other options. The challenge with assessing sustainability is that what is ultimately to be considered is not a historical development, but how the future will be (Stiglitz et al., 2010, p. 61). This is obviously difficult.

Many types of sustainability assessments are described in the literature (e.g., Singh et al., 2012). They can be said to be of four main types: (1) Dashboards of indicators, (2) Composite indices, (3) Footprints of resource use, and (4) "Sustainability-adjusted" measures of welfare and wealth (Stiglitz et al., 2010; GGKP, 2016; Bracco et al., 2019). Dashboards present sets of indicators that directly or indirectly relate to sustainability, without ranking or weighting them. Creating a broad set of indicators is a necessary first step in any analysis of sustainability, since sustainability is complex by nature and a list of potentially relevant variables must be established (Stiglitz et al., 2010, p. 63). The dashboard framework makes a broad assessment across all dimensions of sustainability possible. However, the link between the value of an indicators and sustainability may not always be clear (Stiglitz et al., 2010, p. 63), and it can be difficult to compare situations when individual indicators vary in amplitude and direction of change (Bracco et al., 2019).

Composite indices can help such comparisons, but weighting, aggregation, and normalization, which is required to go from several sustainability indicators to one, requires implicit value-judgements, and cannot always be scientific (Böhringer and Jochem, 2007; Bracco et al., 2019). If a clear outcome can be defined and measured, composite indicators can be calculated by scientific methods, but for sustainability this is difficult (Nardo et al., 2005). While the authors behind composite indices of sustainability often are very explicit on how the weighting is done, the normative foundations or implications are rarely justified or made explicit (Stiglitz et al., 2010, p. 65). Also, a difference in score on a composite index between two entities does not give information on why this has come about—rather, it is like an invitation to study the underlying components closely (Stiglitz et al., 2010, p. 65), thus returning to a dashboard of indicators. Both dashboards of indicators and composite indices on sustainability are criticized by Stiglitz et al. (2010) for lacking a well-defined notion of what sustainability means.

The "footprints"-approach to measure sustainability is about estimating the over-use, under-investment in, or pressure on resources (Stiglitz et al., 2010, p. 67). Such indicators tend to consider the use or flow of one or a few resources that affect stocks of resources that future generations' welfare will depend on, like the stock of greenhouse gases in the atmosphere. For broader footprint-estimates, one needs to find an appropriate metric and ways to aggregate, which gives the same sort of challenges as in making other composite sustainability indices (Stiglitz et al., 2010, p. 67). The conceptual link between the estimated footprint and sustainability is however usually clearer than with the two types of assessments explained above. The same goes for the fourth type of sustainability assessment; measures of GDP (gross domestic product) and wealth that try to systematically correct for elements that matter for sustainability and which are not included in standard GDP calculations (Stiglitz et al., 2010, p. 65). While footprints can be calculated for activities by individuals or industries, the adjusted GDP estimates typically estimate status for countries or even larger entities, and are thus less relevant for indicating the sustainability of aquaculture as an activity.

How should sustainability assessments aiming to inform a general public be different from when they are aimed at industry actors, authorities, researchers, or other experts? The Bellagio Sustainability Assessment and Measurement Principles (Bellagio STAMP) (Pintér et al., 2012) give some guidance for effective communication: One should use clear and plain language, present information in a fair and objective way that helps to build trust, use innovative visual tools and graphics to aid interpretation and tell a story, and make data available in as much detail as is reliable and practicable. That the presentation is considered to be without bias is seen as important for building trust, as is engagement early on with users of an assessment (Pintér et al., 2012).

## Aquaculture and Sustainability Indicators

Aquaculture is a very diverse activity globally (Garlock et al., 2020), and its development will have impact on food nutrition, human well-being, and global environmental health (Gephart et al., 2020). Monitoring its development along all dimensions of sustainability will be crucial to understand and govern that development (Krause et al., 2015). Sustainability comparisons across the diversity of aquaculture technologies and species, geographical, political, and socio-economic contexts can be relevant and useful. There are even sustainability comparisons for animal protein providers across meat and fish (Coller FAIRR, 2020). Yet, it is obvious that sustainability assessments also need to be tailored to more specific situations and contexts to give information relevant for national and regional challenges.

There have been many attempts at making comprehensive indicator sets for the sustainability of aquaculture. A workshop in 2006 proposed 78 indicators on sustainability for aquaculture in Europe, across nine different themes (Consensus, 2006). Many indicators are included in various certification schemes for aquaculture. Osmundsen et al. (2020a) mapped the indicators of eight widely used certification schemes and found that they contained altogether 1,916 indicators, ranging from 52 to 468 indicators per certification scheme. They also found that environmental indicators dominated, and that other dimensions were poorly covered.

It is quite common that companies in a value chain demand that those they buy products or services from are certified according to specific certification schemes (Gutierrez and Thornton, 2014). For the consumers, the large number of certification schemes can be confusing (Gutierrez and Thornton, 2014). Despite this, certification schemes are quite commonly used. However, seafood consumers are not the only intended target group for the aquaculture industry's use of certification schemes. Persons living in the vicinity of aquaculture production may have concern about the environmental, economic, and social impacts of aquaculture, and some certification schemes target such aspects (Aas et al., 2019; Osmundsen et al., 2020a). This may be one way for the industry to strengthen their social license to operate (Kelly et al., 2017; Mather and Fanning, 2019; Sinner et al., 2020). Even though some social and socio-economic sustainability indicators have been proposed and exist, this is the sustainability dimension that seems to have the poorest coverage generally (FAO, 2009; Alexander et al., 2020; Krause et al., 2020). For doing trade-offs between different sustainability aspects, it could help if data on the different effects of aquaculture were comparable (Zheng et al., 2009), like economic data (Knowler, 2008), but such data seems to be largely missing (Mikkelsen et al., 2020). Some indicators are used directly in the authorities' management of aquaculture, for example in in Norway (Osmundsen et al., 2020b, NFD, 2015), but there is also clear criticism of authorities in some countries being too slow to incorporate indicators in management (Milewski and Smith, 2019). The relative fuzziness of the sustainability term has also led to what some authors call a power struggle between authorities and industry actors over how it should be interpreted and have operational consequences (Aarset et al., 2020).

As this paper mainly is about making sustainability indicators for Norwegian aquaculture, which again is dominated by salmon farming, a brief introduction of that is warranted. Since the start of the Norwegian salmon farming industry in the late 1960s, it has developed into a significant industry, where Norway is now the world's biggest exporter of farmed salmon, and companies originating from Norway are also major players in the other salmon-producing countries, including Chile, Scotland, and Canada (Hersoug et al., 2019). In Norway, there are around 1,000 localities for salmon farming along nearly the full length of the long Norwegian coast, of which around 60% have production at any given time. The industry provides jobs and income (Johansen et al., 2019), especially in rural areas (Johnsen et al., 2020) where decreasing employment and population numbers in general have been observed (Iversen et al., 2020a). The impacts of salmon farming have varied over the years, as have which impacts are in focus in the public debate, including environmental (Taranger et al., 2015; Olaussen, 2018), economic, and social impacts (Hersoug et al., 2021).

The dominating open net pen concept has proven economically very successful, but production costs have increased sharply the latter years, due to increased feed prices and costs for prevention, treatment, and mortality associated with pathogens including salmon lice (Iversen et al., 2020b). Consolidation of the industry and its ownership, as well as changes in production technology and subsequent changes in labor use have led to an increasingly skewed distribution of benefits from the industry between different municipalities with fish farms (Hersoug et al., 2021). This has led to challenges with the industry's social legitimacy (Hersoug et al., 2021).

The public management of aquaculture in Norway has emphasized different aspects of sustainability over the years, but even from the very first (temporary) Aquaculture Act of 1973 both environmental, economic, and social sustainability concerns were included. With the Aquaculture Act of 1991 the term sustainable development ("bærekraftig utvikling") were explicitly put in its objective (§1), and has remained there through later revisions of the legislation (Mikkelsen et al., 2018). Regular monitoring and reporting are required regarding i.a. the parasitic salmon lice, diseases, biomass, and pollution situation below pens, and the authorities can force reduced or closed production or other restrictive measures due to environmental or social concern (Mikkelsen et al., 2018). New salmon farming licenses have been issued in rounds that have emphasized as diverse priorities as rural development, industrial development, ownership, fish health, the environment, and industry's willingness to pay for new capacity (Hersoug et al., 2019). A government white paper in 2015 launched the ambition to devise a system of "predictable and environmentally sustainable growth in Norwegian salmon and trout farming" (NFD, 2015). This ended in the so-called "traffic light system," established in 2017; an assessment of the extra induced mortality on wild salmon and trout stocks due to salmon lice originating from the salmon farms dictate in which regions salmon production capacity can increase (green light), must be reduced (red light), or stays the same (orange light), and companies' willingness to pay for more production capacity decide which companies actually get any increased capacity (Hersoug et al., 2021). The problems with social legitimacy have also led the authorities to introduce two different taxation/redistribution schemes that shall ensure economic benefits for all municipalities and counties that have salmon farms (Hersoug et al., 2021).

## Methodology

The process to establish the web-portal has to a large degree involved answering the same questions that are posed in this article, and thus that process largely constitutes the method to answer the questions. One important function has been to organize the input and involvement of different actors, experts, stakeholders, and the general public, with their competence and perspectives, into the considerations necessary to choose and present indicators so that relevance and trustworthiness are achieved. The overall process took several years, and went through a pre-project, phase one of the main project, and is now (March, 2021) in phase two of the main project. **Table 1** gives an overview of the individual projects and major elements in them. The projects have been financed and owned by the Norwegian Seafood Research Fund (FHF). This section also specifically presents a survey to the general public and the method for theme and indicator selection.

### The Pre-project

The aims of the pre-project were to (i) identify criteria for holistic sustainability indicators to be included in the portal covering environmental, economic and social sustainability, (ii) consider data availability and data sources and efficient methods for collection and processing of data, and (iii) suggest set-ups for presentation (Andreassen et al., 2016). The process to fulfill these aims included a review of scientific and government literature, certification schemes, and sustainability reports from aquaculture companies, supplemented by a workshop with relevant stakeholders and representatives from research institutions. The result was an overview of possible criteria, indicators and data sources, ending up with 26 potential indicators across 10 "focus areas" (Andreassen et al., 2016). It was recommended to have a balance between indicators covering environmental, economic, and social sustainability in a web portal. This also became an important point when the Norwegian Seafood Research Fund decided to fund the main project.

### The Main Project

In the first phase of the main project the aim was to get the portal established and openly available. This phase should also define the target group. In the second phase it was to run and further develop the portal. The core project group was set up with members from research institutions Nofima (project lead) and SINTEF Ocean, to ensure competence and also independence from the aquaculture industry. BarentsWatch was also member of the core project group, as partner responsible for web publication. BarentsWatch has an open information system on oceans and marine use at www.barentswatch.no, and has 10 ministries and 29 directorates and research institutions as partners. By establishing the aquaculture sustainability web-portal on the Barentswatch platform, one hoped for efficient technical production and maintenance of the portal, and that it would find users among those that already used the Barentswatch platform.

Two additional groups were formed to support the development of the portal in the first phase. The first was a quality assurance group with members from Norwegian universities and research institutes, an environmental NGO (Bellona), and from a consultancy [Teigen Consulting, Institute for Policy Analysis and Development (INPAD)]. The second was a so-called steering group appointed by the project owner and funder, with four members from aquaculture companies. The steering group should, as stated in their mandate from FHF, contribute to the project reaching its objectives, to maximize the benefits for the industry, and that the results of the project is implemented in the industry. The steering group explicitly did not have authority to "influence the project in a way that could weaken the scientific management" of it[1]. Both the members of the quality assurance group and the steering group gave valuable inputs as experts and stakeholders, but Nofima and SINTEF

[1] It was also stated explicitly that if assumptions or framework for the project from FHF itself, steering group or reference groups was considered to possibly affect the quality or legitimacy of the project, the project leader must point this out to FHF immediately. FHF no longer appoint "steering groups" for their projects, but rather professional councils ("Faglig råd") (FHF, 2020).

**TABLE 1 |** Main characteristics of pre-project and main project's phases 1 and 2.

| | Pre-project | Main project phase 1 | Main project phase 2 |
|---|---|---|---|
| Aims | Scope relevant issues for making a portal | Develop and establish the portal | Operate and further develop the portal |
| Period | 2015–2016 | 2016–2018 | 2019–2021 |
| Literature review | Yes | Yes | Yes |
| Document analyses | Yes | Yes | Yes |
| Data assessment | Yes | Yes | Yes |
| Expert input | Workshop | Quality assurance group; direct contact | Professional council; direct contact |
| Stakeholder input | Workshop | Quality assurance group; steering group | Professional council |
| User input | | Survey; direct contact | Direct contact |
| User test | | Yes | |

Ocean have been responsible for the final choice of themes, datasets, indicators, and the presentation in the portal.

## Target Group

One possible division of target groups are between "specialists" and "citizens"/"the general public" (Eurostat, 2017, p. 22), which differ in their needs for and abilities to understand detailed statistical information. It can also be specifically about their previous knowledge about the aquaculture industry. Within the general public, Eurostat (2017, p. 23) lists the following as possible subgroups: policy-makers, youngsters, University students, pensioners, families, representatives of the civil society, generalist journalists. The choice of target group(s) can affect all aspects of the web portal. The more precisely the target group can be defined, the easier it will be to approach it to get useful input regarding choice of themes and indicators, the geographic and timewise resolution for them, the format for presentation, and more. It will likely also be less need for making compromises regarding these choices.

The preproject report (Andreassen et al., 2016) emphasized the need to clarify the target group(s) for the web-portal. While leaving this to the main project, it did however mention both decision makers and "ordinary people," and that they had received inputs especially about media, consumers of farmed salmon, and local and regional decision makers relevant for aquaculture. In the main project additional and more specific target groups were considered in a workshop with the project researchers and persons from BarentsWatch, and in discussions with members of the steering group and quality assurance group. Additional groups mentioned included politicians, NGOs, and individuals concerned with regional development and sustainability, persons and organizations from other industries, and especially also those with little prior knowledge of the aquaculture industry.

## Selecting Themes and Indicators

To select themes, identify and collect data, select or construct indicators and make a web-presentation of them has been an iterative process. **Figure 1** sketches the workflow in the main project. The selection of themes and identification of data sources (1 and 2 in the **Figure 1**) used the list from the pre-project as a starting point. The project aimed to select indicators based on existing data, and thus not create or collect primary data itself. The motivation was to get a first version of the portal operative without having to wait for new data to be collected.

As data was identified and collected, and draft versions of indicators (3 in **Figure 1**) were constructed, certain challenges appeared. In some cases, the available data was found to be too limited for the breadth or complexity of the theme, and indicators based on them would likely give an incorrect picture of its status or development. In other cases, the problem was the high number of relevant datasets making it difficult to select a reasonable subset suitable for presentation on a webpage. An example of the latter was for the planned theme Safe and Healthy Food. A very large number of both nutrients and contaminants in farmed salmon are monitored regularly in Norway (IMR, 2020). Of the ca. 80 contaminants monitored, 17 have an official maximum threshold, and both were considered too many to be presented on a webpage in the portal. Another data-related challenge was data only being available from some years back. Was it likely or unlikely that they were so outdated as to give a wrong impression of today's situation? For greenhouse gas emissions, available data were from 2007, and it was easy to conclude they could not be used. Data on feed ingredients and their conversion to energy and proteins in the fish were from 2012/2013, and they were included.

To construct indicators from datasets it was necessary to consider the most relevant aspects for aquaculture sustainability. This included geographic level (national/regional/local), time periods (year, month, week) and if indicators should have values relative to how the aquaculture sector developed over time (size or activity level), or to the environmental, economic or social context the industry operate in.

When suitable indicators had been constructed, the next step was to design a webpage for the theme (4 in the **Figure 1**). After designing a template to be used across themes, the focus moved to the concrete content for each theme's webpage. Quality assurance (5) was conducted through several mechanisms. The quality assurance group gave input in meetings or email to selection of themes and indicators and their presentation. When the portal was approaching version 2, a user-test was carried out where the users were asked to find answers to certain issues/questions by using the portal. How they used the webpages was observed and they also commented on their experience. The user-test gave input that was useful for the specific design of the webpages,

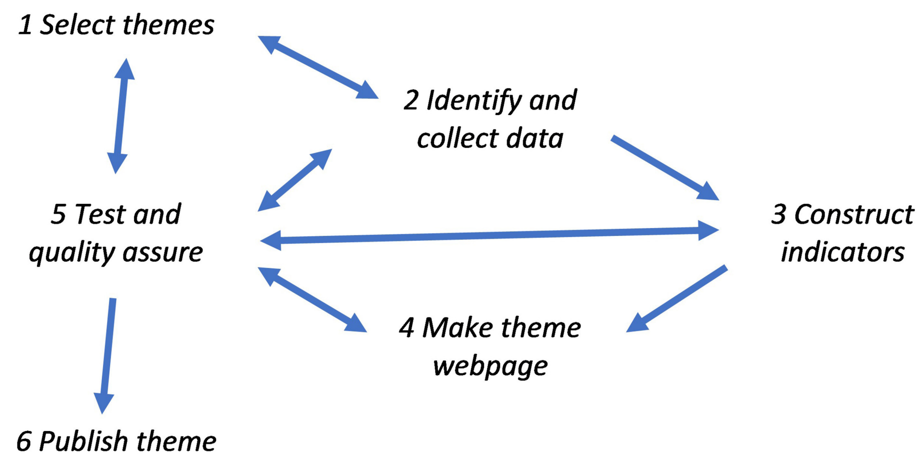


**FIGURE 1 |** Sketch of workflow in main project to select and design indicators.

layout of diagrams, and on wording. In addition to the feedback from these groups, a nationwide survey gave important input to quality-assurance.

## Survey

The nation-wide survey was conducted to get input on how important different topics on aquaculture were for the respondents, and important factors for a web-portal on aquaculture to be credible. The survey was conducted 6 March to 12 April 2018 as a web survey and was performed by the survey company Norstat based on their panel of respondents. The survey was representative with regard to age-groups and gender for the general population in six regions covering all of Norway, and had 630 respondents. This gives, with the total number of inhabitants of Norway 18 years or older as the survey population, a 95% confidence interval of maximum ± 3.9 %.

The 33 themes covered by the survey were selected based on a literature review (Andreassen et al., 2016), workshops, and meetings with representatives from research, aquaculture industry, and environmental NGOs with knowledge on aquaculture and sustainability, and a mapping of the availability of relevant data for themes.

# RESULTS

This section presents results on relevant and selected themes (based on the defined target group, choice of sustainability assessment, and survey results), what affects trustworthiness, the set of criteria for choosing themes and indicators, and important process elements and issues when making the web-portal.

The chosen purpose and target group is pivotal when assessing which themes and indicators that will be relevant for a web-portal on the sustainability of aquaculture. It also affects what kind of sustainability assessment type that will be best suited, and how the presentation on the web pages should be. The selected target group was described as "anybody interested in facts about the aquaculture industry," and understood as the part of the general public that has finished school. Those with little prior knowledge on aquaculture were emphasized as part of the target group, as were local and regional politicians and bureaucrats, journalists, and high school students. This means that aquaculture experts are outside of the target group, though they could find it useful as a resource to easily find updated facts.

The purpose of the portal is to provide facts about the sustainability of aquaculture in Norway, giving a balanced view of environmental, economic, and social dimensions, and focusing on salmon and trout farming. Aiming to help facilitate a fact-based public debate, the portal must give information on many different themes, rather than presenting just a composite index or a "footprint." Thus, a dashboard/set of indicators was selected as the sustainability assessment approach.

The issues identified by the target groups as relevant or of interest were chosen as a starting point for which themes or indicators could be used. The survey provided valuable information on that. The proportion of respondents from the survey who found a theme "Important" or "Very important" is shown in **Figure 2**, together with the proportion who answered "Don't know." The majority of respondents found 31 of 33 themes to be important or very important, showing that sustainability was perceived as a broad concept, across both environmental, economic, and social issues, and also management/governance. Still, themes related to environment and social issues do dominate as the most important. Several themes have relevance for more than one of the sustainability dimensions. Fish disease can, for example, affect economy, environment, and fish welfare, where the latter could be seen as a social/ethical issue.

The respondents found the following themes especially important: Safe food (85% answered Important or Very important), Fish disease (81%), Monitoring and control of production (80%), Salmon lice and lice control (80%), Healthy food (79%).

In addition to the target group's interest in various themes and indicators, their actual importance for sustainability issues

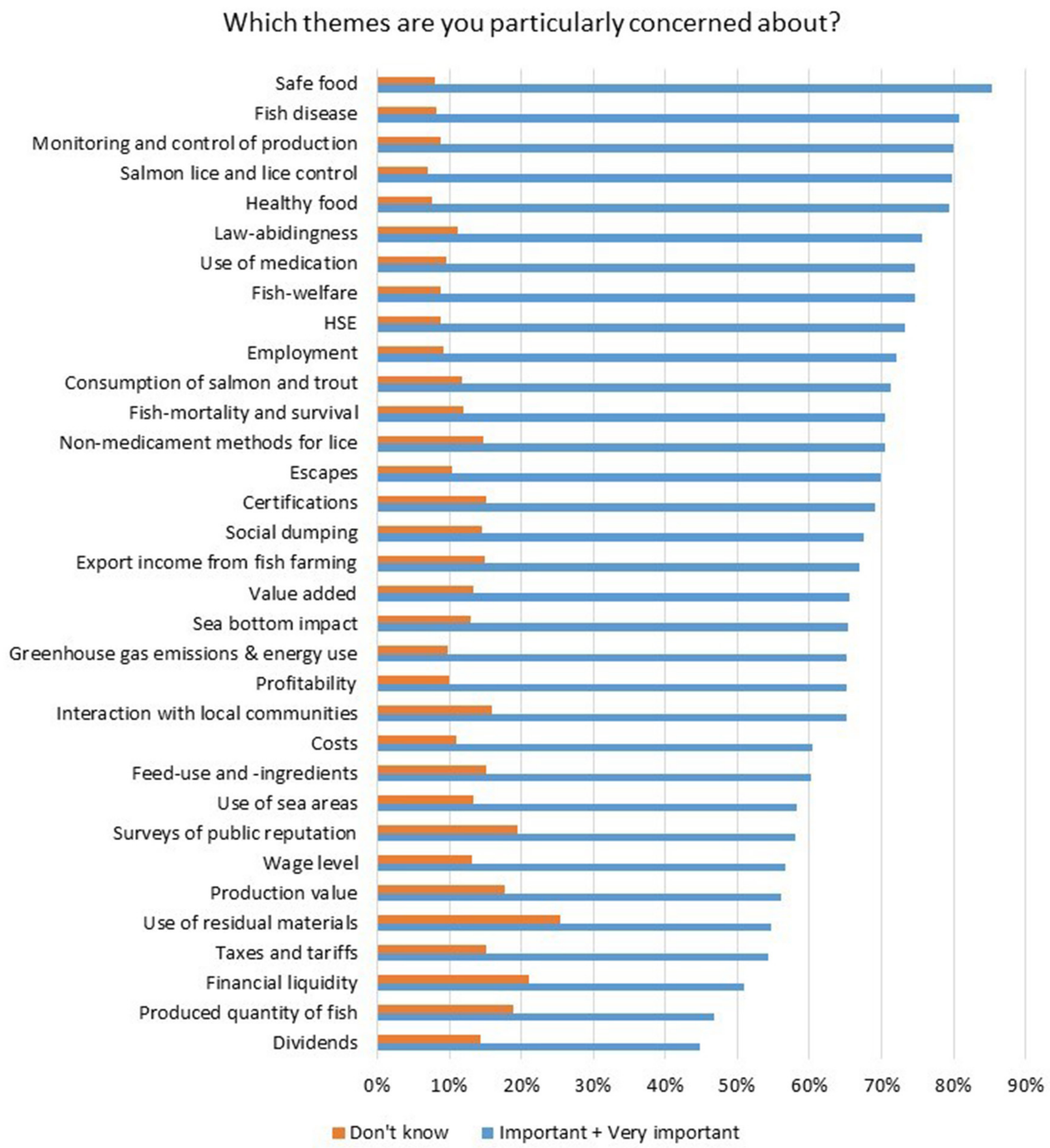


**FIGURE 2 |** Survey results: Share of respondents that find themes on aquaculture "Important" or "Very important," or do not know.

related to aquaculture matter for their relevance. Consideration of this was based on scientific literature, what was emphasized in legislation and regulation, and expert and stakeholder opinion.

Several other aspects than relevance were important for the selection of themes and indicators, including some practical aspects. The set of criteria for choosing themes and indicators that the project ended up using is:

- Themes and indicators shall cover environmental, economic, and social sustainability.
- The indicators chosen for a theme must together shed light on significant aspects of the theme.
- The indicators must be clearly related to the effects of aquaculture, and not be strongly influenced by other factors.
- The indicators shall be based on existing data sets.
- Data are publicly available and from objective/authoritative sources.
- The collection and handling of data can be done practically and cost-efficient.
- Data are suitable for presentation on a webpage.

**TABLE 2 |** Themes in the portal, as of March 2021.

| Environment | Economy | Social |
|---|---|---|
| Disease | Costs | Area use |
| Emissions from fish farms | Feed composition and origin | Certifications |
| Escapes | From feed ingredients to produced fish | Employment |
| Fish mortality and losses in production | Production value | Job absence |
| Greenhouse gas emissions | Profitability | Nutrients and unwanted substances |
| Impact on wild salmon | Value added—contribution to GDP | Occupational injuries |
| Sales of pharmaceuticals | | Societal contributions, taxes, and charges |
| Salmon lice | | |
| Utilization of residual raw materials | | |

Based on this, the current version of the portal (as of March 2021) has the 22 selected themes presented in **Table 2**, sorted across the three main dimensions of sustainability.

The survey also included questions on what makes a web-portal credible. For this, all the alternatives listed got a high share of "Important" and "Very important" (**Figure 3**), ranging from 61 to 83%. That the data presented are based on research was seen as the most important criteria (83%), followed by that the data source is stated (80%). That the data are quality assured by a quality assurance group (78%), and that research and research institutions have been responsible for making and presenting the indicators (74%) were also considered important. A categorization of the answers in the "Other" category found that 18 respondents stated that the portal or actors behind it had to be "independent," 14 that the language had to be understandable, 13 that data had to be openly available/documented, and 9 that the portal had to be easy to navigate/orientate in. Sixty-nine of the "Other" responses were not relevant for the portal as such.

Most of these points on credibility from the survey were either already decided for the portal, like the organization of the project with a group of researchers responsible for decision making and using only publicly available data, or were added or made more pronounced. The latter included clearly referring to data sources and additional information, and striving to present and describe the themes and what the indicators show neutrally and objectively.

A number of other considerations were made for the design of the theme pages. They all have the same basic design (**Figure 4**), in part to make it easier for the users to orientate and find information once they start using the portal. The lead paragraphs sum up or present important aspect of the theme. If the link to sustainability is not obvious, the main text explains this. This is considered especially important as the target group also includes those that have little prior knowledge of aquaculture in Norway, but even for those that are familiar with the aquaculture industry this may not be obvious. Special terms and indicators are explained in the text or in separate information boxes. The status or development may be summed up in a sentence or two. Information on monitoring, control, or management may also be briefly described. The key figures are for the last year, or the latest full year there is data for. The diagrams with indicator values show development or regional variation, or a combination of the two. Below the diagrams follows information on the source(s) for the dataset, when the page was last updated, and where more information can be found. The latter includes links or reference to webpages, reports, scientific articles, or legal documents.

Each theme page can have several indicators, that may be updated at different time intervals. Counting the indicator with most frequent update for each theme, one of the themes have weekly updates, two have monthly updates, twelve have annual updates, and eight have irregular updates. The ones that are irregularly updated are based on research project data, as are some of the annually updated ones. The other indicators are generally based on data that the authorities publish from monitoring of and mandatory reporting by the aquaculture industry. Most of the indicators give figures covering all of Norway, but two themes have data on county level.

It is an aim to keep the indicators in the portal up to date and present new data as soon as they are published. Therefore, automatic transfer of data and updating of indicators is used as much as possible. This is practical and cost-efficient. It does however put limitations on the text on the theme pages, as it cannot refer to specific indicator values in a way that risks it being outdated and wrong when indicators are automatically updated. Currently four themes have indicators with automatic updating.

In addition to the individual theme pages, the portal has several general information pages: The start page with an overview of all the themes, About the Norwegian aquaculture industry, Sustainability, Selection of themes, an overview of the data sets used and their origin, About us, and a Newsletter page with archive and subscription options. Especially the page on the Norwegian aquaculture industry and the one on Sustainability are made with those with little prior information on aquaculture in mind.

There has not been any formal evaluation of the process to establish the portal, but some reflections on this can still be presented, based on the core group's experiences from the process. Having a core project group consisting of researchers independent from the aquaculture industry clearly strengthens the credibility of the portal. While these researchers must have knowledge of the aquaculture industry and about sustainability, with the starting point that the portal should present data on both the environmental, economic, and social dimensions of

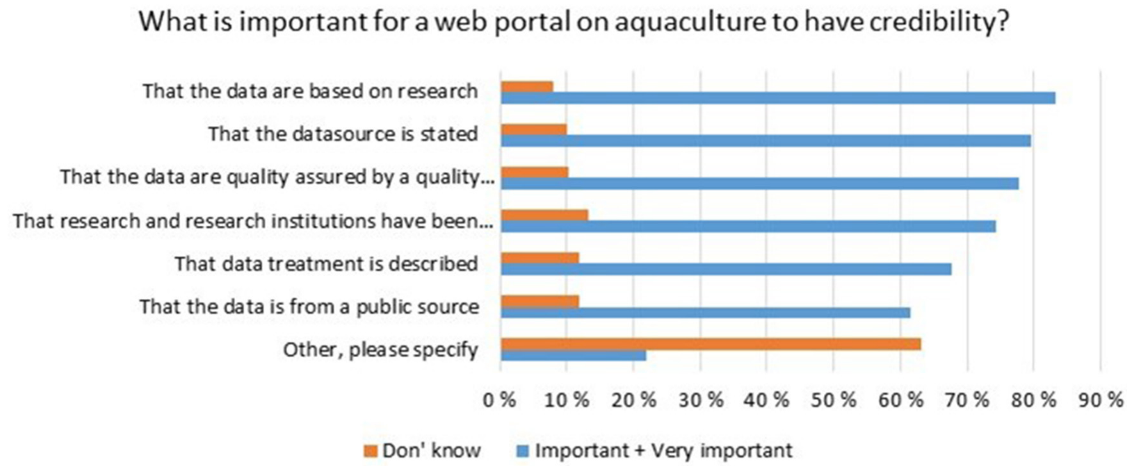


**FIGURE 3 |** Survey results: Share of respondents that find issues “Important” or “Very important” for a web portal on aquaculture to be credible.

sustainability, it is also clear that the core project group cannot have expert competence in all the relevant fields. Alternatively, if the core group should cover all fields it would be a very large project group and it would be difficult to organize an effective work process. Being able to draw on experts in different fields has therefore been essential. This goes both for getting *ad-hoc* support from experts for individual themes and indicators and getting input on the broader aspects from the experts that followed the project over time as members of the quality assurance group and the professional council.

Stakeholders have also contributed positively in the process, but this has mostly been persons from the aquaculture industry and from environmental NGOs. We have also collected input from the general public through the national survey. While the involvement of different stakeholder groups and sub-groups of the general public could have been deeper and more extensive in the project process, this is nearly always the case. We think the level of involvement we had gave sufficient information for deciding on the content and design of the portal. This also when we consider the time and other resources that were available.

## DISCUSSION AND CONCLUSION

Public availability of relevant and trustworthy information on the impacts and management of aquaculture is essential for good governance of the industry (FAO, 2017). The web-portal presented in this article is an attempt to contribute to this for Norwegian aquaculture, covering both environmental, economic, and social sustainability dimensions. To decide on the published version of the portal, a number of challenges have been met and trade-offs made. Several considerations have been taken in deciding on criteria for selecting indicators, on which themes and indicators should be presented, and how they should be presented. For those to design similar types of sustainability web-portals, decisive factors for the choices made must stem from the objectives with establishing such a portal and the defined target group.

It is more difficult to define the needs of the “general public” than other target groups. The general public can be defined in many ways, and it can be segmented in many ways (Eurostat, 2017). Focusing on some sub-groups out of the wider general public makes it easier to collect input and feedback and make design choices. There is a risk for opposing signals from the different sub-groups, making compromises necessary, and a risk for not meeting the needs of sub-groups that have not been given the chance to give input. Still, it may be easier to tailor the design of the web portal to the needs of some sub-groups rather than trying to sample the wide general public. With sub-groups one can usually resort to focus group techniques to collect input, requiring just a few persons. To get representative input for the whole general public requires many more respondents. Carefully considering if some sub-groups are more important than others could make prioritization easier.

Which themes and indicators are relevant and how they should be presented depend on several factors. The factual relevance for sustainability is clearly a criterion, and experts can help assess this. Whether various stakeholders and the general public think a theme is important should also matter, even if experts do not find the theme very relevant for sustainability. For such a theme it is important to avoid misconceptions, with trustworthy facts and information. If misconceptions about the sustainability of aquaculture are common among the general public their concerns may promote inappropriate decisions by politicians.

Credibility and trustworthiness are essential for a web-portal such as the one presented here. This depends on those who are involved in establishing the portal and which roles they have, how the data presented was obtained, and how it is presented. The limited attention span of those obtaining information from the Internet is a special challenge. Hence the length of texts and the number of indicators on each web page have been

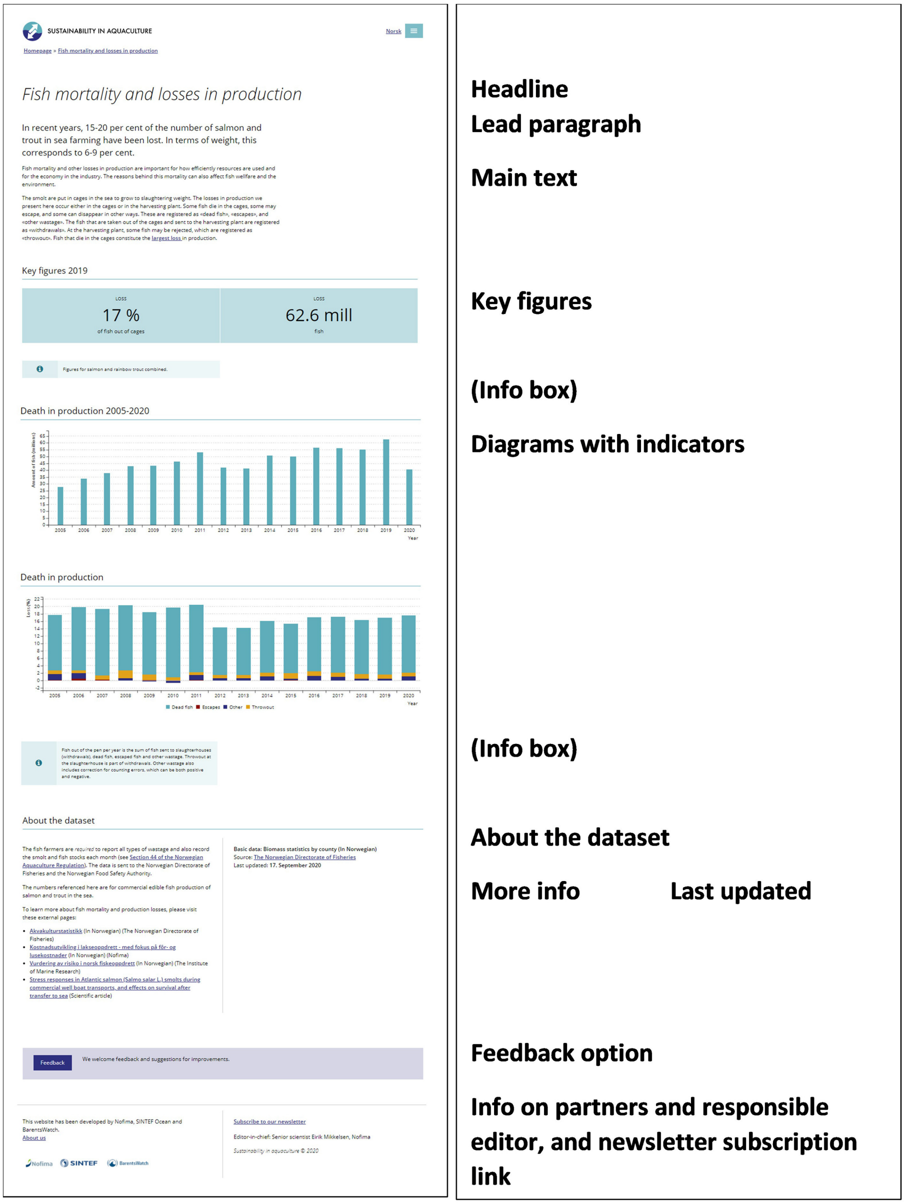


**FIGURE 4 |** Theme page structure.

limited, and this makes it difficult to include all the nuances and reservations that a scientific presentation and objectivity might require. Also, for the texts to be comprehensible to the general public, precise but advanced scientific terms must be replaced with plain language. So, demands on form and presentation challenges precision and objectivity.

The necessary demands of credibility and objectivity might also make it harder to promote and create excitement for the portal, and thus attract users. Much in today's media, both news channels and social media, focuses on conflicts and strong opinions. The portal does not do that, and the portal does not conclude if salmon and trout farming in Norway are sustainable, neither in general terms nor for individual themes. This has to do with how sustainability assessments often are value-based and not science-based (Böhringer and Jochem, 2007). In some cases, it is possible to define a situation that clearly is sustainable. Zero escapees in salmon farming would for example be a sustainable number of escapees. But for most real-world situations it is not possible to judge based on science whether a situation is sustainable or not. How many escaped salmon could be sustainable? Some of the portal's indicators do present the situation in relation to some limits set by the authorities. This concerns, for example, how often fish farms exceed the maximum average number of lice per fish in the farms, or that benthic environment under the pens fails to meet quality requirements. But these limits are set without an exact scientific basis for sustainability. Neither are there scientific criteria for trading different sustainability aspects off against each other. Reid and Rout (2020) propose a very different approach, where sustainability indicators should be defined with a clear choice about what is to be sustained and for whom, and a "radical transparency" on the values and moral imperatives used to determine this. This would then be based on a participatory approach to determining the values and priorities. A major problem with using the approach of Reid and Rout for the web-portal on Norwegian aquaculture's sustainability would be to determine who should decide the values and priorities. The sustainability issues span both local, regional, national, and international concerns as well as the environmental, economic, and social dimension. Even though the general public of Norway is the main target group for the web-portal, it would be unreasonable to let their values determine what should be deemed sustainable across all these levels and dimensions. If it were a matter of considering social sustainability in Norway only, it would be more reasonable.

The portal thus just presents facts on status and development for the indicators and leaves it to the users to make their own judgement about whether or how sustainable the situation is. As such, the portal is open to the general criticism of dashboard-type sustainability assessments of not actually assessing how sustainable the situation is (Stiglitz et al., 2010; p. 62). Sets of sustainability indicators can in principle be transformed into a single measure of sustainability by making a composite index, but there are serious challenges related to both normalization and weighting of the individual indicators in the index (Kwatra et al., 2020). More concerns for sustainability assessment methods are also presented and discussed in Sala et al. (2015). Common shortcomings with the methods proposed, for the purpose and target group of the web-portal on Norwegian aquaculture, is that it is rather technical exercises that will be hard to understand and it may not be clear how the status on concrete issues that the general public can relate to matter for the sustainability. With a themes-based, dashboard approach, the relevance for policy areas is much clearer (Kwatra et al., 2020). Most of the portal's indicators have a timeseries of data that makes it possible to assess if the development related to that indicator is becoming more or less sustainable. Recently, the portal has also added some comparison with other industries and regions. The theme page on greenhouse gas emissions, added in July 2020, compares farmed salmon products from Norway with wild caught seafood products from Norway and also European animal products. Where other such relevant comparisons are available based on scientifically robust methods, we plan to include this in the portal in the future. Among the candidates for this are antibiotics use in animal protein production.

Even though the portal does not conclude whether aquaculture is sustainable or not, the portal can contribute to resolving some conflicts. It is well known that some conflicts are rooted in misinformation or misunderstanding of what is actually the situation. The portal can then help by providing the facts. One example of a misconception that seems to persist with many is that antibiotics is used a lot in salmon farming in Norway. In reality, it has been very low since the 1990s, and much lower than in agriculture.

Positive feedback on the portal has come from persons representing public authorities at different levels and aquaculture industry, both in Norway and abroad. They have found it easy to find information and describe the portal as being able to point out the challenges facing Norwegian salmon farming today. Despite this, the number of visits to the portal is lower than we had expected. As of March 2021, around 20,000 unique visitors (ip-numbers) have been on the portal. About 75% of these are from Norway, while the rest comes from other countries all over the world. Future plans are to improve the promotion of the portal and to investigate more among current and potential users how the portal could become more relevant and attractive to use.

Two measures to make it more relevant and interesting are to make sure that indicators in the portal are based on as up-to-date data as possible, and that data are available on a geographical scale relevant for people's everyday lives. The first published version of the portal was dominated by annually updated indicators for the national level. Increasing the number of automated updates of indicators is one important strategy, and as more data providers offer APIs (application programming interfaces) this becomes increasingly possible. Providing more indicators at county or municipal level should make the portal more interesting for ordinary people, also more relevant for local political and administrative processes. One challenge with offering indicators at the municipal level is to still keep the portal simple to understand and navigate in. Showing data for all of Norway's 226 coastal municipalities as the standard presentation is hardly an alternative, so this will require a design where the users must make some active choices.

The portal's indicators are based on already existing datasets. While this has made it possible to establish indicators and theme pages relatively quickly, it has also meant that some highly relevant themes could not be established due to lack of data. In parallel with working on making indicators for the portal from existing datasets, the research team has also proposed research themes and projects to make new datasets. One example is related to greenhouse gas emissions from aquaculture, where a project was established, and indicators now are present in the portal. Having a possibility to propose new datasets that could be established, and that resources can be made available to collect them, is important for keeping such a portal and its indicator set relevant. Among the areas where publicly available datasets in Norway are insufficient for use in the portal are fish welfare, area use and area conflicts, and freshwater use.

As we have shown, making a web-portal with sustainability indicators for aquaculture for the general public will require trade-offs between several objectives. Even though we have identified some criteria and recommendations for both selecting content and presentation, some discretionary decisions must be made. It is an integrative and overall qualitative decision. The compromises can be a source for never-ending doubt to whether other solutions would be better, but it is better to get such a portal established rather than keep searching for the perfect solution. It is important that facts to assess the sustainability of aquaculture is made easily available to the general public. Nearly half of the countries that reported having aquaculture activities in the latest of FAO's bi-annual surveys on responsible fisheries and aquaculture saw a need for a better framework to manage and benefit from the aquaculture activities (FAO, 2020, p. 100). While other webpages in Norway contain much of the same information that is presented in the Sustainability in Aquaculture web-portal, no other has the broad coverage of relevant themes, quality assured information based on openly available data from objective sources, presented in a form tailored to the general public. The work to improve the portal continues.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

EM contributed to the idea, conceptualization, and writing first draft. All authors contributed to the input on structure, commenting, editing, and approved the submitted version.

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

# APPENDIX

## Info on Survey

The survey was carried out over internet in March 2018 by the Norstat Company, using their panel of respondents. Participation was voluntarily, all responses were anonymous, and the survey was compliant with Norwegian personal data protection regulations for research. **Tables A1**, **A2** shows the breakdown of respondents, which was representative for the population in Norway by age-groups, gender, and region.

**TABLE A1 |** Survey respondents' age, gender, and geography.

| | Sum | Age | | | Gender | | Region | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | <25 | 25–66 | >66 | Male | Female | North | Mid | West | East | South | Oslo |
| *n* | 630 | 73 | 441 | 117 | 316 | 314 | 59 | 86 | 130 | 217 | 57 | 82 |
| Male (%) | 50% | 52% | 51% | 45% | 100% | | 51% | 51% | 51% | 50% | 50% | 50% |
| Female (%) | 50% | 48% | 49% | 55% | | 100% | 49% | 49% | 49% | 50% | 50% | 50% |

**TABLE A2 |** Survey respondents' group belonging.

| Which group do you belong to (several choices possible) | % |
|---|---|
| Authorities, politicians, and municipal administration | 8 |
| Industry | 17 |
| NGOs | 5 |
| Other, please specify | 71 |

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# Farm Production Diversity in Aquaculture Has Been Overlooked as a Contributor to Sustainability

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Like many sectors, the expansion of aquaculture has issues related to sustainable resource use and environmental change. These challenges are widely recognised and are addressed with sectoral strategies. Even when culturing a single species, the specifics of impacts, constraints, and pressures are likely to vary in effects for different farm types. On the other hand, production efficiencies can drive farms towards homogeneity. A simple model is used in this study to demonstrate farm-scale budgets and the pressure to intensify production towards an optimum. A range of interventions can provide incentives for less intensive production: these include price premiums and altered cost bases. Integrated multitrophic aquaculture (IMTA) does not offer a route to less intensive production systems if the productivity of the extractive species (e.g., algae) is linked to the intensity of the fish farm, although alternative incentives for IMTA are possible. Increases in the intensity of production (as stocking density) can be mitigated by increasing farm capacity. An expanded production model suggests that this will lead to larger farms at relatively high stocking densities. Where farms are subject to variable economic and biological processes, this can lead to some combinations of intensity and capacity to have less variable earnings than others. The promotion of diverse aquaculture sectors may allow some of the ecological and social synergies available to smaller farms to be combined at a regional scale with the greater production of large farms. Cost, price and/or regulatory incentives are needed to create diverse production systems.

**Keywords: extensive aquaculture, conservation aquaculture, integrated multitrophic aquaculture, heterogenous, resilience**

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## INTRODUCTION

Aquaculture is considered a key sector for future global food production (Costello et al., 2020). Growth rates in aquaculture are, however, heterogenous (Gentry et al., 2019), with the global rate of growth declining since the beginning of the century (FAO, 2020). The reasons for declining growth rates in aquaculture are varied and include restricted space for farms, public opposition, market issues, diseases, and licencing backlogs. Large-scale strategies are one response to the issues affecting aquaculture. The European Union guidelines for sustainable aquaculture made recommendations for licencing, spatial planning, business competitiveness, and capturing the benefits of shared environmental, welfare, and consumer protection (EC, 2013). China is also emphasising spatial planning and more environmentally sustainable aquaculture (Yu et al., 2020), while the United States focusses on improved regulation, sustainable management, technology, and public understanding (NOAA, 2011). While the current policies focus on improving the number, profitability, and sustainability of farms, they do not explicitly consider that social, resource use and economic optima may occur at different farm capacities or production intensities.

National and regional strategies attempt to influence the evolution of the focal sector. In aquaculture this evolution has often been towards production and economic efficiencies related to increases in scale. Production efficiencies are generally important for expanding the total size of a sector (Nielsen et al., 2016). Salmon aquaculture provides examples of growth trajectories involving increases in net pen capacity and farm production (Asche et al., 2013; Ellis et al., 2016). For example, the numbers of Scottish sites producing 1–50, 50–100, 101–200, and 201–500 t of salmon were approximately equal in the early 1990s. By 2014, the diversity of production had declined, with around half the sites in the >1,000 t category (Ellis et al., 2016). Increases in production scale occur widely, with the majority of European countries showing recent increases in FTE per aquaculture enterprise (Scientific, Technical and Economic Committee for Fisheries (STECF), 2018). The economic incentive to increase production of individual farms can be viewed in terms of profit optimisation. Once a farm is set up, further intensification can increase the profit margin: each additional fish stocked represents additional profit. Stocking increases eventually become unsustainable without additional investment, as biological production starts to become less efficient when crowding-related processes become limiting.

A simple model for the costs, sales and net earnings for a fish farm can be used to demonstrate the processes that tend to scale up and homogenise farm production. Changes in farm earnings may also occur in more complicated systems, such as those involving more than one species in an integrated multitrophic aquaculture (IMTA) system. IMTA involves growing different species together such that the wastes of one species (e.g., fish) supports the growth of one or more separate trophic levels (i.e., "extractive" species such as filter feeders or seaweed). A simple (fish-macroalgae) IMTA system is used to investigate how this type of aquaculture might change the optimum farm scale. Finally, the model can be used to demonstrate how farms of different intensity and capacity might perform in the face of temporal variation in key parameters.

## A FARM-SCALE MODEL

The implications of variations in farm intensity and capacity are likely to be applicable with a range of different species and contexts. The example used here to illustrate farm-scale economics is based on salmon, currently the most valuable aquaculture species in terms of international trade (FAO, 2020). The model could be generalised to describe aquaculture of any fed species and covers a production cycle with starting with juveniles and ending with the harvest of adults. For salmon this is approximately a 2-year process. Salmon farms are generally based on rearing juveniles in sea cages or pens, fed on a pellet diet. The parameters (**Supplementary Data Sheet 1**) of the modelled farm are mostly based on industry figures for salmon (MOWI, 2020).

The total costs for the modelled farm reflect juvenile supply costs, feed costs, harvest costs, and costs of farm infrastructure and labour. The modelled farm buys juveniles (smolts) conditioned to sea water from a hatchery at a fixed cost.

$$\textit{Juvenile supply cost} = J_n.j_p \tag{1}$$

Where $J_n$ is the number of juveniles purchased and $j_p$ is the price per juvenile. The stocking rate is used in this paper as a measure of farm intensity.

Feed costs [the main component of farm budgets, MOWI (2020)] are made up of the feed consumed by harvested adults, and the feed consumed by fish that die before harvest.

$$\textit{Feed cost for harvested adults} = A_n\left(h - j_w\right) fcr.f_c \tag{2}$$

Where $A_n$ is the number of adults, $h$ is the harvest weight, $j_w$ is the weight of juveniles purchased, the feed conversion ratio, $fcr$, is the weight of feed used divided by the weight gain by fed fish, and $f_c$ is the cost of the feed. The feed conversion ratio is probably density dependent (Liu et al., 2015; Wang et al., 2019), with more feed needed per kilogram of fish as densities increase. Costs rise with higher values of the $fcr$, while a density dependent $fcr$ increases costs with stocking intensity (**Supplementary Material**). A density dependent $fcr$ is not, however, included in the model for reasons of parsimony: $fcr$ is modelled as a constant, with the impact of density included solely through a density dependent mortality rate.

$$\begin{aligned}&\textit{Feed consumed by fish that die before harvest}\\&= J_n\left(m_1 + \frac{m_2}{C}.J_n\right)\frac{\left(h - j_w\right)}{2}.fcr.fc\end{aligned} \tag{3}$$

To estimate the food "lost" to individuals that do not reach harvest, density independent ($m_1$) and density dependent ($m_2$) mortality rates are used. The capacity of the farm ($C$) reflects the volume that fish are reared in, so that density dependent mortality is reduced when crowding in mitigated by more (or larger) fish cages. The fish that die early are assumed, on average, to have half the mean weight gain that fish have at harvest. Density dependent mortality reflects observations of reduced welfare at higher stocking rates (Santurtun et al., 2018). Mortality is not well-characterised. Not only is mortality commercially sensitive, repeated experiments at stressful densities would be both expensive and ethically hard to justify. Disease is likely to have higher impacts at greater densities if transmission is facilitated by crowding.

The harvest cost is based on the fraction of the fish remaining following gutting ($gwt$), the fish weight at harvest ($h$) and a cost per kilogramme of fish harvested ($h_c$):

$$\textit{Harvest cost} = A_n.h_c.h.gwt \tag{4}$$

Buying and maintaining infrastructure, salaries, and repaying interest on loans are assumed to generate a farm cost per fish generation. A reasonable capacity for the target farm initially simulated is six fish cages, each of 35,000 m$^3$ volume. With the parameter values used in this study, this gives an adult stocking rate just below the threshold for welfare effects (Turnbull et al., 2005). Actual costs will vary by country and with management and investment decisions. What was felt to be a reasonable figure for the initial model farm was chosen, given an estimated initial equipment cost (in Norway) of 3.5–4.5 million Euro (MOWI, 2020). If the capacity of the farm is fixed, costs only vary with the stocking rate of smolts. Greater investment allows more, or larger, cages, such that:

$$C = I.v_c \tag{5}$$

Where $C$ is the volumetric capacity of the pens in the farm ($m^3$), $I$ is the investment cost required per harvest cycle and $v_c$ is the rate at which investment is converted into farm volume.

The value of fish farm sales is a function of number of fish surviving to harvest, the gutted weight and the sale price per kilogramme ($s_p$).

$$Sales = A_n.h.gwt.s_p \tag{6}$$

Where $A_n$ is related to the initial stocking density by:

$$A_n = J_n\left(1 - m_1 - \frac{m_2}{C}.J_n\right) \tag{7}$$

Net farm earnings are sales minus total costs. The model's equations can be added to a spreadsheet (**Supplementary Material**) to investigate farm budgets.

Seaweed is used to illustrate an extractive species growth alongside a salmon farm (an IMTA implementation). A seaweed farm does not require additional costs beyond set up and maintenance/harvest costs. Costs for a 1000 t, annual harvest farm were based on an extrapolation of the figures for a *Laminaria digitata* farm (Watson and Dring, 2011). It was assumed that efficiencies could be found so that production of seeded ropes and maintenance of a seaweed farm could be achieved for €200,000 per annum. Wet seaweed was assumed to be sold ($e_p$) for €2 $kg^{-1}$ (Watson and Dring, 2011).

While there is evidence for promotion of kelp growth in the vicinity of fish farms (Kerrigan and Suckling, 2018), the size of this effect is likely to depend on many factors, such as farm layout and current speeds. In the absence of a well-defined response in the literature, the influence of additional nitrogen available to seaweed configured in an IMTA with a salmon farm was assumed to follow a Michealis-Menten type relationship.

$$Seaweed\ harvest = s_b + \frac{s_{max}.T_f}{k_S + T_f} \tag{8}$$

Where $s_b$ is the baseline seaweed harvest in the absence of nutrients from the fish farm, $s_{max}$ is the maximum harvest possible, $T_f$ is the total food used by the farm, an index of potential nutrient supply to the environment, and $k_s$ is the half saturation constant (gives a measure of how quickly the nutrients supplied by a fish farm saturate the seaweed's capacity to respond).

Different scenarios were used to illustrate how farm economics may vary under scale related assumptions. Earnings examples are first developed using a fixed farm capacity (so that farms vary only in stocking density), before allowing both stocking density and farm investment in capacity to vary. The effect of an organic salmon price premium was illustrated using a sales price increase from €5.9 to €8.9 $kg^{-1}$ for fish grown at adult densities below 10 kg $m^{-3}$ (using the 6 × 35,000 $m^3$ pen volume as a reference). The effect of finding cheaper farm set ups at low smolt density (e.g., using pre-existing ponds) can be illustrated by halving the fixed costs below a density threshold. Finally, the influence of cost and price variability can be simulated by a Monte Carlo process: selecting parameter values from a range around the mean.

## OPTIMAL FARM INTENSITY

The overall pattern for the simulated farm with fixed capacity is for costs to rise as inputs (juveniles stocked) increase (**Figure 1A**). The smallest farms do not make a profit, as costs exceed sales. As the number of juveniles stocked increases, earnings rise before eventually starting to decrease [a similar result has been reported for a cod model (Björnsson et al., 2012)]. The decreases in sales and earnings occur as a result of declines in the adult population due to progressively stronger mortality as the initial stocking density rises. The scenario of an earnings collapse with very high stocking rates represents a realistic outcome. A very high stocking density would probably result in complete mortality, with no juveniles successfully growing to adulthood.

For a salmon farm based on the model and parameters of **Table 1** (with a six pen capacity costing €3 million), the weight of adults to be harvested from 1.1 million smolts would be 4,217 t, mortality 0.15, gutted weight yield per smolt of 3.22 kg, and final stocking density of 20.1 kg $m^{-3}$. These values are consistent with industry norms (MOWI, 2020). The model implies that farms more intensive than 4,200 t may be more profitable. Environmental constraints, regulation, and/or increased risks (e.g., all investment in a single location) are probably reflected in a lower farming intensity than the modelled peak being considered relevant in the salmon farming yearbook (MOWI, 2020). The possibilities of increased profit from larger and potentially more intensive farms are, however, illustrated by proposals within the industry for production volumes over 10,000 t at offshore and onshore farms.

## PROMOTING DIVERSE FARM PRODUCTION INTENSITIES

If most species grown in aquaculture have a production scale where profitability is maximised, there a number of ways in which a diversity of scales can be achieved. Taking the simple model presented here, steps in the sales price, such as thresholds below which the product is more valuable, can be a means for lower and higher intensity production to coexist (**Figure 1B**). The production and marketing of organic salmon grown at densities of $<$10 kg $m^{-3}$ is an example of how price variability can create economic viability at different farm intensities. As an alternative, or alongside changes in the price structure, the cost base can be

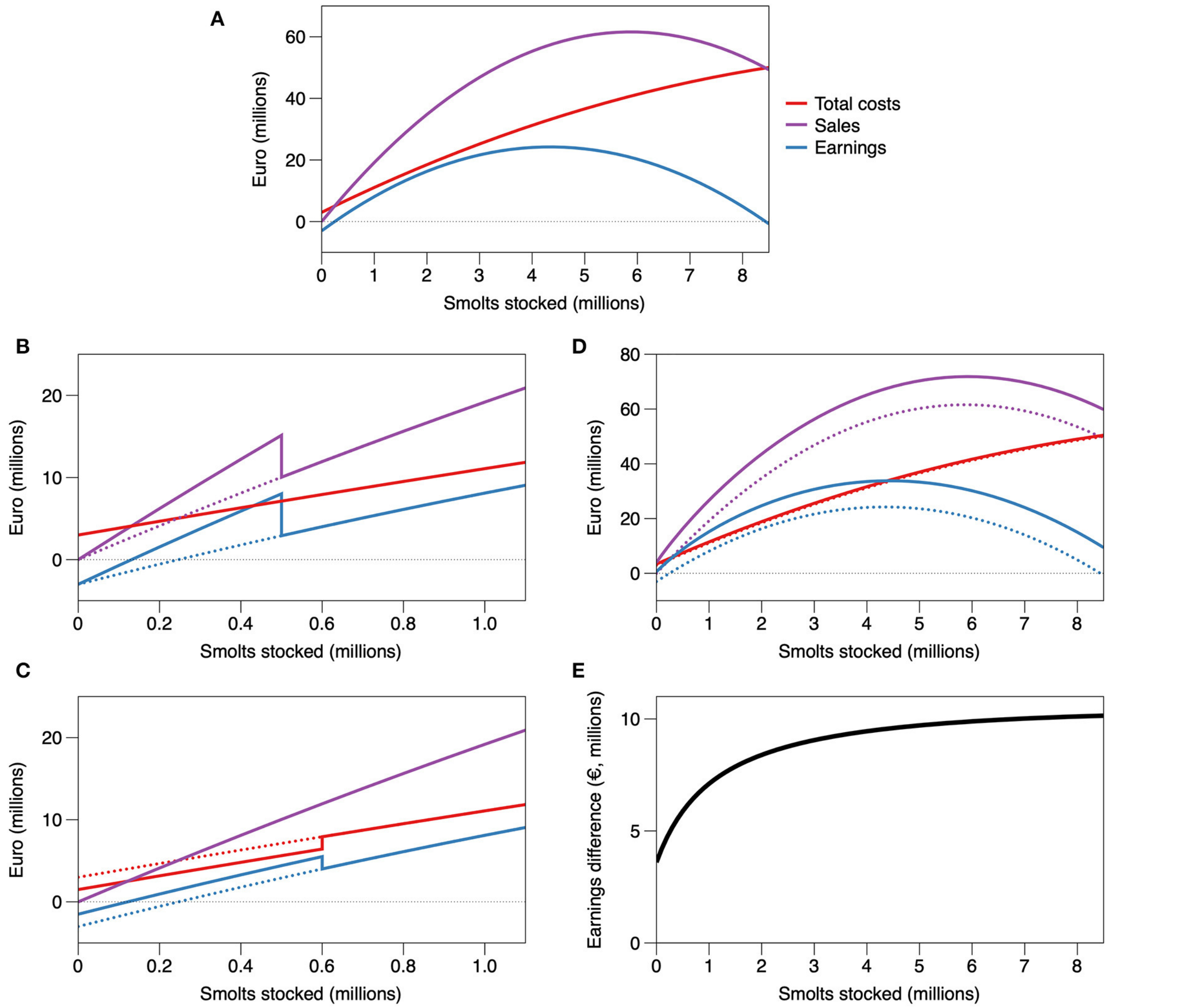


**FIGURE 1 |** Modelled costs, sales value, and net earnings for a fish farm at a fixed pen capacity (6 × 35,000 $m^3$). **(A)** Showing earnings across a range of juvenile (smolt) stocking densities, **(B)** Impact of a price premium (sales at €8.9 $kg^{-1}$) below a stocking threshold, as occurs for organic salmon, **(C)** Impact of reduced fixed costs below a certain stocking level (costs reduced by 50% below 0.6 million smolts as an example), **(D)** Integrated multitrophic aquaculture (IMTA) at different smolt stocking levels, comparing IMTA and fish-only farms, **(E)** Difference between the earnings of IMTA and fish-only systems. Dotted lines in **(B–D)** indicate the original values in panel **(A)**. Some graphs are truncated at 1.1 million smolts as this is the figure used in the industry handbook (MOWI, 2020).

altered. For example, it may be cheaper to use pre-existing ponds like the esteros (Yúfera and Arias, 2010) of southern Europe rather than to use more costly new infrastructure (**Figure 1C**). While lowering feed costs is a priority for carnivorous fish, a focus on routes to profitability for small farms may further incentivize diversifying production with omnivorous or herbivorous species. Changes to the way personnel and social capital are invested in production [community-based aquaculture (Bradford et al., 2020)] could also offer opportunities to change the cost base, including varying the cost of licences, to target profitability of less intensive production. In a full life cycle assessment (Samuel-Fitwi et al., 2013; Liu et al., 2016), there are likely to be a number of points where specific benefits could be subsidised or linked to the market to support a range of farm intensities and capacities.

A potential innovation in aquaculture is to expand the range and prevalence of integrated multitrophic aquaculture (IMTA). Looking at the relative prevalence of IMTA in Asia and Europe, it is tempting to conclude that IMTA suits small scale operations, while established large-scale fish farmers in Europe are not incentivised to complicate their businesses by adding less profitable extractive species (Hughes and Black, 2016). The simple economic model of a fish farm suggests that a small-scale optimum for IMTA profitability is not inevitable (**Figure 1D**). If growth of the extractive species is stimulated by the waste production of fish, the difference between farm earnings with and without IMTA is likely to mimic this growth response (**Figure 1E**). This means that two unintended consequences are possible: (a) the optimum IMTA

**TABLE 1 |** Parameter values and variables of the farm model.

| Parameter | Explanation | Value | References |
|---|---|---|---|
| $f_c$ | Feed cost | €1.3 $kg^{-1}$ | (MOWI, 2020) |
| *fcr* | Feed conversion radio | 1.2 | (MOWI, 2020) |
| *gwt* | Gutted weight fraction | 0.84 | (MOWI, 2020) |
| *h* | Harvest weight | 4.5 kg | (MOWI, 2020) |
| $h_c$ | Harvest cost | €0.4 $kg^{-1}$ | (MOWI, 2020) |
| $j_p$ | Juvenile price | €1.70 | (MOWI, 2020) |
| $j_w$ | Juvenile weight | 1 kg | (MOWI, 2020) |
| $k_s$ | Seaweed harvest half saturation | 5,000,000 kg | This study |
| $m_1$ | Density independent mortality | 0.06 | This study |
| $m_2$ | Density dependent mortality | $1.68 \times 10^{-2}$ $m^3$ $smolt^{-1}$ | This study |
| $s_b$ | Baseline seaweed farm size | 1,000 t | This study |
| $s_{max}$ | Maximum seaweed harvest | 2,000 t | This study |
| $s_p$ | Sales price for gutted fish | €5.9 $kg^{-1}$ | (MOWI, 2020) |
| $v_c$ | Rate of change in farm capacity | 0.07 $m^3$ €$^{-1}$ | This study |
| - | Fixed cost for seaweed harvest | €200,000 | This study |
| $e_p$ | Sales price for seaweed wet wt. | €2 $kg^{-1}$ | (Watson and Dring, 2011) |
| **Variables** | | | |
| $A_n$ | Adult numbers | | - |
| $J_n$ | Juvenile numbers | | - |
| $T_f$ | Total feed use by farm | kg | - |
| *I* | Farm investment in capacity | € | - |
| *C* | Farm capacity | $m^3$ | - |

profitability is at a higher farm intensity than the original fish monoculture, and (b) the rate of return for marginal increases of juvenile stocking is greater in IMTA than in monoculture. Both consequences would make increasing juvenile stocking numbers attractive for IMTA farmers and would disincentivize less intensive production.

A policy intervention that could be used to incentivize IMTA is a credit that directly rewards the removal of carbon or nitrogen (Chopin et al., 2012) by seaweed. Using a tax that increases the costs of intensive production (e.g., a nitrogen tax) can produce a lower optimum production density (i.e., a steeper total costs curve in **Figure 1A**). On its own, however, a nitrogen tax does not tend to incentivise the least intensive farms. As costs are added to all farms, the least intensive farms also become less profitable. This reflects the finding that such Pigouvian taxes can reduce production intensity, but at the expense of the viability of less intense farms (León-Santana and Hernández, 2008). Adding tax credits for nitrogen removal in IMTA produces the same response as **Figure 1E**: the gross value of the credit is likely to match the stimulation of extractive species growth when increasing fish densities. Encouraging a range of farm intensities would need a carefully set up, and potentially complex, tax and credit system. Low intensity IMTA may therefore need the type of price incentive that exists for organic aquaculture (van Osch et al., 2017), or an explicit subsidy for the ecosystem benefits, and/or synergies between culture species that can only be realised at lower farm intensity or capacity.

## BENEFITS AT DIFFERENT FARM CAPACITY AND INTENSITY

While increasing the intensity of production eventually reduces earnings, investments to scale up farm capacity can mitigate this. The farms with the highest earnings are likely to have a large capacity and to stock high numbers of smolts (**Figure 2A**). Low capacity-high intensity or low intensity-high capacity farms are not financially viable. The basic economic incentives therefore promote both larger and more intensive farming.

Earnings vary in separate harvests in the Monte Carlo simulations. Broadly speaking, earnings variability increases with mean earnings. The contours in **Figure 2B**, however, do not quite match those of **Figure 2A**. This indicates that farms of similar earnings may have different temporal variance in their earnings over time.

In aquaculture, disease represents one of the sources of variability between years. Temporal prevalence of diseases may be linked to environmental cues like anomalously warm temperatures (Oldham et al., 2016), leading to outbreaks that track environmental variability. The impacts of disease are also likely to be density dependent, where higher densities lead to greater transmission and individuals being more stressed (Turnbull et al., 2005). If the Monte Carlo simulations are restricted to reflect dominance by density dependent processes, earnings variability is concentrated in the high intensity-lower capacity farms (**Figure 2C**).

The changes in variance with farm capacity and intensity imply that a diverse collection of farms may have more stable earnings than a homogenous sector. This type of benefit-of-diversity effect has been seen in agriculture for comparisons of yield in response to climate variability (Reidsma et al., 2010). A range of farm types may also dampen the tendency for the cycles in profitability in aquaculture. Such cycles are often associated with cash flow and trade issues, for example in the salmon farming industry (Asche and Bjørndal, 2011).

Growth of farm capacity and intensity over time may cause some positive synergies to be lost. In many areas of Europe, fish farms are based in peripheral communities, giving them particular socio-economic importance for the coastal areas where they are based. Smaller operators may need to differentiate their offer to persist in the market, competing on quality, supply to local markets or through innovation in processing and packaging (Llorente et al., 2020). Larger companies and farms be disconnected from the adjoining community. For example, fish from a large and intensive farm may not be available locally (Bresnihan, 2016). With no distinctive produce to offer tourists, additional benefits do not accrue to the community. Collaboration, by sharing resources

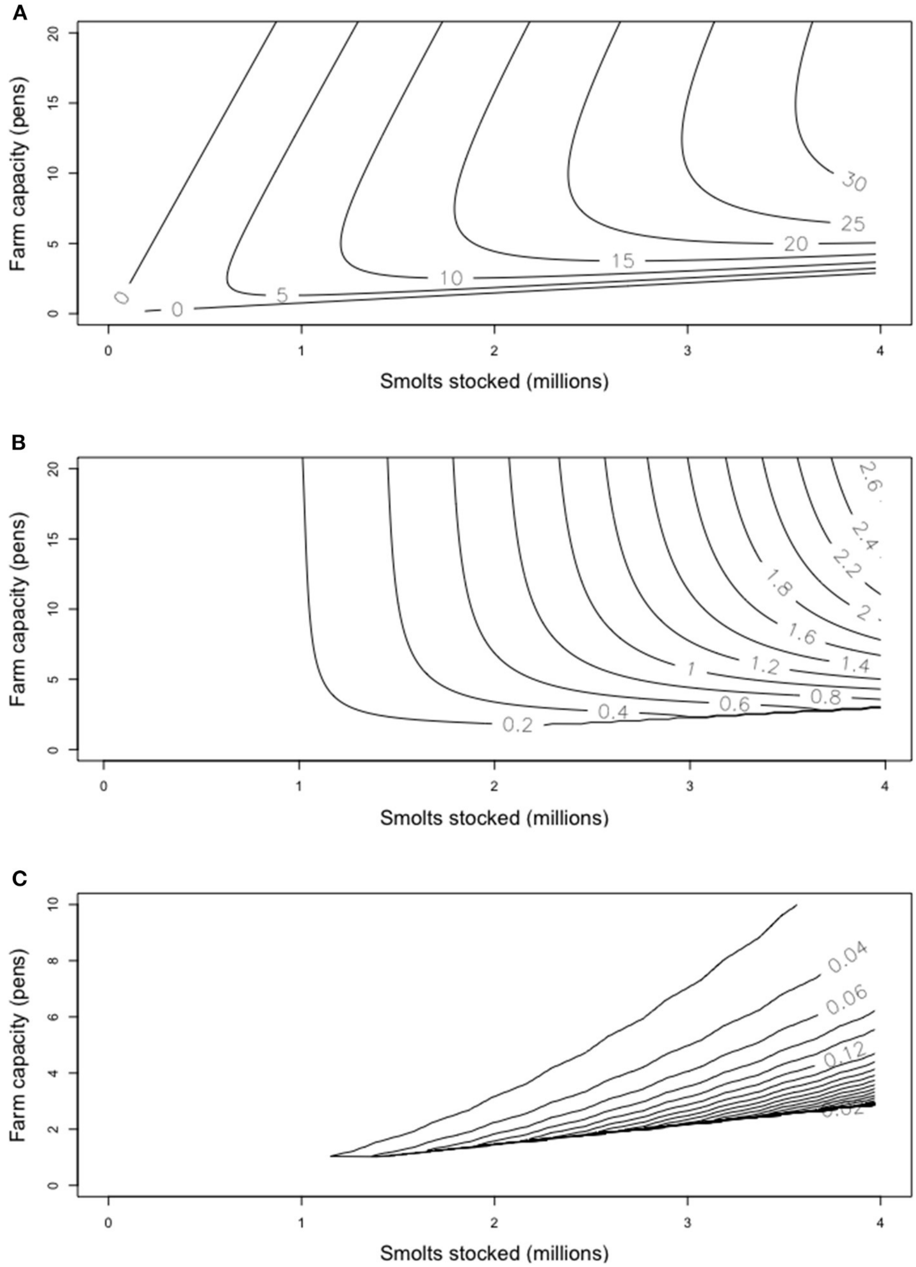


**FIGURE 2 |** Results from 50 simulated production cycles for farms at different stocking densities and capacities (expressed as number of 35,000 $m^3$ pens). **(A)** Average earnings (million Euro); **(B)** Variance in earnings for simulations where all parameters except harvest weight vary by 2.5%, chosen from a uniform distribution; **(C)** Variance in earnings when only the density dependent mortality rate varies by 2.5%.

and experience among smaller local businesses, may create wider social benefits in terms of shared community values and resilience. Both formal and informal cooperation among small entities in the aquaculture sector can help businesses persist (Cush and Varley, 2013).

A further synergy, perhaps more available to small capacity and low intensity aquaculture producers, is the opportunity to develop alongside conservation (and other sectors). This is particularly relevant in areas like coastal waters, where there is limited space available for aquaculture. Aquaculture can have positive local influences on ecosystems, including through the provision of habitat and through ecosystem services, for example if extractive organisms are being grown (Froehlich et al., 2017). Of course much needs to be done to find the appropriate scale and type of locally synergistic aquaculture (Le Gouvello et al., 2017). It seems likely that locally-based enterprises are best placed to have the networks, local knowledge and flexibility to find these synergies.

## CONCLUSION

The benefit of stressing a diversity of farm types in aquaculture strategies is that this approach is inclusionary. Diversity as a goal avoids casting the debate as one of intensive or extensive aquaculture at a national or regional level ("sea sparing" or "sea sharing"). While the impacts of larger farms will vary with context and location, the challenges of maintaining and expanding aquaculture production will not be met without intensive, high volume production. Accepting and promoting diversity, however, increases the range of situations in which aquaculture can be developed. The concept of scale-dependent synergies with different aspects of economic, social or ecological sustainability allows a farm diversity-promoting framework to integrate with the ecosystem approach to aquaculture (FAO, 2008). Diverse aquaculture sectors are more likely to produce the heterogenous and flexible production systems identified as key to resilient global food production (Troell et al., 2014; Urruty et al., 2016). The challenges are to gather the appropriate data on farm production, including for other species and implementations of IMTA, and to develop policies that enable diversity without having unintended consequences at any particular scale.

## DATA AVAILABILITY STATEMENT

The original contributions generated for the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.655346/full#supplementary-material

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# Characteristics and Dynamics of the Freshwater Fish Market in Chengdu, China

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The drivers and characteristics of trends in aquatic product consumption are a crucial component of fish food system sustainability. The Chinese market for aquatic products is the largest in the world, yet little has been published on the characteristics of the freshwater fish market. This Paper draws on interviews with key informants to understand the social characteristics of the freshwater fish market in Chengdu, Sichuan province. Price, food safety and quality, freshness and local culinary traditions are important influences on patterns of freshwater fish consumption. However, imported species such as pangasius and branded products are increasing in popularity, indicative of changes in the Chengdu freshwater fish market and the Chinese market for aquatic products more generally.

**Keywords: seafood, China, consumption, Sichuan, freshwater fish, carp**

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## INTRODUCTION

The drivers and characteristics of trends in aquatic product consumption are increasingly recognised as a crucial component of fish food system sustainability (Béné et al., 2015; Belton et al., 2018; Bogard et al., 2019). China is the largest consumer of aquatic products globally, and, like the broader Chinese food market, is changing rapidly (Villasante et al., 2013; Zhai et al., 2014; Zhou et al., 2014; Fabinyi et al., 2016). Due to the sheer scale of this market, gaining a better understanding of key market dynamics is crucial—both from an economic perspective for those who supply the market (Rabobank, 2012; Zhou et al., 2014) and from an environmental perspective for those interested in how such aquatic product consumption trends may affect global stock sustainability (Villasante et al., 2013; Fabinyi et al., 2016). This paper aims to describe some of the key social characteristics of the freshwater fish market in Chengdu, and discusses some of the implications of this for the Chinese aquatic product market more broadly.

Considerable attention has focused on the consumption of imported seafoods in China, in particular of endangered or vulnerable species, and those of high value (Villasante et al., 2013; Shea and To, 2017; Purcell et al., 2018; Wang and Somogyi, 2018, 2020; Zheng et al., 2018; Harkell, 2019; Wang et al., 2019). In recent consumer studies, for example, Wang and colleagues have investigated factors affecting consumer preferences for sustainable shellfish (Wang and Somogyi, 2018), and on luxury seafood more broadly (Wang and Somogyi, 2020), while Zheng et al. (2018) focus on consumer intentions for wild salmon.

However, there has been limited attention to patterns of freshwater fish consumption in China in the literature (Xian, 2016). This is likely due in part to the fact that freshwater species, in general, tend to be less economically higher-valued than their marine counterparts in China. In a recent study of luxury seafood in China, for example, almost all of the species classed as 'luxury' were marine species (Wang and Somogyi, 2020). Additionally, many of the aquatic products commonly consumed in China that inspire concerns about the sustainability of capture fisheries are marine (e.g., sea cucumbers, shark fin, groupers, many types of shellfish). This means that the freshwater fish market has generated less attention from economic and environmental sustainability perspectives, mirroring broader patterns documented in the literature for the 'forgotten' inland [freshwater] fisheries (Cooke et al., 2016; Funge-Smith and Bennett, 2019), of freshwater aquaculture (Belton et al., 2020), and of seafood trade more generally (Belton and Bush, 2014).

Yet, the Chinese seafood market remains overall dominated by freshwater fish consumption (Chiu et al., 2013), and there are at least two significant reasons to gain a better understanding of the Chinese freshwater fish consumer market. Firstly, aquaculture is increasing rapidly across the globe, and in particular, freshwater aquaculture is responsible for an increasingly significant level of food consumption (Edwards et al., 2019). While freshwater fish do not tend to be as valuable as marine species per piece, the overall volume of the Chinese freshwater fish market makes it hugely economically significant, and many producers see China as a potential market to sell their products (e.g., Rabobank, 2012). Secondly, from an environmental sustainability perspective, the production and consumption of herbivorous fish such as carp and tilapia is seen as relatively less harmful than many higher-trophic level marine species (Little et al., 2016). Understanding how to promote the consumption of such relatively environmentally sustainably produced fish—and not just reduce the consumption of fish with negative environmental impacts, such as shark fin—is therefore a goal of environmental non-government organisations and policymakers (see e.g., China Blue, 2019).

National level statistics on aquatic product consumption in China do not take into account out-of-home consumption, nor do they describe down to species-level (Chiu et al., 2013). As such, most academic literature on Chinese freshwater fish consumption exists through scattered surveys (e.g., Chiu et al., 2013; Fabinyi et al., 2016; Xian, 2016), although there is also a very significant literature on freshwater fish production in China (e.g., Cao et al., 2015). This paper aims to address the gap in the literature on the Chinese freshwater fish market through a qualitative case study of the Chengdu freshwater fish market. As an exploratory study, the focus is on understanding key characteristics of this market including prices, common freshwater fish products and social contexts of consumption; and on key drivers of change. Findings on the characteristics and dynamics of the freshwater fish market in Chengdu then forms the basis for a wider discussion that compares these features to other, more well-studied aquatic product markets in China, and on the implications for policymakers.

## MATERIALS AND METHODS

Chinese consumer aquatic product preferences are highly diverse according to many factors, such as age, education, gender, wealth and region (e.g., Fabinyi et al., 2016; Wang et al., 2018). Chengdu is a useful case study to examine freshwater fish consumption because, unlike the major coastal cities of China, its regional cuisine (Sichuan cuisine) includes a relatively large proportion of freshwater fish. It is considered to be a 'second-tier' city in China, which is undergoing processes of rapid economic and social change broadly similar to many other second-tier cities. While luxury seafood consumption and that of imported products is more commonly associated with first-tier cities (Wang and Somogyi, 2020), freshwater fish consumption, much of which is domestically produced, is more prevalent in inland, second-tier cities.

The research design broadly followed that of Fabinyi and Liu (2014) and Fabinyi et al. (2017) in that it did not directly interview consumers, but considered traders and restaurateurs as key informants on market characteristics and dynamics, and as such a qualitative approach was more appropriate. The goal of the interviews were to establish key characteristics of the freshwater fish market in Chengdu in terms of prices, commonly consumed species, and the social context of consumption; and key trends and drivers of change.

Semi-structured interviews were conducted with 6 restaurateurs, 2 farmers and 12 traders (from supermarkets, local wet markets and wholesale markets). Interviews were conducted together with a research assistant who helped with introducing the topic and its significance as well as asking a variety of questions and then facilitating the interview by interpreting answers if required. The interviews purposively targeted different types of restaurants and seafood traders; the goal was not to attain a random sample but to obtain 'saturation', a standard and well-established concept in qualitative research that refers to the process in data collection where each new interview brings little or no new information (Morse, 1995; Grady, 1998). The interviews were transcribed and translated into English, and data analysis involved manually coding and identifying emergent themes (Bernard, 2006). Informed consent was obtained for all interviews.

## RESULTS AND DISCUSSION

### Commonly Consumed Freshwater Fish in Chengdu

**Table 1** shows the various kinds of freshwater fish commonly available for purchase at markets in Chengdu. The species that are most prevalent in wet markets, restaurants, and supermarkets include grass carp (*Ctenopharyngodon idella*, caoyu 草鱼), big-headed carp (*Aristichtys nobilis*, hualian 花鲢 or pangtouyu 胖头鱼), silver carp (*Hypothalmichthys molitrix*, bailian 白莲), crucian carp (*Carassius auratus*, jiyu 鲫鱼), longsnout catfish (*Leiocassis longirostris*, jiangtuan 江团), channel catfish (*Ictalurus punctatus*, qianyu 钳鱼 or suobianyu 梭边鱼), pangasius (pangasius spp., basa 巴沙鱼), and loaches (*Misgurnus anguillicaudatus*, niqiu 泥鳅).

All can be easily sourced live in Chengdu, with the exception of pangasius which was either: (1) sold frozen at wholesale markets and supermarkets or (2) served as part of a

**TABLE 1 |** Commonly consumed freshwater fish in Chengdu.

| Common name (Chinese) | Common name (English) | Scientific name/group | Price per kg in USD[1] for typical serves |
|---|---|---|---|
| Caoyu 草鱼 | Grass carp | *Ctenopharyngodon idella* | 1.2–1.5/500 g, Tongwei 3.4/500 g |
| Hualian 花鲢/pangtouyu 胖头鱼 | Big-headed carp | *Aristichtys nobilis* | 1.6, 2.2/500 g, Tongwei: 3.4–3.5/500 g Restaurant: 3.7–4.1/person OR fish head 3.8–7.1/person |
| Bailian 白鲢 | Silver carp | *Hypothalmichthys molitrix* | 0.7–1.5/500 g, Restaurant: 2.5-2.6/person OR fish head 3.7–3.8/person |
| Jiyu 鲫鱼 | Crucian carp | *Carassius auratus* | 0.9–1.9/500 g, Tongwei: 3.2-3.7/500 g, Restaurant: 7.1/dish, 2.9/soup |
| Basa 巴沙鱼 | Pacific dory, basa, Pangasius, catfish | *Pangasius bocourti* | Frozen: 2.0–3.5/500 g; Restaurants: 2.8/200 g |
| Jiangtuan 江团 | Longsnout catfish | *Leiocassis longirostris?* | 1.5–4.4/500 g, Restaurant: 21.9/hotplate (Tongwei fish) |
| qianyu钳鱼/suobianyu 梭边鱼 | Channel catfish | *Ictalurus punctatus* | 2.6/500 g, Tongwei: 3.6/500 g, Restaurant: 4.0–5.1/person |
| Niqiu 泥鳅 | Loaches | *Misgurnus anguillicaudatus* | N/A |
| Luyu 鲈鱼 | Perch | *Perca* | 4.4/500 g, Tongwei: 8.7/500 g |

[1] *(1 USD= 6.8 CNY as at Jan 15th 2019).*

prepared meal in restaurants (Interview with Restauratuer 28 December 2018).

In general, there is a two-tiered pricing structure for the sale of live fish – those that are marketed under the Tongwei brand are sold at a premium in comparison to the exact same species of fish from other sources (Tongwei is a major seafood company in China with a large presence in Sichuan; see "Tongwei Group" section for a full description of the reasons behind these price differences). For example, the lowest priced Tongwei crucian carp was selling for $3.2 US/500 g in comparison to $0.9 US/500 g for the unbranded. The prices of grass carp ($3.4 versus $1.2 US/500 g), big-headed carp ($3.4 versus $1.6 US/500 g) and channel catfish ($3.6 versus $2.6 US/500 g) follow a similar pattern.

Many of these fish are consumed at home, for example big-headed carp is popular in Chengdu and locals might prepare it akin to cold-pot fish whereby a pot including delicate slices of fish, vegetables and tofu would be served in a Sichuanese broth accompanying plain steamed rice. The 'cold-pot' refers to the absence of a heat source on the dining table as the fish is served ready-to-eat, as opposed to 'hot-pot' whereby diners play an active role in cooking at the dining table. In restaurants, prices of freshwater fish depend on the serving style: (1) cold-pot fish is often shared between two or more people whereby diners choose one type of fish and are charged a specified amount per person—though the fish is typically served banquet style; (2) grilled fish and other Sichuan style fish dishes such as fish with pickled vegetables (suancaiyu 酸菜鱼) are generally priced per dish à la carte style from $5.8 US/dish. As an example, cold-pot silver carp is priced from $2.5 US/person but grilled Tongwei channel catfish is $20.4 US/plate. A further distinction in price is required for cold-pot silver carp fish head which was available at $3.7 US/person—many consider the fish head as a delicacy. The Tongwei longsnout catfish was the highest priced fish among selected casual restaurants in Chengdu at $21.9 US/hotplate (Interview with Waiter 28 December 2018). Grilled fish is popular among a wide range of clientele, especially for social settings. Premium fish such as perch (luyu, *Perca*) and Mandarin fish (guiyu, *Siniperca chuatsi*) are mainly sold to wealthier consumers, whereas "ordinary people eat silver carps and grass carps" (Interview with Vendor 31 December 2018).

## Sourcing of Freshwater Fish in Chengdu

Freshwater fish in Chengdu is widely available through numerous outlets. Innumerable small-scale fish farms located within Sichuan or other nearby provinces such as Hubei underpin this supply chain by cultivating fish until they are of sufficient size and ready to be transported alive in specialised trucks to either: (1) wholesale markets such as Baijia wholesale market in Chengdu, or (2) supermarkets. Large supermarkets in particular tend to have a greater range of fish for sale (such as frozen pangasius), and at a higher price compared to local markets. Wholesale markets generally supply vendors from smaller neighbourhood wet markets, restaurants and some independent consumers. Such local wet markets also supply (sometimes by delivery) to restaurants and are more accessible to the public.

The largest wholesale fish market in Chengdu is the Baijia market on the outskirts of the city. Fish at the Baijia wholesale market tend to come from Meishan city, or Hubei and Jiangsu provinces (Interview with Vendor 20 January 2019). Another large fish market named Qingshiqiao exists closer to the heart of Chengdu, providing the general public greater accessibility to a range of seafood products sourced from different parts of China. There are also a great number of smaller local markets that are oriented towards serving their local neighbourhood. Pangasius is mostly sourced from Vietnam in frozen form and has enjoyed a rise in popularity recently. This product is mainly available in supermarkets and large wholesale markets because it requires cold chain storage.

### Tongwei Group

Tongwei Group is a major Chinese conglomerate that has integrated production, distribution and sales channels for freshwater fish. It was mentioned by many as having a significant role to play in the production of freshwater fish. Its supply network depends mainly on two aquaculture locations—one in Hainan and the other in Sichuan. There is a separate Tongwei wholesale market in Chengdu named *Sanlian* (三联) where Tongwei branding, colours and signage are predominant.

The brand name is seen to confer trust to customers about food safety. As one vendor at a smaller store claimed, "The company does not use chemicals or pesticides, so the fish is safe to eat, and quality is guaranteed" (Interview with Vendor 17 January 2019). The reputation and recognition of Tongwei products is further enhanced by its modern distribution channels—its fish are sold through online platforms including JD.com, China's largest online retailer. Furthermore, Tongwei is a supplier for various international supermarket chains including Ito Yokato and Carrefour.

Despite its reputation, there are some vendors who believe the price premium is not justified. For example, when one vendor was asked about differences between Tongwei fish and other fish, the response was "Actually, they are pretty much the same, but Tongwei is good at advertising and made itself a big brand" (Interview with Vendor 20 January 2019). However, the consensus concerning Tongwei is that it uses its technology to produce the best quality fish feed on the market, as one restaurateur puts it: "Good feed makes good fish" (Interview with Restauratuer 28 December 2018). Furthermore, one farmer of longsnout catfish suggested that the key to good fish is using good quality fish feed, and then mentioned they use Tongwei fish feed (Interview with Farmer 24 January 2019).

## Food Quality and Food Safety

Food safety is an ongoing concern in China, including in the freshwater fish sector (Xu et al., 2012; Fabinyi et al., 2016), as one vendor explains: "About seven or eight years ago there was a rumour that some grass carp were fed with bad feed and their meat tasted strange" (Interview with Vendor 22 January 2019). Many interviewees perceived that regular inspections by higher authorities serve to prevent malpractices within the fish cultivation industry. For example, one vendor from a wholesale market mentioned that the market is inspected every three to four days by the market management so as to dissuade any malpractices relating to fish feed, whereas another was confident that there are no harmful substances in the fish feed owing to tighter inspections by government representatives (Interview with Vendor 22 January 2019). Freshwater fish were contrasted positively with pork, which had suffered from recent outbreaks of African swine fever in China:

"Fish won't catch any diseases, they are not like pigs or chickens, which are more susceptible to disease outbreaks, so customers feel safe to buy them" (Interview with Vendor 22 January 2019).

"People are cautious about eating pork this year because of the swine fever, so fish prices are much higher than in previous years" (Interview with Vendor 31 December 2018).

It is uncommon for vendors or restaurants in Chengdu to list the origins of fish that is sold, and transparency and traceability standards are low. For example, although consumers tend to have an aversion to the so called 'eight-barbel catfish', one vendor said that restaurants may serve this as channel catfish as she suggested that most customers aren't able to distinguish between these kinds of fish—especially once sliced and prepared (Interview with Vendor 14 January 2019).

## Local Food Culture in Chengdu

Chengdu was formally declared by UNESCO to be a city of gastronomy in 2011 in recognition of the city's distinctive culinary culture. Perhaps the most distinctive characteristic of Sichuanese cuisine is the use of Sichuan peppercorns and chillies, which are commonly combined and used across a wide range of dishes. Another aspect of Sichuanese food culture is the use of freshwater fish. Fish is served in various ways including hot-pot (huoguo 火锅), cold-pot fish (lengguoyu 冷锅鱼), grilled fish (kaoyu 烤鱼) and various braised fish dishes such as fish with pickled vegetables (suancaiyu 酸菜鱼). With hot-pot, the customer is in charge of cooking whereas the other dishes are prepared in the kitchen and are served ready to consume directly—often with plain steamed rice. Furthermore, the act of consuming these dishes is somewhat more experiential and social compared to other choices of meals such as a bowl of noodles which might be consumed individually. Hot-pot in particular is often used as a way to welcome guests to Chengdu and is often enjoyed by groups of people as a social occasion.

The kinds of fish that are used in hot-pot differ slightly, for example, loaches are well-suited for hot-pot due to their small size, and do not tend to be used in other fish preparations. However, crucian and grass carps are suited for skewering and grilling due to their body shape, whereas big-headed carp are generally used to prepare cold-pot fish as its meat is the tenderest out of the most commonly consumed freshwater fish in Chengdu (Interview with Vendor 22 January 2019). Fish head is commonly reserved and served separately as it tends to be more highly prized for perceived cultural and nutritional reasons. It therefore commands a higher price along the supply chain including at the local wet market and in restaurants. Fish maw is also considered a specialty, and this by-product of gutting live fish as requested by customers at a local wet market can be sold to other customers. The practice of keeping fish alive at markets and in restaurants highlights the importance of freshness in Chinese cuisine and was emphasised in multiple interviews.

Although taste is personal and subjective, certain attributes of freshwater fish are highly valued. The quantity and size of the bones, the perceived tenderness of the meat, the scales and the perceived cleanliness of the fish are all important factors. Fish fillets tend to be sliced thinly for dishes such as fish with pickled vegetables (suancaiyu 酸菜鱼) so as to "make flavour go into the fish more easily" (Interview with Restaurateur 31 December 2018). Sichuanese are also very discerning when it comes to matching particular types of fish with certain cooking techniques. A restaurateur explained that marine fish are usually steamed although the kinds of fish that are commonly consumed in Chengdu would be "not delicious and smelly" if steamed. He described how to offset the 'fishy' smell using other techniques such as slicing the fish thinly, washing the slices thoroughly and mixing the slices with garlic, ginger, salt and scallions (Interview with Restauratuer 31 December 2018). Furthermore, another pointed out how it might be a waste to use expensive fish for many Sichuanese dishes as the flavours can be seen to overpower the natural flavour of other more expensive fish (Interview with Restaurateur 18 January 2019). Although taste and flavour are held in high regard in Chengdu, the fact that locally consumed fish tend to be seen as good value for money also contributes to their popularity.

Fish is particularly popular during Lunar New Year celebrations (otherwise known as the Spring festival) as the word for 'fish' (yu 鱼) is a homophone for the word 'riches' (yu 余 ), which means many Chinese equate fish with prosperity and surplus. One restaurateur described that during the Lunar New Year: "We always buy good fish, expensive fish for this festival. We usually buy better fish during the Spring Festival. It's usually the big fish. Silver carp can weigh as much as 5kg and it tastes good" (Interview with Restauratuer 31 December 2018).

This suggests that even if the working class aren't able to celebrate special occasions with premium fish, they will still endeavour to purchase larger species of commonly consumed fish. With regards to doing business in this industry, most interviewees merely mentioned business was steady. However, one vendor elaborated that "retail sales are indeed not as good as before, we mainly deliver to restaurants now", suggesting that the consumption of freshwater fish has shifted away from home prepared meals as more people enjoy the luxury of affording to dine-out (Interview with Vendor 22 January 2019). This upward mobility is reflected in the comments of another vendor: "Now we have to sell more (perch and Mandarin fish) than before, as our life is getting better and better (i.e. rapid economic development of China). We used to sell less perch and Mandarin fish" (Interview with Vendor 31 December 2018).

## CONCLUSION

Changing consumer preferences for aquatic products are a crucial driver of outcomes in fish food system sustainability (Tlusty et al., 2019). While the literature on the Chinese market, the largest in the world, has been dominated by analyses of consumer preferences for marine products, farmed freshwater fish provide an increasingly important aspect of consumer diets (Belton et al., 2018), and have long been a significant component of aquatic product consumption in China. This paper has addressed this gap in this literature by focusing on the relatively neglected freshwater fish market in China, describing the characteristics and trends of the freshwater fish market in Chengdu. Further research is needed to address the regional and sampling limitations of this study through quantitative surveys of consumer preferences, value chain dynamics (e.g., Wang et al., 2019) and for studies of freshwater markets across broader or multiple regions of China.

Overall, the study found that the freshwater fish market in Chengdu has similar characteristics to Chinese aquatic product markets in first-tier cities, and to luxury, largely marine markets (Fabinyi and Liu, 2014; Fabinyi et al., 2017; Wang and Somogyi, 2018, 2020; Wang et al., 2018). Firstly, similar values inform consumer preferences for fish. In particular, perceptions about food safety, freshness, cost and local culinary traditions are all important influences over how and what freshwater fish are consumed. Secondly, while carps are still widely consumed by people at home, at restaurants and remain the most common type of fish, there are reports that eating out at restaurants is becoming more common as incomes rise (Zhou et al., 2014), and a growing demand for branded (e.g., Tongwei) and imported (e.g., pangasius) fish. In particular, the apparent rise in pangasius consumption mirrors national reports of trends of increased consumption (Craze, 2019; Harkell, 2019).

Taken together, the findings suggest that the Chinese freshwater fish market is not just a market for cheap, domestically produced products that are largely consumed at home, but dynamic in that it increasingly incorporates branded products, imported products, and eating out at restaurants. While domestically produced carps will continue to be important for the lower end of the Chinese freshwater fish market for the foreseeable future, the freshwater fish market is also changing towards increased out of home consumption, and consumption of imported products—trends usually associated with the luxury, largely marine market in first-tier cities (Wang and Somogyi, 2020). These findings suggest that strong opportunities exist to promote new freshwater species, brands and alternative product forms. For environmental NGOs and others seeking to promote the consumption of more environmentally sustainable seafood in China, this presents an opportunity to complement the negative campaigns against shark fin and other unsusutainably harvested marine products with a positive campaign focusing on more environmentally sustainable freshwater fish consumption. Overall, this paper provides further evidence for the ongoing significance of farmed freshwater fish products as a component of wider, changing trends in consumer aquatic product preferences.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because a condition of the ethics protocol was that raw data would only be accessed by the researchers due to confidentiality. Requests to access the datasets should be directed to michael.fabinyi@uts.edu.au.

## ETHICS STATEMENT

The research was approved by the Human Research Ethics Committee of University of Technology Sydney (Human Ethics Approval Number ETH18-3075). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

MF: research design. JF: data collection. JF and MF: data analysis and manuscript preparation. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Food Systems

REVIEW
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# Wild and Farmed Arctic Charr as a Tourism Product in an Era of Climate Change

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The topic investigated is the social-ecological system of Arctic charr (*Salvelinus alpinus*) fishing and aquaculture as a tourism product in an era of climate change. Arctic charr is a resilient salmonid species that was traditionally an important part of the sustenance economy in Arctic and Subarctic communities as a source of fresh food throughout the year. Arctic charr populations have declined in recent years, in part due to climate change. These changes in the freshwater ecosystems in turn affect the cultural and economic traditions of freshwater fishing and consumption. This development has consequences for the tourism industry as hunting, fishing and consuming local and traditional food is important in branding tourism destinations. Fisheries are no longer the source of this important ingredient in the Nordic culinary tradition, instead aquaculture production supplies nearly all the Arctic charr consumed. In this paper, we pool the resources of an interdisciplinary team of scholars researching climate change, freshwater ecology, aquaculture and tourism. We integrate knowledge from these fields to discuss likely future scenarios for Arctic charr, their implications for transdisciplinary social ecosystem approaches to sustainable production, marketing and management, particularly how this relates to the growing industry of tourism in the Nordic Arctic and Subarctic region. We pose the questions whether Arctic Charr will be on the menu in 20 years and if so, where will it come from, and what consequences does that have for local food in tourism of the region? Our discussion starts with climate change and the question of how warm it is likely to get in the Nordic Arctic, particularly focusing on Iceland and Norway. To address the implications of the warming of lakes and rivers of the global north for Arctic charr we move on to a discussion of physiological and ecological factors that are important for the distribution of the species. We present the state of the art of Arctic charr aquaculture before articulating the importance of the species for marketing of local and regional food, particularly in the tourism market. Finally, we discuss the need for further elaboration of future scenarios for the interaction of the Arctic charr ecosystem and the economic trade in the species and draw conclusions about sustainable future development.

**Keywords: arctic charr (*Salvelinus alpinus*), climate change, aquaculture, tourism, food in tourism, fisheries, social ecological system**

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## INTRODUCTION

This is a conceptual study underpinned by the notion of socio-ecological system (SES) that Ostrom (2009) describes as a platform to gather, analyze and organize knowledge derived from different scientific areas. Guimarães et al. (2018) argue that extending such interdisciplinary research from the academic community to other sectors results in a transdisciplinary approach that lends itself to addressing sustainability issues. A solid knowledge base is important to engage trans-sectoral participation, define the problem and address it.

The SES in question is not an ecosystem in the conventional sense as a place-based entity but rather a value chain. The research problem is that of climate change impact on the value chain of Arctic Charr in regions of the North Atlantic. More narrowly defined the relationship of climate change and freshwater ecosystems; with the Arctic Charr, a species traditionally harvested for food and a local tourism product, as a case in point. We bring together and integrate knowledge from tourism, marketing, climatology, ecology, fish biology and aquaculture to provide a base for the discussion of viable future scenarios for the Arctic charr value chain in an era of climate change. This combined overview of recent research is a foundation on which to develop scenarios that may or may not, go against the grain of social representations of the relations between tourism, climate change and sustainability (Moscardo, 2012). This can contribute to knowledge-based action to meet the UNWTO goal: "Adapt tourism businesses and destinations to changing climate conditions" (2009, p. 11). A truly transdisciplinary project needs a sound epistemological foundation across fields of study and/or disciplines.

While climate change has become one of the key issues in discourses on tourism sustainability even to the extent of overshadowing other sustainability concerns (Moscardo, 2012), the dynamics of climate change, biodiversity and the tourism value chain is rarely considered. Research on tourism and climate change focusses on impacts and mitigation rather than an exploration of relations, networks and the interface between tourism and other industries (Prideaux et al., 2013; Jenkins, 2017). This is a heritage of instrumentalism noted in the research on sustainability issues in general. Tourism sustainability discourses have been described as limited to conservation of resources without recognizing that resources are "a complex and dynamic concept, evolving with changes in the needs, preferences and technological capabilities of society" (Liu, 2003, p. 461). An implication of this is to conceptualize nature as a dynamic context or system, rather than simply as the venue for tourism or as a service/experience scape (Margaryan, 2018). To do this, tourism research needs to be inter- if not transdisciplinary and applying mixed and/or multi-method approaches (Farrell and Twining-Ward, 2005; Becken, 2013; Khoo-Lattimore et al., 2019).

Tourism in the Nordic Arctic and Subarctic region has grown fast in terms of tourist arrivals, and so have the impacts of tourism on economies, societies and environment. Social ecosystem issues such as these are an under researched aspect of the tourism development, which needs to be addressed from a broad knowledge base to inform sustainability measures such climate change adaptation. "As climate defines the length and quality of tourism seasons, affects tourism operations, and influences environmental conditions that both attract and deter visitors, the sector is considered to be highly-climate sensitive" (UNWTO, 2009, p. 2). Climate change is of particular importance for Arctic tourism due to rapid change and perceivable impacts, which may affect the availability and supply of traditional local food.

Kelman (2009) talks of twin concerns regarding climate change and tourism in the Arctic: "The possible impact of climate change that may affect the viability of the tourism activities and the impact of tourism activities on the natural landscape" (2009, p. 96). The latter concern may be exasperated by the increased access to the Arctic envisioned by Valsson (2009). Increased demand for the region as a tourism destination as the temperatures approximate what is desirable in tourism, is one of the conclusions of Nicholls and Amelung (2015).

Typical tourism concerns pertain mostly to the physical impact of tourism on the destination, the presence of tourists in fjords and mountains bringing emissions, garbage and sewage into the region. Our interest lies in a rarely considered aspect, how the value chain of a species, including food and recreation in tourism is impacted by climate change. This is an important aspect as tourists are people with a basic need for nutrition. In the service economy and not the least in the experience economy logic, needs should not just be met, but transformed into an integral part of the tourism experience (Prebensen et al., 2018).

Arctic charr was traditionally an important source of food in the Arctic and Subarctic. Seasonal catches of Arctic charr were a staple in the diets of indigenous people such as the Inuit and Sami peoples (Johnston, 2002; Casi, 2020). Arctic charr is widely presented as local and traditional Nordic food. An interest in authentic food experiences is part of the global trend in tourism to search for "the local" where food and food culture are central in that context (Jönsson, 2013). The concept "local food" embraces a relation to a place and is ideologically connected to values such as environmental protection, biodiversity, social responsibility and fair trade (Sundbo, 2013). This makes local food an essential agent in tourism and destination development.

We will articulate the roles Arctic charr plays in tourism, as a local food provided by aquaculture and as an attraction in recreational freshwater fishing. We review recent research on climate change, that is global warming in the Arctic before moving on to discuss the effects this has on Arctic charr growth and production and we further elaborate the emerging threats that are associated with higher water temperatures. Then we integrate the implications for Arctic charr in freshwater ecology, aquaculture and tourism concluding with outlining possible future scenarios for further elaboration.

## MATERIALS AND METHODS

We conducted a literature survey for each of the following topics: Climate change in the Arctic, Freshwater ecology of Arctic charr, Arctic charr aquaculture, food in Nordic tourism, Tourism and climate change and Arctic Charr as a tourism product. Each group of experts wrote a narrative review of the state of art on their particular topic, which the author team reviewed and commented. Based on these reviews, we suggest potential future scenarios for the Arctic Charr SES and the implications discussed and presented as avenues for tourism marketing and product development around Arctic Charr in the Nordic Arctic and Subarctic region.

The global warming scenarios used here are based on the greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC) for its latest assessment report published in 2014. These trajectories have been applied to drive global climate models within the so-called 5th Coupled Model Intercomparison Project (CMIP5), producing quantified estimates of temperature change around the world. The estimates of warming in the Arctic discussed in this paper is based on this CMIP5 output.

## TEMPERATURE CHANGE IN THE ARCTIC

The first question we posed is; how warm will it get in the Arctic? Worldwide temperature measurements provide clear evidence for global warming during the past century, with temperatures having increased by more than 1°C relative to the preindustrial era in the late 1800's (Morice et al., 2020). This warming has been particularly expressed in the Northern Hemisphere extra-tropics, (to which the Nordic Arctic and Subarctic belong) where this rise in temperature exceeded 1.5°C. These changes have not been linear. A first warming phase between about 1900 and 1940 was followed by a period with stable conditions and even slight cooling that lasted until around 1980. Since then, Northern Hemisphere extra-tropics have experienced pronounced warming. This warming has been stronger in winter than in summer. The year 2016 was the warmest year on record and 2020 a close second (GISTEMP Team, 2020).

These three phases can also be recognized at a regional level, although the expression can be different in terms of degree of warming and timing. If we compare Iceland with Norway, clear differences are evident. For instance, in Reykjavik, Iceland, the warming exceeds the signal for the Northern Hemisphere extra-tropics, with mean annual temperatures increasing by 2.5°C in the last 100 years. Here, the seasonal contrast is as expected, with warming of more than 3°C in winter over the last 100 years, but around 2°C in summer. The timing in Reykjavik was also different from the hemispheric data, with the early warming phase continuing into the 1940's, while the second phase ended later, with the 1980's being still relatively cold. In contrast, in Norway, the annual warming over the last century was more similar to that for the Northern Hemisphere extra-tropics. However, there are substantial differences within this country, with the northern parts of Norway having experienced stronger warming since 1900 (around +2°C annual mean) than the south (around +1.5°C).

IPCC has used numerical climate models to make projections about future climate change, based on different scenarios for anthropogenic greenhouse gas emissions. According to these model results, annual mean temperatures will further increase in the decades to come, depending on the used scenario (Collins et al., 2013). In their fifth assessment report, the IPCC applies four different greenhouse gas concentration trajectories, referred to as "representative concentration pathways," or RCPs. These four RCP-scenarios are RCP2.6, RCP4.5, RCP6 and RCP8.5. The RCPs represent different global socio-economic scenarios, and their names reflect the radiative forcing (in $W \cdot m^{-2}$) in 2100 relative to preindustrial levels. RCP2.6 represents a decrease in the global greenhouse gas levels in the 21st Century following the Paris Agreement of 2015, whereas RCP8.5 implies an extreme scenario with a continuous rise in greenhouse gas emissions. For Iceland, the climate models project an additional annual mean warming compared to the present level ranging between +0.5°C (RCP2.6) and +3°C (RCP8.5). The high-end projections for SE Norway are a bit more extreme with +4°C for RCP8.5.

This prognosis raises the question what does it mean for Arctic charr? To address this question we provide a background on the species to explain how it will likely respond to a warming climate both in nature and in aquaculture.

## ARCTIC CHARR AS A SPECIES

### Distribution

Arctic charr have the northernmost distribution range of any fish species (Klemetsen et al., 2003). It has circumpolar distribution throughout the Arctic and into the temperate zone (Maitland, 1995; Klemetsen et al., 2003; Klemetsen, 2013). As glaciers receded during the end of the Pleistocene, some 11 thousand years ago, Arctic charr colonized emerging freshwater systems in their wake (Maitland, 1995). The success of Arctic charr as a pioneer species depends in part on their ability to survive and grow at lower temperatures than other freshwater species (Brännäs, 1992; Siikavuopio et al., 2010) as well as possessing significant phenotypic plasticity that allows them to acclimate rapidly to and exploit very different habitats (Klemetsen, 2010). Some populations of Arctic charr spend their entire life cycle in freshwater while others are anadromous and migrate to seawater for feeding during the summer months, but all spawn in freshwater lakes and rivers (Klemetsen et al., 2003). Watersheds with stable conditions opened possibilities for ecological specialization and evolutionary adaptations of separate populations to different habitats. As a result, many lakes possess two or more phenotypically and genetically distinct morphs of Arctic charr that differ in behavior, size and shape and utilize different niches, but in many cases descend from a single postglacial invasion of a founding population (Wilson et al., 2004; Gössling et al., 2012).

### Population Trends: Effects of Climate Change, Diseases and Commercial Catches

There are indications that Arctic charr populations are declining. Indeed, since the 1980s, catches of anadromous Arctic charr in rivers in Norway (Svenning et al., 2012, 2016) and Iceland are reduced (Malmquist et al., 2009; Jeppesen et al., 2012; Thordardottir and Guðbergsson, 2017; Thordardóttir and

Gudbergsson, 2020). In the United Kingdom and Ireland, Arctic charr populations have declined and several populations have gone extinct (Maitland, 1995; Winfield et al., 2010). The decline is clearly related to various anthropogenic factors such as eutrophication, damming, afforestation, and exploitation; however, it is likely that climate change is also an important factor (Maitland, 1995; Klemetsen et al., 2003; Winfield et al., 2010).

The mechanisms by which climate change affect the decline of Arctic charr populations can be varied (Crozier and Hutchings, 2014). Thus, increased temperatures may primarily affect charr distribution by compromising egg and embryo development or through increased disease load as temperatures increase. The temperature limits for development of good quality eggs during the summer and especially in the autumn, just prior to spawning, are between 8 and 12°C (Gillet, 1991; Jeuthe et al., 2013, 2015; Olk et al., 2019; Imsland et al., 2020) and the thermal limits for successful ovulation are under 10°C. Temperature requirements for embryonic development are even lower, e.g. 4–6°C (Skúlason et al., 1989; Gillet, 1991) and, therefore, increased temperature during the summer, autumn and even into winter can contribute to reduced recruitment of juveniles that may contribute to the decline of populations. A second factor that can contribute to reduced numbers of Arctic charr is increased disease load with increasing temperatures. Thus, Proliferate Kidney Disease (PKD), caused by the myxozoan endoparasite *Tetracapsuloides bryosalmonae*, has been an emerging disease in freshwater salmonids in the northern hemisphere for the last three decades (Burkhardt-Holm et al., 2005; Kristmundsson et al., 2010; Okamura et al., 2011; Svavarsdottir, 2016; Bruneaux et al., 2017; Mo and Jørgensen, 2017). Water temperatures exceeding 15°C over several days, stimulated the proliferation of *T. bryosalmonae* and outbreaks of PKD (Hedrick et al., 1993; Tops et al., 2009; Okamura et al., 2011; Bruneaux et al., 2017; Mo and Jørgensen, 2017). With climate change, outbreaks of PKD are expected to increase in the future.

Furthermore, warming of Arctic charr habitats has considerable ecological effects, which can contribute to unfavorable changes, e.g. in charr mobility patterns (Goyer et al., 2014) and different competitive situations with incoming species. For example, the decline in anadromous Arctic charr populations in NV-Iceland has been paralleled with rising numbers of sea-run brown trout (*Salmo trutta*) in these systems (Ferguson et al., 2019; Thordardóttir and Gudbergsson, 2020). It is clear that with increasing temperatures, many habitats that the Arctic charr now occupy will become inhospitable for the species and the catches of wild fish will decline in many regions of the Nordic Arctic and Subarctic. However, the decline of wild populations does not have a major effect on the availability of Arctic charr on the menu. Most of the commercially available Arctic Charr is already farmed and will be in the future as the aquaculture production of the species is growing.

Commercial catches of Arctic charr have never been large but during the 19th and early 20th centuries, Arctic charr was pickled and canned in the Canadian Arctic, Labrador and Greenland for export to Europe (Johnston, 2002). Similarly, between 1939 and 1987, the pelagic charr morph (*murta* in Icelandic), from the Icelandic lake Þingvallavatn, was caught and canned mainly for export (Snorrason et al., 1992). FAO reports catches of wild Arctic charr from 1963 to 2018 (FAO, 2020), however, these records are likely incomplete. For example, catches in Canada are only recorded in 2018 (69 MT) which is odd and may suggest that recreational and sustenance fishing is under reported. Therefore, Arctic charr fisheries may be somewhat higher than suggested by the FAO reports (Johnston, 2002). There are peaks in catches for example in France in 2012 (283 MT) and in Sweden in 2015 and 2016, 419 and 310 MT that may represent over 20 fold increase from previous or following years. Thus, the total reported annual catches range from 63 MT to 419 MT with an average of 186 MT.

## ARCTIC CHARR AQUACULTURE

Arctic charr have proven to be ideal for aquaculture in Nordic countries: Growing better at lower temperatures than other freshwater species and tolerating high rearing densities (Brännäs, 1992; Brännäs and Wiklund, 1992; Jobling et al., 1993; Brännäs and Linnér, 2000; Siikavuopio et al., 2010; Sæther et al., 2013, 2016; Imsland et al., 2019). The rapid growth of aquaculture in recent years has had its opponents and the discussion has been in the media (Schlag, 2011; Bacher, 2015; Froehlich et al., 2017). Among the main issues raised against aquaculture are the environmental impacts of waste from fish farms and the potential effects of mixing of aquaculture fish with wild populations.

Arctic charr in Iceland is primarily produced in intensive land based flow-through farms. Most of these farm use brackish water 7–12°C for the production. The Arctic charr production in Sweden is primarily in net cages set up in oligotrophic lakes that are reservoirs for hydropower production (Sæther et al., 2013). In Norway, Arctic charr is also produced in cages in lakes as well as in land-based systems. In Iceland, Sweden, and Norway, selective breeding programs are in place for Arctic charr. The total production of Arctic charr has increased progressively since 1987, and for 2019 it can be estimated 8300–8500 MT. The main producers are Iceland (∼60%), Sweden (∼27%), Norway (5%), Canada (3%), and Austria (3%). Other countries reporting Arctic charr production in recent years are Italy, Latvia, USA and the UK. The companies producing Arctic charr are very small compared with the large multinational companies in salmon farming. In Iceland, over 90% of the production comes from three companies and in Sweden the production is dominated two companies. Only one Arctic charr farm in Iceland has successfully branded its production and some smaller farms add value to their production by smoking the fish. In Norway, there are several smaller producers. Most of the production in Iceland is for export, while in other countries it is mainly for the domestic market.

As is the case for wild populations, increased ambient temperatures have affected Arctic charr production in Sweden (Jeuthe et al., 2013, 2015, 2016) and in Scotland primarily by increasing mortalities during the early developmental stages. However, chilling of rearing water for brood fish and incubation of eggs may remedy the problem. Survival rates during early development stages of aquaculture Arctic charr in Iceland, where temperatures are lower, are consistently higher than in Scandinavia.

Increasing and fluctuating temperatures may compromise the flesh quality of both wild and aquaculture fish. Relatively small differences in temperature (<5°C) are enough to elicit these changes (Ginés et al., 2004; Imsland et al., 2020). Arctic charr in many lakes develop a muddy off-flavor during the late summer due to accumulation of geosmins in the flesh. This can also occur in farmed charr where recirculating aquaculture systems are used for the production (Houle et al., 2011), although purging the fish in good water for a week or two will remove the off-flavor. Lower temperatures (<10–12°C) promote better quality in terms of freshness, color, and texture (Ginés et al., 2004; Imsland et al., 2020). Professional taste panels determined the quality of the charr in these studies, but the differences are likely large enough for the average consumer to discern. This can also create seasonal differences in quality where the annual rearing temperatures fluctuate with higher quality in winter than in summer. The quality of Arctic charr in recirculating aquaculture systems, that operate at a relatively high temperature and with little water exchange, may also be impaired (Houle et al., 2011). However, negative effects of high temperature on flesh quality may be mitigated by short term starvation before slaughter (Imsland et al., 2020).

The aquaculture of Arctic charr has primarily developed in Nordic and Alpine countries where climate conditions are favorable and the species is part of the local and traditional diet. Therefore, both environmental and cultural factors have contributed to the growth of Arctic charr aquaculture. In fact, one of the main challenges of marketing charr is that international markets are not very familiar with the species and its superior quality. Most of the production in countries other than Iceland is for the domestic market, including restaurants that cater to the tourism market. Essentially all Arctic charr available in stores or on the menus of restaurants, offered as new Nordic food, are farmed.

Given that aquaculture is the main source of Artic charr it will remain on menus in the future although wild stocks may decline. However, it is not clear to what degree increased temperature may affect the flavor and quality of Arctic charr. Given the importance of the species as a local food in the domestic market, this should be seen in context with the seasonality of the market, notably tourism as a market for Arctic charr. This leads us to consider the trends in tourism that make Arctic charr interesting as a case.

## ARCTIC CHARR IN THE TOURISM MARKET

Recreational activities in nature such as fishing are an important part of the product portfolio of tourism in the Nordic, Arctic and Subarctic regions. Seasonality is a defining trait of tourism in the regions: "As climate defines the length and quality of tourism seasons, affects tourism operations, and influences environmental conditions that both attract and deter visitors, the sector is considered to be highly-climate sensitive" (UNWTO, 2009, p. 2). Summer has been the high season of tourism in the region, but over the decade 2009–2019 winter tourism has doubled, leaving the shoulder seasons of spring and fall as the low season.

Water ecosystems are a resource in tourism as an attraction for a wide range of water based activities, which will be affected by climate change. The quality of the water, its ecosystem, the spatial/geological and aesthetic qualities of the waterway are important to keep the standard of the attraction (Gíslason et al., 1999; Sun and Hsu, 2019). This applies in niche tourism products such as angling tourism and lake tourism where wild Arctic charr is a resource. In Iceland, about 1.4% of international tourists say that they have gone fishing during their visit, which makes it one of the least popular outdoor recreational activities. In contrast, 8.5% of domestic tourists went fishing, making it one of the most popular activities (Ferðamálastofa, 2016).

The Arctic charr is a case supporting the claim that "Animals as food or as food for animal attractions is one of the most, if not the most, significant and pervasive use of animals in tourism" (Lamoureux, 2018, p. 2). While this is true, recent trends in tourism show an increased interest in tourism experiences that afford an opportunity for learning and growth (Prebensen et al., 2018). In this regard, it must be noted that nature is the main tourist attraction in the region (Fredman and Tyrväinen, 2010). Nature based products and services for tourists range from consumptive such as fishing and food tourism, to non-consumptive such as watching wildlife. An important aspect of nature-based tourism is educational and meets the need of an interested and well-educated audience for natural scientific information and inspiration. Which means that a local species is not only of interest as prey or food, but also as part of natural and cultural heritage.

The Arctic charr is of great importance as natural heritage and affords the opportunity to educate about developmental and evolutionary ecology. Winfield, Berry and Iddon account for the recognition of the cultural importance of Arctic Charr heritage for the Windermere. They speak of a shift from the Arctic Charr as "a provisioning ecosystem service in the form of food for local and distant human populations, to now providing a range of cultural ecosystem services encompassing cultural, spiritual, historical, recreational, and educational dimensions" (Winfield et al., 2019, p. 17). This potential for tourism product development is yet to be developed in the Nordic Arctic and Subarctic region where Arctic charr has so far mainly served as a food product.

Bessière pointed out already in 1998 that rural areas were seen as places for entertainment and leisure for urban residents, and that local food and food tourism presented economic potential for rural communities (Bessière, 1998). The tourism market craves healthy, uncontaminated and locally produced if not wild, food (Counihan and Van Esterik, 2016). The destination marketing campaigns for the Nordic countries and the North Atlantic over the last decades have focused strongly on meeting the culinary demands of this market. A case of this is the salmonid fish Arctic charr (*Salvelinus alpinus*), which today is common on the menu of restaurants in the region, often presented under the banners of New Nordic Food, Slow food or regional and local food labels.

In consumer tests and with professional taste panels, Arctic charr scores consistently higher than either Atlantic salmon (*Salmo salar*) or rainbow trout (*Oncorchynchus mykiss*) due to its milder flavor and texture (Johnston, 2002). In the words of Mrs Beeton, in her classic 19th century English cookbook:

> The Char—This one is the most delicious of fish, being esteemed by some superior to the salmon. It is an inhabitant of the deep lakes of mountainous countries. Its flesh is rich and red, and full of fat. The largest and the best kind are found in the lakes of Westmoreland, and, as it is considered a rarity, it is often potted and preserved. (Beeton, 2000).

Over the last couple of decades, national and regional agencies have implemented food tourism initiatives to attract tourists and promote places (Hall et al., 2003; Sims, 2010; Everett, 2012, 2016). Crossing national borders in the Nordic region, local food and place was at the center when The Nordic Council of Ministers kicked off the project New Nordic Cuisine in 2005. It was a "follow up" of the New Nordic Cuisine manifesto, launched in 2004 in Copenhagen, by a group of Nordic chefs. At that time, Nordic chefs generally became more aware of regional and local food and more visible in international contests such as the Bocuse d'Or competition, a biennial famous cooking award held in Lyon, which until then had mostly been won by French chefs (Nordic Council of Ministers, 2015). The New Nordic Cuisine manifesto embraces purity, season, ethnics, health, sustainability and quality—features attributed to the Nordic food. This joint Nordic project was systematically developed and promoted to strengthen the Nordic countries as a worthwhile tourism destination, and to give the Nordic cuisine, suffering a rather negative perception at the time, a new image (Haraldsdóttir and Gunnarsdóttir, 2012).

The criticism that the idea of New Nordic Cuisine was to a great extend borrowed from the Nouvelle Cuisine (and the Slow Food movement) did not ring loud (Leer, 2016). Shared cultural roots, a political image of democratic, liberal welfare states and geographical location were applied, with emphasis on the robust unbridled Nordic nature fostering clean and fresh ingredients. Low temperatures, short light summers and long dark winters create an important frame in the discourse, where Nordic climate and soil was supposed to sustain a unique characteristic in the Nordic food (Haraldsdóttir and Gunnarsdóttir, 2012; Leer, 2016).

Turning to another highly important trend, local food in tourism, there is a market for both farmed and wild Arctic charr. The idea of food and the meal experience has changed over the last decades (Belasco, 2008; Trubek, 2008; Jönsson, 2013). According to the ethnographer Håkon Jönsson the search for "the local" is the most extended global trend today (Jönsson, 2013), food and food culture are central in that context. Contemporary middle class food consumer culture is highly engaged with ethical and environmental issues where consumption of local food fits perfectly in (Leer, 2016). There is however, a contradiction in the demand for the local food as it is dependent upon global forces, such as international tourism (Pétursson, 2013; Haraldsdóttir, 2015). Research has suggested that convenience and price play an important role in the decision of purchasing organic, fair trade or local food on everyday basis (Sims, 2009). Thus, in order to be ethical and environmental friendly people travel and buy local food, some to support local communities, many to satisfy their desire to try something new and exotic as well as to experience local traditions through food (Haraldsdóttir, 2015; Leer, 2016). It should however be noted that while people are very positive toward purchasing and consuming local food when traveling, there is a gap between intention and consumption that can partly be explained by lack of marketing and branding of local products (Birch and Memery, 2020). This makes local food an essential agent in socially and culturally sustainable tourism and destination development.

## DISCUSSION

The rising temperatures alter the whole ecosystem from the reproduction of Arctic charr in the wild to the experience of tourists visiting destinations in the Arctic and Subarctic. The disappearance of ice and snow, which changes the visual experience of landscapes and the plight a few wild species such as the Polar bear have caught attention. Warming climate drives species north, but the effect of climate on fish that are popular tourist products has hardly been discussed. Concerns over wild Atlantic salmon for instance focus more on perceived threat from salmon farming than on climate change as a contributing factor to decline in wild stock.

Warmer waters are a threat to the Arctic charr affecting both their reproductive cycle, pressure from pests and diseases and competition (Skúlason et al., 1989; Gillet, 1991; Okamura et al., 2011; Jeuthe et al., 2013, 2015; Olk et al., 2019; Imsland et al., 2020). To answer the question of how warm it will get in the Arctic we have the prognosis of rising temperatures by +0,5°C to +4°C (IPCC,) but the rise will most likely not be linear over the next 20 years. Furthermore, there will be regional and local variations and microclimates depending for instance on water source, level of glacial melting and depth of lakes.

These variations present an opportunity for the Arctic charr due to its plasticity and resilience through rapid adaptation to diverse habitats (Klemetsen, 2010). Nevertheless, it is safe to assume that because of warmer climate, wild populations will disappear from many waterways and that Arctic charr fishing will diminish even further.

This does not mean that Arctic charr will become extinct and disappear from the menu. The Arctic charr consumed in the world comes to the largest extent from Arctic charr aquaculture (FAO, 2020). While warmer waters may pose difficulties for farming in lakes, the land-based production in closed systems is less sensitive to climate change. It is therefore possible to preserve local stock through cultivation.

The aquaculture production will secure an abundant year-round supply of Arctic charr in the future. In contrast, commercial catches of charr are small and seasonal. The supply of farmed charr is likely to increase while wild populations will likely decline further. Increasing temperatures may affect aquaculture production of Arctic charr where rearing temperatures are over 10–12°C, although chilling water, where possible, during critical production stages may ameliorate this effect. The method used to produce the charr determines the effects of climate change on the production. Where charr is produced in tanks at relatively low temperatures with well water of good quality, the effects of climate change on the production will be minimal. In contrast, the effect of climate change will be much greater when the charr are produced in cages in lakes or reservoirs where the ambient temperature can be comparatively high during the summer.

Arctic charr is marketed as pure traditional Nordic food with references to the cool, pristine waters of the region. The traditional supply of Arctic charr was through fisheries, but nearly all the charr prepared for tourists comes from aquaculture. This raises questions regarding authenticity and the suitability of farmed Arctic charr as a substitute for wild fish. Are customers seeking local and traditional food ready to accept farmed charr instead of wild fish? Consumer choices are complicated when it comes to choosing and buying fish (Rickertsen et al., 2017; Pulcini et al., 2020). Price, quality, nutritional value and health concerns are important, but also ethical issues such as sustainability of production and welfare of fish (Regnier and Bayramoglu, 2017; Banovic et al., 2019; Reig et al., 2019). Consumers are also a very diverse group and their attitude to aquaculture varies considerably (Bacher, 2015; Froehlich et al., 2017). Therefore, it is likely that the acceptance of farmed Arctic charr as a replacement for wild fish will vary among consumer groups and it is not at all clear if this is a major issue for restaurant customers. Given the findings of Birch and Memery (2020) this depends much on the marketing information to customers.

The environmental impacts of Arctic charr farms depend on the production methods. Cages are open and, therefore, uneaten feed and feces from fish will increase the organic load from the fish farms. This can lead to more organic productivity in oligotrophic reservoirs (Eriksson et al., 2010). Escapes from the net cages and the mixing of aquaculture fish (from breeding programs) with wild populations present certain risks. However, strict regulations about fish farming in the Nordic countries require environmental impact assessments that estimate the potential risks with regards to nutrient loading and risks to wild populations (Young et al., 2019). The environmental impact of land-based aquaculture is less than from cages in lakes and the sea. Filtering of the effluent from the farms removes organic particles and the probability of escapes from tanks is much lower than from cages. These issues are actively debated for Atlantic salmon aquaculture (Bacher, 2015; Froehlich et al., 2017; Young et al., 2019), but much less or not at all for Arctic charr farming. Therefore, it is not clear how important these opinions are when customers make their choices from Nordic menus.

There are no studies comparing consumer preferences for wild or farmed Arctic charr. Consumers may have preconceived ideas about the quality of wild and aquaculture fish, and in many cases consumers believe wild caught fish to be healthier and of better quality than aquaculture fish (Kole, 2003; Kole et al., 2003; Rickertsen et al., 2017; López-Mas et al., 2021). However, there is no evidence that farmed fish are of inferior quality to wild caught fish although there may be differences in texture and other sensory characteristic (Kole et al., 2009). The quality of wild fish is likely to vary throughout the year due to temperature fluctuations being lower in summer than in winter. In addition, geosmins may impart unpleasant muddy flavor to the flesh during late summer, which is high tourism season in the Nordic Arctic and Subarctic region. Therefore, the quality of wild fish is lowest when most tourist are visiting the Nordic countries. The quality of farmed charr is more constant, especially where water temperature is low. Therefore, farmed Arctic charr are a better option for restaurants.

Arctic charr will remain a traditional food, rooted in the natural and cultural heritage of the region. Today the biggest producers operate in the Arctic and Subarctic region and their product can be labeled local in the region. However, it is possible in an era of globalization to move production elsewhere and this would be a threat to the branding of Arctic charr as integral to the New Nordic cuisine for example.

The Arctic charr is a species that is of great value in imparting knowledge about ecology, natural and cultural heritage. This aspect can be explored to a greater extent in nature-based tourism in the region. The climate change discourse in and around has lacked focus on important concerns such as loss of biodiversity, landscape and ecosystem changes and the social and cultural impacts (Farrell and Twining-Ward, 2005; UNWTO, 2009; Bock, 2016). The Arctic charr provides a good case in point for these factors.

## CONCLUSION

This review suggests that Arctic Charr as a local, traditional food in the Nordic Arctic and Subarctic region will be increasingly in demand in a growing market, both domestic and tourist that craves local, sustainably produced and healthy food. This is however, only one of the three main roles that Arctic charr can play in tourism. It is to a limited extent prey for tourists who like to fish it; it is a popular local and traditional food and it is of great interest as natural heritage.

Typical tourism concerns in the Nordic Arctic and Subarctic center on the physical impact of tourism on the destination, the presence of tourists in fjords and mountains bringing emissions, garbage and sewage into the region. Our interest lies in a rarely considered aspect, tourism and the food chain. This is an important aspect as tourists are people with a basic need for nutrition. In the service economy and not the least in the experience economy logic, needs should not just be met, but transformed into an integral part of the tourism experience as culinary tourism and nature-based tourism. The characteristics of the Arctic charr, the great plasticity and resilience are factors that could feature in product development. That is, the natural history of the Arctic Charr might both be conceptualized as an attraction in itself through nature and natural heritage based tourism as educational tourism and as an added value to the food experience.

Among the research gaps that we have identified are: (a) better measuring and modeling of how biological and physical systems in water will change as a consequence of climate change; (b) measures and models of how the industries using Arctic charr as a resource; aquaculture and tourism will be impacted. Such data will enable the formulation of scenarios and actions in response to these changes. One area of likely change is the species mix as species move, adapt or become extinct from ecosystems as they become warmer. For the Arctic charr this presents a scenario of an even narrower distribution further north, at higher altitudes and in deep lakes. From an evolutionary ecology perspective, monitoring how Arctic charr adapts in the current climate crisis may have significant implications.

Further research is also needed on the economic impacts of climate change on the industries using Arctic charr. For aquaculture, a future scenario will likely involve increased effort and resources devoted to controlling water temperature and water quality. The pen aquaculture in lakes is more vulnerable to the warming climate than closed land-based systems, which will have implications for the economic prospects of the sector.

This review suggests a path forward in research and practice that answers the call for a closer collaboration between tourism researchers and natural scientists in exploring what climate change might mean for Arctic charr, aquaculture and tourism.

## AUTHOR CONTRIBUTIONS

GH: corresponding author, conceptualization, wrote the abstract, discussion and conclusions, coherence between sections and general editing of the manuscript according to the journal style as well as co-authoring the Arctic Charr in the tourism market section. HR: conceptualization, authored the section on climate change. HT: conceptualization, authored the section on Arctic charr and aquaculture and contributed to the section on tourism and Arctic charr as a species. LH: co-authored the section on Arctic charr and tourism, marketing of arctic charr as part of destination branding and arctic charr as local food. SS: conceptualization, contributed to the chapter of Arctic Charr as a species, worked on coherence between sections. TRO: co-authored the section on Arctic Charr as a species and reviewed referencing for the whole document. TJO: co-authored the of the section on Arctic charr as a species. All authors contributed to the article and approved the submitted version.

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REVIEW
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# Seafood in Food Security: A Call for Bridging the Terrestrial-Aquatic Divide

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The contribution of seafood to global food security is being increasingly highlighted in policy. However, the extent to which such claims are supported in the current food security literature is unclear. This review assesses the extent to which seafood is represented in the recent food security literature, both individually and from a food systems perspective, in combination with terrestrially-based production systems. The results demonstrate that seafood remains under-researched compared to the role of terrestrial animal and plant production in food security. Furthermore, seafood and terrestrial production remain siloed, with very few papers addressing the combined contribution or relations between terrestrial and aquatic systems. We conclude that far more attention is needed to the specific and relative role of seafood in global food security and call for the integration of seafood in a wider interdisciplinary approach to global food system research.

**Keywords: food security, seafood, food system, food and nutrition security, interdisciplinary**

## INTRODUCTION

Seafood, including the full range of animals and plants produced in water and encompassing both marine and freshwater environments, makes an important contribution to global food security—an estimated 59.6 million people depend on capture fisheries and aquaculture for their livelihoods and nutrition, and a further 3.2 billion people rely on fish to provide 20% or more of their average per capita intake of animal protein (FAO, 2018). This consumption of seafood is particularly important for low income regions of the world where plant and animal seafoods are a major source of essential nutrients including long-chained polyunsaturated omega-3 fatty acids (Michaelsen et al., 2011; Lund, 2013), and vitamins and minerals such as calcium (Larsen et al., 2000), iron, zinc, and vitamin A (Roos et al., 2007).

Despite the importance it makes to the global diet, attention has only recently turned to the importance of "sea-food security." The role that seafood plays, both currently and into the future, has been highlighted in several recent global science-policy documents (e.g., HLPE, 2014; United Nations, 2015). The overall message encapsulated in these reports, complimented by a growing academic literature, is that the role of seafood in food security is not only significant but also largely underestimated. However, much of the literature on seafood security is "siloed" with attention given to the role of marine and freshwater animal and plant production consumption largely in isolation from the terrestrial food with which it is consumed (Béné et al., 2015).

Isolating out seafood from the rest of the food system is problematic for several reasons. First, aquatic and terrestrial food production is intrinsically linked, given their use of the same finite resources and the feedback cycles which connect them—perhaps most obvious when agricultural water pollution impacts on aquatic food production systems (Parris, 2011), and given the increasing reliance of fed aquaculture on terrestrial feed ingredients (Naylor et al., 2021). Second, understanding the relative impact of aquatic and terrestrial foods, in terms of climate emissions, land use, and resource use is essential to enable "whole plate" sustainability assessment and planning (Hilborn et al., 2018; Parker et al., 2018; Poore and Nemecek, 2018; Tsakiridis et al., 2020). Third, understanding sustainable nutrition also means understanding the relative contribution of seafood in contrast and combination with terrestrial foods—both in absolute nutritional terms (Willett et al., 2019) and in terms of replacing terrestrial proteins such as beef (Tilman and Clark, 2014; Davis et al., 2016). While growing attention is being given to the importance of understanding the role of seafood from an integrated food systems perspective (Béné et al., 2015; Blanchard et al., 2017; Gephart et al., 2017; Cottrell et al., 2018; Bogard et al., 2019; Halpern et al., 2019; Tlusty et al., 2019; Tezzo et al., 2020; Bennett et al., 2021), it is not clear to what extent the contribution of seafood is considered in the context of food security both alone and in combination with terrestrial food production.

In this paper we fill these gaps by reviewing the ways in which the academic literature on food security published between 2007 and 2017 has addressed the contribution of aquatic and terrestrial food production to food security within the wider global food system. In doing so we consider food security from a food system perspective (Ericksen, 2008; Ingram, 2011) that integrates production, processing, distribution, and consumption of food with food security outcome categories of availability, access, and utilization, as well as impacts on environmental, social, and economic sustainability dimensions. We also explore how the contribution of seafood has been treated in this literature in terms of weighing the contribution of fisheries and aquaculture to nutrition with its wider social, economic, and environmental impacts in different parts of the world. Finally, following the ambitions of food systems research to recognize the multi-faceted nature of food production, trade and consumption, we explore the degree to which sea-food security has been taken up through interdisciplinary research approaches (following Horton et al., 2017).

The following section describes the scoping review methodology we adopted for this study as well as the parameters used to delimit our literature search and document analysis. We then present the results of the review, focusing on the prevalence of seafood in relation to terrestrial livestock and crops in the light-touch review and the content of papers specifically focused on seafood in terms of the importance given to seafood, the quality of this analysis and the degree to which an interdisciplinary food systems perspective is currently applied. Finally, we discuss the potential for future research to integrate the role of seafood more centrally in global food systems research.

## METHODS

We adopt a scoping review methodology to map key areas of recent literature related to seafood's role in food security and identify research gaps in the existing literature (Arksey and O'Malley, 2005). Following Munn et al. (2018), we determined that a scoping review is better suited to our objectives than other types of literature synthesis, such as systematic reviews, because we are interested in providing an overview or map of the current evidence rather than addressing the feasibility, appropriateness, meaningfulness, or effectiveness of the methods within this literature. A further benefit of a scoping review is that while they make use of an *a priori* protocol and aim to be transparent and reproducible, they allow more flexibility for including review papers as well as qualitative and quantitative research. As argued by Peterson et al. (2017), this makes scoping reviews particularly well suited to complex and interdisciplinary areas of literature such as food security.

We delimited the scoping review to seven key themes related to food security: "production," "nutrition," "behavior," "consumption," "modeling," "resource use," and "safety." These themes were inductively generated by the Sustainable Seafood Consumption Initiative (SSCI)[1e] based on interdisciplinary research experience, and agreed at the first SSCI international meeting, which brought together and provided input from over 50 experts representing more than 15 countries across Europe, South East Asia, Africa, and North America, from a diverse range of disciplines and a mixture of terrestrial and aquatic food research backgrounds. These themes were intended to ensure papers were incorporated in the review from a variety of disciplines and with a number of different disciplinary perspectives on food security.

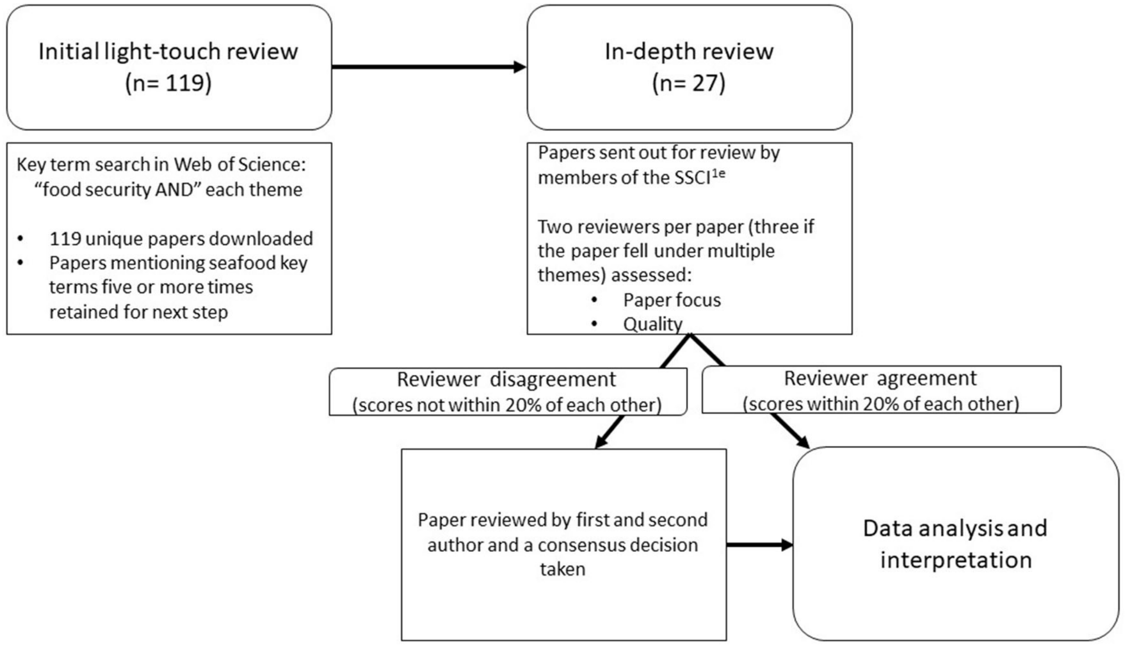


**FIGURE 1 |** Overview of scoping review methodology used in this paper. Themes included in the key term search: nutrition, behavior, production, consumption, modeling, resource use, and safety.

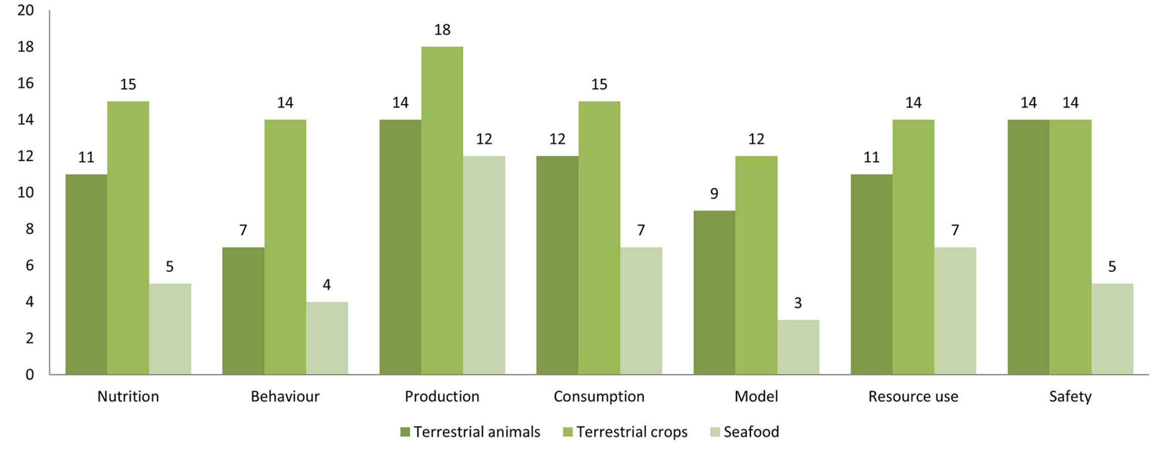


**FIGURE 2 |** Number of papers mentioning each food category five or more times, by theme.

The analysis aimed to identify differences in representation of seafood compared to terrestrial food among these themes and was implemented in two stages: 1. an initial light-touch review that identified potentially relevant papers to the topic, and 2. an in-depth review of papers for a range of important characteristics (**Figure 1**).

## Initial Light-Touch Literature Review

The Web of Science, one of the fourteen academic search engines found to meet all performance requirements to be suited to being a principal literature search source (Gusenbauer and Haddaway, 2020), was selected as the database for this project due to its inclusion of over 73 million pieces of data, replicability of search strings, and advanced search settings. For works published from 2007 to January 2018, the first 20 papers available in English, sorted by relevance, were downloaded for seven combinations of keywords—"food security" AND each individual theme: "nutrition," behavior (searched as "behavi*r", to include both UK and US spellings), "production," "consumption," modeling (searched as "model"), "resource use," and "safety." This resulted in 140 papers, 21 of which were duplicates (i.e., these papers were in the first twenty papers listed for two or more themes), giving a total of 119 unique papers across the seven themes (see **Supplementary Materials** for a full list of papers and themes).

Using the Web of Science "topic" search function meant that the key words from this review were searched for within the paper's title, author-selected keywords, keywords plus (words or phrases that frequently appear in the titles of an article's references), and abstract, allowing for a broader sample than if only those papers with the review keywords in their titles or author-selected keywords were returned.

Each paper was manually reviewed to determine the number of times key terms relating to seafood (fish, seafood, seaweed, etc.), terrestrial crops (rice, wheat, vegetable, etc.), and terrestrial animal-source foods (beef, chicken, dairy, etc.) were used. Five or more mentions of any combination of key terms for the seafood category was set as the threshold for further review; where a paper mentioned key terms relating to seafood, terrestrial crops, or terrestrial animals five or more times, it was deemed possible that this food category was a core component of this paper. Where a paper mentioned a given food category less than five times, this was assumed not to be a substantive element of the paper, for example in reference to the use of similar methods in another system, or in introduction or discussion sections as an area for further study.

Comparisons were made of the number of papers mentioning each food category five or more times by theme (**Figure 2**). In order to determine whether papers were focusing on only one food category, or whether papers were more likely to consider multiple food categories, the number of papers mentioning only one food category five or more times, those mentioning two food categories five or more times, and those mentioning all three food categories five or more times were quantified (**Figure 3**).

## In-depth Paper Reviews

A total of 27 papers mentioned seafood key terms five or more times and were reviewed in-depth. Expert reviewers were sought through the SSCI[1e] and each paper was assigned for review according to area of expertise. Reviewers were asked to answer

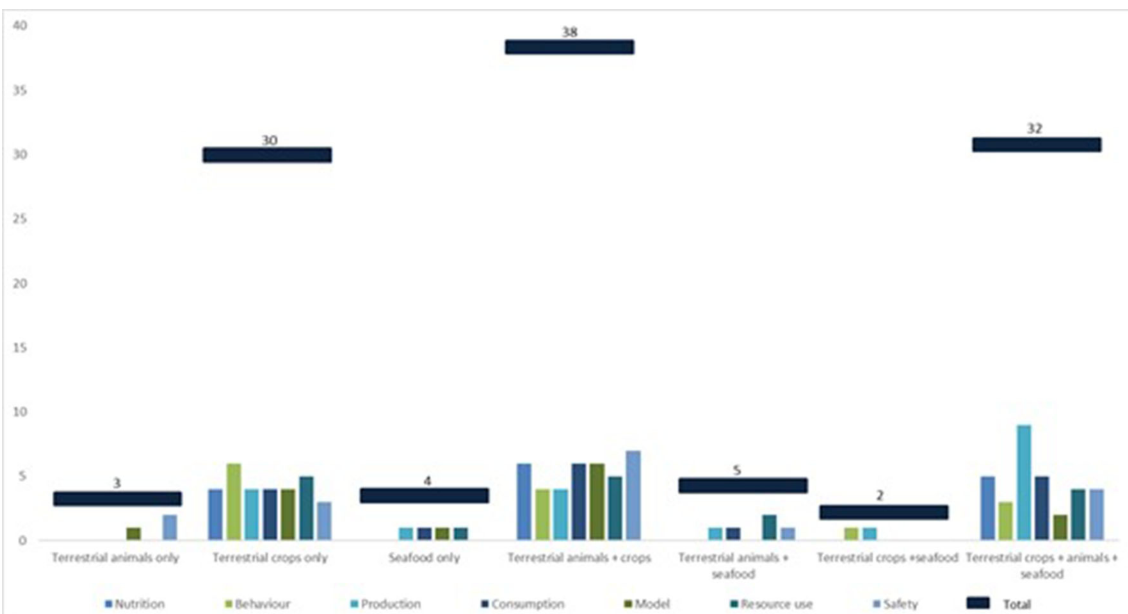


**FIGURE 3 |** Number of papers mentioning each food category and/or combination of food categories five or more times. Duplicated papers, those which appeared in multiple themes' literature reviews, are counted only once. Total refers to the total number of papers mentioning each food category and/or combination five or more times.

**TABLE 1** | Reviewer template for considering paper focus.

| | Possible responses |
|---|---|
| How integral is seafood to this paper? | 1— Not very, e.g., seafood is only mentioned in introduction and discussion in passing<br>2— Moderately, e.g., paper uses seafood as an example, but doesn't provide much detail/analysis<br>3— Very, e.g., seafood is a core topic of the paper |
| Which countries/ geographical areas are the focus of this paper? | Free text response |
| Is the focus on over- or under-consumption of food? | Underconsumption, overconsumption, neither under nor overconsumption, both under and overconsumption |
| Level of interdisciplinarity? | 1— mono-disciplinary, e.g., paper uses standard biological methods without discussion of other areas<br>2— paper includes some interdisciplinary elements, e.g., paper uses biological methods but includes a brief economic analysis<br>3— paper is highly interdisciplinary, e.g., paper uses biological outputs to inform an economic model |

**TABLE 2** | Reviewer template for considering paper quality [adapted from Béné et al., 2016].

| | Criteria | Possible responses |
|---|---|---|
| Validity | Are the findings substantiated by the data and has consideration been given to limitations of the methods that may have affected the results? | Yes, No, Partially |
| | Are there problems in applying the method to some research question(s)? | Yes, No, Partially |
| Rigor | Is the context or setting adequately described? | Yes, No, Partially |
| | Is (are) the research question(s) clear? | Yes, No, Partially |
| | Is the method used appropriate to answer the research question(s)? | Yes, No, Partially |
| | Is the method applied correctly? | Yes, No, Partially |
| | Is there evidence that the data collection was rigorously conducted to ensure confidence in the findings? | Yes, No, Partially |
| Reliability | Is the data analysis rigorously conducted to ensure confidence in the findings? | Yes, No, Partially |
| | Is the methodology adequately described to ensure confidence in the findings? | Yes, No, Partially |
| Any other comments or notes | | |

a series of questions relating to paper focus (**Table 1**) and quality (**Table 2**).

Quality was assessed using the methods presented by Béné et al. (2016), which calculate a percentage score based on answers to nine questions in the categories of validity, rigor, and reliability. Where this method was not suitable for a given paper (e.g., theoretical papers or reviews), quality was not assessed. An overall quality score was calculated for each paper, based on each reviewer's answers. Where differences between reviewer answers were >20%, the lead and second author reviewed the paper and took a consensus decision regarding quality. Overall quality levels were classed as: high quality—required the paper to have scores of over 0.75 for all three of validity, rigor, and reliability; moderate quality—had at least one score below 0.75, but at least two scores above 0.5; and low quality—where at least two of the scores fell below 0.5.

Where reviewers disagreed about issues relating to paper focus, the first author reviewed the paper in question and took a final decision. The majority of data regarding paper focus and quality were summarized according to theme and across the whole dataset. As no papers were listed as having a focus on overconsumption of food alone, this is not reported further.

Final scores were calculated by taking an average of the responses to the question "How integral is seafood to this paper." Where this score was below 1.5, the answer was deemed to be "Not very integral" between 1.5 and 2.49 was deemed to be "Moderately" integral and ≥2.5 was deemed to be "Very" integral. The same method was used to assess the level of interdisciplinarity, based on the use of, or discussion of, multiple discipline perspectives on the research question. For example, a paper which used only standard biological methods would be considered mono-disciplinary, while a paper which used biological analysis to inform an economic analysis and presented both results would be considered highly interdisciplinary. In order to determine to what extent the representation of seafood in the literature is simply a result of local importance in the diet, for countries/geographical areas, comparisons are drawn between the level of importance of seafood in the paper and the importance of fish to diets in that country in terms of % total protein supply coming from seafood.

# RESULTS

## Prevalence of Seafood in Relation to Terrestrial Livestock and Crops in the Light-Touch Review

The results of the light touch review reveals that terrestrial crops were the most frequently represented in the sampled papers across all themes with the exception of food safety, where terrestrial animals (generally the second most commonly represented) were represented in an equal number of papers. In contrast, the number of papers mentioning seafood accounted for less than half of those reviewed in each theme (**Figure 2**).

The majority of papers, however, were not specific to a single food category and included key terms for two or three categories of food. The most common combination of these terms, for 32% of papers, related to terrestrial animals and crops (**Figure 3**). Twenty-two papers mentioned all three food categories at least five times. The least common combination was terrestrial crops and seafood, accounting for only two papers, followed

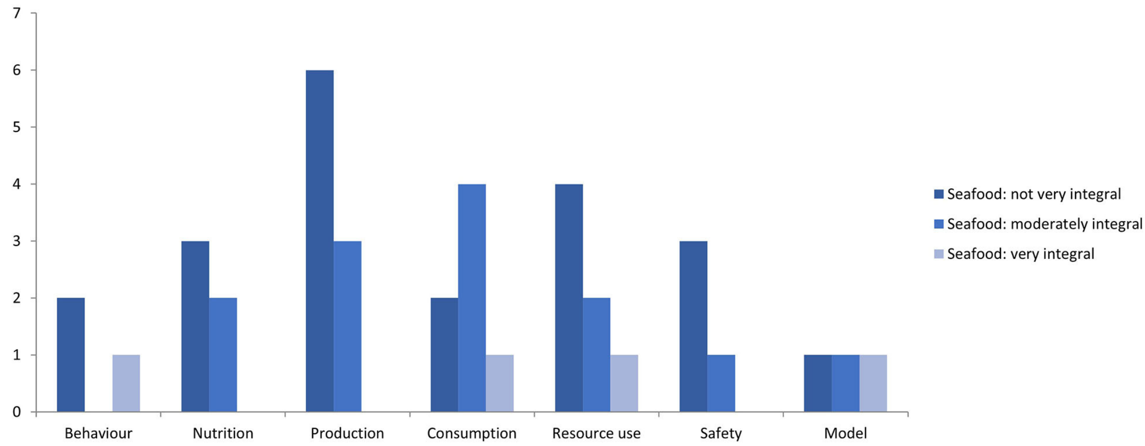


**FIGURE 4 |** Importance of seafood to the papers, by theme.

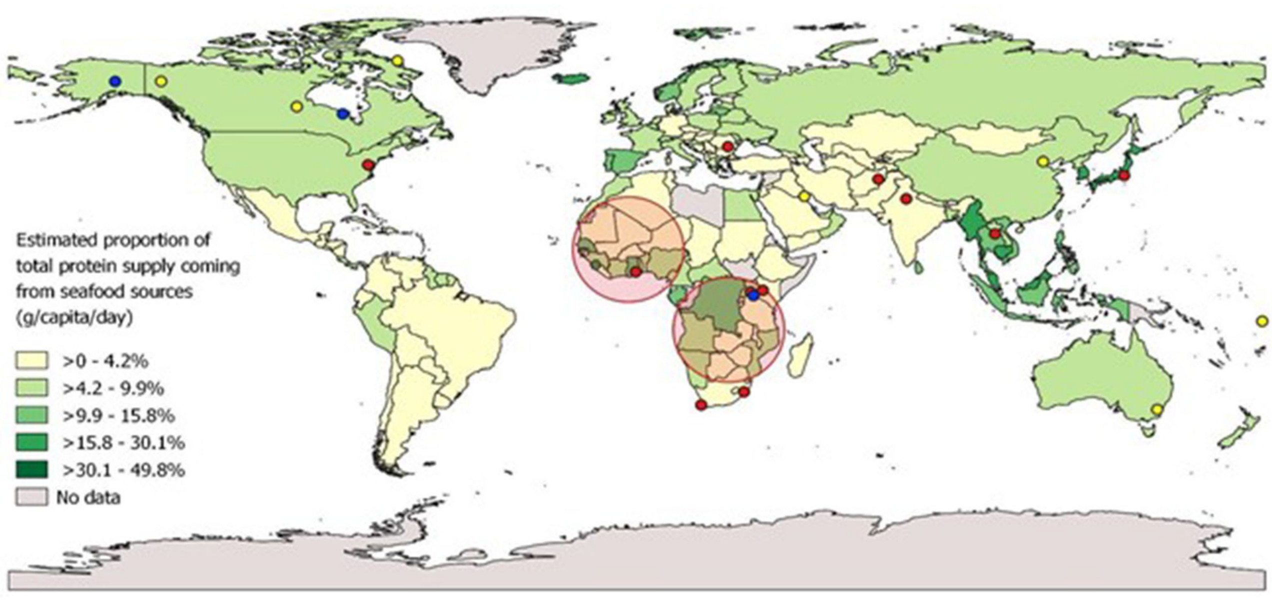


**FIGURE 5 |** Geographic distribution of papers reviewed in-depth. Papers with a global scope are not represented. Where papers focused on an entire country, their geographic location is given as the capital city. Two papers considered multi-country regions—these are indicated by the two large circles (these circles do not delineate the exact area covered), one of which was relating to West Africa, and one relating to Sub-Saharan Africa. Colors show how integral seafood was to this paper—blue dots indicate seafood was very integral, yellow that seafood was moderately integral, and red that seafood was not very integral. Green country shading indicates the estimated proportion of total protein supply derived from seafood (calculated as the sum of total fish and total other aquatic protein supply) in 2013, as per FAOSTAT food balance sheet data (FAO, 2017). The map was prepared in QGIS and values were categorized using Jenks natural breaks classification to show groups in the data.

by terrestrial animals and seafood (five papers). This indicates a general lack of research cutting across both terrestrial and aquatic systems in comparison with terrestrial-terrestrial systems (**Figure 3**). The least common food category was terrestrial animals, though both terrestrial animals and seafood were discussed individually far more rarely than terrestrial crops (three papers on terrestrial animals only, as compared with four for seafood only, and 30 for terrestrial crops only).

## In-depth Analysis of Papers Mentioning Seafood key Terms Five or More Times

### Level of Importance of Seafood

Seafood was "very integral" to only three out of the 27 papers subject to in-depth review, and moderately integral to a further eight of these papers. It was not deemed integral to the remaining majority of papers. Some variation exists by theme, both in terms of total number of papers reviewed and in respect to seafood

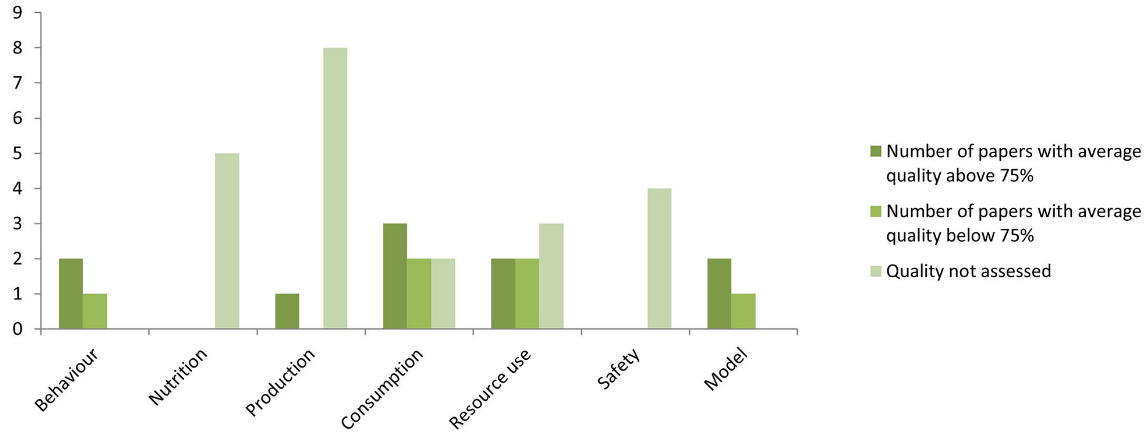


**FIGURE 6 |** Quality assessment by theme. Note that due to some papers being present under multiple themes, the number of papers in this figure does not add up to 27.

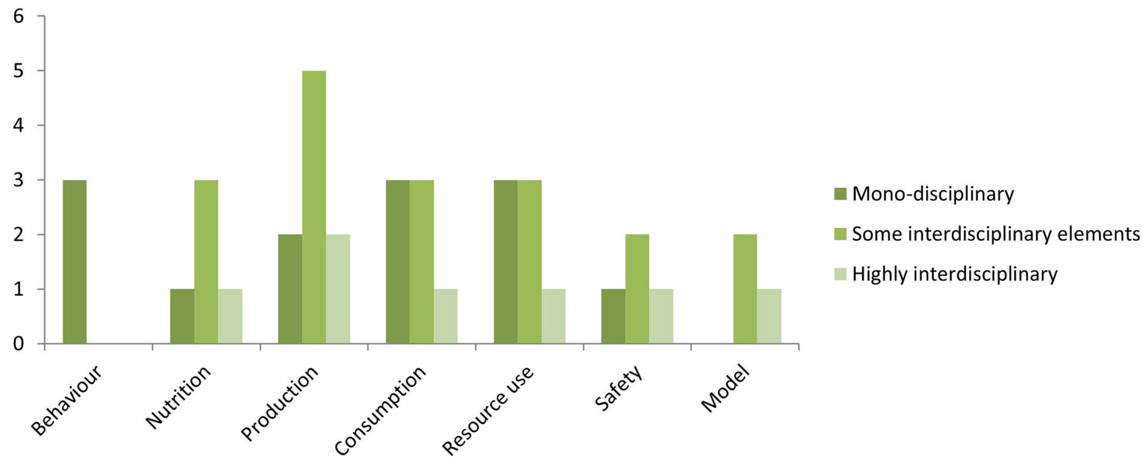


**FIGURE 7 |** Level of interdisciplinarity, by theme.

integrality, with papers in the "Modeling" theme equally split between not very integral, moderately integral, and very integral, and more than half of papers in the "Consumption" theme rated seafood as moderately integral (**Figure 4**). The "Production" theme, by contrast, has no papers where seafood was deemed very integral, despite having more papers reviewed than any other theme.

## Geographic Distribution

Papers reviewed came primarily from North America, Africa, and Asia, with few papers from Europe and Australia, and none from South America (**Figure 5**). Seafood was very integral to all but one of the North American papers; this is in sharp contrast to the papers from Africa, where seafood was not very integral to all but one. It is therefore not simply the case that seafood was very integral in papers from countries where it plays an important role in diets, and not integral in countries where it does not. Three papers were considered to be global in scope—these are not included in **Figure 5**, but in all cases, seafood was classed as not very integral.

## Paper Quality

Out of the 27 papers reviewed in depth, 13 were review or theoretical papers, and so were not given a quality score. The high proportion of review papers in this sample highlights the depth of primary literature relating to food security. Of the remaining 14 papers, 8 had an average quality score of over 75% and were deemed to be of high quality, and 6 of under 75%. For themes where papers could be assessed by quality, the number of papers with an average quality below 75% never exceeded the number of papers with an average quality above 75% (**Figure 6**).

## Paper Interdisciplinarity

Over 70% of papers reviewed in-depth were considered to be mono-disciplinary, with six papers having some interdisciplinary elements, and only two papers being considered highly interdisciplinary. Some variation among themes is evident, with all "Behavior" papers being mono-disciplinary, while more than half of the papers from the "Nutrition" and "Production" themes had some interdisciplinary elements (**Figure 7**). "Model" was the only theme which did not contain any mono-disciplinary papers.

## DISCUSSION

Seafood was not integral to the majority of the 27 papers reviewed in-depth across all themes, and appears to be particularly under-represented in relation to nutrition, production, and safety, themes where no papers were deemed to have seafood as a very integral component. However, seafood is not totally absent from the reviewed literature, as evidenced by the fact that key seafood terms were mentioned at least five times in multiple papers under each theme. Given the importance of terrestrial crops to food security, it is unsurprising that these production systems are most prevalent in the food security literature reviewed.

Overall, the review reveals a low degree of integrated food-systems thinking as represented by the few papers that combined seafood with both terrestrial crops and terrestrial animals. The terrestrial food security literature does in contrast integrate terrestrial plant and animal production more substantially. The lack of attention given to understanding the interlinked role of seafood for food security highlights a clear set of gaps in the recent food security literature. First, it currently fails to adopt a whole-plate approach to nutrition that would enable a clearer understanding of the relative importance of water and land-based foods and the future challenges of changing patterns of availability. Second, at the production end, there is an ongoing need to understand the consequences of further feed-based intensification as aquaculture continues to grow and depend on a growing share of both terrestrial and aquatic plant-based feed stock (Troell et al., 2014). Third, it fails to draw attention to the multiple facets of transitioning to a holistic understanding of sustainable food systems that considers the relative consequences of terrestrial and aquatic foods in terms of food safety, feedback from land and sea-based behavioral change and the wider ecosystem level feedback from resource use.

The lack of an integrated food systems approach is also evidenced by the geographical spread across the papers reviewed. The lack of attention to seafood in the papers reviewed was not a function of where the research had been undertaken. In more than half the papers with a single country focus, seafood made up at least 5% of total protein supply—for context, seafood makes up 5% or more of the protein supply in 89 countries, and <5% in 88 countries (FAO, 2017). Further, the local importance of seafood in diets did not link clearly with the importance of seafood in the reviewed papers, despite the fact that seafood can be critical to communities vulnerable to poverty and nutritional insecurity (de Roos et al., 2018) and could continue to support food security as the global population increases, particularly in the Global South (Béné et al., 2015). Further study, specifically assessing the representation of seafood in the food security literature from these regions could help to clarify these findings. Such an understanding is important because regions where fish is a key component of the diet, such as South East Asia (FAO, 2017), are often also areas where climate change is expected to have a disproportionately high impact on public health, as well as economic, political, and resource security (Kumaresan, 2011). Specific groups, such as coastal indigenous peoples, who are highly vulnerable to climate change, are also highly reliant on seafood, with a per capita consumption which is 15 times higher than their non-indigenous counterparts (Cisneros-Montemayor et al., 2016). For Pacific Island countries and territories, for example, where subsistence fishing provides a key source of dietary protein, forecasts predict that even well-managed fisheries will struggle to meet demand in 2030 (Bell et al., 2009). In this region, redistribution of fish due to climate change poses a serious threat to food security, one which may require policy intervention and negotiations to ensure long-term resource conservation (Bell et al., 2021). Such region-specific research is needed to ensure local seafood system sustainability, with knowledge sharing across regions allowing best practice to spread rapidly and underpin global sustainability. Seafood from aquaculture may increasingly support food systems as they become more sustainable (Béné et al., 2019). In this context, it is worth noting that there is at best a weak connection between fisheries and aquaculture policies; given the products of each are often considered substitute goods by the consumer (and this can extend to terrestrial goods such as chicken), better integration seems key to policy-making for food security. The lack of papers focusing on South America is also worth noting, and may reflect either a lack in publications relating to (sea)food security in this area, or a lower number of papers relating to South America published in English during the time frame selected for this review.

The weak interdisciplinarity observed in the reviewed papers suggests that important components from a food systems perspective, such as sustainable seafood in a dietary context, may be lacking integrated attention. Similarly, research on seafood needs to better contextualize the role of aquatic products within the broader food system, including consideration of the trade-offs for different food types in a balanced diet. Despite calls for interdisciplinary research to address the challenge of food security (Ingram, 2011; Yu et al., 2012; Horton et al., 2017; Bogard et al., 2019), and calls for researchers to move outside the epistemic bubbles of a single research discipline in order to increase accountability (Huutoniemi, 2016), this finding highlights the dominance of research in single discipline silos. Therefore, despite the evolution in problem context over the period assessed in this literature review—broadly toward the need for integrated and interdisciplinary research (e.g., United Nations, 2015; FAO, 2019; Willett et al., 2019)—the papers reviewed do not reflect this, highlighting an important research gap and raising the question of structural issues which may be preventing the widespread uptake of interdisciplinary research in the area of (sea)food security. Of interest, however, is the fact that none of the papers where seafood was deemed very integral included author affiliations to research institutes with seafood key terms in their names, suggesting these issues are of some interest to more generalist organizations.

One limitation not addressed in this paper is the question of whether seafood is under-represented in the food security literature because of a lack of research, or, whether seafood research was not included due to a lack of the use of the term "food security" in the seafood literature. However, given that a search in Web of Knowledge for "food security" (alone giving 25,123 papers) *and* "crop" gives 6,998 results, "livestock" gives 1,200, "fish" gives 1,052, it seems unlikely that it is a lack of the use of this keyword alone which has given rise to this outcome. The similarity in number of papers returned for "livestock" and "fish" is particularly interesting, and suggests that researchers in these areas are equally likely to highlight the food security aspects of their work.

Due to the time scale of the papers assessed in this work (2007–January 2018) a number of important publications which were published after this date are, by definition, excluded from this analysis. Work done on the potential for fish to provide key micronutrients for sustainable diets (Hicks et al., 2019), and the inclusion of seafood in recent conceptualisation of sustainable food systems (Bogard et al., 2019; Halpern et al., 2019), as well as the inclusion of seafood as a potentially important component of the EAT-Lancet reference diet (Willett et al., 2019), all point to a growing literature working to integrate seafood more fully into sustainable food systems discussions. This paper should therefore be seen as offering insight into a particular slice of time, which could, in future work, be compared to later periods of time to assess the growth and integration of this area of research in the wider sustainable food systems discourse. This study is also limited in scale, assessing 119 papers taken from a vast corpus, and while 118 papers is the average sample size seen in a review of 494 scoping studies (Tricco et al., 2016), further analysis may identify additional research gaps of interest.

While it is difficult to assess what proportion of the literature would constitute an ideal representation of seafood, it is clear from this review that seafood is rarely included as a core component of the food security papers reviewed, despite the fact that seafood forms a potentially important component of a healthy and sustainable diet. The significant growth in fisheries and aquaculture production since the middle of the twentieth century, and especially in the past two decades, has enhanced the world's capacity to consume diverse and nutritious food. Global apparent fish consumption has, on average, increased faster than population growth since 1961 (3.2% as compared to 1.6%), and exceeded terrestrial animal meat consumption for all categories other than poultry (FAO, 2018)—though concern has been raised over such comparisons of fish and meat figures, particularly around differing reporting processes and a lack of comparison made on an edible portion basis (Edwards et al., 2018). Food fish consumption has increased from 9.0 kg per capita per year in 1961 to 20.2 kg per capita per year in 2015, with preliminary estimates suggesting even higher rates of consumption in 2016 and 2017, at 20.3 and 20.5 kg per capita per year, respectively (FAO, 2018). These figures do not, however, highlight the large variation in annual consumption both globally (with, for example, an estimated 58 kg consumed per capita in Japan, and 2.4 kg per capita in Yemen) and within continents (27.3 kg per capita in Ghana as compared with 4.6 kg per capita in Kenya) (Guillen et al., 2019). While increasing seafood consumption can play an important role in providing sufficient protein, it is also particularly valuable for preventing micronutrient deficiencies, with high production scenarios having the potential to prevent an estimated 166 million cases of inadequate micronutrient uptake by 2030 with important improvements in areas of low food security such as Sub-Saharan Africa and Southeast Asia (Golden et al., 2021).

Understanding and acknowledging seafood's role in addressing global and regional food security issues must be accompanied by efforts to ensure that seafood production is sustainable. The FAO estimates that world marine fish stocks within biologically sustainable levels decreased from 90% in 1974 to 68.6% in 2013 (FAO, 2019). More work is needed, in research and in practice, to reverse this trend by adequately managing wild and farmed seafood to reduce the overfishing, biodiversity loss, and ecosystem disruption that can result from poorly managed seafood production. Understanding the role of seafood is important for several interrelated Sustainable Development Goals, including zero hunger, good health, and well-being, climate action, and life below water (United Nations, 2015). While progress has been made toward sustainability in aquaculture in recent years (Naylor et al., 2021), more research is needed into the role of seafood for food security in relation to implementation of these goals. Increasing the sustainability of seafood production systems relies on research that bridges the terrestrial-aquatic divide—this review shows that this critical junction has many opportunities for food systems researchers. Further work, including systematic reviews in order to obtain a comprehensive view of the state of the literature in this area can help to identify research priorities and guide policy decisions. Research on aquaculture, which has the potential to enhance the resilience of global food systems through diversification and improved efficiency (Belton and Thilsted, 2014; Troell et al., 2014), is also essential in order to ensure adequate seafood production in a sustainable manner. Greater recognition and understanding of the role of plant and animal aquatic foods in global and local food security could result in more resources to support these efforts.

## AUTHOR CONTRIBUTIONS

SS, RAN, and DL contributed to conception and design of the study. SS conducted the initial light-touch review, conducted the analysis, and wrote the first draft of the manuscript. SS, RAN, EA, NA, GA, GB-S, BB, MB, JB, SB, PC, MC, PE, ME, LF, JF, AG, IG, FI, AK, MK, FK, WL, A-AM, BM, RN, BK-P, AP, BR, NR, ER, AS, TS-M, SKS, ST, KT, MTr, MTl, RV, JY, and WZ conducted the in-depth reviews. SS and RAN agreed paper classification where reviewers disagreed. LF created the GIS map. All authors contributed to manuscript revision, read, and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

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# Commercial Seaweed Cultivation in Scotland and the Social Pillar of Sustainability: A Q-Method Approach to Characterizing Key Stakeholder Perspectives

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Finding the right way to move forward with seaweed cultivation requires the relevant stakeholders to reach agreement on what goals/limits to set and subsequently what measures should be taken to achieve them. Using a Q-method approach and an analytical framework based on in-put legitimacy and the four pillars of sustainability, we discuss the answers of a diverse set of stakeholders to the question: how should commercial seaweed cultivation in Scotland develop? Our results reveal three main discourses. The first focused on environmental and social sustainability, the second on accessing global markets, economic and environmental sustainability and the third prioritized jobs and social and institutional sustainability. The areas of consensus across the factors included the perception that large-scale and multi-national owned farms are not the ideal model for development of the industry in Scotland. All participants advised that the current regulatory regime for seaweed cultivation requires improvement. These results are discussed within the analytical framework and a prediction of the factors required to establish a legitimate seaweed cultivation industry in Scotland is presented.

**Keywords: legitimacy, Q method, seaweed, sustainability, coastal zone management**

## INTRODUCTION

The need to source materials for food, fuel, chemical and pharmaceutical industries from sustainable supplies is growing. The marine environment has long provided these resources, with seaweeds supplying everything from alginates and carrageenans for toothpaste through to salad for dinner. The Food and Agricultural Organization of the United Nations analysis shows that there has been a global increase in seaweed production of 7.6% between 2004 and 2014, much of which is based in China (FAO, 2018). However, the opportunities that seaweed presents as a potentially sustainable resource have been recognized across Europe, which has led to several research projects and companies exploring commercialization (Van den Burg et al., 2019; Froehlich et al., 2019). While many seaweeds can be harvested from the wild there is a growing opposition to kelp harvesting specifically, led by fishers, environmentalists, and local communities. Hence, countries in the North Atlantic, both east and west, look to seaweed cultivation as a solution.

While seaweed cultivation holds potential for "blue growth" (e.g., Froehlich et al., 2019), it also generates new challenges as it is set within the context of escalating competition for the use of ocean and coastal areas and resources. As such, there is the possibility that this newly emerging activity could add to conflicts in the coastal zone that are likely to relate to all aspects of sustainability; natural, economic, social and institutional. For example, large-scale cultivation can have a different impact on the biophysical marine environment than small-scale cultivation. However, as this is a new industry in Europe, the effects on the environment at any scale are still uncertain (Campbell et al., 2019). Local ownership has the potential to generate different benefits for local communities than multinational ownership, both creating varied but strong links between social and economic sustainability. Finally, how the sector should be organized in terms of regulation will impact issues such as who is included in governance processes, and where accountability lies if something goes wrong—be it environmental, social, or economic. Finding the right way to move forward with seaweed cultivation requires that the relevant stakeholders reach compromise on what goals to aim for and subsequently what measures should be taken to achieve them (Raadgever et al., 2008). In order to realize this, it is pivotal to elicit stakeholders' perspectives to understand what a "successful" seaweed cultivation sector would look like.

Taking a constructivist approach to these issues and using Q methodology, we explore stakeholders' perception of seaweed cultivation within the context of the concept of legitimacy, described in more detail later on in this paper. Legitimacy is argued as key to ensuring sustainable management of resources in line with good governance ideals, and to safeguard the stability of social, political and economic systems (Suchman, 1995). We use Scotland as a case study, as the Scottish government has identified seaweed cultivation as an industry that can contribute to the blue economy with particular potential for rural, island and coastal communities (The Scottish Government, 2017). In addition, the West Coast is already host to several test sites and small-scale commercial operations. In this study, we explore how stakeholders, that is, seaweed cultivators, scientists, regulators, supply-chain services and interested community representatives, view the current processes around seaweed cultivation and its development. We investigate if the process of establishing seaweed cultivation as a new industry in the coastal zone is perceived as legitimate or not, and what it will take to achieve legitimacy. In order to answer this, we ask: *how should commercial seaweed cultivation in Scotland develop?*

In the following sections, we will present the current context of seaweed cultivation in Scotland, including the consenting regime and relevant social and legal processes it interacts with, before describing the theoretical framework we used to conduct the study and analyze the results.

## CURRENT SEAWEED CULTIVATION CONSENTING REGIME

The aquaculture consenting procedure in Scotland is currently characterized by the marine planning regime, comprised of national and supranational frameworks (see **Figure 1**) and several different national (Scottish) and regional (county level) authorities, government agencies and licenses (see **Table 1**).

Prior to 2016 there were no commercially operating seaweed farms in Scotland, and no regulations to suit. However, in 2012 the Scottish Government conducted a Strategic Environmental Assessment for seaweed cultivation (Marine Scotland, 2012) and in 2017 concluded a consultation process started in 2013, through the publication of the Scottish Seaweed Cultivation Policy Statement (The Scottish Government, 2017). The Statement sets out seven policies (P), of which the first and fifth are of particular relevance to this study. Policy one asserts that *"In principal, the Scottish Government is supportive of small-medium farm seaweed cultivation...*[1]*"* subject to planning and environmental regulation. Policy five states that *"Other marine users and activities should be considered in the siting of farms"*. The other five policies relate to biosecurity (P2), location of farms in relation to water quality (P3), survivability and suitability of equipment (P4), site suitability including visual impacts (P6), and general support for integrated multi-trophic aquaculture (P7).

Although seaweed cultivation is viewed by government and some regional level organizations as an industry that has the potential to expand in a sustainable manner (Argyll Bute Council, 2017; The Scottish Government, 2017), it will be competing for space in an already busy inshore marine environment. In addition, there are currently industries operating in this area which are not identified as competitors by the Scottish National Marine Plan but are by local communities and businesses. For example, perceived negative impacts on the tourism industry are often a cited as a reason for objecting to planning applications for finfish aquaculture (Billing, 2018). Although there are efforts currently underway to improve understanding around the potential impacts that seaweed cultivation might have in Scottish waters (see for example the H2020 projects Genialg and MacroFuels), it is currently not known what scale of seaweed cultivation is required for economic feasibility (Van den Burg et al., 2016), what environmental impacts different scales might imply (Campbell et al., 2019), or the potential conflicts or synergies that might arise in relation to other users of the sea and local communities that will host the industry.

## LOCAL CONTEXT: SEAWEED HARVESTING AND CULTIVATION

Kelp forests around the UK are biodiverse and provide several ecosystem services including: habitat for species of inherent and commercial value (e.g., European lobster, Atlantic cod, Pollock, seals, and otters); coastal defense through wave attenuation and dampening and; health and wellbeing benefits for humans through interaction, cultural significance and economic reliance (Smale et al., 2013). In 2017, a Scottish company submitted a proposal to harvest up to 33,000 tons of kelp (*Laminaria hyperborea*) per year from coastal waters in western Scotland. The kelp was to be used as a raw material for the production of

[1]"Small to medium" scale farms are classified by the Scottish Government as 0-50x200 meter lines (The Scottish Government, 2017).

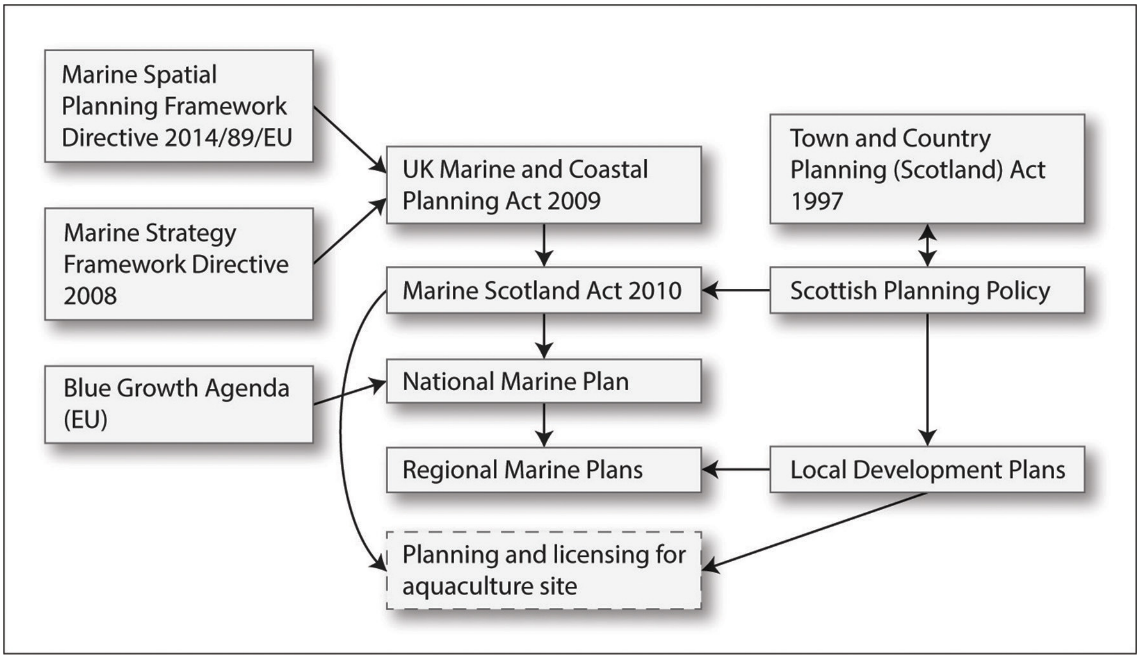


**FIGURE 1 |** Rough guide to the marine planning regime in Scotland as described by Brooker et al. (2019) in addition to Billing (2018). Dotted lines show processes that include local level stakeholder and community engagement.

biomaterials including alginate and nanocellulose. The proposal was opposed by fishers, fish-farmers, hand-harvesters of seaweed, coastal and island communities, the general public, public figures (including Sir David Attenborough) and some environmental NGOs. Opposition included a social media campaign, media coverage, and a petition signed by 14,000 people.

Following this public controversy, several amendments were made to the Crown Estate Bill under consideration at that time, by the Scottish Parliament. The final amendment (14ZA) was accepted by Parliament on 21 November 2018 and prohibits any mechanical removal (for commercial purposes) of 5 species of *"wild kelp from the seabed"* that *"would inhibit the regrowth of the individual plant"*. Listed species were *Laminaria hyperborea*, *L. digitata*, *Saccharina latissimi*, *Saccorhiza polyschides* and *Alaria esculenta* (Scottish Parliament, 2018). Given that the main meristem of *L. hyperborea* is at the top of the stipe (i.e., the base of the frond) (Burrows et al., 2018), this effectively outlaws mechanical harvesting of this species for its alginate-rich stipe.

*Laminaria hyperborea* can be farmed, but existing strains have a low yield of alginate under farm conditions. *Saccorhina latissima* is currently farmed and has a good content of alginate. However, providing the biomass needed for commercial purposes would require farms covering at least 30 km$^2$ (at harvestable densities of 10 tons per hectare) (Bak et al., 2018). However, the Scottish Seaweed Cultivation Policy Statement determines support for seaweed cultivation in farms of up to 1 hectare. The Statement does not consider large sites on the grounds that they are not at present technically, environmentally or economically feasible (The Scottish Government, 2017). In this context, a review of the *"regulatory regime of all kelp harvesting activity up to and including farming"*, was announced on 20 November 2018 by the Scottish Environmental Secretary, Roseanna Cunningham and is currently underway (The Scottish Government, 2019b).

## THEORETICAL FRAMEWORK

### Legitimacy

Legitimacy theory is concerned with understanding what makes something—a process, an institution, a governance structure, in our case an industrial activity and its regulation—acceptable within a socially constructed system (Suchman, 1995). It plays a key role in policy development and democracy as is found in a large body of literature within anthropology, philosophy, organizational studies and more (e.g., Weber, 1946; Jentoft, 2000; Wilson, 2009; Bjørkan, 2011). In general, legitimacy is assumed to induce compliance, encourage participation and lower costs to those seeking it. Suchman (1995) defines legitimacy as:

> "…a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs and definitions." (Suchman, 1995, p. 574)

Given the aim of this article is to try and understand the characteristics that might make a seaweed cultivation industry in Scotland acceptable to stakeholders and local communities, within, at the time of writing, a limited regulatory framework, this definition of legitimacy fits well. However, we choose to take the approach of Scharpf (1999) in trying to understand the requirements of legitimacy (in-put and out-put), rather than the four typologies described by Suchman (1995). Our

**TABLE 1 |** The current consenting regime for cultivating seaweed in Scotland.

| Application | Authorizing regulator/monitoring agency | Legislation | Additional information |
|---|---|---|---|
| Marine license | Marine Scotland Licensing Operations Team (MS-LOT) | Marine Scotland Act 2010 | The application requires an assessment of areas of concern such as Special Areas of Conservation, Special Protected Areas, Special Sites of Scientific Interest, Marine Protected Areas, Ramsar sites, shellfish harvesting areas, and marine archaeology. It might also require a pre-application public consultation. If so, a report of the consultation should be submitted with the application. This should include those who were consulted, when, where, and how. MS-LOT will consult with statutory consultees including the Northern Lighthouse Board, statutory Harbor Authority, Scottish Natural Heritage, Scottish Environmental Protection Agency, Historic Scotland, Royal Society for the Protection of Birds, and the relevant District Salmon and Fishery Board. A Marine License is normally granted for 6 years. Determination of an application is 14 weeks, although it can take longer. |
| Seabed lease | The Crown Estate Scotland | Crown Estate Act 1961 and The Scotland Act 2016 | The Crown Estate Scotland encourages any applicants to contact them before applying for a lease to check whether the site is available. |
| Habitats regulations appraisal (if necessary) | MS-LOT, Crown Estate Scotland, relevant Local Authority, Scottish Environmental Protection Agency | The Conservation (Natural Habitats, and c.) Regulations 1994 | Scottish Natural Heritage are the advisory agency and if a Habitats Regulations Appraisal is required, SNH must be consulted by the competent authority. |
| None | Scottish Natural Heritage Scottish Police Force | Wildlife and Natural Environment (Scotland) Act 2011, Wildlife and Countryside Act 1981 | It is an offense to grow any plant species outside of its native range, including seaweed. SNH provides guidance to the competent authority on whether the activities applied for under a Marine License are compliant with these laws. |
| Works license policy 2017 | Shetland Islands Council | Zetland County Council Act 1974 | A Work License is required from the Shetland Islands Council for the cultivation of seaweed within the Shetland County Council Area. |
| Planning permission | Local Planning Authority/Local Council | Town and Country Planning (Scotland) Act 1997 | Planning permission is required for any land side infrastructure such as new slipways and drying facilities. |

choice is made on the basis that the industry we are studying is not yet commercialized and we therefore cannot assess or observe the actions of the organizations running the operations, nor the audience (interested parties, stakeholder, or local communities).

Scharpf (1999) distinguishes between in-put and out-put legitimacy, where in-put legitimacy refers to procedure and participation and out-put legitimacy relates to consequences, problem-solving capacity and effectiveness (see also Bäckstrand et al., 2010). Some authors claim that if in-put legitimacy is high, this can increase the out-put legitimacy (see for instance Risse, 2004). Others argue that high out-put legitimacy can compensate for low in-put legitimacy (Sharpf, 1999). Dingwerth (2007) proposes four dimensions of out-put legitimacy: (1) policy effectiveness; (2) institutional effectiveness; (3) compliance effectiveness; and (4) environmental effectiveness. Although touching on out-put-legitimacy, our main focus as reasoned in the previous paragraph, is on the three dimensions of in-put legitimacy; (1) participation and inclusion; (2) democratic control and accountability; and (3) argumentative practice and deliberative quality (Bäckstrand et al., 2010).

Legitimacy assessments rest on a complex interplay between the decision-making processes and the out-put of these processes. In practice, the dialectic relationship between in-put and out-put legitimacy makes it difficult to clearly distinguish between procedural and substantive sources of legitimacy (Connelly et al., 2006). Through concepts such as overall legitimacy (Bäckstrand et al., 2010; Birnbaum, 2015) and throughput legitimacy (Schmidt, 2013) scholars have tried to overcome the dichotomy between in-put and out-put legitimacy: "*There is widespread agreement in scholarly literature that in-put and out-put legitimacy are closely connected and that legitimacy can neither be attained by inclusion nor by effectiveness alone*" (Hogl et al., 2012, p. 14).

Our aim in this paper is not to discuss or emphasize the dichotomous aspects of legitimacy. Rather, the data has pointed us toward dimensions related to in-put legitimacy. Relating in-put legitimacy to our Scottish context, we ask if the policies and norms for seaweed cultivation are being developed in a transparent, fair, inclusive and accountable manner, and form effective institutions for problem-solving and performance. We focus mainly on how stakeholders would like the seaweed cultivation sector to develop, or in line with the legitimacy definition above: what actions are desirable, proper, or appropriate in the seaweed cultivation sector as perceived by stakeholders. Given that in-put legitimacy is geared to democratic principles, this article can be understood as

**TABLE 2 |** Statements/opinions (concourse) on seaweed cultivation in Scotland chosen by the authors from the Q-sample.

| Environmental sustainability | Social sustainability | Economic sustainability | Institutional sustainability |
|---|---|---|---|
| 7 Seaweed cultivation should take place offshore | 14 Seaweed cultivators should engage with local communities | 4 Seaweed cultivation in Scotland should be developed for local markets | 9 Seaweed cultivators should communicate with other users of the sea |
| 10 Environmental sustainability of seaweed cultivation should be a priority | 19 Seaweed cultivators should provide transparent information about farming techniques to the public | 3 Local economic benefits should be put above nation-wide economic benefits | 12 Co-operatives are a viable development option for seaweed cultivation companies |
| 18 Seaweed cultivation is more environmentally acceptable than finfish cultivation | 16 Seaweed cultivators should be aware of the social contexts that they work in | 11 Seaweed cultivation should look to the circular economy as a model for development | 1 Large-scale seaweed farms run by multi-national companies is the way forward |
| 15 The current regulatory processes for seaweed cultivation are fit for purpose | 8 Seaweed cultivation should enrich communities through traditional uses and knowledge re-enforcement | 5 Seaweed cultivation in Scotland should be developed to be globally competitive | 2 Locally run small to medium scale seaweed farms are the way forward |
| 17 Seaweed cultivation should be prioritized over other uses of the marine environment | 13 Seaweed cultivation should provide community benefits and local jobs | 6 Seaweed cultivation in Scotland should be developed for regional and national markets | 20 Seaweed cultivators should rely on regulators to establish best-practice guidelines |

a contribution in terms of giving voice to stakeholders and be a part of "the good argument" (Hogl et al., 2012). We do not argue that there is a direct link between a legitimate seaweed cultivation sector, little conflict and effective decision making. However, we do argue that it is key to understand stakeholders' perception to try to navigate these issues as best as possible, to realize the benefits of industry development and avoid the pitfalls.

Legitimacy is not observable as such, which makes it a challenge to directly measure. However, as a starting point we assume a link between the four pillars of sustainability and legitimacy for the seaweed cultivation sector. Based on this assumption, we have chosen statements for our Q method that represent the social, economic, environmental and institutional sustainability of the seaweed sector (**Table 2**). In the next section, we describe the four pillars of sustainability in relation to legitimacy, before describing our Q method approach in detail.

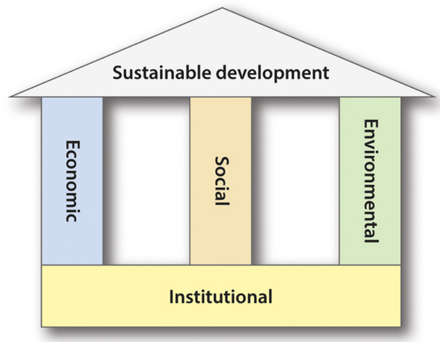


**FIGURE 2 |** The environmental, economic and social sustainability are the pillars, and the foundation is made of institutional sustainability, which consists of management and governance. After Nofima AS, inspired by University of York and Chemical Industries Association, 2005.

## Sustainability and Legitimacy

The Scottish Government is supportive of Blue Growth, within the parameters of sustainability of environment, economy and society (The Scottish Government, 2019a). The concept of "sustainability" was launched in the "our Common Future" report (1987), defined as development that meets the needs of the present without compromising the ability of future generations to meet their needs. Over time, the concept has become holistic, including economic, social and institutional dimensions in addition to the environment. These dimensions are co-dependent, and **Figure 2** is often used to illustrate this (Nofima, 2018).

Social sustainability is closely related to the social acceptability and legitimacy of an industry (Provasnek et al., 2017), in our case, seaweed cultivation.

In this paper we are primarily concerned with exploring the factors that stakeholders perceive as linked to legitimacy for seaweed cultivation. We argue that legitimacy there is a relationship between legitimacy for the industry and the four pillars of sustainability.

# Q METHODOLOGY

Q-methodology is a technique developed in the 1930's (Stephenson, 1953) to explore individual phenomena such as opinions, perspectives and attitudes (Watts and Stenner, 2012). It is a way to investigate various views of a specific topic within a group, and it combines the strength of quantitative and qualitative research methods (Watts and Stenner, 2012). There are typically six phases to Q-method: (1) development of the concourse, (2) development of the Q-sample (statements), (3) development of the P set (informants), (4) the Q sort, (5) data analysis, and (6) interpretation.

The informants were asked to arrange the set of statement—the "Q-set" —across a normal distribution (bell curve) that indicates agreement/disagreement (see **Figures 3–5** for example). We chose a relatively flat bell curve since the informants are knowledgeable about the issue at hand (Watts and Stenner). The selected group of informants ranked the statements in relation to one another, in this case from 4 to −4. The result of each informants ranking is called the Q sort. Each Q sort was then

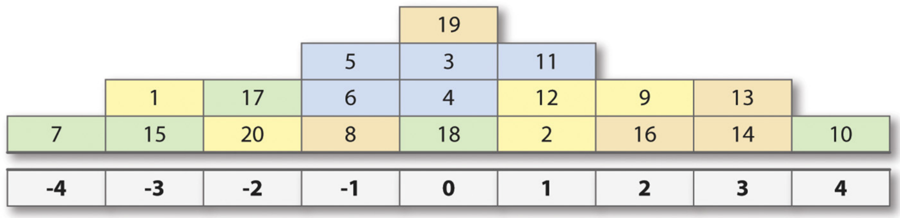


**FIGURE 3 |** Ideal sort for factor 1. Factor name was chosen based on statements 7 and 14. Color coding is based on the four pillars of sustainability (green = biological sustainability, blue = economic sustainability, Red = social sustainability, and yellow = institutional sustainability).

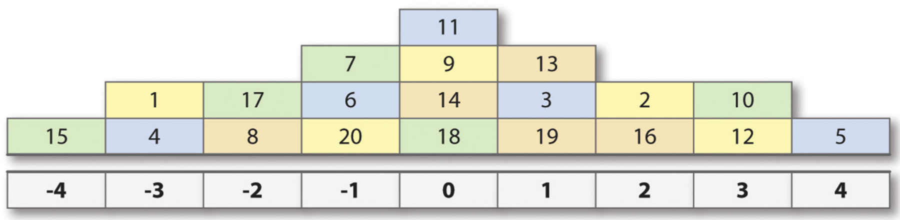


**FIGURE 4 |** Ideal sort for factor 2. Factor name was chosen based on statements 15 and 5. Color coding is based on the four pillars of sustainability (green = biological sustainability, blue = economic sustainability, Red = social sustainability, and yellow = institutional sustainability).

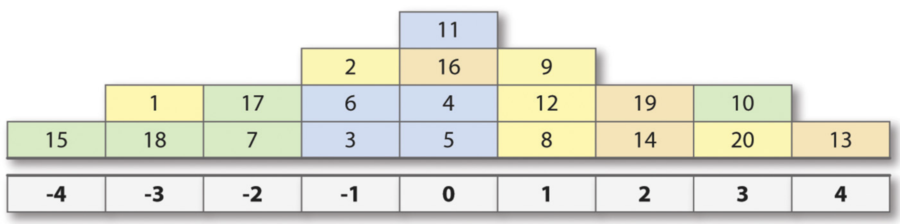


**FIGURE 5 |** Ideal sort for factor 3. Factor name was chosen based on statements 15 and 13. Color coding is based on the four pillars of sustainability (green = biological sustainability, blue = economic sustainability, Red = social sustainability, and yellow = institutional sustainability).

analyzed using a software called PQmethod. We factor-analyzed the Q sorts to find a small number of ideal factors that capture an acceptable amount of the studys overall vector variance (Watts and Stenner, 2012). Hence, the narratives presented are derived using a statistical process (Principal Component Analysis) and are the products of any subset of the participants who revealed similar views through the distribution of the sorted statements (Donaldson and Eden, 2005). Each factor or narrative are hence "idealized sorts" and not necessarily the exact Q sort of any participant (Webler and Danielson, 2009). For this article, we chose a solution with three factors that represent groups of shared societal perspectives, and used automatic flagging. Finally, we analyzed each of the three factors in detail in order to write a descriptive narrative.

## Administering the Q Sort

The aim of the concourse survey is to provide a comprehensive understanding of the range of opinions that exist on the topic at hand. This study forms part of the H2020 GENIALG project, where the Scottish Association for Marine Science is investigating the social acceptability of seaweed farming in several case studies across Europe, of which Scotland is one. Semi-structured interviews, workshops, and document analysis formed some of the activities in the Scottish case study (data was collected in 2017–2019). Based on the findings of these activities, the authors collected a large number of statements for the Q-sample. In order to reduce these to a manageable number that we could situate through rich contextual data, we used the four pillars of sustainability to sift them: environmental, social, economic and institutional sustainability. This resulted in 20 statements shown in **Table 2**.

Participants undertaking the Q sort were asked to talk through their opinions on individual statements, why they chose to rank them as they did, and open comments on the subject area. This approach arguably provides both theoretical and empirical observations. Setting the results within context and offering a narrative to underpin the factor (Webler and Danielson, 2009). It is necessary to

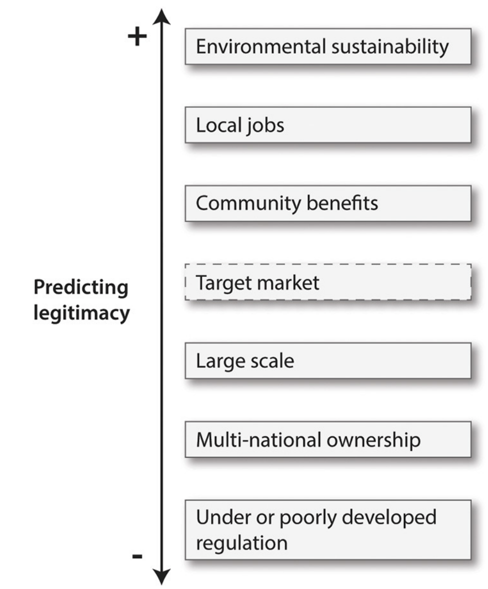


**FIGURE 6 |** Characteristics predicting a legitimate seaweed cultivation sector in Scotland, based on the results of all three factors. Boxes in black are likely to be less legitimate, boxes in gray are likely to be more legitimate, and the dashed line box shows the characteristics that is neutral.

define perspectives before conducting a survey to measure the frequency of occurrence of perspectives in a population (Webler and Danielson, 2009).

Since the respondents, or "P-Sample", are not selected in order to produce generalizable "patterns within and across individuals" (Barry and Proops, 1999, p. 339), a limited number of participants is acceptable and appropriate (Watts and Stenner, 2012). The number of participants ($N = 16$) fits within the standard of the literature (Webler and Danielson, 2009). The 16 participants chosen were relevant to the question as they were; (1) already involved in the seaweed cultivation or harvesting industry, are currently undertaking science on seaweed cultivation, or (2) are interested in starting up a seaweed cultivation business or service, or (3) are regulators, or are seaweed industry association representatives (see **Table 3**).

## FINDINGS

As mentioned above, three distinct perspectives, or patterns, emerged from the factor analysis of the Q sort. Cumulatively, these explained 72% of the variance between the 16 Q sorts, shown in **Table 4** (P1 = 25%, P2 = 25%, P3 = 22%).

We understand the three factors as discourses, and we analyzed these based on the "crib-sheet method" (Watts and Stenner, 2012). This means that while we focus on the distinguishing statements, which are those statements differing the most between the three discourses, we also address what the discourses agreed on, known as the consensus statements, as well as the statements in between. We give the three discourses titles based on their idealized sorts: (1) Environmental and social sustainability focus; (2) Economic and environmental sustainability with a global market focus and; (3) Social and institutional sustainability with local jobs as a priority. The Q sort value for each statement is found in **Table 5**.

### Factor 1—Environmental and Social Sustainability Focus

Five participants significantly associated with this factor; one from science, one from regulation, one seaweed cultivator, and two from wild seaweed harvesting (Q Sort 1, 2, 4, 8, 12). The main focus of this factor is environmental sustainability and social responsibility with a strong emphasis on local jobs and communication with local communities and other marine users by seaweed cultivation companies. This factor disagrees most strongly with the statement that seaweed cultivation should take place off-shore. It also feels that the current regulatory regime is not fit for purpose, however participants were aware of ongoing efforts to improve regulation and regulatory agencies knowledge of the industry. This factor is neutral about issues related to economics and comparisons between seaweed and finfish cultivation.

### Factor 2—Economic and Environmental Sustainability With a Global Market Focus

The interviewees that represent factor two are three community representatives, one from science, and one seaweed company (Q Sort 3, 5, 10, 11, and 13). Factor two is very critical of the regulatory regime as it is perceived as slow and embryonic, with the regulators taking too much time to make decisions. This is the only factor that feels strongly that seaweed cultivation should focus on global markets, supplied by small to medium scale, locally run farms. Communication, collaboration and education featured heavily in discussion about why the participants disagreed with seaweed cultivation run on a large scale by multi-national companies or offshore and being prioritized over other uses of the sea. This factor is the one that is spread the most across the four pillars of sustainability and is also the only factor that feels strongly about economic aspects.

### Factor 3—Social and Institutional Sustainability With Local Jobs as a Priority

This factor is made up of participants from supply-chain/service sectors (Q Sort 6, 7, 9, and 15). That participants feel very strongly that seaweed cultivation should focus on community benefits and local jobs, through an industry which is socially and environmentally sustainable. Linked to this, factor three strongly disagrees that large-scale seaweed farms run by multi-national companies is the way forward. Equally, this factor does not agree that markets should be constrained, but rather they should develop where there is demand, whether that be local, regional, national, or international so long as it provides local jobs. Despite not scoring communication and transparency as highly as possible it was a running theme throughout the comments about the statements. This factor, like all of the others, thinks that environmental sustainability is central and does not think that the current regulatory regime is fit for purpose.

**TABLE 3** | Overview of participants per sector.

| Community representatives | Science | Regulation | Harvesting | Seaweed cultivation company | Supply chain/service sector |
|---|---|---|---|---|---|
| 5 | 2 | 1 | 2 | 2 | 4 |

*In the idealized q sort, 5 community representatives, 2 scientists, 1 regulator, 2 from harvesting sector, 2 seaweed cultivation companies and 4 from the supply chain/service sector were flagged by the automatic flagging in PQ method.*

## Cross-Factor Consensus

Statements that were not ranked significantly differently between perspectives are termed areas of consensus. Four statements were non-significant for all perspectives at $p > 0.05$, as seen in **Table 6**. This means that the three factors felt similarly about the statement, both in terms of agreeing or disagreeing. It is clear that large-scale seaweed farms run by multi-national companies and limiting industry development to regional and national markets is not the optimal way forward according to all factors. Likewise, all factors agreed strongly that the environmental sustainability of seaweed cultivation should be a priority. Participants described the responsibility of this priority as being shared between cultivators and regulators, with an emphasis on collaboration between the two. This was to ensure there is enough knowledge to develop an efficient system for both regulation and good practice. There was variation across the participants as to whether good practice should be enforced by regulators, led by industry, or a mix of both. Some of the participants suggested that good practice is linked with social acceptability and in one case, the term "social license" was used.

**TABLE 4** | Factor matrix (Q sort results) where "X" indicates a defining sort using automatic flagging in PQ method.

| | | Factors | | |
|---|---|---|---|---|
| **Q sor** | **Stakeholder** | **1** | **2** | **3** |
| 1 | Science | 0.7504X | 0.3158 | 0.0461 |
| 2 | Harvester | 0.8054X | 0.1711 | 0.3792 |
| 3 | Science | 0.5045 | 0.5724X | 0.0928 |
| 4 | Regulation | 0.5786X | 0.3915 | 0.3518 |
| 5 | Community representative | 0.2558 | 0.6704X | 0.2270 |
| 6 | Supply-chain | 0.1939 | 0.0809 | 0.8520X |
| 7 | Supply-chain | 0.0587 | 0.4332 | 0.5022X |
| 8 | Seaweed cultivation company | 0.7188X | 0.2291 | 0.5153 |
| 9 | Supply-chain | 0.2110 | 0.5033 | 0.7317X |
| 10 | Community representative | 0.2921 | 0.8009X | 0.0540 |
| 11 | Community representative | 0.1752 | 0.8259X | 0.1859 |
| 12 | Harvester | 0.6815X | 0.3513 | 0.2898 |
| 13 | Seaweed cultivation company | 0.2395 | 0.8112X | 0.3051 |
| 14 | Community representative | 0.4582 | 0.5203 | 0.5155 |
| 15 | Supply-chain | 0.3618 | 0.1584 | 0.8196X |
| 16 | Community representative | 0.6938X | 0.1373 | 0.5795 |
| | **% expl. variance** | **25** | **25** | **22** |

# WHAT COULD A SUCCESSFUL SEAWEED CULTIVATION SECTOR LOOK LIKE?

In the interests of brevity, the following section explores the most prominent and contextually relevant of our results in relation to the four pillars of sustainability and our legitimacy framework. It should be noted that there is not a specific section focusing on social sustainability, as it was found to be inextricable linked with environmental, economic, and institutional sustainability and is therefore interwoven throughout the sections in our discussion. The difficulty of defining the characteristics of the pillar of social sustainability as distinct from the other pillars within the context of seaweed cultivation in Scotland, is evident.

## The Social Importance of Environmental Sustainability

Across all factors, participants disagreed strongly with the statement that "*The current regulatory processes for seaweed cultivation are fit for purpose*". When we categorized the statements in **Table 2**, this one was placed under the "environmental pillar" of sustainability, as we assumed that the regulations would lead to environmental sustainability. However, the Q sorting revealed differences in the interpretation of the issue.

Factor 1 (environmental and social sustainability focus) disagrees with the statement as participants perceive that there is currently no effective regulatory process. Prominent reasons for this perspective included marine licensing being viewed as too broad to be an efficient mechanism for regulation and that there is currently no testing of cultivated or harvested seaweeds (for heavy metals, contaminants etc.) bound for human consumption markets (Wood et al., 2017). Most participants noted that the regulations are based on other industries rather than specific knowledge of seaweed cultivation, advising that this is a recipe for social and environmental issues. Factor 2 (economic and environmental sustainability with a global market focus) bases their disagreement with the statement on the complexity of the situation, arguing that where there is work underway between the regulators and cultivators, it is viewed as "not there yet". Put differently, the participants stated that regulation is embryonic, decision-making is slow, and not suitable for seaweed cultivation. Finally, Factor 3 (social and institutional sustainability with local jobs as a priority) disagrees because the participants had not heard of any regulatory processes and are therefore assumed that there are not any or they are not adapted to seaweed cultivation.

There was acknowledgment across the factors that regulators are making an effort to learn, but also that cultivators have an opportunity to develop good-practice that goes above and beyond

**TABLE 5 |** Factor Q sort values for each statement.

| # | Statement | Factor arrays | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| 1 | Large-scale seaweed farms run by multi-national companies is the way forward | −3 | −3 | −3 |
| 2 | Locally run small to medium scale seaweed farms are the way forward | 1 | 2 | −1 |
| 3 | Local economic benefits should be put above nation-wide economic benefits | 0 | 1 | −1 |
| 4 | Seaweed cultivation in Scotland should be developed for local markets | 0 | −3 | 0 |
| 5 | Seaweed cultivation in Scotland should be developed to be globally competitive | −1 | 4 | 0 |
| 6 | Seaweed cultivation in Scotland should be developed for regional and national markets | −1 | −1 | −1 |
| 7 | Seaweed cultivation should take place offshore | −4 | −1 | −2 |
| 8 | Seaweed cultivation should enrich communities through traditional uses and knowledge re-enforcement | −1 | −2 | 1 |
| 9 | Seaweed cultivators should communicate with other users of the sea | 2 | 0 | 1 |
| 10 | Environmental sustainability of seaweed cultivation should be a priority | 4 | 3 | 3 |
| 11 | Seaweed cultivation should look to the circular economy as a model for development | 1 | 0 | 0 |
| 12 | Co-operatives are a viable development option for seaweed cultivation companies | 1 | 3 | 1 |
| 13 | Seaweed cultivation should provide community benefits and local jobs | 3 | 1 | 4 |
| 14 | Seaweed cultivators should engage with local communities | 3 | 0 | 2 |
| 15 | The current regulatory processes for seaweed cultivation are fit for purpose | −3 | −4 | −4 |
| 16 | Seaweed cultivators should be aware of the social contexts that they work in | 2 | 2 | 0 |
| 17 | Seaweed cultivation should be prioritized over other uses of the marine environment | −2 | −2 | −2 |
| 18 | Seaweed cultivation is more environmentally acceptable than finfish cultivation | 0 | 0 | −3 |
| 19 | Seaweed cultivators should provide transparent information about farming techniques to the public | 0 | 1 | 2 |
| 20 | Seaweed cultivators should rely on regulators to establish best-practice guidelines | 2 | −1 | 3 |

**TABLE 6 |** Agreement across factors: those statements that do not distinguish between any pair of factors.

| # | Statement | Factor arrays | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| 1 | Large-scale seaweed farms run by multi-national companies is the way forward | −3 | −3 | −3 |
| 6 | Seaweed cultivation in Scotland should be developed for regional and national markets | −1 | −1 | −1 |
| 10 | Environmental sustainability of seaweed cultivation should be a priority | 4 | 3 | 3 |
| 17 | Seaweed cultivation should be prioritized over other uses of the marine environment | −2 | −2 | −2 |

*Those listed here at the statements that are non-significant at $P > 0.05$.*

the law. When exploring this in terms of sustainability and legitimacy, the perception of lack of institutional effectiveness is perceived as a barrier to seaweed cultivation. However, we also see how the in-put end of legitimacy (that is participation, deliberation, and control) is potentially being constructed through willingness to learn and collaborate between regulators and cultivators.

All factors agree that "*Environmental sustainability of seaweed cultivation should be a priority*". Participants in Factor 1, which rate this statement at 4, reasoned that there *"is no logical reason why it can't be [environmentally sustainable]"*, that it would be beneficial to have a form of aquaculture that has net positive environmental impact, and that both of these considerations will improve the social acceptability of the industry. Factor 2 rates this statement at 3. However, the reasoning provided by stakeholders for their choice was based on morality: *"it will keep me awake at night if it is not sustainable;" "it's about bringing people along with the industry and that will only happen if it is sustainable;" "to ignore environmental sustainability is madness"*. Moral legitimacy, as defined by Suchman (1995) is "sociotrophic"—in other words, is based on "the right thing to do", reflecting the values and beliefs of the individual as well as socially constructed norms. In this case, moral legitimacy could be linked with in-put legitimacy, given the former has been related to procedure and process (Weber, 1971 in Suchman, 1995). Factor 3 also rated this statement at 3. One stakeholder made an important point about the current emergent state of the seaweed cultivation industry in Scotland and the opportunities this position presents for sustainable development, best described in their own words:

> *"Agriculture and aquaculture should strive for environmental sustainability. Here there is the opportunity for seaweed cultivation to have a positive impact on the environment if it's done correctly and we keep an eye on genetics and diseases. What is the point if it isn't? Seaweed cultivation in Scotland is in the privileged position not to have engrained poor environmental standards, if you start off from the perspective of environmental sustainability then it sets a good baseline to develop from."*

All factors disagree that "*Seaweed cultivation should be prioritized over other uses of the sea*". The reasons behind this disagreement were very similar and can be summarized as; the sea has too many uses and is important to too many people to have seaweed cultivation as a priority. We postulate that this view is related to seaweed cultivation being a new "player" in the coastal zone, hence, it does not take priority over other more traditional uses such as fishing or even farming salmon. Interestingly, both Factors 1 (environmental and social sustainability focus) and 2 (economic and environmental sustainability with a global marked focus) are neutral about the statement *"Seaweed cultivation being more environmentally acceptable than finfish*", while Factor 3 (social and institutional sustainability with local jobs as a priority) disagrees quite strongly with this. The differences in opinion around this statement are related to the trade-offs that finfish aquaculture represents in Scotland. On the one hand, offering full time jobs and economic potential in rural coastal areas, and on the other causing environmental impacts (Galparsoro et al., 2020).

Despite variation in reasoning and in some cases values, there is a shared desire across all factors and individual participants, that seaweed cultivation should be developed to have as little impact on the environment as possible. Further, that environmental sustainability offers pathways to legitimacy for the industry as it was perceived to be a key component of decision-making (opposing or supporting developments) by local communities, other users of the sea and interested parties.

### Institutional Sustainability and the Issue of Scale

Across all factors, stakeholders disagree strongly with the statement *"large-scale seaweed farms run by multi-national companies is the way forward*". This is unsurprising, given the current context of media scrutiny into multi-national owned finfish aquaculture (Billing, 2018), and the Scottish Government Seaweed Cultivation Policy Statement (focusing on small and medium scale farms) (The Scottish Government, 2017). Factors 1 and 2 argued that a large-scale model would defeat the point of environmental sustainability and would lead to less community benefits, and contribute less to rural coastal development. Many of the participants provided the example of salmon farming as a negative association between large corporations and sustainability goals. Nevertheless, resigned pragmatism was evident in participant perceptions as they note that these types of companies have capital, and therefore advised that the large-scale model might in fact, be the way that seaweed cultivation does develop. Interestingly, Factor 3's disagreement with this statement was on the same basis as the other two but diverged through the perception it is difficult to hold multi-national companies accountable for any negative actions or impacts (either social or environmental). The same participants argued that the industry should develop at the scale necessary (be it small, medium or large scale), but monopolies on any level are undesirable and damaging to local communities. From these perspectives, it could be argued that large-scale seaweed cultivation is seen as economically legitimate, but not socially or environmentally legitimate.

The issue of scale is therefore perceived as institutional and relates to all pillars of sustainability. Who should be allowed to cultivate seaweed and at what scale is seen as having an impact on (1) local benefits, (2) jobs, and (3) environment. This means that the institutional and regulatory structure of the seaweed cultivation industry should, at the least, recognize that local perceptions of a legitimate industry are not likely to stretch to large-scale, multi-national ownership. In turn, this understanding should inform the approach of those who embark on commercial-scale seaweed cultivation in Scotland, where the three attributes listed above should be at the forefront of good-practice, operational strategies, and communication with local communities, other users of the sea and interested parties.

### Economic Sustainability and Which Market to Target

All factors disagree on the statement "*Seaweed cultivation in Scotland should be developed for regional and national markets*". However, they do not feel strongly about it, rating it at −1. Stakeholders in Factor 1 had some reservations as they think that the industry should not exclude international markets, but should not be wholly focused on them either. Stakeholders in Factor 2 focused on the current lack of local and regional markets, advising that tapping into already developed markets could provide the opportunity for innovative, high value products. Linked with this is the perception (and evidence seen here: Scotland Food Drink, 2018) that seafood branded as "Scottish" is increasingly competitive in international markets. Factor 3 argues that since the national market is quite small or under-developed, any market should be developed as long as there is enough demand. In sum, all factors think that there is a need to balance local, regional, national, and international markets (economic sustainability) with local jobs and community benefits (social sustainability) and environmental sustainability.

## PREDICTING LEGITIMACY FOR SEAWEED CULTIVATION

Sustainable blue growth in coastal and marine areas in line with the stated objectives of Scotland's National Marine Plan (Marine Scotland, 2015) raises new challenges and demands. Such growth will increase the number and variety of activities and hence the spatial and temporal diversity and number of stakeholders in the coastal zone. In our study, we have investigated how the new industry of seaweed cultivation in the Scottish coastal zone should develop, as perceived by a wide variety of relevant stakeholders. We have linked the concept of legitimacy with the four pillars of sustainability, to further investigate what this perception will entail for future management. Our results show a diverse range of characteristics that stakeholders emphasize as most important regarding sustainability. However, it is also evident that stakeholders share some views on what a "successful" seaweed sector would look like.

We see that the factors agree that the top priority for seaweed cultivation is to ensure it develops in an environmentally sustainable way, and that a small-scale approach with a focus on the local benefits such as job creation is more desirable than a large-scale approach. Moreover, there is a general consensus that production should be for all markets, even if the reasoning behind this view differs across factors. We found that there is a general agreement that the regulatory processes are not fit for purpose, and further discussion with participants suggests that in their current form, they are an obstacle for effective management. We also want to underline that while communication and transparency does not score very highly in the Q sort it was a running theme throughout conversations with participants about the statements.

There are also some diverging views, and here we will only point to the most relevant. To Factor 1 (environmental and economic sustainability focus) environmental and economic sustainability is less important for developing the sector in a legitimate manner than local social benefits. For Factor 2 (economic and environmental sustainability with a global market focus), seaweed cultivation in Scotland should be developed to be globally competitive, at the same time as prioritizing social sustainability through local scale cultivation and business models that support is the way forward (e.g., co-operatives). The overall priority of Factor 2 is environmental and economic legitimacy. This is also the only factor that rates the economic aspects of seaweed cultivation as important relative the other statements. Factor 3 (social and institutional sustainability with local jobs as a priority) is mostly concerned with issues relating to social and institutional legitimacy, where local jobs and robust regulation are viewed as key.

As this is a new industry, there is little empirical evidence about its legitimacy regarding both processes (in-put) for seaweed cultivation and the effectiveness (out-put) of the different dimensions. What we find in our analysis is that there are both shared and diverging viewpoints about how seaweed cultivation should develop in the future in order to be legitimate and, arguably, more effective and sustainable. In line with (Raadgever et al., 2008) we argue that this overview of stakeholders' perspectives can be useful for the development of seaweed cultivations as it can help to; (a) set the research agenda; (b) identify differences in values and interests that need to be discussed; (c) create awareness of issues among a broad range of stakeholders; and (d) characterize potential development scenarios. This last statement is especially true in the context of seaweed cultivation in Scotland as it is an emergent industry that holds a lot of promise, but also has some potential pitfalls (Cottier-Cook et al., 2016). In this article we have pointed to some key issues that can improve the overall legitimacy of seaweed cultivation (**Figure 6**). This research suggests that a successful seaweed industry is perceived as one that is environmentally and socially sustainable, where local benefits and local jobs are key. We found there is potential to improve the current regulatory processes in place for seaweed cultivation in Scotland, which could empower those who want to diversify into it, at the same time as improving trust in the industry for those who are skeptical.

### Implications for Theory and Practice for Sustainable Seaweed Cultivation

Reaching national blue growth goals within the framework of sustainable development, can be hampered if regional and local social contexts are not accounted for (Hersoug, 2013; Rybråten et al., 2018; Osmundsen et al., 2020). As such, it is important to recognize that the coastal zone is far from empty, with several sectors, uses and users vying for space at any one time. As seaweed cultivation is a nascent industry in the North Atlantic, with much touted potential for various sustainable value-chains (e.g., pharmaceuticals, nutraceuticals, biofuel, bioplastics, to name a few) (Van den Burg et al., 2019), characterizing the potential for it to be perceived as legitimate by a diverse range of key stakeholders, is an important issue to explore. However, studies on stakeholder perceptions are typically based on qualitative data (Barry and Proops, 1999; Bjørkan and Veland, 2019) which to some, especially the natural sciences, industry and regulators who are traditionally trained in quantitative approaches can be vague and diffuse (see for instance Law, 2004). To address this issue of language and understanding across disciplines and sectors, we used Q method in a novel way, combining rich qualitative narrative, with quantitative data, set within the four pillars of sustainability. We hope that this can help more disciplines draw clear lines of understanding between sustainability and perceived legitimacy of coastal activities to stakeholders, and strategies for developing legitimacy for blue growth industries. Hence, we suggest that Q-method, styled in this way, is an approach that has the potential to increase positive impact of qualitative studies by making them more approachable to those outside the social scientific community. This is not a critique of qualitative methods, rather, an understanding that in order to contribute to the solutions to real-life problems, we must find a way to communicate across disciplines and sectors. Simply put, Q allows us to pinpoint issues that will generate areas of consensus and conflict, providing a fundamental understanding of stakeholder perceptions of how blue growth sectors should develop.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

MB led the conceptualization, methodological development, and use of software for the article (PQ method). S-LB realized the Q-sorting interviews in Scotland. Both authors analyzed the findings and wrote the article. All authors contributed to the article and approved the submitted version.

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# Engineering A Low-Cost Kelp Aquaculture System for Community-Scale Seaweed Farming at Nearshore Exposed Sites *via* User-Focused Design Process

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For over 50 years, government fishery agencies have recognized the need to transition excess fishing capacity in coastal waters to aquaculture. For the most part, investment strategies to move wild capture and harvest efforts into aquaculture have failed since the technology and capital expense for entry, such as large fish pens, was not conducive for acceptance. In contrast, low trophic level aquaculture of shellfish and seaweeds is suitable as an addition to the livelihoods of seasonal fishing communities and to those displaced by fishery closures, especially if vessels and gear can be designed around existing fishing infrastructures, thus allowing fishers to maintain engagement with their primary fishery, while augmenting income via aquaculture. In this study, an inexpensive, lightweight, and highly mobile gear for kelp seaweed farming was developed and tested over a 3-year period in southern Maine, USA. The system was different from existing kelp farming operations used in nearshore waters that use low-scope mooring lines, and heavy, deadweight anchors. Instead, a highly mobile, easy to deploy system using lightweight gear was designed for exposed conditions. The entire system fit into fish tote boxes and was loadable onto a standard pickup truck. The seaweed system had small but efficient horizontal drag embedment anchors connected to a chain catenary and pretensioned with simple subsurface flotation. The system was able to be deployed and removed in less than 4 h by a crew of three using a 10 m vessel and produced a harvest of 12.7 kg/m over an 8-month fall-winter growth period. The target group for this seaweed research and development effort were coastal fishing communities who move seasonally into non-fishing occupations in service industries, such as construction, retail, etc. An economic assessment suggests farmers would realize an 8% return on investment after3 years and $13.50/h greater income as compared to a non-farming off season job at minimum wage. This low-cost seaweed farming system for fall-winter operations fits well into a "livelihood" strategy for fishing families who must work multiple jobs in the offseason when their main fishery is unavailable.

**Keywords: aquaculture engineering, kelp, seaweed, aquaculture, ocean-food-systems, fisheries diversification**

## INTRODUCTION

In many global regions where small boat, community scale, coastal commercial fishing communities persist, aquaculture has been proposed as a livelihood alternative or supplement. While not operating at large, industrial scales, many commercial fishing interests possess much of the capital infrastructure (boats, gear, etc.), on-the-water knowledge and experiences needed to become part-time or seasonal ocean farmers. However, investments and initiatives to decrease coastal fishing efforts and replace it wholly with aquaculture have failed unless complete closure of a fishery was mandated and a large government investment made in aquaculture as an alternative livelihood. For example, gill net fishing in the Cedar Key region of Florida, USA was prohibited by federal law in 1994. A transition to calm aquaculture became a successful alternative for more than 350 gillnet fishers through a long term, expensive, federally funded job-retraining program (Stephenson, 2013). However, the complete collapse of a fishery need not occur for fishers to diversify in aquaculture. An owner-operated bioengineering approach to develop aquaculture in fishing communities can be pursued whereby approaches are developed with fishing communities to be complementary, supplemental incomes to fishing, not a total replacement to fishing.

### The Gulf of Maine as a Case Study

The marine economy of coastal Maine, United States of America (USA) is one such case study where taking a preemptive, livelihoods-diversification approach to the adoption of aquaculture is yielding dividends. The Maine marine economy is almost entirely dependent on the nearshore landings of the American lobster (*Homarus americanus*). At the recent industry peak in 2016, lobster landings in the nearshore state fishery approached 60,000 tmt with an ex-vessel value of $533 million USD. The fishery is the keystone of the ocean-foods based economy in Maine; comprising 74% of total commercial landings across all fisheries by value, supporting 4,500 licensed commercial harvesters (ME DMR, 2021). Dependence on a single fishery in an ocean ecosystem warming faster than 90% of all other ocean regions (Pershing et al., 2015) represents considerable risk not only to the individual commercial fisher but the marine economy as a whole. A recent study by Le Bris et al. (2018) suggested that while the Maine lobster fishery may be more resilient than its collapsed southern New England counterpart (ASMFC, 2015) due to adaptive management strategies (e.g., escape slot sizes, minimum and maximum size limits, and conservation of egg-bearing females), the fishery still faces long-term climate driven vulnerability and likely declines. In fact, this reality may already be playing itself out. Since reaching peak landings in 2016 in both volume and value, both landings and value have since declined, dropping from 60,000 mt (2016) and $540 million to 43,545 mt and $405 million in 2020 (ME DMR, 2021).

Diversification from a fishery's landings could defray risks associated with single species dependence and mark a return to the legacy of diversified, multi-species harvesters in the Gulf of Maine region. However, Maine's commercial fisheries are effectively "locked" into a single species permitting approach, decreasing adaptability, and increasing risk and vulnerability for the many owner-operated harvesters. Maine's evolution to become a fisheries monoculture has occurred due to the confluence of: (1) The splitting of commercial fisheries licensing from only six licenses prior to 1977 (lobster, shellfish, marine worms, scallops, and a general category for other species) to now 23 license types across 16 fisheries, and (2) The collapse or decline of non-lobster fisheries, resulting in restricted access to commercial licenses. The rate of additional new lobster licenses over the past 25 years for example, is only 0.6/year (Stoll et al., 2016). With the changing climate placing uncertainty on species recovery (e.g., cod; Pershing et al., 2015) fishermen are "stuck" in their respective fisheries, unable to diversify by harvesting multiple species as in the past.

Aquaculture has been promoted as a potential diversification outlet for commercial fishers in the Gulf of Maine as it has in many global fisheries regions (S. Belle, personal communication). However, additional capital and operating investments to engage in new aquaculture operations are considered carefully by fishers. Clear information on returns to additional capital outlays (both human and monetary) are important to fishers as nearshore coastal fleets remain overcapitalized, and risks surrounding market development and increased volatility due to ocean climate change, among other risks are considered. A recent survey of fisherman on island communities in Maine indicated that outside of boats, there was very little overlap in capital equipment needed to engage in aquaculture, and that additional procurement of non-fisheries related capital equipment was an impediment to adoption of aquaculture (Love, 2016). This contradiction in the perception of aquaculture's diversification potential vs. reality is an important one. In order for commercial fishers to add ocean farming to their livelihoods a need exists to minimize the impact of four barriers to entry: (1) capital, (2) equipment, (3) knowledge, and (4) time.

Bivalve shellfish farming is a growing and lucrative sector of the coastal aquaculture industry worldwide. It has considerable market potential for expansion, especially in the northern temperate and peri-Arctic oceans for blue mussels (*Mytilus edulis*), American oysters (*Crassostrea virginica*), and sea scallops

(*Placopecten magellanicus*). However, bivalve farming methods are capital, equipment, and knowledge intensive. Moreover, in the north, these species require significant time to harvest and consequently delay the generation of additional income (18–24 months for mussels; longer for scallops and oysters). Bivalve aquaculture as a result is unlikely to serve the purpose to provide a simple, low-cost gateway to starting ocean farming for coastal fishing communities as they exhibit all four barriers to entry.

## Gulf of Maine Kelp Farming as a Supplemental Livelihood

For northern temperate oceans aquaculture of seaweeds, especially sugar kelp (*Saccharina latissima*), and other kelp species have fewer constraints. The farming of marine macrophytes is a global industry that continues to grow. In 2014, the sector was worth $6.4 billion USD (Cottier-Cook et al., 2016), growing to an estimated $13.1 billion USD in 2018 (FAO, 2020). Seaweeds are used in myriad products from human foods to toothpaste to exploratory research in biofuels and livestock feed. As with other seafood products, the USA imports the vast majority of seaweed from foreign producers (Piconi et al., 2020). This represents encouraging potential as domestic markets and value-added seaweed products are developing rapidly. The economic model for kelp aquaculture in Maine mirrors the existing way commercial fishing operates with the immediate dockside sales of raw product. Kelp is a fall-winter crop that comes to harvest size in less than 6 months; typically seeded in October–November and harvested in April–May. This eliminates the need for a multiyear husbandry commitment and is countercyclical to the traditional inshore summer lobster fishery. Kelp farming requires a skill set, knowledge base, social license, and equipment similar to those already possessed in abundance by established fishermen. These factors make seaweed aquaculture a logical option for fishers to adopt, as the model decreases all barriers to entry.

From 2015 to 2020, harvest of farmed sugar kelp in Maine increased more than 3,000% from 6.6 mt wet weight. While official Maine state datasets for 2021 are not yet available, the harvest will likely exceed 450 mt (Atlantic Sea Farms, personal communication). Demographic information on seaweed farm operators is not available. However, the largest value added kelp product producer in the state (Atlantic Sea Farms) works with 24 partner farmers, 21 of which are also commercial lobster fishers (Gershenson, 2020) indicating that the adoption of kelp farming by lobster fishers in Maine is already occurring. While farmed macroalgae is a multibillion-dollar enterprise world-wide, farmed seaweed from traditional production regions in China, South Korea, and Japan is traded at commodity scales yielding prices and markets in which kelp farms in the United States of America (USA) and the European Union (EU) cannot compete (FAO, 2017). Instead, emerging markets for kelp products in the USA and EU focus on high value niche food and health products (Grebe et al., 2019) This allows growers to operate smaller farms profitably, however even with domestic market price advantages, seaweed farming remains a largely a low-value, high-volume practice resulting in thin margins for producers. Given the part-time, supplemental nature of the current model of the Maine kelp farming sector, it is critical that every component of the farming process be cost-optimized for capital expenditure, efficiency of deployment, use, and harvest to ensure the greatest returns to the farmer. However, the current system design is cumbersome, immobile, and moorings are more or less permanent. These aspects make small scale adoption by fishers difficult. Moreover, Maine boasts >5,600 km of highly convoluted, rugged, and energetic coastline, and the areas close to shore are crowded with multiple user groups and stakeholders. As the industry grows the number of inshore, protected sites suitable for kelp growing will become limiting. However, there is ample opportunity to scale the sector by siting farms not offshore, but in nearshore exposed sites (Costa-Pierce and Chopin, 2021). It should also be noted that the same climate change driven environmental stressors impacting the American lobster also impact all macroalgae in the Gulf of Maine. Kelp forests are declining globally and the Gulf of Maine mirrors the trend (Filbee-Dexter et al., 2016; Filbee-Dexter and Wernberg, 2018; Witman and Lamb, 2018). While these changes are unlikely to be entirely overcome, challenges related to ocean warming are likely to be exacerbated closer to shore. Placing systems in higher energy conditions further from shore can help alleviate some of this risk through site selection. However, this requires sophisticated, well-engineered testing in the laboratory and field to ensure viability and survivability in these types of oceanic conditions. To overcome these constraints, inexpensive, lightweight, and highly mobile gear must be developed that can withstand high energy ocean conditions associated with exposed sites.

Currently the predominant gear-model employed by commercial seaweed farms in Maine is based on a model described by Flavin et al. (2013). This model is designed for calm waters and utilizes large, deadweight moorings with nearly vertical mooring lines. While suitable for protected waters, this model is costly to assemble and deploy, requiring large vessels capable of transporting 500–2,500 kg moorings to deploy the farm, and dictates the size of the farm be large from the outset to reach the economy of scale needed for profitability and permanence, since deadweight moorings are costly and difficult to move or reposition. Additionally, this system is suited only to the calmest of waters since the near-vertical moorings and the large surface flotation needed result in significant variations in tension as the water depth varies through tidal cycles. This results in a lack of tension in the system that can lead to slack moorings, drift of culture lines, and snap loads on the system in waves when the tide is low, and high tensions and difficult operations when the tide is high. Any of these factors can lead to failure of system components and potential loss of product. As farmers look to expand and scale up, innovations in farm designs for the many high energy sites available in nearshore oceans are needed to optimize the farming process to increase margins and to open areas to farming that previously would have been considered too exposed to operate in.

## Offshore and Exposed Kelp Farm Innovation

Innovations in engineering for seaweed farms have been occurring since the 1970s when the concept of biofuel production via offshore cultivation of *Sargassum* spp. was proposed (Bak et al., 2020), and more recently via the specter of co-location with offshore wind installations (Harkell, 2021), and furthermore via a reemergence of the biofuel concept (Harris et al., 2021). The design and testing of offshore and exposed seaweed cultivation platforms has been reviewed by Roesijadi et al. (2008), Langan and Buck (2017), and most recently by Bak et al. (2020). Commonplace among these assessments is complexity of design, high capital cost necessitating the need for scaling to achieve profitability, and the need to develop specialized mechanization and production flow processes specific to the husbandry platform. Examples of offshore cultivation rigs highlighting these issues are large ring structures deployed in the 2000s for cultivation of *S. latissima* within offshore wind structures (Buck and Buchholz, 2004, 2005) and tension leg platforms developed by the Korean Institute of Ocean Science and Technology for cultivation of *Saccharina japonica* (Chung et al., 2015). In both cases, the complexity of engineering and cost of operation proved insurmountable, and neither are currently employed commercially.

A system in use since 2010 by Ocean Rainforest at a nearshore exposed site in the Faroe Islands called the Macroalgae Cultivation Rig (MACR) has been successful, and lessons can be gleaned from its simplicity (Bak et al., 2018). The MACR system consists of a 500 m long polysteel line (30 mm) suspended horizontally between two surface floats affixed to four mooring lines held in place with 1–15 t steel anchors each. From this backbone, 10 m vertical grow lines seeded with *S. latissimia* are attached, each with a surface buoy (Bak et al., 2018). The system has survived 4 m significant wave heights over multiple years indicating good survivability in exposed environments (Bak et al., 2018, 2020). However, with many vertical grow lines and a four-point mooring system, the cost of such a system would still likely be prohibitive for a small to medium scale, fishermen owner-operated farm operations. While this much simplified approach does reduce costs by comparison, it still requires purpose-built equipment and vessels to operate and harvest (Bak et al., 2018).

## User-Focused, Social-Ecological Design Process

A rigorous design process is necessary to improve profitability and function of farming platforms intended for community scale applications in nearshore exposed environments for existing commercial fishers, as in Maine. In general, the design of offshore structures requires an engineered approach since risk can be substantial. This is especially true for industries such as oil/gas and wind where failures could be catastrophic. The same level of risk and return on investment does not necessarily exist for simpler, single owner operator kelp farming systems. Therefore, an ocean engineering approach is typically not applied. System optimization is needed so that exposed site gear is specified for the commercial fishery operator. Systems need to be designed to provide a solution to a problem, focused on the mechanical components in a precise, methodical, and mathematical fashion (Lindbeck, 1995; Haik, 2003). Because there is no pre-existing end user in traditional offshore seaweed farm system design, the engineering process is free to innovate and produce production systems that require acutely designed components from deployment through harvest and processing.

The criteria for design can be derived from the 30 commercial fishers who are also operating commercial scale kelp farms in the Gulf of Maine. Design criteria must consider the existing infrastructure in the form of fishing equipment and vessels that need to be repurposed to the greatest extent possible to assure profitability. Moreover, the dominant kelp farming model in Maine operates under the owner operated commercial fisheries model whereby harvesters bring product to port where it immediately changes hands to a processor or distributor. The existence of end users of the product (the kelp farming system) necessitates an innovative social-ecological industrial design approach.

# METHODS

In this applied research, a combined social-ecological industrial with ocean engineering design approach was used to establish a framework for developing a kelp farming platform for a specific target user group; namely, coastal owner operated fishing families who seek to employ seaweed farming in nearshore, exposed sites, as a product diversification tool for supplemental income. We have implemented a low-cost seaweed farming system for fall-winter operations that fits well into a livelihood strategy for rural coastal communities who must work multiple jobs in the offseason when their main fishery is unavailable due to seasonality, regulations, etc.

## Design Criteria

A design framework for seaweed farm engineering was developed to meet current industry needs and challenges. To assess industry priorities and desires for system function, our research team had informal conversations with several industry members currently farming *S. latissima* in the Gulf of Maine and leveraged the field research teams experience in operating a pre-existing experimental 200 m kelp farm of a different design over 3 years from 2015 to 2018. As part of this design process, our team sought to both satisfy engineering design goals (scalability, survivability, yield), blended with a system design meeting the needs of the growing inshore seaweed farming industry.

## Site Characterization and Monitoring

The project focused on an actual application to design, deploy, seed and harvest sugar kelp at a site with a State of Maine, Limited Purpose Aquaculture (LPA) license with the dimensions of 0.3 × 122 m (Conkling, 2021). The LPA is located in Saco Bay Maine (USA) with full exposure to the east (**Figure 1**). The site has a nominal mean sea level of 15.2 m with bottom substrate composed mostly of sand and a mean tidal range of 2.7 m. While the site is within 3 km of the shore, it is exposed to

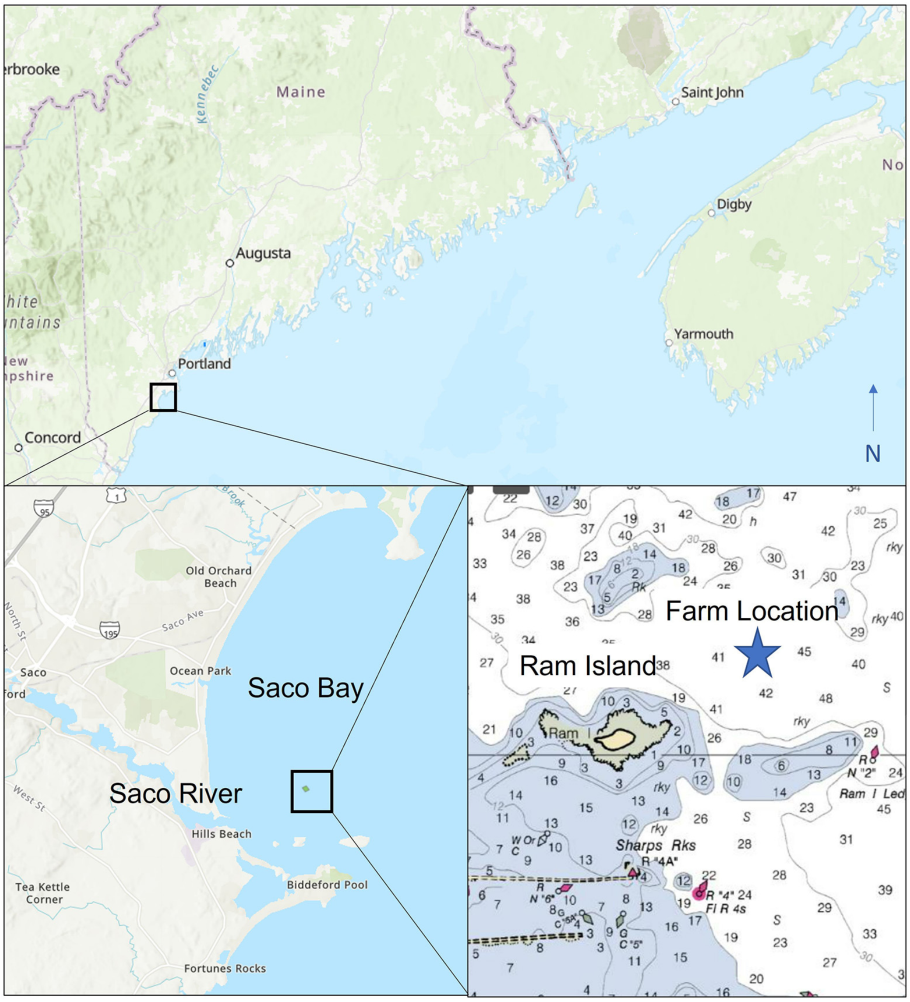


**FIGURE 1 |** The field study was conducted at a 0.3 by 122 m LPA site in Saco Bay Maine (USA). While the site is only about 2.5 km from the shore, it is completely exposed to the east.

Nor'easter storm events (from the east) from the Gulf of Maine. One extreme event, called the Patriot's Day storm, occurred on 16 April 2007. Wave simulation hindcast modeling described in Xie et al. (2016) for this storm yielded significant wave heights at the site on the order of 4–5 m with a dominant period of 11 s. Return period analysis using long term datasets from the National Oceanic and Atmospheric Administration, National Data Buoy Center, Station 44007 buoy showed that the Patriot's Day event exceeded the 50-year storm condition. In addition to waves, typical currents at the site are associated with the M2 tides, though a strong, seasonal, surface component is influenced by the Saco River flow. To investigate oceanographic conditions, a NORTEK Acoustic Wave and Current Profiler (AWAC) was deployed near the site. Datasets showed a predominant, semi-diurnal tidal ellipse with a major axis oriented in an east-west direction with current magnitudes approaching 0.3 m/s. This orientation was critical for placement of anchors to be in line with the tides. The measured current magnitude was multiplied by 1.85 to estimate a 50-year return current speed of 0.56 m/s, using methods from the Norwegian Standard NS 9415 (DNV-RP-C25, 2010).

## Farm Design and Component Selection

The initial design process focused on three criteria. Initially the farm must (1) fit within the lease site, (2) keep the gear as light as possible. Once the initial design components were specified, the farm was constructed, deployed, seeded, and assessed for biomass yield. With the known amount of biomass, the system was then evaluated for criterion (3) to be designed for the exposed, 50-year storm condition.

To fit within the lease site, the design incorporated a 122 m kelp grow line pre-tensioned with subsurface flotation at the corners with opposing anchor lines (**Figure 2**). The kelp line was situated in an east-west orientation aligned with the major axis of the tidal currents. It was important to define the orientation since this detail was required for the LPA application. The kelp line was held at 2.1 m below the surface with three support structures made with off the shelf rope, PVC pipe, and lobster

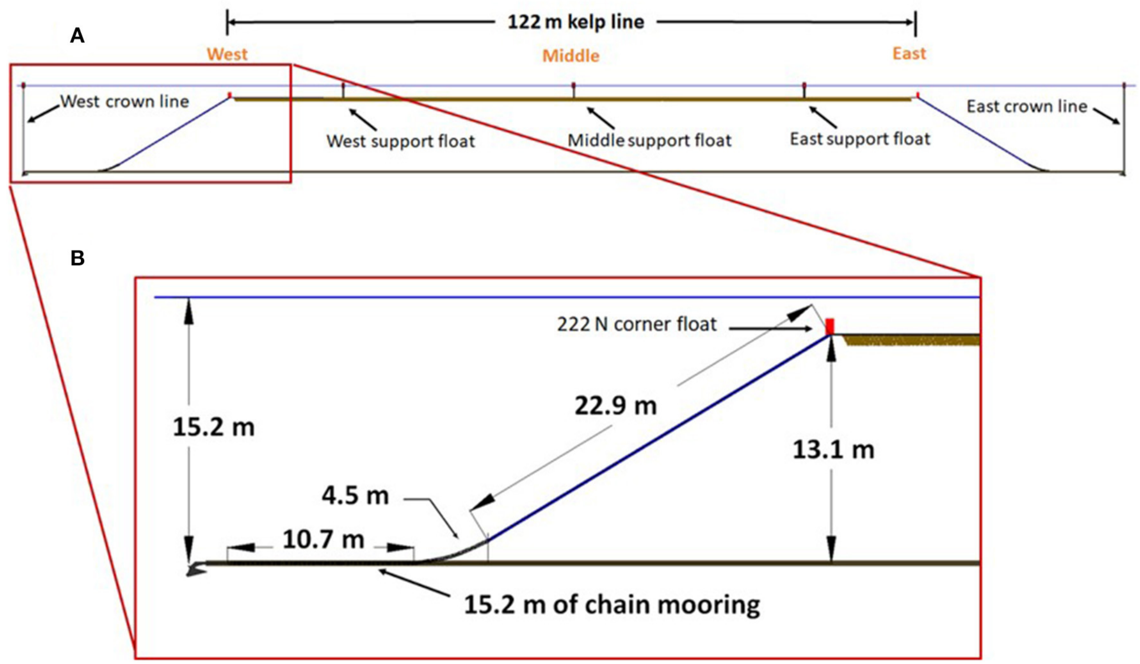


**FIGURE 2 | (A)** The dimensions of the kelp aquaculture system deployed at the exposed site. **(B)** Mooring line detail only depicted for the western leg as the eastern mooring is identical.

floats at east, middle and west locations. Anchor lines extended to the seafloor at an angle of 32° to the horizontal to a depth of 15.2 m. At the seafloor, the system was designed to include a section of 15.2 m chain with one end attached to the anchor line (**Figure 2B**). In this design approach, 1/3 of the chain is pulled up into the water column by the subsurface flotation forming a spring-catenary that provides pretension to the system preventing snap loads. Two-thirds of the chain is situated on the seafloor and is connected to a drag embedment anchor. Drag embedment anchors are efficient when loaded horizontally with some having a holding power up to 50 times the weight. The intent was to eliminate the use of a 6672 Newton (N) concrete block typically used in the region as described in Flavin et al. (2013). The resulting anchor leg geometry has a scope of 3:1, achievable in part with the use of 15.2 meters of chain.

Component specification also considered operational capabilities for the gear to be as light as possible as defined by design criterion #2. Since many fishing vessels have limited deck equipment like "A-frame" structures and high-capacity winches, the intent was to size the gear to be under 445 N so that two people could handle the components. The first step was to specify the weight of the chain in the catenary to offset the flotation at the corner of the kelp line. This was done by submerging two lobster buoys, for a total 222 N of flotation at each corner. To maintain the geometry, the anchor legs each incorporated a 16 mm, long-link, galvanized steel chain weighing 222 N/4.5 m. This chain has a working load limit of approximately 31 kN. The geometry with the catenary shape was verified using mooring system design techniques described in Faltinsen (1990). With 222 N of buoyancy and the specified geometry at the corners, pretension values of 356 and 418 N were calculated for the horizontal kelp and anchor lines, respectively. The anchor and kelp line components were specified with 25 mm of three-strand nylon rope having an estimated breaking strength when spliced of approximately 108 kN. The drag embedment anchors were also specified, each having a weight of 0.49 kN and an estimated holding capacity of 24.5 kN. The system was deployed and seeded on 30 October 2018 with kelp harvested on 22 May 2019. With the estimated biomass yield, the 122 m kelp farm system components were evaluated for the 50-year storm condition (criterion #3).

## Seed Production

"Brood stock" was collected from wild sporophytes showing development of ripe sorus tissue, identified as possessing differentiated sorus tissue laterally along the central axis of the distal frond. Ripe sorus tissue was targeted as being thickened and distinct from somatic tissues having a dark color, non-translucent opacity and raised tissue margin. Sori was harvested by cutting the blade distally from the meristematic tissues, leaving behind the hold fast, stipe and meristem to allow regrowth of the thallus. Collected tissue was stored in coolers with ice packs for transport to the nursery facility.

Sorus tissue was immediately prepped for spore release in the nursery by first removing all somatic tissue and trimming sori into approximately 3 × 5 cm portions with a clean razor blade. Visually obvious epiphytes and tissue imperfections were also trimmed and or scraped from the tissue in the same fashion. Sori were then rinsed thoroughly with 0.25 µm filtered seawater (FSW) and bathed for 30 s in a 10% betadine solution diluted with FSW. Following the betadine rinse, sori were rinsed again with FSW and conditioned for spore release by placing between paper towels dampened with FSW and incubating in dark conditions at 8°C for 24 h. Spore release was then induced by placing prepared tissues in 10°C FWS and monitored for release with light microscopy. Spore densities were quantified with a haemocytometer. Sporing was considered complete when zoospore densities were adequate to achieve 10,000 spores/ml concentration in inoculation tube water.

The spores were allowed to settle on PVC pipe spools of 5.1 cm diameter wrapped with 165 m of #9 nylon tufting twine (1.07 mm diameter) by placing them in 4 L settlement tubes and inoculated with FSW containing ∼10–20,000 spores/ml. Settlement spools were incubated at 12°C for 24 h, after which spools were transferred to 75 L culture tanks. Culture tanks were maintained at 12°C with a 12:12 light-dark photoperiod. Nutrients were provided via Guillard's (F/2) nutrient media. Water changes were conducted weekly to maintain cleanliness and adequate nutrient levels. Spools were inspected daily for gametophyte and sporophyte development and maintained in culture tanks until sporophytes were 2–5 mm in length. The seed spools that were eventually deployed on the farm were settled on 10-September-2018, introduced to the nursery on 11-September-2018 and then deployed to the experimental farm site on 30-October-2018.

## Farm and Biomass Monitoring

Farm monitoring was targeted at twice monthly during deployment. Due to the exposed nature of the site, this was often not possible due to weather, air temperature, or adverse sea conditions. Sampling intensity was increased during the spring (March–May) as more weather days became available and as kelp growth accelerated.

During site visits, the farm system was inspected for position and integrity to the greatest extent allowable by the weather conditions. Soft connections, and surface floatation connection points were inspected for wear and chaffing.

Biomass monitoring was conducted by collecting all kelp individuals from a 10 cm section of farm (linearly along the culture rope). Since sampling was destructive, and given the small nature of the farm, 10 cm was chosen as a biomass that was acceptable to remove from the farm at frequent intervals without appreciable impacting the final yield of the farm, and thereby the engineered structure's performance and behavior. During each sampling event, three replicate 10 cm samples were targeted: one each from the east, middle, and west portions of the farm. Samples were stored in individual plastic bags and kept cool and moist until processing.

Samples were processed for total wet weight. Each individual sporophyte was also processed for total wet weight, blade weight and stipe weight. Individual length and width measurements were also taken for all sporophytes sampled: Total length, blade length, as well as blade width along basal, medial and apical portions of the blade. Presence absence of sorus tissue was noted within each sample.

## Economic Analysis

A basic capital expenses to gross income and initial rate of return assessment was conducted. The assessment was limited to capital expenses required for purchasing farm components for a single 122 m longline. Assumptions were made that farmers were existing commercial fishers in which case infrastructure of on water operations were already in ownership (i.e., boats, trailers, trucks, etc.) and that expenses for the farm would be only the new capital outlay needed. Seed costs and farm-gate crop values were estimated from current market values in the region and the extensive personal experience of the research team.

# RESULTS

## System and Deployment and Productivity

The components that were specified for the farm system was pre-measured, cut and stored in standard black fish totes to be transported in a standard pickup truck (**Figure 3A**). The lightweight gear fit easily on a 10 m, landing craft style research vessel (**Figure 3B**). Note that in **Figure 3B** only one anchor assembly is shown. The system was deployed and seeded on 30 October 2018.

The kelp farm was monitored throughout the winter season of 2019. In early February 2019, a site survey indicated that the 122 m farm had maintained its position at the exposed site with kelp starting to grow to lengths of 10–30 cm (**Figure 3C**). Inclement weather continued, but the next site survey on 20 March 2019 showed an even distribution of kelp growing on the line. By April 2019 the biomass was estimated at 5.7 kg/m (**Figure 3D**) and at 12.7 kg/m at harvest in May (**Figure 3E**).

Total wet weight biomass at time of harvest was extrapolated from the measured biomass sub-samplings at time of harvest determined to be 1546.1 kg wet weight total over a 122 m grow line. Peak biomass was 12.67 kg/m (±0.4 kg) at harvest (5/22/2019, day 107). A logistic growth curve for biomass ($N$) as a function of time ($t$) was calculated using:

$$N(t) = \frac{KN_o}{N_o + (K - N_o)\, e^{-r(t)}}$$

The growth curve was fitted between the initial ($N_0 = 0.1$ kg/m) and the final ($K = 12.7$ kg/m) yield values with a rate ($r$) obtained from the dataset using the techniques described in Masters and Ela (2007) (**Figure 4**). Finding where the slope of dN/dt is equal to zero identifies the maximum growth rate, which occurred on 10 April with a value of 0.2 kg/m/d.

Individual sporophyte weight followed similar trends to overall biomass however with sporophyte measurements beginning on 3.25, the data represent the linear portion of the growth curve thereby allowing for linear regression as opposed to logistic regression. Sporophyte growth rate by wet weight over the growing season was 0.9 g/day starting at a minimum of 26.5 g (± 16 g) when first measured on 3/25 and ending at a maximum average weight of 83.3 g (± 50 g) (**Figure 5**).

## Structural Performances

Each component of the structure withstood the growing season without failure. However, to verify structural survivability

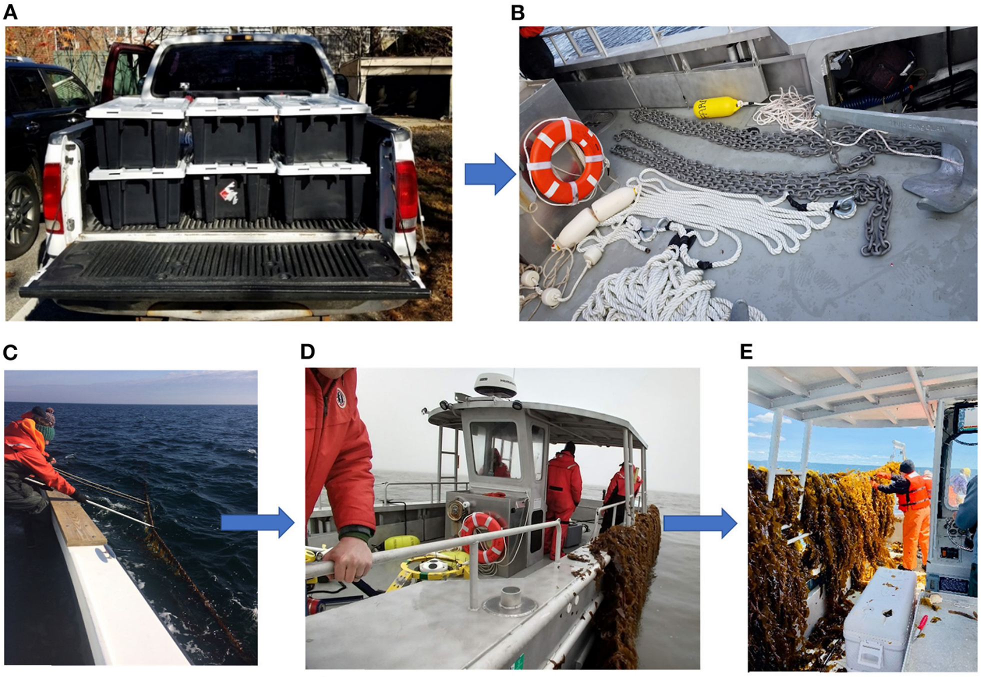


**FIGURE 3 | (A)** The components of the farm fit into fish totes loaded in a standard pickup truck. **(B)** The gear was loaded on a 10 m landing craft research vessel. Note that only one of the two anchor assemblies are shown. **(C)** In February, the kelp was growing on the intact system. **(D)** Growth continued and in April, biomass was estimated at 5.37 kg/m and **(E)** harvested at 12.67 kg/m on 22-May-2019.

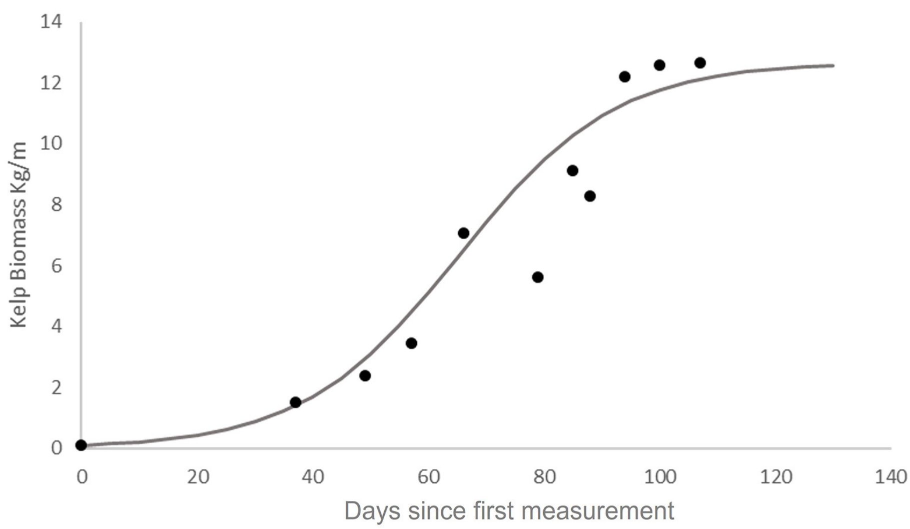


**FIGURE 4 |** Kelp biomass data fit to a logistic growth curve.

for the 50-year storm condition (criterion #3), a set of numerical modeling simulations were conducted using the previously described biomass yield characteristics. Simulations were conducted using a dynamic finite element numerical modeling approach that incorporates macroalgae hydrodynamics as drag areas per unit length derived from Fredriksson et al. (2020). This modeling approach solves the equations of motion of each element at each time step as summarized in NOAA's Basis-of-Design Technical Guidance for Offshore Aquaculture Installations in the Gulf of Mexico (Fredriksson and Beck-Stimpert, 2019). Wave and current loading on elements (including biomass elements) is incorporated into the model using a Morison equation formulation (Morison et al., 1950) modified to include relative motion between the structural

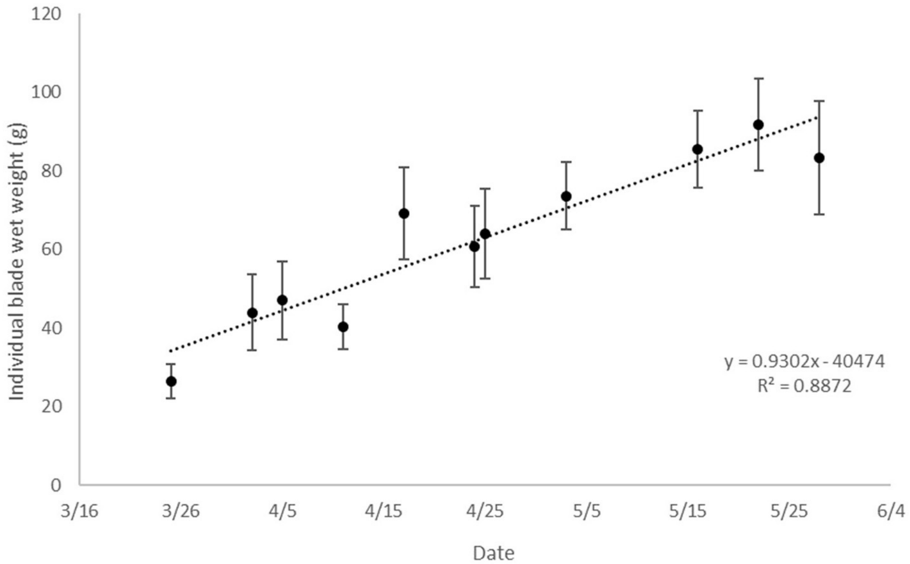


**FIGURE 5 |** Mean individual sporophyte wet weight over time during linear growth phase. Linear regression shown. Error bars represent standard error.

**TABLE 1 |** Environmental input parameters for extreme storm loading on the farm system.

| Current speed uniform with depth (m/s) | Current direction relative to backbone (degrees, °) | Significant wave height (m) | Peak wave period (s) | Wave heading relative to farm system (degrees, °) | Water depth including tidal elevation (m) | Kelp biomass (kg/m) | Kelp length (m) |
|---|---|---|---|---|---|---|---|
| 0.56 | 0 | 4.5 | 11 | 0 | 16.7 | 12.5 | 1.3 |
| 0.56 | 45 | 4.5 | 11 | 45 | 16.7 | 12.5 | 1.3 |
| 0.56 | 90 | 4.5 | 11 | 90 | 16.7 | 12.5 | 1.3 |

element and the surrounding fluid. For elements intersecting the free surface, buoyancy, drag, and added mass forces are multiplied by the fraction of the element's volume that is submerged.

Input to the model included an irregular sea-state time series with a significant wave height of 4.5 m and a dominant period of 11 s. The 50-year estimated current speed was taken to be uniform with depth and applied in the same direction as the waves. In the design simulations, load cases were configured with the waves and current at 0°, 45°, and 90° orientations to the farm with 0° being aligned with the grow line. The kelp was modeled as a series of 1 m aggregates knowing the yield (12.5 kg/m), mass density (1,054 kg/m3), and length (1.3 m) obtained from field datasets. With this information, aggregate weight and buoyancy was calculated and drag area values per unit length applied. Inputs to the model are included in **Table 1**.

For each load case, the maximum expected tensions, and forces in a 1-h storm were calculated assuming an extreme value distribution of the maximum loads. The capacities of the mooring components were divided by the maximum expected tensions and forces to compute a factor of safety for each component (**Table 2**).

**TABLE 2 |** Component capacities, design loads, and resulting factors of safety.

| Component | Component capacity (N) | Maximum expected load (N) | Factor of safety |
|---|---|---|---|
| Anchor | 24,500 | 16,227 | 1.5 |
| Chain | 32,864 | 16,227 | 2 |
| Mooring Line | 108,000 | 16,227 | 6.7 |
| Backbone | 108,000 | 10,739 | 10.1 |

*N, Newton; Factor of Safety, measure of greater component resisting capacity over assumed loading experienced by the component.*

The American Bureau of Shipping (ABS) recommends a safety factor of 1.82 on synthetic ropes and 1.67 for chain (ABS, 2012). The American Petroleum Institute recommends a safety factor of 1.67 on chain moorings and recommends that additional chain diameter be incorporated to allow for material lost to corrosion (API, 2005). The U.S. Navy Geotechnical Handbook (Naval Facilities Engineering Service Center, 2012) recommends a safety factor of 1.5 for drag embedment anchors. Thus, the specified structural components meet these standard requirements.

**TABLE 3 |** Itemized list of farm components and field operations equipment.

| Supplies | Detail | Quantity | Cost (each) | Total | Source |
|---|---|---|---|---|---|
| Anchors | 0.49 kN Claw | 2 | $520.00 | $1,040.00 | Hamilton Marine |
| Chain | 16 mm, 4.5 m | 2 | $230.00 | $460.00 | Hamilton Marine |
| Shackles | 16 mm Galv | 4 | $13.00 | $52.00 | Hamilton Marine |
| Thimbles | 16 mm Galv Heavy Duty | 4 | $8.00 | $32.00 | Hamilton Marine |
| Mousing wire | Lockwire stainless 0.032′ diam | 1 | $20.00 | $20.00 | Grainger |
| Grow and Mooring Line | 1″ nylon 3 strand (600′ reel) | 1 | $844.00 | $844.00 | Hamilton Marine |
| Crown Line | 5/8″ nylon 3 strand (52 lb) | 1 | $171.00 | $171.00 | Hamilton Marine |
| Floatation | Lobster Buoy 7 × 16 seamaster | 10 | $11.00 | $110.00 | Hamilton Marine |
| PVC | 3/4″ schedule 40 PVC 10′ | 3 | $6.00 | $18.00 | Lowes |
| Seed | seeded twine (61 m) on spools | 2 | $150.00 | $300.00 | Atlantic Sea Farms |
| Leasing costs | Limited purpose aquaculture | 1 | $100.00 | $100.00 | ME Dept Marine Resources |
| | | | Total | $3,147.00 | |
| **Equipment** | **Detail** | **Quant** | **Cost (each)** | | |
| Vessel | 20–40′ lobster vessel | 1 | in-kind | | |
| Truck | Ford F150 or similar | 1 | in-kind | | |
| Trailer | high-capacity utility trailer | 1 | in-kind | | |

## Economic Analysis

An economic analysis was conducted in constant dollars over a 3-year period considering the small-scale operations of the Maine working waterfront as an opportunity to supplement fishing activities during the offseason. In this context, the offseason represents October to May opposite the lobster fishing months. The analysis included the capital costs for the equipment specified for survivability at the exposed site (**Table 3**). It was assumed that the equipment would have a minimum design life of approximately 3 years with only minor additions of $200 at the beginning of years 1 and 2. The dataset included yearly seed and permit costs of $300 and $100, respectively. The capital and yearly expenditures were applied in the procedure at the beginning of the budget year (**Table 4**). Labor, fuel, and revenues were applied at the end of the budget (**Table 4**) as if for tax purposes. Tax and depreciation was not included in the analysis because proceeds would most likely be lower than the requirement for filing.

Labor was first modeled assuming minimum wage at $12.75/h for a total of 40 h/year ($510) (ME DOL, 2022). The time requirement was estimated from the following offseason schedule:

- October: 8 h for system preparation
- November: 8 h for deployment
- December–April: 2 h each month for system monitoring
- May: 8 h for harvest
- June: 6 h for equipment storage.

Yearly fuel costs were estimated assuming a 10 m lobster vessel burning diesel at 1 gallon/h for 40 h at a price of $3.50/gallon ($140/year). Revenues were based on the values provided in **Table 4** from a total yield of 1546.1 kg wet weight total over a 122 m grow line measured from the Saco Bay site. The yield value was adjusted by 10% due to blade and holdfast trimming (1394.4 kg). Revenues were based on a price of $1.65/wet kg resulting in $2301 per year. This pricing is based on the author's professional experiences in the kelp industry in Maine. Over the past 10 years, farm-gate prices have varied from $1.10–$2.20 USD/wet kg. $1.65/wet kg represents the median of this spread and was verified by current sellers. It should be noted that this price is representative and that no kelp grown on the experimental farm was sold, to avoid competition with the commercial kelp farming community.

An internal rate of return analysis (i) was then performed using the gross income cash flow column in **Table 4**. This was calculated by setting the Net Present Worth (*NPW*),

$$NPW = \sum_{n=0}^{N} \frac{c_n}{(1+i)^n}$$

to a value of zero and solving the series iteratively for internal rate of return (i). In Equation (2), $c_n$ are the cash flow values, $n$ is the year from 0 to 3 and $N$ is the total number of years. At minimum wage, the offseason lobster fisher would return approximately 8.6% of their investment, though profits would be minimal. The analysis was also done for a 0% rate of return by increasing the labor rate, which occurred at $4.75 above the minimum wage. Therefore, the lobster fisher could pay themselves $17.50/h and break even. Note that this analysis assumes that the infrastructure (vessel, truck, trailer, etc.) is paid for during the fishing season and is appropriate for handling the lightweight gear designed for the exposed kelp farming operations.

## DISCUSSION

Scale is one of the most controversial aspects of aquaculture today. In the nearshore oceans of much of the western hemisphere which are common property resource areas, scaling issues play a central role in the political and regulatory obstacles to advancing aquaculture (Knapp and Rubino, 2016; Stead, 2018).

**TABLE 4 |** Three-year analysis of expenses, revenues, and initial rate of return (IRR).

| Year | Labor | Seed | LPA | Fuel | Equipment | Revenues | Gross income |
|---|---|---|---|---|---|---|---|
| 0 | $0.00 | ($300.00) | ($100.00) | 0 | ($2,747.00) | $0.00 | ($3,147.00) |
| 1 | ($510.00) | ($300.00) | ($100.00) | ($140.00) | ($200.00) | $2,300.78 | $1,050.78 |
| 2 | ($510.00) | ($300.00) | ($100.00) | ($140.00) | ($200.00) | $2,300.78 | $1,050.78 |
| 3 | ($510.00) | $0.00 | $0.00 | ($140.00) | $0.00 | $2,300.78 | $1,650.78 |
| | | | | | | IRR | 8.606% |

In the Western hemisphere, a barrier to the growth of aquaculture and in this case, seaweed aquaculture, is the high competition for nearshore ocean space which is crowded with existing users (Goldburg et al., 2001). Areas are less crowded in more exposed regions with higher energy, or seasonally when winter creates harsh conditions.

Size of individual farms is also a critical component of scale. Siting conflicts increase proportionally with the size of the space occupied. Globally, in emerging seaweed farming economies a disconnect exists between the rhetoric and the reality that successful commercial farms are all relatively small and focused on producing seaweed for human consumption. The disconnect often centers on development of industrial scale seaweed farms aimed at producing large amounts of product on a single site, often for feed, fuel, or sale of carbon credits (Costa-Pierce and Chopin, 2021). The State of Maine is one of the only jurisdictions in the world to simplify scaling by allowing easy entry into small scale ocean aquaculture of low trophic level aquaculture species (seaweeds, shellfish) in a "limited purpose aquaculture permit" (LPA) (Conkling, 2021) which has alleviated barriers to entry for small scale seaweed farming. Thus, for expansion of new owner operated fishing interests, two aquaculture developmental models are available for them: (1) "scaling out," or (2) "scaling up." Scaling up of ocean space for aquaculture remains regulated though an ocean-leasing structure tiered by size. This tired system has size limitations the upper bounds beyond which social license to operate become limiting. By contrast, the LPA license allows for scaling out; allowing for geographic expansion, while constraining the overall footprint of any one farm. This tool has allowed for a rapid scaling out of sea seaweed farming sector in Maine.

While the LPA licensing tool, unique to Maine, has alleviated some of the siting conflicts with regards to farm footprint, it does not alleviate conflicts related to siting of farms close to shore. Generally, stakeholders increase in both number and diversity with increasing proximity to shore. Maine boasts 5,600 km of highly rugose shoreline with many protected bays, inlets, fjards, and islands. While the waters around these features are attractive for seaweed aquaculture due to quiescent waters and proximity to shore, they are impacted by many potential conflicts including but not limited to commercial fishing, recreational boating, riparian landowner viewsheds, conservation areas (seagrass beds, nesting seabirds, etc.), shipping, and other aquaculture farms (bivalves). However, there is major opportunity for expansion of seaweed aquaculture just outside these areas; not "offshore" but "near-shore, exposed" sites that remain close to shore, but offer more energetic oceanographic conditions with which the aforementioned conflict agents often do not overlap. The coast of Maine is ∼360 km straight line distance from New Hampshire to Canadian borders. If this straight light were drawn along the outer edges of every inshore island and bay, state waters would still extend another 4 km from shore. This means there is at least 1,700 km$^2$ of available space that is within 4 km from shore in exposed oceanographic conditions.

These areas are attractive for scaling out seaweed aquaculture especially as a supplemental livelihood to existing commercial fishers and these individuals have the local ecological knowledge needed to operate in these more challenging oceanographic sites. In this dynamic and rapidly changing sector, the primary challenges to expansion can change quickly. As recently as 2019 for example, Grebe et al. (2019) posit market access as a primary blockade to increasing kelp production. However, as of 2021 seaweed markets for domestic value added food and nutraceutical products are expanding rapidly as companies continue to pursue innovative new products and expand markets (Atlantic Sea Farms, personal communication). If this trend continues, it is assumed that perspective farmers will first assess the ability of the market to bear increased production prior to engaging in farming. Beyond this assessment, the limitation to entering farming then becomes farm system design that is suitable to operate safely and predictably in these nearshore exposed sites. As discussed previously, engineering approaches to farm system design are not often employed that small scales, and yet this is exactly what is needed for a scaled-out systems approach to sector growth to be successful.

The system designed and tested in this study demonstrates the value of user-focused design process. Design criteria were delineated based on knowledge of the intended user; existing small scale fishers who would farm as a livelihood augmentation, not a livelihood alternative. This type of social-ecological focused design process has identified as a priority to helping the sector minimize environmental impacts and stakeholder conflicts as well as amplifying social benefits (sustainability and resiliency in coastal communities and economies) (Grebe et al., 2019). Maximizing overlap of existing equipment, namely vessels, was prioritized as was minimization of capital outlay needed to acquire and assemble the system as well as minimize or eliminate the need for specialized parts or equipment. The resulting system not only satisfies the factors of safety in design to survive and produce in high energy ocean environments, but is comprised of components easily sourced from an outlet already familiar to commercial fishers; the marine supply store. Moreover, all system components were sized in order to be easily deployable and serviceable from a prototypical Gulf of Maine lobster boat. All components could be assembled and or fabricated on shore and packed efficiently for transport and ease of deployment (**Figure 3**).

In terms of crop yield the system produced 1546.1 kg wet weight total over a 122 m grow line. peak biomass was 12.67 kg/m (± 0.4 kg), in line with biomass production on kelp farms grown in protected portions of the same Saco Bay region (Grebe et al., 2021). Assuming a 10% biomass loss due to trimming at harvest, at a price point of $1.65/kg wet weight, this would yield the farmer a gross revenue of $2,301. From a standard return on investment analysis over 3 years, at this crop yield and farm gate price, our analysis shows a farmer can see an 8% return on investment over 3 years. However, a more nuanced perspective should be taken when assessing the economics of livelihood augmentation in small scale, seasonal commercial fishers that accounts for the opportunity costs and benefits of engaging in ocean farming as demonstrated by Mazumdar (1989). If one assumes that a seasonal harvester would typically take non-fisheries facing jobs during the off season, the revenue gained vs. labor invested from seaweed farming should be compared against revenues should that individual have worked those hours in a more traditional off-season vocation. In our case, if we assume the farmer would otherwise have worked a job benchmarked to minimum wage (12.75/h), the income would have been $510 over the 40 h worked. Once the initial investment is recovered, an annual return of $1,050/season that already includes wages represents a $13.50 increase in wages/h when compared to the same individual working 40 h at another job at 12.75/h; a significant incentive to farm seaweeds to enhance fishing family livelihoods.

## CONCLUSION

Seaweed farming could have widespread impacts on coastal communities from a socio-economic perspective given the technology is relatively simple and requires a very small initial capital investment. Our seaweed system was intentionally designed to limit barriers to deployment and operability to traditional fishing interests as it could be adopted easily by those with a knowledge of working on the ocean.

Small scale seaweed systems meet the demands of rural fishing communities and regional food markets. Small-scale farmers acquire knowledge and ability to scale up if favorable business models develop and would allow these new entrants to integrate into larger, national, and global markets, creating new value chains and trade. Scaling up inherently increases social, regulatory, and operational complexities and risky, whereas scaling-out allows for multiple adopters and development of cooperatives and regional hubs to consolidate and process products.

The farm system tested is very small, constrained by what is allowable with a single LPA from the state of Maine. However, even at this scale however, the financial analysis suggests a farmer can break even after 3 years utilizing a system that allows migration of farms to more energetic ocean environments using cost efficient, readily available components. Individuals can hold multiple LPAs in Maine or may pursue larger standard leases upon which this same farming system could be employed. Important next steps will be to assess the scalability of this farm design to understand how costs and labor demands scale with increasing farm size (i.e., length). If, for example, the most expensive components of the farm could be held relatively constant (moorings) while increasing the length of the culture line and minimally increasing labor demands then profitability of this farm design becomes increasingly attractive.

Facilitating industry growth at a community scale will require both scaling up of farms, but also scaling out with many small scale farms operating in more exposed nearshore sites. This study highlights the need for engineered approaches to seaweed farm design at scales previously considered too small to be required. This approach should be explored broadly, and beyond Maine not only with kelp farming but for other community scale, low trophic level aquaculture sectors that may benefit from exploring the opportunity for farming nearshore exposed ocean areas.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

AS-G: conceptualization, resources, methodology, investigation, formal analysis, writing lead-original draft, writing—review, and editing. DF: conceptualization, methodology, investigation, formal analysis, supervision, project administration, funding acquisition, writing-original draft, writing—review, and editing. TD: conceptualization, methodology, software, investigation, formal analysis, writing—original draft, writing—review, and editing. ZM-H: resources, writing-original draft, writing—review, and editing. BC-P: conceptualization, resources, project administration, writing—original draft, writing—review, editing, and funding acquisition. KJ: resources. All authors contributed to the article and approved the submitted version.

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# Fad, Food, or Feed: Alternative Seafood and Its Contribution to Food Systems

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Aquatic foods, or "seafood", are an integral part of the global food system that contribute significantly to many dimensions of human wellbeing, including livelihoods and food and nutrition security. Fish, molluscs, crustaceans, algae and other aquatic foods are of particular importance in low- and middle-income countries as a source of employment, income, and nutrition for many poor and vulnerable people, including women. Global concern over the ability of fisheries and aquaculture to sustainably meet future seafood demand is driving improvements in technology and management. It has also inspired the emergence of plant-based and cell-based seafood, collectively termed "alternative seafood". Growing investment, consumer demand, and participation by major food companies in the alternative seafood sector necessitate an evaluation of potential opportunities and challenges alternative seafood poses to food systems. This paper explores key economic, social, and environmental implications associated with production, distribution, and consumption of alternative seafood and its interactions with fisheries and aquaculture over the next decade, with specific emphasis on low- and middle-income countries. Available data on current supply and projected growth suggest that alternative seafood may account for almost eight percent of global seafood supplies destined for human consumption in 2030. Assuming current production techniques and expected technological development, the sector has potential for reduced environmental impacts relative to the existing fisheries and aquaculture sectors. However, its potential to impact livelihoods, food and nutrition security, and the environment remains largely a matter of conjecture due to the lack of robust data. Mechanistically, it is believed that growth of alternative seafood supplies will lessen demand for "conventional" seafood and/or meat, a scenario with implications for livelihoods, food and nutrition security, and the environment. Such changes are contingent on technological development, human and institutional behavior, market forces, and ecological linkages and as such, remain speculative. Nevertheless, as a novel sector, new food, and potential alternative to conventional seafood and/or meat, society has an opportunity to shape the growth of alternative seafood and its contribution to national and global development goals. This paper identifies knowledge gaps that require further research to inform inclusive, equitable, and sustainable development and governance of the emerging alternative seafood sector.

**Keywords: alternative seafood, plant-based, cell-based, livelihoods, food and nutrition security, environment, aquatic health, biodiversity**

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## INTRODUCTION

Increasing awareness of challenges to our food systems—climate change, public health, ecosystem disruption, environmental degradation, human rights violations, and animal welfare—is driving major changes in food production and consumption. Increased public exposure to shocks like COVID-19 appear to be accelerating consumer demand for change globally (Knight et al., 2020; Love et al., 2021; White et al., 2021), with static or declining national averages of meat and other terrestrial animal-source food consumption in many high-income countries (HICs), albeit with changing composition of food consumption (Godfray et al., 2018; Attwood and Hajat, 2020). Consumers are also demanding greater transparency about provenance, production methods, environmental sustainability, and social responsibility. However, the complexity and decentralization of value chains for conventional aquatic foods (hereafter "seafood") make this difficult to achieve equitably and effectively (Bailey et al., 2016; McClenachan et al., 2016).

Seafood is an integral part of the global food system that contributes significantly to livelihoods and food and nutrition security, especially in low- and middle-income countries (LMICs) (Hicks et al., 2019; FAO, 2020). However, at a time of significant and unprecedented stress on aquatic ecosystems, concern mounts regarding the sustainability of present supplies and our ability to meet future demand (Barange et al., 2018; GFI, 2019; FAO, 2020). Plant-based and cell-based seafood, collectively termed "alternative seafood", have rapidly emerged over the past half decade and are often promoted as part of the solution to these concerns. Plant-based seafood products seek to mimic the taste, texture, appearance and/or nutritional properties of conventional seafood, so consumers can enjoy the sensory and/or nutritional experience and reduce their seafood intake. Cell-based seafood is grown directly from cells of aquatic animals and as such, is comprised of the same cell types and may be arranged in the same three-dimensional structures as its conventional counterpart.

The emerging alternative seafood sector lacks statistics and public monitoring systems, but recent projections indicate that plant- and cell-based seafood may claim 0.14 and 7.5% of the conventional seafood market by volume by 2030 (Marwaha et al., 2020). These estimates say more about the perceived disruption value of the sector than the likely impacts on food systems, as it remains to be seen if alternative seafood will be a fad, retain its place as a food for human consumption, or be used differently altogether, such as for animal feed.

Few studies have evaluated the potential of alternative seafood to impact food systems, especially in LMICs. This review explores key economic, social and environmental implications associated with production, distribution, and consumption of alternative seafood and its interactions with fisheries and aquaculture over the next decade, with specific emphasis on LMICs. Our analysis relies on the available evidence in peer-reviewed literature, reports and other gray literature, some of which is extrapolated from research on alternative terrestrial meats. The paper covers the potential of alternative seafood to impact food systems; economic implications, especially regarding trade and livelihoods; social implications, specifically for food and nutrition security; environmental implications, focused on natural resources use and health of aquatic ecosystems; and recommendations for further research.

## ALTERNATIVE SEAFOOD AND ITS POTENTIAL TO IMPACT FOOD SYSTEMS

Traditional (e.g., tofu, tempeh) and whole food (e.g., mushrooms, jackfruit) alternatives to meat and seafood have been eaten for centuries, but their sensory and nutritional attributes differ from conventional meat and seafood (Kyriakopoulou et al., 2019). Alternative seafood often better emulates its conventional counterparts in effort to gain acceptance by conventional seafood consumers, as evidenced by growing investment from public and private sectors, consumer demand and participation by major food companies (Marwaha et al., 2020). Alternative seafood comprises all plant-based, fermentation-derived and cell-based seafood alternatives that mimic the taste, texture, appearance and/or nutritional properties of conventional seafood (Marwaha et al., 2020). Fermentation-derived seafood is considered with plant-based seafood here but does have its own unique characteristics (GFI, 2020a).

Plant-based seafood encompasses structured plant-, algae- or fungus-derived foods designed to replace conventional seafood either as standalone products or within recipes (GFI, 2019; Marwaha et al., 2020). Aquatic plants and algae consumed in their natural form (Aasim et al., 2018) are not discussed here. Plant-based seafood is typically comprised of a combination of legume proteins, soy protein, wheat protein, rice, vegetables, mycoproteins, seaweed, algal oil and plant oils (**Table 1a**). The plant proteins mainly come from terrestrial sources and are processed with water, flavoring, fat, and binding and coloring agents to mimic the sensory, and to some degree the nutritional, attributes of conventional seafood (Kyriakopoulou et al., 2019). Almost 30 companies across Europe, North America and Asia have emerged with plant-based versions of breaded fish filets and cakes, shredded and raw tuna, smoked and raw salmon, and shrimp, which are available for purchase at major food retailers and online platforms (**Table 1a**) (Marwaha et al., 2020). These visceral equivalents are often targeted at conventional seafood consumers (Stephens et al., 2018), but public research and regulatory support, especially regarding novel ingredients and production technologies, are needed to widen market acceptability and accessibility, which remains low (Kazir and Livney, 2021).

Cell-based seafood is produced through the cultivation of aquatic animal cells, and as such is genuine animal tissue that aims to replicate the sensory and/or nutritional profile of conventional aquatic animal foods (GFI, 2019; Marwaha et al., 2020). Cells are generally grown in bioreactors that regulate temperature, nutrients and other conditions (e.g., dissolved oxygen, pH) to optimize growth, then concentrated and structured to produce commercial products (Rubio et al., 2019). This allows for the isolated production of desired cuts with fewer public health concerns, reduced human and animal

**TABLE 1a** | Current plant-based and fermentation-derived seafood producers, products, and main protein sources (as of 29 July 2021).

| Plant-based and fermentation-derived seafood producers | | | | | |
|---|---|---|---|---|---|
| **Company** | **Location** | **Product** | **Primary protein (if unavailable, primary ingredient excepting water)** | **Availability** | **Website** |
| AquaCultured Foods | Chicago, Illinois, USA | Fish (unspecified) | Fungi | - | https://www.aquaculturedfoods.com/ |
| Atlantic Natural Foods | Nashville, North Carolina, USA | Shredded tuna (Tuno$^{TM}$) | Soy protein | United States, Europe | https://atlanticnaturalfoods.com/tuno/ |
| Bonsan | Surrey, UK | Fish fillets; Shredded tuna | Soybean | United Kingdom | https://www.bonsan.co.uk/ |
| betterfish | Berlin, Germany | Shredded tuna; Tuna spread | Macroalgae | - | http://betterfish.de/ |
| BY2048 | Canada | Salmon slices; Salmon pieces | Carrot | Canada | https://www.by2048.com/ |
| FRoSTA AG | Bremerhaven, Germany | Fish cakes; Breaded fish fillet | White bean, hemp protein | Germany | https://www.frosta-ag.com/en/ |
| Gardein | Richmond, British Columbia, Canada | Breaded fish fillet | Soy protein concentrate, wheat flour | North America | https://www.gardein.com/ |
| Good Catch Foods | New York, New York, USA | Shredded tuna; Fish sticks, Breaded fish fillet; Crab cakes; Fish cake | Pea protein isolate, soy protein concentrate, chickpea flour, lentil protein, faba protein, navy bean flour | North America, Europe | https://goodcatchfoods.com/ |
| Growthwell Group (OKK and Su Xian Zi brands) | Singapore | Squid; Prawns; Abalone; Shrimp; Sea cucumber; Lobster; Seafood balls | Konjac, soy protein, or mushroom (depending on the product) | Asia, North America | https://growthwellfoods.com/ |
| Hooked Foods | Stockholm, Sweden | Shredded tuna | Soybean, algae | Sweden | https://www.hookedfoods.com/ |
| iglo | Hamburg, Germany | Fish sticks | Rice flake, wheat flour | Germany | https://www.iglo.de/green-cuisine |
| Ima | London, England, UK | Raw salmon | Wheat flour | United Kingdom | https://www.instagram.com/weareima/?hl=en |
| Jens Møller Products ApS (Vegan Zeastar brand) | Herning, Denmark | Roe (Cavi-Art®, Tosago®) | Macroalgae | Denmark | https://caviart.com/ |
| Kuleana | San Francisco, California, USA | Raw tuna (Akami) | Pea protein | United States | https://www.kuleana.co/ |
| Linda McCartney Foods | Leeds, England, UK | Fish cakes; Fish goujons | Soy protein, wheat protein, chickpea flour | United Kingdom | https://lindamccartneyfoods.co.uk/ |
| Mimic SeaFood | Madrid, Spain | Raw tuna | Tomato, macroalgae (kombu) | Spain | https://mimicseafood.com/ |
| Nestlé | Vevey, Switzerland | Shredded tuna (Sensational VUNA) | Pea protein, wheat gluten | Switzerland | https://www.nestle.com/stories/plant-based-seafood-tuna |
| New Wave Foods | San Francisco, California, USA | Shrimp | Mung bean | - | https://www.newwavefoods.com/ |
| Novish | Breda, Netherlands | Fish sticks; Fish nuggets; Fish burgers | Wheat protein, pea protein | Netherlands | https://www.novish.eu/ |
| Ocean Hugger Foods | Brooklyn, New York, USA | Raw tuna (Ahimi®);<br>Raw eel (Unami$^{TM}$) | Tomato;<br>Eggplant | United States | https://oceanhuggerfoods.com/ |
| Odontella | Bordeaux, France | Salmon slices (Solmon®) | Macroalgae (Undaria pinnatifida, Himanthalia elongata, Ascophylum nodosum), pea protein | France | https://www.odontella.com/fr/odontella-accueil/ |
| The Plant Based Seafood Co. | Gwynn's Island, Virginia, USA | Breaded scallops; Breaded shrimp; Lobster crab cakes | Vegetable root starch | United States | https://plantbasedseafoodco.com/ |
| Prime Roots | Berkeley, California, USA | Lobster ravioli | Koji | United States | https://www.primeroots.com/ |

*(Continued)*

**TABLE 1a** | Continued

| Plant-based and fermentation-derived seafood producers | | | | | |
|---|---|---|---|---|---|
| **Company** | **Location** | **Product** | **Primary protein (if unavailable, primary ingredient excepting water)** | **Availability** | **Website** |
| Quorn | Stokesley, England, UK | Fish sticks; Breaded fish fillet | Rice flake and flour, wheat flour and starch, mycoprotein, maize flour | North America, Europe | https://www.quorn.co.uk/ |
| Revo Foods | Wien, Austria | Salmon slices; Salmon spread | Pea protein | - | https://revo-foods.com/ |
| Save da Sea Foods | Victoria, British Columbia, Canada | Salmon slices | Carrot | Canada | https://www.savedasea.com/ |
| Seasogood | Utrecht, Netherlands | Shredded tuna | Soy protein concentrate | Netherlands | https://seasogood.com/ |
| SoFine Foods | Landgraaf, Netherlands | Fish nuggets; Salmon fillets; Fish burgers | Soybean | Netherlands | https://www.sofine.eu/ |
| Sophie's Kitchen | Sebastopol, California, USA | Shrimp; Crab cakes; Breaded fish fillet; Salmon slices; Shredded tuna (Toona) | Pea protein and starch | United States | https://www.sophieskitchen.com/ |
| Tesco | Welwyn Garden City, England, UK | Breaded fish fillet; Fish cakes | Soy protein | United Kingdom | https://www.tesco.com/groceries/en-GB/ |
| Upton's Naturals | Chicago, Illinois, USA | Banana blossom (as a fish fillet substitute) | Banana blossom | United States | https://www.uptonsnaturals.com/ |
| Vbites | Corby, England, UK | Fish sticks; Tuna pate; Fish cakes; Salmon slices; Breaded fish fillet | Soy protein, wheat starch, ground flax | United Kingdom | https://www.vbites.com/ |
| Vegan Finest Foods | Netherlands | Raw tuna (No Tuna); Raw salmon (Zalmon); | Tapioca starch; | Netherlands, United Kingdom | https://veganfinestfoods.com/ |
| | | Shrimp (Shrimpz); | Soy protein; | | |
| | | Calamari (Kalamariz); | Thickener (Locust bean gum, seaweed gum, modified starch); | | |
| | | Cod (Tasty Codd) | No data | | |

**TABLE 1b |** Current cell-based seafood producers, products, and progress to date (as of 29 July 2021).

| Cell-based seafood producers | | | | | |
|---|---|---|---|---|---|
| **Company** | **Location** | **Primary product** | **Other products** | **Progress** | **Website** |
| ArtMeat | Kazan Russia | Sturgeon | - | 2023 - Anticipated market launch of sturgeon | http://artmeat.pro/ |
| Avant Meats | Hong Kong China | Grouper | Fish maw (dried swim bladder of croaker); Fish fillet (unspecified) | Late 2021 - Anticipated market launch; Nov 2020 - Fish fillet tasting; Oct 2019 - Fish maw tasting | https://www.avantmeats.com/ |
| BlueNalu | San Diego California USA | Mahi mahi | Bluefin tuna | Late 2021 - Anticipated completion of commercial pilot production facility market launch of mahi mahi; Dec 2019 - yellowtail tasting | https://www.bluenalu.com/ |
| Bluu Biosciences | Berlin Germany | Atlantic salmon; Rainbow trout; Carp | - | 2023/2024 - Anticipated market launch; Late 2022 - Anticipated prototype of un- or semi-structured product (e.g. fish tartar fish sticks fish balls) | https://www.bluu.bio/ |
| Cell Ag Tech | Toronto Ontario Canada | Fish (unspecified) | - | - | https://cellagtech.com/ |
| Cultured Decadence | Madison WisconsinUSA | Lobster | - | 2022 - Anticipated tasting | https://www.cultureddecadence.com/ |
| Finless Foods | Emeryville California USA | Bluefin tuna | Sea urchin; Eel; Fugu (poisonous pufferfish) | Sept 2017 - Carp tasting | https://finlessfoods.com/ |
| Magic Caviar | Amsterdam Netherlands | Caviar | - | - | https://www.magiccaviar.com/ |
| Sea-Stematic | Johannesburg South Africa | Fish (unspecified) | - | 2023 to 2025 - Anticipated market launch | https://sea-stematic.com/ |
| Shiok Meats | Singapore | Shrimp | Lobster; Crab | 2022 - Anticipated market launch; Nov 2020 - Lobster tasting; Mar 2019 - Shrimp dumpling tasting | https://shiokmeats.com/ |
| Wildtype | San Francisco California USA | Coho salmon (sushi-grade) | - | 2025 - Anticipated market launch of salmon; June 2019 - Salmon tasting | https://www.wildtypefoods.com/ |

welfare issues, and novel opportunities for shorter and more transparent value chains and localized production. Currently, the nine companies producing cell-based seafood are based in North America, Asia, and Europe and focus on higher value species including bluefin tuna, crab, fish maw, grouper, lobster, mahi mahi, salmon, shrimp, and sturgeon (**Table 1b**). Rapid development of the industry is marked by growing investment, with recent involvement by the public sector (Dolgin, 2020; National Science Foundation, 2020) and partnerships between cell-based seafood producers and major food companies (Marwaha et al., 2020). Although no cell-based seafood products have received regulatory approval, it is anticipated in Singapore by 2022, with sales in Japan and approval in North America, Europe, and Australia expected to follow (Waltz, 2021). Sales will be targeted at wealthier markets (e.g., fine dining, HICs) as extremely high prices preclude wider market penetration. This is mainly due to a range of technological limitations, including optimized and scalable production (e.g., appropriate cell lines and scaffolding, optimized media formulations and cell culture densities, scalable bioreactors), and natural resources use, specifically energy and water (Rubio et al., 2019; Potter et al., 2020). It is widely agreed that public research would create a foundation of shared scientific knowledge to help advance the sector (Potter et al., 2020) and be necessary to bring cell-based seafood to mass markets and poorer consumers (Dolgin, 2019).

Alternative seafood is promoted for its potential to increase the sustainability and resilience of food systems without requiring significant behavioral change from consumers (GFI, 2019; Wurgaft, 2020). This stance is framed around the continued increase in seafood demand and belief that significant reductions in global seafood consumption are unlikely (FAO, 2020; Wurgaft, 2020). However, impacts on food systems are dependent on many factors ranging from the development of production to methods of consumer adoption. To see positive change, production must be well-governed and uphold social and environmental standards. The adoption of alternative seafood must also be coupled with sufficient disadoption of conventional seafood and/or meat, which itself is influenced by many factors including price, taste and accessibility (Halpern et al., 2021). Although plant-based seafood is mainly accessible in wealthier markets and the introduction of cell-based seafood is expected to be concentrated in wealthier markets, if these products are responsibly produced and the adoption transition happens at scale, the partial replacement of wild or farmed seafood could impact global food systems. These changes will likely be experienced in HICs, but there may be indirect effects on livelihoods, food and nutrition security and the environment in LMICs. However, demand projections for alternative seafood are subject to great uncertainty, largely because the current market share is small, so it remains unclear if the scale of adoption will be significant enough to create measurable improvements (Halpern et al., 2021).

As a novel sector, new food and potential alternative to conventional seafood and/or meat, governments, intergovernmental organizations, and businesses have an opportunity to shape the growth of alternative seafood to contribute to national and international goals for inclusive, equitable, and sustainable food systems (Herrero et al., 2020). This paper primarily explores how alternative seafood might impact food systems if it can indeed augment global seafood production, while acknowledging other methods to sustainably increase seafood supply (Cabral et al., 2020; DeWeerdt, 2020), decrease loss and waste (Kruijssen et al., 2020), and better distribute nutrient-rich foods (Ahern et al., 2021) are likely of more immediate relevance to improving livelihoods, food and nutrition security, and the environment, especially in LMICs.

## Economic Implications

The following section explores how current development and future projections for alternative seafood may affect global seafood markets and livelihoods, especially of small-scale actors in the conventional seafood sector.

### Global Markets

Significant development and rapid investment in alternative seafood has occurred over the past half decade (GFI, 2021c). Major food companies have invested in or partnered with plant-based producers (e.g., Bumble Bee Foods and Good Catch Foods, Tyson Ventures and New Wave Foods) and others have acquired or started their own lines of plant-based seafood (e.g., Nestle's Vuna, Van Cleve Seafood's The Plant Based Seafood Co.). A few cell-based seafood producers have also seen investment and partnerships from major incumbents (e.g., Cargill, Griffith Foods, Nutreco, Pulmuone, Rich Products Corporation, Sumitomo, Thai Union). Early research on the science of cell-based seafood by the public sector (Benjaminson et al., 2002) provided a starting point for much of the current development by the private sector, but there is renewed advocacy to secure consistent public sector support for both plant- and cell-based seafood (116th Congress, 2020; Dolgin, 2020; National Science Foundation, 2020).

Involvement by incumbents and the concentration of producers in HICs raises concern over increased consolidation in value chains that can perpetuate power disparities (Santo et al., 2020), but it remains unclear how alternative seafood will act in global markets. Before COVID-19, and increasingly so since, we have seen increased consumer demand for alternatives to animal-source foods and better transparency in value chains (Attwood and Hajat, 2020). These trends are expected to continue as consumers improve their food literacy (De Backer et al., 2021). However, at <1% of the conventional seafood market (GFI, 2020b), it is yet to be seen if alternative seafood will play a significant part in this transition.

There may be more opportunity for widespread adoption if price parity with conventional seafood is reached. Although key protein inputs are generally much less expensive than animal-source proteins, plant-based seafood tends to retail for a premium (Rubio et al., 2020). Prices may become more competitive as start-up costs are recovered, input supplies and processing are optimized, and economies of scale are reached (Specht, 2019). The cost of cell-based seafood remains prohibitive largely due to expensive growth factors in cell culture media, though capital expenses can also be significant (Risner et al., 2021; Vergeer et al., 2021). With further research and development it is postulated that cell-based seafood may be produced at less than USD 6 per kg of edible product by 2030, placing it at price parity with many types of conventional seafood (Vergeer et al., 2021). In the meantime, cell-based seafood may prove viable as a minor ingredient in hybrid seafood alternatives or as high-value products (e.g., bluefin tuna, fish maw). However, implications for food systems also depend on how adoption occurs. If it lasts, will alternative seafood compete with conventional seafood, conventional or alternative meat, or other foods, and result in significant substitution? Or, as with the development of aquaculture, will alternative seafood simply expand the global market and supply?

Alternative seafood may also help improve sustainability of other sectors. For example, plant-based seafood and associated production technologies (e.g., fermentation) could be adapted to produce novel, accessible ingredients for aquatic animal feeds that reduce reliance on wild capture fish or improve fish and human nutrition (Cottrell et al., 2020; Marwaha et al., 2020). The development of alternative seafood may also stimulate and support other sectors (e.g., seaweed farming) that, with appropriate management, can help reduce impacts of climate change (Duarte et al., 2017; Froehlich et al., 2019; Roque et al., 2021).

### Livelihoods

Alternative seafood production depends on a transdisciplinary group, including farmers, biologists, chemists, engineers, and factory workers. If alternative seafood were to significantly displace conventional seafood production, there may be significant changes in livelihoods, specifically in terms of income and employment, of aquatic food system actors. A mass shift from conventional seafood to alternative seafood could disrupt current employment in seafood production and processing, as well as upstream in the value chain (e.g., vessel construction, gear fabrication). However, downstream employment opportunities (e.g., packaging, transport) may increase as alternative seafood, especially cell-based seafood, will require similar handling as conventional seafood, although the actual distribution of benefits may aggravate existing inequalities (Marwaha et al., 2020).

As alternative seafood grows, research and policies that allow marginalized aquatic food system actors to retain their place in conventional value chains or participate in alternative seafood value chains are needed. Since alternative seafood will likely be mainly available in HICs in the next decade, effects may be felt by actors in LMICs that increasingly produce seafood for export to HICs (FAO, 2020). It is expected that change would be concentrated in industrial fishery or aquaculture operations, which may manifest as increased unemployment or competition for low wage or dangerous jobs, but the focus on alternatives for high value species may also directly affect small-scale fishers and farmers producing high value species (e.g., shrimp, grouper, snapper, yellowtail) (Marwaha et al., 2020). Appropriate measures in LMICs may be necessary to protect workers, support livelihood diversification or conversion (GFI, 2021a), and develop key domestic seafood markets.

If the adoption of alternative seafood in place of conventional seafood reduces pressure on aquatic ecosystems, it may further benefit marginalized actors whose traditional livelihoods have been compromised by industrial fishing operations. However, the scale at which this must occur is unclear and should be further explored (Cottrell et al., 2021). Given current projections for the next decade, it is unlikely that alternative seafood will cause fisheries and aquaculture to reduce their current scale of operation. Rather, this will be due to broader adoption and enforcement of environmental regulations, reduced availability of water and production locations, increasing incidence of aquatic animal diseases, and decreasing productivity gains (FAO, 2020).

## Social Implications

The implications of alternative seafood on key social indicators, with an emphasis on nutrition and food security, namely availability, access, utilization, stability, agency, and sustainability, are reviewed here.

### Food and Nutrition Security

Plant-based seafood is generally promoted as having comparable nutritional value to conventional counterparts. However, this must be systematically evaluated as there are key nutrients (e.g., vitamin A, vitamin B12, riboflavin, calcium, iron, zinc) that are difficult to adequately secure from solely plant-source foods (Murphy and Allen, 2003). Plant-based seafood may also be developed to help balance diets rather than replace conventional seafood in diets (e.g., high dietary fiber content, vitamin and/or mineral fortification) (Kyriakopoulou et al., 2019). Although there is limited evidence of the nutritional value and health effects of plant-based seafood consumption, plant-based meat generally contains similar nutrient composition (i.e., macronutrients, readily available minerals) as their conventional counterparts (Bohrer, 2019) and can lower several cardiovascular disease risk factors in healthy adults (Crimarco et al., 2020). Nutritional equivalency, however, depends on the specific formulation of the plant-based product and what it replaces in diets. As such, health implications regarding ingredient types, degree of processing and final nutritional profile of plant-based seafood has raised concern, especially for nutritionally vulnerable populations (Monteiro et al., 2019).

There is little information about the nutritional value of cell-based seafood (Potter et al., 2020), though it is often claimed that it will be comparable or superior to their conventional counterpart and can be tailored to meet dietary needs and preferences (Datar and Betti, 2010; Rubio et al., 2020). Seafood is a nutrient-dense source of high quality, highly bioavailable proteins, lipids and micronutrients, however, some compounds (e.g., omega-3 fatty acids, vitamin B12, heme iron) not synthesized by muscle cells must be supplemented in cell-based seafood (Datar and Betti, 2010). More research on the metabolism of essential compounds and methods for supplying these compounds (e.g., media formulation, co-cultures, genetic engineering), including the development of appropriate supply chains for supplemented compounds, is necessary to optimize nutritional value of products (Datar and Betti, 2010; Rubio et al., 2019, 2020; Fraeye et al., 2020). The controlled production process allows for more direct customization, which can be used to refine organoleptic or nutritional properties, and minimization of food safety concerns, including contaminant accumulation and zoonotic diseases (Datar and Betti, 2010; Gauthier, 2015; Johnson and Schantz, 2017). However, novel aspects of cell-based seafood production that can affect food safety, including the necessity of antibiotic use (Thorrez and Vandenburgh, 2019; Post et al., 2020), require further research (Ong et al., 2021).

It is also unclear if alternative seafood will improve key indicators of food security—availability, access, utilization, stability, agency and sustainability (HLPE, 2020). Plant-based seafood shifts proteins up the supply chain by moving protein sources, including some traditionally used for animal feed, toward consumption by humans as ingredients for extending or replacing animal-source proteins (Boland et al., 2013). Cell-based seafood allows for the isolated production of desired cuts, so inputs are directed to the edible portion and not on other developmental or metabolic functions. Additionally, the production of alternative seafood is not dependent on proximity to aquatic environments so there is potential to bring alternative seafood value chains to inland or urban areas which may improve local food and nutrition security (O'Meara et al., 2021), though barriers of economic accessibility and other social or cultural norms must be addressed (Halpern et al., 2021). However, concentration of these products in HICs may limit their availability to a wealthy elite (Rubio et al., 2019), or consumers may simply adopt alternative seafood in addition to their current animal-source food intake or in place of other more sustainable foods. Despite this, supporters claim that based on the size of the conventional seafood industry, if alternative seafood displaces even a small portion of conventional supplies over the next couple decades it could improve aquatic ecosystem health, which might stimulate recovery of coastal and other small-scale fisheries and in turn, improve food and nutrition security in these areas. Although the potential for these ripple effects are debated (Halpern et al., 2021), any transition to achieve them will require support from governments and the alternative and conventional seafood sectors to, for example, promote alternatives for species that would maximize economic, social and environmental benefits (GFI, 2021b), especially in LMICs.

Increased production, decreased loss and waste, and better distribution of nutritious foods are required to ensure adequate food and nutrition security of growing populations (Willett et al., 2019). Information regarding the nutritional value, potential to improve indicators of food security and methods of adoption of alternative seafood is largely speculative. There is no doubt a combination of methods is necessary to sustainably meet growing global demand for nutrient-rich foods, so further research on complementary solutions is merited.

## Environmental Implications

The environmental implications of alternative seafood are determined by all segments of the value chain, including input sourcing, production techniques and consumer adoption. The following sections focus on environmental indicators indicative of natural resources use, which is largely associated with production and upstream segments of the value chain, and aquatic ecosystem health, largely associated with consumption patterns. However, many other factors, including eutrophication potential, acidification potential and ozone depletion, should also be accounted for in a balanced environmental assessment (Halpern et al., 2019).

### Natural Resources Use

Given the paucity of data specific to alternative seafood, estimates of environmental impact are derived from available assessments of both alternative meat and seafood. Areas where they are expected to differ are noted. Estimates are given per kg of product since the potential nutritional value of alternative seafood is not limited to certain nutrients, like protein.

One study to date has quantified the greenhouse gas emissions associated with plant-based seafood as 1.5 kg $CO_2e$ per kg of product (farm to factory gate), though these are fermentation-derived mycoprotein products (Quorn Foods, 2019). The estimate is comparable to those for plant-based meat (range = 0.9–6.94 kg $CO_2e$/kg; median = 2.4 kg $CO_2e$/kg) (Santo et al., 2020). Estimated emissions from plant-based meat vary, but are mainly distributed between inputs, processing and packaging (Santo et al., 2020). Plant-based seafood may also have lower emissions if inputs from aquatic ecosystems (e.g., algae) can be sustainably produced and significantly integrated in products.

Cell-based seafood is expected to have more efficient production processes than conventional counterparts, though no formal environmental impact analyses have yet been published. Anticipatory estimates of greenhouse gas emissions from cell-based meat range from 1.69 to 25.4 kg $CO_2e$ per kg of product (median = 5.44 kg $CO_2e$/kg), but rely on simplifications and assumptions regarding inputs, processes and technological development since no facilities are currently producing at scale (Scharf et al., 2019; Santo et al., 2020). The energy required for product manufacture is responsible for a large proportion of emissions from cell-based meat (Santo et al., 2020; Sinke and Odegard, 2021), but cell-based seafood is expected to have lower energy requirements because of the greater tolerance of fish muscle tissue to cooler temperatures, a wider range of pH, and lower oxygen requirements during growth (Rubio et al., 2019), and thus may have lower emissions than cell-based meat.

Median emission estimates for plant- and cell-based meat are lower than that for farmed fish (median = 6.52 kg $CO_2e$/kg) and crustaceans (median = 9.87 kg $CO_2e$/kg), though the actual difference depends on the degree of decarbonization along the value chain, and the estimate for cell-based meat is higher than that of wild tuna (median = 2.86 kg $CO_2e$/kg) (Santo et al., 2020; Sinke and Odegard, 2021). The use of $CO_2e$ to compare greenhouse gas emissions is contested, especially in animal agriculture, because of the varying atmospheric lifespans and global warming potentials of different greenhouse gasses (Garnett, 2011; Lynch et al., 2021), so research on appropriate metrics to measure climate impacts in food systems is merited.

No estimates of land use for alternative seafood production are available but estimates for alternative meat range between 0.41 and 5 $m^2$ year per kg of plant-based meat product (median = 2.47 $m^2$/kg) and 0.19–8.03 $m^2$ year per kg of cell-based meat product (median = 1.27 $m^2$/kg). Both median estimates are lower than that of farmed fish (median = 5.6 $m^2$/kg) but higher than that of farmed crustaceans (median = 0.82 $m^2$/kg) (Santo et al., 2020). Improved feed conversion ratios for alternative seafood contribute to land savings, but actual land use will depend on input ingredients, production methods and volumes. For plant-based seafood specifically, dependence on soy, wheat and palm oil could impede sustainability (Santo et al., 2020). However, the potential for local, underused, and/or novel ingredient use has implications for ecosystem health and biodiversity, local income generation, and diet diversification.

Fresh water use for alternative meat production is estimated in fewer studies, ranging from 13.4 to 202.9 L per kg of plant-based meat product (median = 71.6 L/kg) and 106.3–773.2 L per kg of cell-based meat product (median = 397.5 L/kg) (Santo et al., 2020). There are no available estimates for alternative seafood. The median estimate of fresh water use for plant-based meat is lower than those of farmed fish (non-pond, median = 284 L/kg; pond-raised, median = 10,705 L/kg) and farmed crustaceans (median = 9,258.6 L/kg), while the estimate for cell-based meat is lower than those of pond-raised fish and farmed crustaceans (Santo et al., 2020).

Reductions in use of natural resources are likely to be spatially heterogeneous as they will be influenced by patterns of production, trade and consumption. Research regarding the factors and enabling environment for alternative seafood that contribute to reduced natural resources use, and how this might be designed and effectively implemented to fit within the planetary framework (Springmann et al., 2018), is crucial for informing sound interventions for environmentally sustainable food systems.

### Aquatic Ecosystem Health

The potential conservation outcomes of plant- and cell-based seafood are discussed collectively since the proposed mechanism is the same, but the probability of these outcomes may differ. Proponents of alternative seafood generally posit it as an additional seafood supply that can help meet growing seafood demand without increasing pressure on aquatic ecosystems, eventually displacing conventional seafood to varying degrees, ranging from a cessation of the most harmful forms of fishing to complete displacement, for further conservation outcomes (GFI, 2019; Marwaha et al., 2020). To achieve conservation outcomes, including reduced human impact on aquatic environments, recovery of fish stocks, and other collateral ocean benefits, a series of sequential conditions must be met. Most notably, consumers must consistently substitute conventional seafood with alternative seafood at sufficient scale to substantially reduce demand for conventional seafood, which must translate to a decrease in price that is passed on to fishers and farmers who as a result, produce less (Farmery et al., 2020; Halpern et al., 2021). Because all the conditions are dependent on interactions between technological development, human and institutional behavior, market forces, and ecological linkages, the potential contribution of alternative seafood to improving aquatic ecosystem health remains speculative (Halpern et al., 2021).

Alternative seafood may have greater influence on aquatic ecosystem health if it augments or displaces the conventional supplies of certain species—namely, species that are overfished, difficult to farm without wild juveniles, or farmed species that rely on fishmeal and fish oil from poorly managed fish stocks (Halpern et al., 2021). However, this outcome is still dependent on the conditions outlined above, including those associated with demand-driven interventions (Roheim et al., 2018).

In LMICs, subsistence fishing and fish farming dominate and are essential for local livelihoods and food and nutrition security, making it unlikely that alternative seafood will have direct conservation outcomes (Halpern et al., 2021). Alternative seafood may, however, have indirect conservation outcomes if it slows the intensification of large-scale commercial fishing efforts and unsustainable aquaculture practices by providing less resource-intensive alternatives (Bell et al., 2017; Halpern et al., 2021).

Research on fish stocks in need of conservation, ecologically meaningful indicators for aquatic ecosystem health, the effect of alternative seafood on conventional seafood demand and potential negative outcomes, especially for displaced fishers or fish farmers, is necessary to characterize the extent of direct and indirect conservation outcomes associated with alternative seafood.

## DISCUSSION AND CONCLUSIONS

Accelerating the development, commercialization and availability of alternative seafood is of growing interest for many who envisage inclusive, equitable, and sustainable food systems. This paper explores the foundation of this association through key economic, social and environmental impacts that are especially relevant to the millions of people in LMICs who depend on fisheries and aquaculture in diverse ways. Available literature and data suggest there is potential for alternative seafood to impact local and global food systems, but the nature and extent of these impacts depends on if and how the sector reaches scale, consumer behavior and governance. **Figure 1** presents the discussed potential impacts of alternative seafood on LMIC food systems and offers some preliminary indicators for consideration when assessing the emerging sector, though they are worth revaluating regularly given the pace of development.

### Future Research

As an emergent food sector, society can influence the growth of alternative seafood to help achieve positive domestic and international outcomes. Further research on important knowledge gaps should inform appropriate development and governance of the alternative seafood sector. We recognize that some important issues including decent and meaningful livelihoods, social and gender equity, and animal welfare, although little discussed here, need further exploration.

It is essential to understand how markets for plant- and cell-based seafood are likely to develop in different regions, the main drivers of this development, and how these markets will interact with those for conventional seafood. Current growth projections are extrapolated from the alternative meat sector and the trajectories of individual businesses. However, the emerging nature and current small size of the alternative seafood sector makes it difficult to predict how it will interact with other sectors and be adopted by consumers. Government guidance is necessary, especially regarding broader societal impacts, such as production methods that allow for more consistent, reliable, and localized seafood supplies that are more resilient to food system shocks, as most recently and dramatically highlighted by the global COVID-19 pandemic.

Concrete policy and programme recommendations are necessary to guide the development of plant- and cell-based seafood to generate well-governed value chains that maximize societal benefits. This first requires an understanding of how plant- and cell-based seafood value chains are likely to differ from those of conventional seafood and an understanding of the influence of markets, policies or stakeholders on its development. It is also important to determine which areas of plant- and cell-based seafood value chains offer the greatest opportunities for decent employment, especially for women, youth and other marginalized groups.

For plant- and cell-based seafood to contribute to food and nutrition security, they need to successfully enter growing markets. There is first a question of accessibility of plant- and cell-based seafood to consumers in various geographic regions, economic classes, and cultural and social groups. Decisions by plant- and cell-based seafood producers regarding species, product form, and inputs can be made with intentions to reach specific markets. Likewise, there are important questions regarding the nutritional potential of plant- and cell-based seafood, how the nutrient profiles compare with those of conventional seafood, and how they might best be used as nutrient delivery platforms, especially where food-based solutions to hunger and malnutrition are being considered.

Further research around environmental impacts requires an assumption of how plant- and cell-based seafood will be adopted and development of a standardized, transparent assessment methodology that facilitates comparison between wild, farmed, plant-based and/or cell-based seafood. Standardized baseline data of species, product types, production systems, natural resources requirements, including energy, water, and land, and other inputs, including nutrients and feed, are also needed. With regards to aquatic ecosystem health, further research may explore various indicators of recovery and their associated timelines, the impact of species-specific changes in production, and enabling

| Dimension | Impacts | Impacts | Cell-based seafood | | Plant-based seafood | |
|---|---|---|---|---|---|---|
| | | | Capture fisheries | Aquaculture | Capture fisheries | Aquaculture |
| **Economic** | **Global markets** | Economic development | Will create new business and trade opportunities; Widespread consumer adoption could influence economic contributions of capture fisheries and aquaculture | | | |
| | **Livelihoods** | Employment generation | Will generate new employment opportunities, but many may require different skills; Could influence employment in capture fisheries and aquaculture | | | |
| | | Poverty reduction | Likely to favor creation of skilled employment; Could disrupt employment of poor and marginalized people in capture fisheries and aquaculture | | | |
| **Social** | **Food and nutrition security** | Availability | Available in some LMIC markets but restricted to higher value products | | | |
| | | Access | Unlikely to be cost-competitive in LMIC markets beyond higher value products | | | |
| | | Utilization | Reduced concerns of contaminants and food fraud | | Reduced concern of contaminants; Increased concerns of processing and lack of key nutrients from animal source foods | |
| | | Stability | More sheltered from climate and seasonal changes; Can more easily change production to match demand | | | |
| | | Agency | Localised production opportunity; Concerns of industry consolidation and associated loss of food soverignty | | | |
| | | Sustainability | Reduced environmental footprint expected; Unknown impact on value chains and actors of capture fisheries and aquaculture | | | |
| **Environmental** | **Natural resources use** | Greenhouse gas emissions | Potential for increased control of emissions expected to lead to reductions; Highly variable baselines for comparison | Potential for increased control of emissions expected to lead to reductions; Highly variable baselines for comparison | | |
| | | Land use | Greater land use expected as capture fisheries generally use little | Actual inputs and their land requirements unknown; Highly variable baselines for comparison | Greater land use expected as capture fisheries generally use little | Highly variable formulations and baselines for comparison |
| | | Fresh water use | More fresh water use expected as capture fisheries are non-consumptive users | Potential for increased control of water use expected to lead to reductions; Actual inputs and processes and their water requirements unknown; Highly variable baselines for comparison | More fresh water use expected as capture fisheries are non-consumptive users | Potential for increased control of water use during manufacture expected to lead to reductions; Highly variable formulations and baselines for comparison |
| | **Aquatic ecosystem health** | Change in fish biomass | Highly variable as influenced by patterns of production, distribution, consumption, and ecology | | | |

**Potential contribution, relative to capture fisheries or aquaculture**

Better | Ambiguous | Lesser | No data

**FIGURE 1 |** Summary of the economic, social and environmental contributions of alternative seafood production, trade and consumption in LMIC food systems by 2030, as compared to capture fisheries and aquaculture. Source: Authors' interpretation of the literature cited in this review.

conditions or policies that allow for aquatic ecosystem recovery, including control of overfishing and illegal, unreported, and unregulated catches, especially in areas relied on by small-scale fishers and fish farmers.

Plant- and cell-based seafood may eventually generate similar food system outcomes, but the major differences in production, regulation, and marketability require some separate lines of research. Public and independently funded fundamental research may help level the playing field. Other research areas outside the scope of this review will likely influence the growth of the alternative seafood sector and also merit research, including seafood coproduct valorisation, use of plant-based extenders in seafood, and substitutes or alternative production methods for high quality animal feed ingredients, such as fishmeal and fish oil.

The potential of alternative seafood to contribute to inclusive, equitable, and sustainable food systems remains to be seen. Alternative seafood may complement existing initiatives for sustainable fisheries and aquaculture but could also introduce new stressors on food systems. The longevity of its popularity, its contributions to food and nutrition security, and its potential influence on the conventional seafood sector will help define its place as an emerging fad, common food, or feed ingredient. If, however, alternative seafood is here to stay, it is crucial that its development is supported by sound evidence, social and environmental standards are upheld, and planning and management is integrated with that of fisheries and aquaculture. Since the direct impacts of alternative seafood may be concentrated in HICs, at least initially, it is imperative that other methods to improve livelihoods, food and nutrition security, and the environment in LMICs are realized.

## DATA AVAILABILITY STATEMENT

The data generated for this study can be found in the WorldFish Dataverse at https://dataverse.harvard.edu/dataverse/worldfish.

## AUTHOR CONTRIBUTIONS

MP: conceptualization, funding acquisition, and project administration and supervision. NM and MB: literature and data curation. NM, MB, and MP: manuscript preparation. All authors contributed to the article and approved the submitted version.


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# Prospects of Low Trophic Marine Aquaculture Contributing to Food Security in a Net Zero-Carbon World

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To limit compromising the integrity of the planet, a shift is needed towards food production with low environmental impacts and low carbon footprint. How to put such transformative change towards sustainable food production whilst ensuring food security into practice remains a challenge and will require transdisciplinary approaches. Combining expertise from natural- and social sciences as well as industry perspectives, an alternative vision for the future in the marine realm is proposed. This vision includes moving towards aquaculture mainly of low trophic marine (LTM) species. Such shift may enable a blue transformation that can support a sustainable blue economy. It includes a whole new perspective and proactive development of policy-making which considers, among others, the context-specific nature of allocation of marine space and societal acceptance of new developments, over and above the decarbonization of food production, vis á vis reducing regulatory barriers for the industry for LTM whilst acknowledging the complexities of upscaling and outscaling. This needs to be supported by transdisciplinary research co-produced with consumers and wider public, as a blue transformation towards accelerating LTM aquaculture opportunities in a net zero-carbon world can only occur by considering the demands of society.

**Keywords: marine aquaculture, food security, zero-carbon, transdisciplinarity, blue transformation, narrative, private sector**

## INTRODUCTION

With continued human population expansion, the production and accessibility of healthy and nutritious food (food security) is becoming a top priority in the global context. There is, however, clear evidence that human exploitation of natural resources has exceeded a range of planetary boundaries, thereby jeopardizing the preservation and sustainment of ecosystem functions from the biome level to global scales (Steffen et al., 2015; Newbold et al., 2016; Willett et al., 2019). These consequences are further enhanced by climate change, one of the most severe crises of our time, with far reaching implications on food security worldwide (Fanzo et al., 2018; IPCC, 2019a,b).

In general, food production has a range of impacts such as land conversion, overuse of freshwater resources, greenhouse gas (GHG) emissions, energy use, biodiversity loss and nutrient imbalances (Cordell et al., 2009; Hasegawa et al., 2020; Karstens et al., 2020; Herrero et al., 2021). Currently, food production generates 26% of overall global greenhouse gas emissions, underlining the need to move away from the most environmentally-costly and damaging production systems (Poore and Nemecek, 2018). This challenge will not diminish as human populations are predicted to reach ∼10 billion by 2050 (UN, 2019), placing an increasing strain on natural resources and raising the question of how to feed a populated world in a sustainable manner (Aksnes et al., 2017; Willett et al., 2019; FAO, 2020) without exceeding 1.5 degree warming (Rockström et al., 2017; Warszawski et al., 2021).

Thus, a transformation of food production systems is needed to meet the challenge of simultaneously adhering to the planetary dimensions, food security and human health requirements (Gordon et al., 2017; Willett et al., 2019; Kaiser et al., 2021). Transformation is hereby understood as "a fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" (Brondizio et al., 2019). As this conceptualization remains rather abstract, we follow the review by Scoones et al. (2020), which identified three basic perspectives on transformation: structural, systemic and enabling transformation. We here focus on the systemic perspectives on transformation dimensions that are rooted in socio-ecological and socio-technical systems thinking and how these surface in marine food production. In concurrence, the UN Sustainable Development Goals (SDG) support this much needed change by provoking new normative reasoning (Leach et al., 2018), raising the question to what extent farming the oceans help provide food security in the Anthropocene and contribute to meeting SDGs (Gentry et al., 2017; Troell et al., 2017).

Using this description of the challenges faced as a baseline, the following sections will describe the co-produced view of *what* can be done (sections Shifting Food Production to Aquatic Lower Trophic Levels, and The Contribution of Low-Trophic Mariculture to Blue Food Production), and *how* this can be achieved (sections Defining a Vision for a Sustainable Blue Economy Transformation, Balancing Narratives of LTM Aquaculture Expansion With Societal Realities, and Concerted Implementation of the Blue Transformation), with the aim to provide a framework for integration of LTM aquaculture into future, sustainable, food systems in a net zero-carbon world.

## SHIFTING FOOD PRODUCTION TO AQUATIC LOWER TROPHIC LEVELS

Global animal protein production (meat, dairy and fish) occupies over 80% of farmland, but produces only 37% of human food protein and 18% of calories (Poore and Nemecek, 2018). It has been argued that the greatest gains in decarbonizing global food production will come from a transition from animal to plant-based foods, with benefits also from intermediate actions in shifting animal production to those farming systems with demonstrated lower environmental impacts and GHG emissions (Poore and Nemecek, 2018; Gephart et al., 2021). Such a shift would not only reduce the direct and indirect climate impacts of animal production but could also release land for biodiversity conservation and climate change mitigation whilst limiting the drawbacks associated with further expansion of agriculture (Cordell et al., 2009; Herrero et al., 2021). To date, guidelines for changing planetary diets to eat less meat, however, remain focused on eating less terrestrial meats in contrast to advocating more strongly shifting meat consumption toward aquatic, low trophic species, meats. This prevailing narrative is, for example, illustrated in the Planetary Health Plate which still pictures a cow as meat source instead of an alternative aquatic species.[1]

Aquatic food production systems, and in particular farming of extractive (non-fed) low trophic marine (LTM) species (mainly bivalve molluscs and macroalgae), can provide alternatives with lower environmental impacts; i.e., lower GHG emissions and reduced land and freshwater uses (Nijdam et al., 2012; Hilborn et al., 2018; Gephart et al., 2021). LTM species can be grown with lower energy requirements and zero feed or fertilizer inputs, as they extract dissolved nutrients or planktonic/detrital foods directly from the marine environment, and yet are nutrient-dense food sources rich in protein, unsaturated fats and micronutrients (Wright et al., 2018; Hallström et al., 2019; Naylor et al., 2021). Furthermore, LTM aquaculture can also provide a range of valuable non-food ecosystem services such as biodiversity enhancement and eutrophication remediation (van der Schatte Olivier et al., 2018; Gentry et al., 2019; Kotta et al., 2020; Cabre et al., 2021; Naylor et al., 2021; Theuerkauf et al., 2021; The Nature Conservancy, 2022) and may also transform linear nutrient flows from land to the sea into circular systems (Folke and Kautsky, 1992; Petersen et al., 2019; Filippelli et al., 2020; Thomas et al., 2021). Farming of extractive LTM species is one of the most efficient, low-input, low-carbon food production systems, especially when compared to the farming of terrestrial livestock (Hilborn et al., 2018; Gephart et al., 2020). Consequently, redirecting focus from red meat toward aquatic foods with lower environmental impacts and better health profiles should include a larger emphasis on extractive LTM species.

[1]eatforum.org (accessed April 13, 2022).

Accordingly, a shift to LTM aquaculture has the potential to reduce GHG emissions of food production and support more efficient and sustainable use of available resources. However, the linkages and repercussions between environmental impacts and food security need to be thoroughly investigated and communicated. Comprehensive and balanced scientific knowledge of the impacts of different aquaculture species, including the role of LTM species in less carbon-intensive diets, will be needed to promote consumption and market development of low-impact foods. New narratives need to be developed that harness the contemporary societal debates on how to tackle climate change and ensure food security at the same time. As such, this may present opportunities to improve social acceptability of blue foods as a shift to low-impact "blue alternatives" may entail a transition to more sustainable and more nutritious foods compared to other protein sources (Hallström et al., 2019). Hence, social culture and practices, and more specifically, the cultures where seafood consumption is not fully integrated as in Asia, must occupy a central position alongside the economic and social analysis of whether marine aquaculture can contribute to the sustainable blue transformation reaching its full potential (Simpson, 2011; Krause et al., 2015, 2020; Naylor et al., 2021). We understand this blue transformation as being part of the "blue economy" concept (Silver et al., 2015). Blue economy encompasses ocean-based industries *and* the natural assets and ecosystem services that the ocean provides (OECD, 2016; Rayner et al., 2019). As such, it emphasizes the multiple economic and social dimensions of the ocean that can be complementary or even reinforcing under a sustainability lens.

## THE CONTRIBUTION OF LOW-TROPHIC MARICULTURE TO BLUE FOOD PRODUCTION

The prospect of aquaculture contributing significantly to feeding a growing world population has been a vision since the mid 20th century, with its emergence as a new food production sector in the 1950s (Costello et al., 2019). Worldwide, governments, non-governmental (e.g., WWF, TNC, EDF) and international organizations (e.g., UN-FAO, EU, ICES) are responding to this challenge by promoting the "Blue Revolution", "Blue Growth" and, more recently, a "sustainable Blue Economy" that emphasizes zero pollution, zero-carbon, circular economies and biodiversity protection (European Commission, 2021). Development of more sustainable and equitable food production systems is emphasized although how to achieve this vision varies among organizations and institutions (Caswell et al., 2020; Wittmer et al., 2021). It includes, among other aims, the rapid spread and full utilization of aquaculture (Krause et al., 2015; Stevens et al., 2018).

However, despite over 70 years of aspirational policy and pioneering investments, outside China most of the world is still a long way from achieving a transformation in farming the oceans (Caswell et al., 2020; Naylor et al., 2021). Ocean aquatic foods production are estimated to comprise only 4–6% of all human foods today (Costa-Pierce, 2016; FAO, 2020). The global distribution of aquaculture production also remains uneven. Whilst being traditionally conducted in Asia throughout centuries, the rest of the world is yet in nascent stages of aquaculture development (Costa-Pierce and Chopin, 2021). This skewed distribution is currently reflected by 92% of all aquaculture (∼110 million tons annually) being performed in Asia, with the rest of the world combined producing ∼10 million tons (FAO, 2021). Also, much of aquaculture (40%) within Asia is land-based production of freshwater fish. Similarly, the total aquaculture production elsewhere is dominated by diadromous (34%) and freshwater (32%) fish (Naylor et al., 2021). In fact, 73% of the total edible production from global aquaculture originates from freshwater.

Hence, considering aquaculture as a homogenous food production system overlooks the large differences between sub-sectors in terms of potential environmental benefits. Even though the efficiency of fed aquaculture of finfish has improved over time, lowering food conversion ratios and reducing fish meal and fish oil use (Cottrell et al., 2021; Naylor et al., 2021), the production of plant-based feed ingredients may compete with land and water use for human food production (Troell et al., 2014; Gephart et al., 2017). Feeds remain a major contributor of GHG emissions attributed to production of fed aquaculture species (Robb et al., 2017). Emissions from pond farming of catfish, tilapia and shrimp can be higher than pork and chicken and equivalent to that of beef production, while salmon farming has lower impact. However, it is only extractive LTM species that offer the opportunity for substantive reductions in GHG emissions (Hilborn et al., 2018). Hence the greatest transformative potential of aquaculture lies in increasing production and consumption of LTM species as an alternative to continuing to increase red meat consumption.

Despite these potential benefits, aquaculture of extractive LTM species remains in its infancy in most areas outside of Asia, and uptake on a global scale is geographically uneven. Increasing consumption of LTM species as a source of dietary proteins could make a valuable contribution to the transition to a low-carbon food economy. Achieving a significant impact will require a stepwise, transformative change toward farming of LTM species such as bivalve, shellfish and seaweeds. Presently, the combined annual production of these species is only 52 million tons (FAO, 2021), or even less (Porse and Rudolph, 2017), of which less than half may be converted to consumable food (Edwards et al., 2019). This compares to global meat production of 328 million tons in 2020, which is projected to rise to over 374 million tons in the coming decade (FAO, 2021; OECD FAO, 2021). Nevertheless, anticipation of several-fold increase in global LTM production as an alternative to continued expansion of red meat production represents an achievable goal over timeframe that aligns with the urgency of the pathway towards net zero-carbon emissions. One reason for this current imbalance in terrestrial and marine food production is rooted in the terrestrial bias of the human mind that affects human behavior, decision-making and problem-solving (Fuchs et al., (under review); Steinberg and Peters, 2015; Armbrecht and Skallerud, 2019). Although the ocean has long been a food source for humans (especially for coastal communities), it has always been a less accessible and predictable environment for cultivation compared to land. It is from this stance that the oceans on our planet have never been completely included in the thoughts and perception of the majority of humans (Gee, 2019).

## DEFINING A VISION FOR A SUSTAINABLE BLUE ECONOMY TRANSFORMATION

The planetary boundaries framework (Steffen et al., 2011) and the call for societal transformation has spurred discourses on a stronger recognition of intersections between natural and social/cultural dimensions, leading to more inter- and transdisciplinary conversations (Castree, 2014; Blythe et al., 2018; Brondizio et al., 2019; Scoones et al., 2020). This raises an opportunity to reconsider how the oceans are viewed and integrated in socio-economic concepts (Österblom et al., 2017).

Common across competing scenarios of transformative ocean futures (i.e., Gentry et al., 2017; Belton et al., 2020; Costa-Pierce et al., 2021) is the tendency to focus on quantifiable effects of activities, such as the prospects of economic gain or the risk of environmental degradation (Oyinlola et al., 2018). While these are clearly important, responsible ocean development should also consider how the activities affect our ideas about the common good. Indeed, a sustainable blue transformation requires us to reconsider the relationships between the private and public (Steinberg and Peters, 2015; Brugere et al., 2021). This is a crucial question, as the understanding of public-private interactions in marine aquaculture is still blurred. These opposing views surface especially when considering open ocean aquaculture, as this entails investment and operational costs at scale that involves fewer and larger businesses. However, it can be argued that LTM aquaculture systems benefits humanity by offering low-carbon healthy foods, nutrient recapture and clearer water in eutrophic areas, in addition to providing economic profits to a few actors. We recognize that LTM systems will have some environmental costs, the level of which will depend on the geographical context such as oligotrophic vs. eutrophic areas, scale of production, water movements, etc. (Theuerkauf et al., 2021). However, these are substantially less than other forms of food production (including fed aquaculture) and are offset by the benefits (Gephart et al., 2021; Naylor et al., 2021) and are in large reversible within a few years after ceasing the activity.

Thus, the central question is how to put transformative change toward sustainability into practice? It is not only important to develop a vision on what future ocean we want, but also to investigate what needs to be known to change the prevailing and entrenched food systems toward this sustainability vision, how to navigate, nudge and nurture system change, and how to create space for deliberating just transformation (Wittmer et al., 2021). To date, much of the scientific attention has been placed on the technical, engineering and natural sciences, yet as each of the planetary boundary challenges are contested, these cannot be addressed based on only one type of knowledge base. The doughnut economy framework by Raworth (2017) is one noteworthy effort to bridge some of these conceptual islands of knowledge. Indeed, to achieve transformation, different types of knowledge must come together. For example, the global rapid development of marine fed aquaculture over recent decades has been a success story for the triple helix interaction of government, research and industry (Leydesdorff, 2000), since the development of aquaculture is often industry- and technology-led, hand-in-hand with research, and facilitated (or not) by governance arrangements.

Moreover, to achieve transformation the meaning of the term must first be described. The notion of "transformation" is used differently in politics and in science (Blythe et al., 2018). In politics, it is a wake-up call for bolder, multilateral action. In science, different schools of thought elaborate on the conceptual underpinnings for what transformation to sustainability actually entails: What needs to be transformed? Into what? How fast? Who should do it and how? Yet, ambiguities in the definition and pursuit of transformative change are widespread (O'Brien, 2012; Feola, 2015; Costa-Pierce, 2016, 2021; Blythe et al., 2018). Also, transformation requires proactive (rather than responsive) investments and it should aim for a lasting positive change in dominant power relations by favoring equity, fairness, and justice (Chaffin et al., 2016; Cisneros-Montemayor et al., 2021). Transformation is interpreted as relating to a social-ecological change that addresses the underlying idea that "more of the same" will not solve the growing tensions and socio-economic impacts that result from over-using and degrading ecosystems and resource systems and putting further strain on planetary boundaries (Cisneros-Montemayor et al., 2021; Wittmer et al., 2021). Consequently, transformation is considered as a fundamental change-of-path. However, such large-scale fundamental changes cannot be planned and implemented in one piece but will rather involve a number of steps and iterative evaluation to achieve change that in retrospect can be considered as fundamental.

To date, most of the observable contemporary developments in aquaculture are locked in the 20th century technology-fit pathways. This points out to a fundamental dilemma, as already observed by Collingridge (1980). At an early stage of research and development of a new idea, such as low carbon blue food systems, it is impossible to know what the most important impacts (positive and/or negative) on the sustainability dimensions will be (see e.g., Gephart et al., 2020). However, if attempts are not made to identify, predict and mitigate negative impacts, it will often be too late to handle or control them (Collingridge, 1980). An example of this, is the current situation where climate change impacts of terrestrial food systems were not sufficiently predicted. In this sense, narratives and visions provide an important role as a compass for what a transformed system and a desirable future would look like. Consequently, there needs to be some forward view of the potential outcomes of competing visions of a blue transformation under the umbrella of the blue economy concept. In comparison to terrestrial food production systems, aquaculture has many benefits, however there is a risk of similar path-dependencies. In this article, in expansion to earlier propositions (Gentry et al., 2017; Troell et al., 2017; Belton et al., 2020), and in order to avoid a Collingridge dilemma, we propose an alternative vision for the future. This vision includes moving towards a future development of aquaculture that is focused mainly on LTM systems. By this shift, we predict that a significant contribution towards net zero-carbon food systems may evolve.

## BALANCING NARRATIVES OF LTM AQUACULTURE EXPANSION WITH SOCIETAL REALITIES

In accordance with this vision there is, at least from a theoretical perspective, scope for coastal waters to support a significant increase in LTM production (Buck and Langan, 2017; Theuerkauf et al., 2019; Thomas et al., 2019; Heasman et al., 2020). This potential is apparent even in disparities among those nations that already have some coastal marine aquaculture; for which production ranges from <1 MT $km^{-1}$ to more than 500 MT $km^{-1}$ of shoreline (Kapetsky et al., 2013). However, access to this space is by no means pre-emptive (Troell et al., 2017). The barriers to increasing aquaculture in nearshore areas can include, e.g., the availability of suitable sheltered coastal sites that allow cost-effective production, competition for densely-used coastal marine space (Debnath, 2020; Kluger and Filgueira, 2021; St. Gelais et al., 2022), water quality (Cheney et al., 2010; Hassard et al., 2017; Lee et al., 2018; Rodil et al., 2019; Song and Duan, 2019; Xie et al., 2020) and significant regulatory and legislative complexities (Lester et al., 2018). These limitations have led to a focus on marine environments where there may be greater scope for a step change in production through expansion into more exposed coastal sites and more distant open ocean waters.

A narrative has emerged in which optimistic scenarios portray the future of open ocean aquaculture as "the new frontier" for food security (Marra, 2005; Costello et al., 2020). For example, recent analyses have proposed that the suitable ocean space for aquaculture vastly exceeds the requirements for any currently required increase in production—with theoretically more than sufficient space to exceed terrestrial meat production needs many times over (Gentry et al., 2017; Oyinlola et al., 2018). However, such projections are likely over-optimistic as not all this space will be accessible or suitable (Troell et al., 2017, 2022; Theuerkauf et al., 2019). Froehlich et al. (2019) projected 48 million $km^2$ for seaweeds for blue growth to mitigate climate change. Thus, to avoid ending up in a Collingridge dilemma, it is important to recognize the specific requirements, constraints and impacts of LTM aquaculture development. Otherwise, the manner in which LTM aquaculture expansion of both, coastal and offshore exposed areas is moved, puts us at risk of making incorrect assumptions that may undermine meaningful and sustainable expansion, especially when pioneering developments on a very large scale are required to drive a fundamental shift in food supply. Engineering such systems for economic sustainability, within the confines of regulatory and social acceptance, and importance for nutrition and food security (globally), remains a challenge for open ocean LTM aquaculture.

From a technical perspective, the tools and engineering capabilities required to design and de-risk LTM systems for exposed and open-ocean conditions exist (e.g., Dewhurst, 2016; Pribadi et al., 2019; Fredriksson et al., 2020; Heasman et al., 2021; Landmann et al., 2021; Moscicki et al., 2021). This, however, infers significant investments in infrastructure and increases in operational costs compared to nearshore, sheltered areas, representing barriers to entry into the sector for prospective producers of relatively low value commodities such as seaweeds and shellfish. To cope with these increased costs either the value of the end-products must increase and/or the production costs must decrease. To address the latter pushes the sector toward large scale production, which will have to go hand in hand with major shifts in consumer attitudes towards new products and markets in order to achieve large scale incorporation of LTM species into the human food chain and ensure stable markets for the newly produced foods. Whereas in China, early expansion of marine aquaculture focused on LTM species for food security, led by government policy within a socialist market economy (Yu and Han, 2020), elsewhere the evolution of industrial marine aquaculture has tended to focus initially on high value fed species (mostly finfish and shrimp) with potential for high initial returns on investment (Llorente et al., 2020). Consequently, from a societal perspective, if net zero-carbon is a central goal, a fundamental change in the narrative of food system production and re-aligning the contemporary market drivers and incentives will be required.

So far, a contextual approach particularly in terms of what type of aquaculture (nearshore vs. open ocean), and what type of effect at different scales (individual, community, national, regional and international) has been neglected. That said, occupation of large areas of marine space by LTM aquaculture, even in the "distant offshore", may mobilize objections, especially as the scale of farms is likely to reflect the investment and infrastructure required to achieve economies of scale in open ocean conditions and to make a meaningful impact on global food systems. Moreover, moving LTM aquaculture offshore may cause significant ecological and societal trade-offs. For example, roughly 50–60% of coastal waters suffer from nutrient pollution, causing severe ecosystem degradation and loss of important ecosystem services (Howarth et al., 2000; Grizzetti et al., 2021). The effects are most pronounced in nearshore areas, although the severity vary between regions. Extractive LTM aquaculture has been proposed as a tool to remediate this challenge (Petersen et al., 2016; Kotta et al., 2020; Naylor et al., 2021; Theuerkauf et al., 2021). The latter is reflected in the global movement in aquaculture toward developing financial instruments to recognize the roles of (restoration) aquaculture to enhance ecosystem goods and services (The Nature Conservancy, 2021; Barrett et al., 2022). LTM aquaculture may also contribute to circular economies by recovering finite resources from marine coastal environments (Thomas et al., 2021). For instance, 80% of all phosphorous is used by agriculture, and provided business-as-usual scenario, our phosphorous resources are predicted to be depleted in 50–100 years due to the linear flow of phosphorous from land-based agriculture systems into the sea (Sverdrup et al., 2013; Achary et al., 2017). Such ecosystem service benefits by LTM aquaculture species are additional to the reduction in food-related GHG emissions from replacing terrestrial animal source foods (e.g., Naylor et al., 2021). By increasing the societal understanding of how different types of aquaculture impact and benefit different marine environments, increased acceptance may be achieved on a range of scales. Public social acceptance is needed to embrace the value of the blue transformation toward a sustainable blue economy. Social license, as an outcome of a successful, non-formal, institutional exchange between a company and its public, is needed to enable the development of LTM aquaculture (Shindler et al., 2002; Krause et al., 2020).

## CONCERTED IMPLEMENTATION OF THE BLUE TRANSFORMATION

Even though the prospect of open ocean production is often raised as a promising direction, to date the economics, governance and technology of ocean aquaculture favor nearshore environments. Consequently, when matching academic visions with industry and societal realities, the positive vision of open ocean LTM expansion becomes complex. It is not obvious that the predominant scientific perspective on how to move forward is the optimal pathway from either an industry or socio-economic perspective (**Figure 1**).

While new technologies for utilizing natural resources such as farming in open ocean areas are often perceived as a degradation of nature, they can also bring new ways of valuing and relating of societies to marine species and spaces (Cabre et al., 2021). Therefore, we need to identify and consider LTM systems that take advantage of the individual merits found in nearshore and open oceans. For example, open ocean sites will have many of the same social and regulatory challenges of nearshore sites in addition to increased capital costs. Nevertheless, considering the shortcomings of sprawling developments of aquaculture and environmental problems in coastal waters, and the increase in demand for safe seafood, development of aquaculture in the open sea has high validity in many regions of the world.

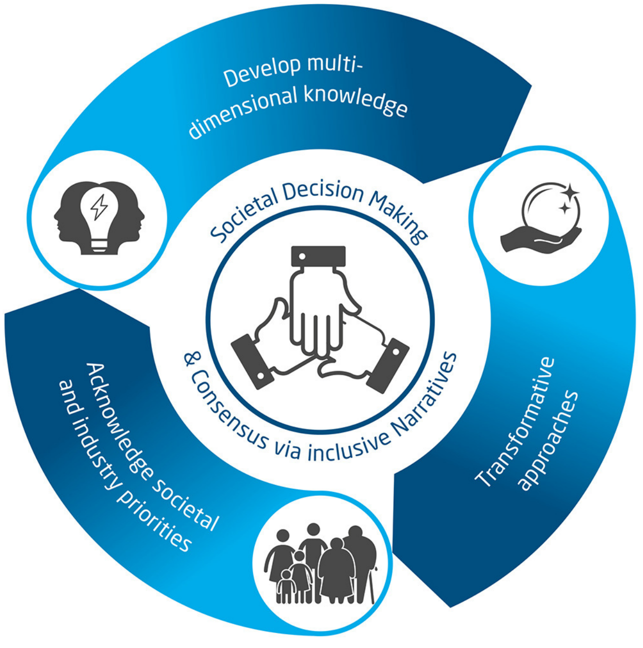


**FIGURE 1 |** Reflexive co-development toward societal decision-making and consensus *via* inclusive narratives. ((C) Y. Nowak/AWI).

While food cannot be produced without changing the environment, whether on land, nearshore or in the open ocean, LTM without feed or fertilizer inputs can generate wider benefits beyond the core activity of food production, including a range of ecosystem services (van der Schatte Olivier et al., 2018; Cabre et al., 2021; Naylor et al., 2021; Theuerkauf et al., 2021). These benefits provide powerful policy drivers for allocation of marine space and societal acceptance of new developments, over and above the decarbonization of food production. If the realization of the potential of LTM aquaculture is a priority, the prerequisites for a sustainable expansion of the LTM sector must be addressed by the establishment of enabling conditions for long-term investment and growth of the private sector. This must be enforced by policy and governance in a careful way that supports industry development of LTM aquaculture, as well as optimizing its socio-economic benefits. This could be achieved through a progressive expansion first into traditionally used sheltered and exposed, highly energetic nearshore areas (St. Gelais et al., 2022), and then, successively, into open ocean sites, if required. Such change cannot be planned and implemented in one piece, but will rather involve a number of steps that, in retrospect, can be considered as fundamental. This entails a "strategy of incremental change with a transformative agenda, where a normative focus on sustainability transformations helps to orient incremental efforts (such as policy change) within a broader narrative of transformative change" (Patterson et al., 2017). This thinking is captured in the notions of "progressive incremental" change (Levin et al., 2012), "directed incrementalism" (Grunwald, 2007), or "radical incrementalism" (Göpel, 2016).

In this sense, narratives and visions provide an important role as a compass for what a transformed food production system, and thus what a desirable future for LTM aquaculture would look like, and how these are embedded in a sustainable blue economy setting. At the same time, the exact outcomes of fundamental change cannot be anticipated and there will be many different options to achieve the desired (i.e., more sustainable) outcomes. This highlights the importance of ensuring that transformations are democratically negotiated and debated broadly within society. To this end, with the help of co-developed ocean narratives that match different knowledge realms, new pathways for a blue transformation toward a blue economy are fostered. Embracing low-trophic extractive species, even large-scale open ocean or exposed nearshore aquaculture enterprises can still represent ethical investments, with an opportunity to reframe the public dialogue about aquaculture, emphasizing climate change mitigation, sustainable resource use and ecosystem services (Hoegh-Guldberg et al., 2019). This may help achieve societal acceptance of a blue transformation on a range of scales from coastal communities to broader societies at large (Froehlich et al., 2017; Mather and Fanning, 2019). Gaining social license will require fostering a paradigm shift in public perceptions informed by interdisciplinary and transdisciplinary research approaches in order to avoid any reinforcement of dystopian narratives of industrialized oceans (Merrie et al., 2018).

## CONCLUSIONS

It needs to be acknowledged that every type of food production does change the environment. Therefore, transformation of contemporary food systems toward net zero-carbon systems will require a pathway that focusses on environmental impacts being better than the alternative rather than elusively aiming for zero environmental impact. This calls for a whole new perspective in policy-making. Under this umbrella, despite overall aquaculture increasing globally, LTM aquaculture remains an underutilized resource with great sustainability potential. So far, blue protein from LTM species is an important, although often forgotten, resource when developing policy and recommendations for a societal transformation of food production and consumption from red meat to green plant-based proteins towards net zero-carbon food systems. Indeed, as pointed out, LTM aquaculture may provide a sustainable food production option to a growing world population, as well as providing both ecological, health and climate benefits. As such, LTM products need to be compared side by side with other marine and terrestrial protein sources in regards to "land" use, ecological and emission impacts in order to support decision making of both, policy makers and consumers. Technical solutions for open-ocean LTM aquaculture exist but a step-wise transformation including expansion in nearshore and open ocean, increased market demand, upscaling, and reduced regulatory barriers for the industry is required for LTM aquaculture to realize this potential and achieve impactful sustainable growth. Overall, to increase the cultivation and consumption of LTM products in society, a transformative change toward a sustainable blue economy is needed of how we perceive, relate to and prioritize the use of coastal and open ocean areas. To this end, a net zero-carbon blue transformation narrative is warranted that includes proactive development and investments by the government, authorities and aquaculture industry that is supported by transdisciplinary research co-produced with consumers and wider public. Indeed, there will be no blue transformation without people—LTM aquaculture opportunities can only be harnessed in tandem with demands of society.

## AUTHOR CONTRIBUTIONS

GK, LLV, and ÅS: conceptualization and methodology. GK, LLV, ÅS, BB, BC-P, TD, KH, NN, PN, KN, KP, MS, J-BT, JW, and AW: investigation and writing—original draft. ÅS, KH, BC-P, and BB: funding acquisition. ÅS: project administration. GK, LLV, ÅS, MT, and FZ: writing—review and editing. All authors contributed to the article and approved the submitted version.

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# The Anthropology of Aquaculture

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Aquaculture is nothing new. It has a long, fascinating history that stretches from antiquity at least 8,000 years ago. What is new is the evolution of aquaculture in modern times into highly intensive monocultures which arose in the 1970–1980's. Modern aquaculture production has grown worldwide but remains concentrated in Asia due to the: (1) increased demands for aquatic foods as explosive population growth occurred in coastal cities with increasing affluence, (2) expansion of scientific and engineering breakthroughs, (3) high export values of aquatic foods, and (4) sharp decline of costs of global to local transport/shipping. The pioneering anthropologist Claude Levi-Strauss brought the idea of "structuralism" to anthropology: the concept that societies throughout history followed universal patterns of behavior. A qualitative document analysis of the key anthropological literature to assess aquaculture developments from antiquity to the beginning of the modern era was conducted to evaluate if there was adequate evidence to support a theory of anthropological "structuralism" for aquaculture in human history. Seven case studies of the cultural/environmental history of aquaculture were reviewed in diverse parts of the world (China, Australia, Egypt, Europe, South America, Canada/USA, Hawai'i). Analysis supports the structural theory that whenever the demands of aquatic/seafood-eating peoples exceeded the abilities of their indigenous fishery ecosystems to provide for them, they developed aquaculture. Modern aquaculture concepts and new communities of practice in "restoration aquaculture" have beginnings in Indigenous anthropology and archeology in aquaculture and point the way for Indigenous nations to engage as leaders of the United Nations Food and Agriculture Organization (FAO) ecosystem approach to aquaculture worldwide. Bringing ancient knowledge of Indigenous aquaculture into the modern context is an essential part of an alternative, "radical transformation" of modern aquaculture. There is an urgent need to develop and promote locally designed and culturally appropriate aquaculture systems that fit into the livelihoods of communities as part of a larger, diverse portfolio of food security.

**Keywords: structuralism, Indigenous aquaculture, Indigenous anthropology, case studies, content analysis**



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## INTRODUCTION

Cultures practicing aquaculture in antiquity have been little examined comprehensively in the anthropological literature. As a result, no unifying theories exist to explain how aquaculture develops, evolves, and fits into human development. Cross cultural analysis tools such as the Standard Cross-Cultural Sample (SCCS) of Murdock and White (1969) and the EthnoAtlas (Gray, 1998) examine over 180 societies anthropologically using many variables but do not classify societies as aquaculture or mariculture-centric rather focus on hunting, gathering, fishing, and animal husbandry, reinforcing this lack of examination.

As aquaculture has grown to be one of the most important protein systems in the world (FAO, 2020) it is vital to examine its ancient environmental/cultural history. Understanding the ancient past will allow a modern appreciation of aquaculture as nothing "new" but as an important part of historical food production. Connections to the ancient past will allow a better appreciation of the diversity of development pathways possible for the future of aquaculture and the divergence of intensive aquaculture in modern times, especially to aquaculture development in the post-World War II era that is believed to be the beginning of the Anthropocene (Waters, 2016).

Modern, industrial, export-driven aquaculture is technologically complex as are its interactions with modern societies (Indigenous, urban, rural, rich, poor, etc.). Communities can either embrace change, develop new values, ceremonies and rituals, and accommodate social transformations, or reject these and continue their social, cultural, and economic evolutions without such disruptive interventions in society such as the rise of aquaculture. Nahuelhual et al. (2019) point to the recent feature of aquaculture in discussions of a "Blue Transition" especially how aquaculture has featured in policy discussions as relieving pressure on wild capture fisheries and contributing to food security and employment of the world's poor. International discussions incorporating aquaculture development as a "blue revolution" place aquaculture into foundational documents on the very nature of the future of food. In these reports aquaculture is connected strongly to the blue economy, blue growth, and blue carbon (Gentry et al., 2017; Hoegh-Guldberg et al., 2019; Willett et al., 2019; Costello et al., 2020). Nahuelhual et al. (2019) point out that a "Blue Transition" is akin to other environmental transitions and emphasize the need for such a transition to include social-ecological feedbacks citing Berkes and Folke (1998) who state that "a social-ecological feedback refers to a situation in which the ecological and the social systems (or components of the two) are connected together such that each system influences the other and their dynamics are thus strongly coupled." In the case of aquaculture, Krause et al. (2015) point to cases of aquaculture development that are a "blue revolution without people."

Many cultures that have relied historically on aquatic foods as their primary source of proteins. Recovering trajectories of Indigenous aquaculture development from antiquity and making connections to modernity opens the full social-ecological panoply of traditional knowledge to evolve alternative developmental pathways for aquaculture. Indigenous communities recovering their pasts are evolving new aquaculture communities of practice that have clear connections from ancestors to modernity. No matter the sources of knowledge used to chart alternative developmental pathways for aquaculture, whether traditional knowledge, scientific, corporate, or some blend, well-planned, transparent, participatory processes are required. Such development alternatives may drag out for longer than both Indigenous and other decision-makers want but, in the end, will lead to shared visions of more sustainable futures.

Since the Cultural Revolution China is recognized as the world's aquaculture leader in production for all forms of aquaculture from ocean to freshwater aquaculture, integrated and non-integrated systems, and for all fed to non-fed typologies (FAO, 2020). China is one of the only nations today where aquaculture production exceeds production from capture fisheries at a scale that is transformative of protein foods on Earth (Naylor et al., 2021). The evolution of aquaculture in China has occurred over thousands of years. China's historical scientific/cultural knowledge systems have contributed directly not only to its modern ascendancy in industrial and scientific areas but also more fundamentally to the adoption of aquaculture as culture.

Too many proposals for modern aquaculture developments post WWII, especially in the "new geographies for aquaculture" outside its traditional places in Asia (Costa-Pierce and Chopin, 2021) have been marketed to societies neglecting their anthropological and environmental histories and without considerations of their allied, cultural, and spiritual backgrounds. The modern case study of industrial aquaculture in Chile by Nahuelhual et al. (2019) demonstrates clearly that the promised blue transition in that country has not occurred as planned and advertised.

Without such knowledge of past cultural advances, societies worldwide will lose one of their greatest opportunities for more socially and environmentally sound forms of food production. The aquaculture profession will continue to limp along, especially in areas with great potential outside of Asia, losing opportunities for aggregating and delivering teachable moments due to the tiresome constraints repeated over and over about a lack of "social license" for aquaculture (Costa-Pierce, 2010; Zajicek et al., 2021). Cultural studies and historical backgrounds can serve as local, place-based ecological and social baselines to evolve the "blue revolution." A "culture of aquaculture" needs to be built on historical foundations so that informed politicians, investors, and communities can make better decisions based upon complete information and timelines of this historically important food innovation that has arisen multiple times in antiquity.

## Historical Evolution of Aquatic Species Management

It is widely accepted that aquaculture arose multiple times in societies as an evolution from capturing and trapping fish (Atlas et al., 2020), to holding and keeping fish, to reproducing, growing, and domesticating fish (Balon, 1995; Beveridge and Little, 2002; Nash, 2011). There are numerous anthropological and archeological studies of capture fisheries from antiquity (O'Connor et al., 2011). Hu et al. (2009) found freshwater fish were a part of the diet of ancient people near Beijing China 40,000 years ago. Steneck and Pauly (2019) describe the "kelp highway hypothesis" for colonizing the Americas from Northeast Asia. The hypothesis states that "saltwater people" (as defined by McNiven, 2003) from east Asia advanced north along western Pacific coasts then east across the sea to rapidly colonize the entire eastern Pacific coast. Archeological findings in Monte Verde in the south of Chile date to 14,500 years B.P. are "more consistent with the idea of a coastal rather than a land-based migration" (Steneck and Pauly, 2019).

The kelp highway hypothesis adds an ocean food systems component to accepted archeological findings on the importance of the "maritime highway" for human migrations in antiquity in Asia/Pacific. The oldest accepted evidence for open ocean crossings by modern humans is the migration to "Sahul," the combined continent of Australia and New Guinea, 47,000 years B.P. (Davidson, 2013; Clarkson et al., 2017; O'Connell et al., 2018). Coastal cultures in the north Pacific relied primarily on the abundant marine resources of kelp ecosystems for their primary sustenance. In the south, Steneck and Pauly (2019) theorized that rich mangrove ecosystems could have sustained similar large-scale coastal colonization's in the Tropics. Erlandson and Braje (2015) assessed if mangrove ecosystems could have facilitated a larger scale maritime colonization of people from East Africa to Oceania.

These hypotheses are intriguing from an evolutionary perspective of ancient aquaculture development from wild capture fisheries, to fish trapping and holding, and onwards to "proto-aquaculture" (Beveridge and Little, 2002). Archeological and anthropological evidence of complex Indigenous knowledge of extensive fish traps, fish holding and onwards to "proto-aquaculture" exists from Taiwan, Japan, and the Ryukyu Islands, Japan, 35,000–17,000 years B.P. (Kaifu, 2015; Fujita et al., 2016). Kaifu et al. (2020) reported evidence that difficult maritime crossings from the north (*via* Kyushu) and south (*via* Taiwan) to the Ryukyu Islands of southwestern Japan occurred some 35,000–30,000 years B.P. They state that "migration to the Ryukyus is difficult because it requires navigation across one of the world's strongest currents, the Kuroshio, toward an island that lay invisible beyond the horizon." Furthermore, "this suggests that the Paleolithic Island colonization occurred in a wide area of the western Pacific was a result of human's active and continued exploration, backed up by technological advancement."

Capture fisheries are the capture and harvest of wild aquatic organisms where no interventions are made to manage or otherwise influence captured organisms by containment, feeding, or application of any aquaculture techniques. Historical fish trapping is the capture of wild aquatic organisms for direct harvest using sedentary, non-mobile gears. Beveridge and Little (2002) defined "proto-aquaculture" as "activities designed to extract more food from aquatic environments, such as: the transplantation of fertilized eggs, entrapment of fish in areas where they could thrive and be harvested as required, environmental enhancements, such as development of spawning areas, enhancement of food, exclusion of competitors or predators, etc., and the holding of fish and shellfish in systems (ponds, cages, pens) until they had increased in biomass or until their value had improved." They distinguished "proto-aquaculture" from aquaculture due to the small degree of control over the life cycle of an aquatic species and the low impact of the intervention on aquatic production. One example cited is the "bundhs" of West Bengal India which are seasonal ponds that fill with water in during the Indian Ocean monsoon first rains and were used to stimulate spawning of Indian major carps over a 100 years ago (Sharma and Rana, 1986). Klinger et al. (2013) pointed out that even in the modern context it is difficult to separate fisheries and aquaculture or to define the various typologies noting there are ancient and modern practices of capture-based aquaculture (Lovatelli and Holthus, 2008). They state that "Numerous seafood species are produced for the global marketplace using a spectrum of methods and cannot be cleanly ascribed as either fisheries or aquaculture."

Aquaculture is defined as the farming of aquatic species in water. Farming implies intervention in the rearing process to enhance production, such as the regular stocking, feeding, protection from predators, etc., plus the individual, community, organization, or corporate ownership of the stock being farmed (Rana, 1998). Modern aquaculture systems are remarkably diverse and comprise the farming of hundreds of species in fed or unfed systems growing domesticated and non-domesticated species with hatcheries having little to no connections to wild genetics. Domestication of plants and animals dates from the Neolithic about 14,000 years B.P. (Zeuner, 1963). Domestication of aquatic species to the level of their separation from wild ancestors, with selection and breeding to create "synthetic species" similar to those produced throughout millennia on land, and in closed aquaculture production networks, is "true" aquaculture (Costa-Pierce, 2003).

Live capture of aquatic organisms in traps for direct harvest is present throughout the ancient and modern world. Nelson (2017) describes the extensive knowledge of tides and fish behavior used to design sophisticated fish traps and weirs over large portion of coastal Taiwan. Traps incorporated curves to incorporate knowledge of the tendency of fish to turn when they hit a curve. At high tides, trap walls were submerged allowing fish to swim over them. At low tides fish were trapped and gathered and people scooped out thousands of anchovies, herrings and other species using simple gears. Hawaiian fish traps (*loko 'umeiki*) are good historical examples as similar designs are present throughout Oceania. They are stone structures built into the sea with low, semi-circular walls that were partially or wholly submerged at high tide and contained numerous openings (lanes) leading into or out of the trap (Kikuchi, 1973, 1976). Siting of fish traps was done by knowledge of longshore currents that transported fish along the shore. The Hawaiian island of Moloka'i had many fish traps owing to the favorable orientation of the island with regard to longshore currents. Lanes in the walls of traps connecting to the sea were used to catch fish migrating down the coastline who were attracted to the surge of water at the lane entrances. Nets laid facing the sea across the opening of the lane captured fish flowing into the trap on an incoming tide. When the tide reversed fishermen faced their nets toward the traps capturing fish as they swam out to sea. It was reported that the right to fish during different portions of the tidal cycle was divided among family groups. Timoteo Keaweiwi in 1853 stated, "Such was the case of Mikiawa Pond at Ka'amola, Moloka'i. When the tide was coming in, the people of Keawanui could set the lanes. When the sea ebbed, the fish belong to Ka'amola" (Summers, 1964).

The next evolution in aquatic species management involved short- to long-term live storage of catches as a form of food storage/banking. Social drivers of development were the provision of sufficient aquatic foods for consumption, ceremonies, increase reliability of supplies, and/or trade to markets which are common strategies found throughout antiquity and are common strategies today. Trapping and holding to ensure fish supplies dates to the Neolithic about 6,000 years B.P. in Europe (European Commission, 2018). Modified fish traps connected to excavated ponds, netted off or channelized shallow areas of lakes, bamboo cages in rivers and irrigation ditches (Costa-Pierce and Effendi, 1988) and traditional floating cages as used in Tonal Sap, Cambodia (Beveridge, 1996) remain worldwide. Detailed traditional knowledge of fish behaviors and tides to trap fish in cages and weirs is preserved in the knowledge systems and literatures of Indigenous cultures and island communities worldwide from the Americas (for salmon, Atlas et al., 2020), Europe to East Africa and throughout Oceania. In modern times, a capture fishery that live harvests wild organisms at early stages in their life cycle, then transports them to aquaculture systems for growout under confinement and management to mature, harvestable adults is referred to as "capture-based aquaculture" (Lovatelli and Holthus, 2008). FAO (2016) estimated that 20% of global aquaculture production today is CBA.

**TABLE 1** | Main historical periods of the seven case studies reviewed.

| | Prehistoric (BC) | Roman (AD) | Early medieval | Medieval | Late medieval | Early modern |
|---|---|---|---|---|---|---|
| Time Periods | 8,000–1,800 | 0–400 | 400–800 | 800–1,250 | 1,250–1,500 | 1,500–1,700 |
| China | x | x | x | x | | |
| Egypt | x | | | | | |
| Australia[a] | x | x | x | x | x | x |
| Europe | | x | x | x | x | |
| South America[b] | x | x | x | x | x | |
| Canada/USA[c] | x | x | x | x | x | x |
| Hawai'i[d] | | | | x | x | x |

[a] *The first Europeans landed in Australia in 1787.*
[b] *The first Europeans landed in South America in 1492.*
[c] *The first Europeans to land in Canada were Vikings who landed on Baffin Island and Labrador in the tenth century. They occupied Anse-aux-Meadows, Newfoundland between 990 and 1,050. John Cabot was the first European to land in Canada after the Viking Age in 1497.*
[d] *The first Europeans landed in Hawai'i in 1778.*
*Grey highlights designate the historical periods of aquaculture reviewed here.*

## METHODS

A narrative review of case studies from seven sites of historical aquaculture development was completed to gain knowledge on recurrent themes (Finfgeld, 2003). Sites were chosen from the historical and anthropological literature over a time span from antiquity ∼8,000 years ago until the mid-1700's, or the Industrial Revolution, which is defined as the 100 years from about 1760 to 1860 when machines transformed industry and the concept of societies and work changed fundamentally (Horn et al., 2010; **Table 1**). A qualitative content analysis (Frankfort-Nachmias et al., 2015) was completed to find if there existed recurrent evidence in case studies of: (1) an aquatic/seafood-eating culture, (2) natural aquatic food resource scarcities, and (3) aquaculture development.

## CASE STUDIES

### China–8,000 Years+

Historical records describe common carp (*Cyprinus carpio)* being raised widely in ponds and paddy fields in China by the first millennium BC and earlier. Nash (2011) stated that carp aquaculture dates to 2,600 B.P. Shijing pottery, the oldest surviving collection of ancient Chinese pottery, shows carp being reared in ponds around 1,140 B.C. Rice paddies in China have been dated to the fifth millennium BC. Nakajima et al. (2019) provide evidence from fish bones excavated from an early Neolithic site in Jiahu, Henan Province that carp aquaculture was practiced there between 6,200 and 5,700 B.C., making aquaculture in China at least 8,000 years old. They state that "a large number of cyprinids were caught during the spawning season and processed as preserved food. At the same time, some carp were kept alive and released into confined, human regulated waters where they spawned naturally and their offspring grew by feeding on available resources. In autumn, water was drained from the ponds and the fish harvested…" Researchers hypothesized three stages of aquaculture development: (1) fishing in carp spawning areas in shallow marshes, (2) creation of hatcheries in the marshes by digging canals and controlling spawning and juveniles harvested, and (3) rice-fish culture and pond aquaculture.

There is documentation of integration of aquaculture into the networks of ponds and irrigation systems of China. Clay models of irrigation systems recovered from graves throughout southern China show that by the Han Dynasty (2,300–1,700 B.P.) fishponds were being employed widely for water storage (Bray, 1984; Li, 1994). An intact rice-field model was found having over 18 varieties of aquatic plants and animals which are used today that included lotus flowers, seeds and leaves, water chestnuts, soft-shelled turtles (*Trionyx sinensis*), grass carp (*Ctenopharyngodon idella*), and goldfish (*Carassius auratus*; Li, 1992).

Areas of southern China had high population densities with culturally advanced cities which reached their peak in the Song (Sung) Dynasty (960–1,276). New rice varieties were introduced from Vietnam. In the floodplains of China soils were excavated to construct elevated areas for homesteads and raising crops. Excavated areas became fishponds. Demands for fish and other aquatic foods increased and the practice of holding and growing fish became widespread as wild stocks became less abundant (Wu, 1985). *Kwai Sin Chak Shik,* a book written during the Sung Dynasty in 1,243 describes how carp fry were transported in bamboo baskets to ponds. Fry were collected in rivers and reared in ponds as recorded in *A Complete Book of Agriculture* written in 1639 (Balon, 1995).

The treatise published by the statesman Fan Li some 2,500 years B.P. describes common carp farming in sufficient detail to provide incontrovertible evidence that advanced fish culture developed in antiquity (Li, 1994). The monograph details the design and layout of fishponds, carp breeding, fry and fingerling rearing techniques. Accounts of the integration of fish culture with aquatic plants and vegetables exist in written records dating from 2,200 to 2,100 B.P. (Yang, 1994). Ruddle and Zhong (1988) describe the Zhejiang Huzhou mulberry-silkworm-fish-crop-animal farming ecosystem in China which is estimated to be more than 2,500 years old. Unfortunately these elegant aquaculture ecosystems have been declining since the 1990's (Edwards, 2009). Balon (1995) stated that domestication of common carp can be traced to the Romans and questioned if a separate center of domestication in ancient China existed. Similarly, Wohlfarth (1984) stated "there is evidence that in China the carp was never truly domesticated, but stocked at most, in a semi-domesticated condition with other fishes." However, Nakajima et al. (2019) provide compelling recent archeological evidence that a separate center of carp domestication in ancient China existed.

## Australia—8,000 Years+

More than 30,000 years ago a volcano known as Budj Bim (Mount Eccles) produced a lava flow (Tyrendarra lava flow) whose flow to the sea changed the watershed drainage patterns in western Victoria, Australia. Over centuries the landscape evolved into large, rich wetlands (Builth, 2006). For thousands of years the Gunditjmara people of Southwest Australia lived in this region in well-populated, permanent settlements (Lourandos, 1987).

McNiven (2015) studied the ancient aquaculture system of the Gunditjmara people as it evolved over 800 years. Gunditjmara engineered and managed water systems in the wetlands to channel and capture short finned eels (*Anguilla australis*) to ensure year round food supplies in an ecosystem over 75 $km^2$ around Lake Condah (Coutts et al., 1978; McNiven and Bell, 2010). Gunditjmara dug ponds and linked the wetlands by channels to direct water and juvenile eels into ponds and weirs in low-lying wetlands. Woven baskets were placed in the weirs to harvest mature eels (McNiven and Bell, 2010). Sophisticated earthworks were engineered to live store seasonal abundances and ensure adequate fish supplies throughout the year.

## Egypt—4,000 Years+

In ancient Egypt fish had sacred as well as prosaic roles in society. They were associated with the cyclical life-giving forces of the Nile and the New Kingdom Egyptian view of the world. Tilapia (*Oreochromis niloticus*) linked to the goddess Hathor and the concept of rebirth (Desroches-Noblecourt, 1954). Brewer and Friedman (1989) detail peculiar beliefs and taboos among the priesthood associated with fish. Although rod and line fishing is believed to have been common among all classes in ancient Egypt, fishing activities of the nobility were limited to fishing from their artificially constructed garden ponds. Their interest in fishing stemmed more from religious rituals associated with death and rebirth and less with pleasure or sustenance (Desroches-Noblecourt, 1954; Brewer and Friedman, 1989). Fishery innovations were present not only in the elites, however, but throughout Egyptian society (Chimits, 1957). Early travelers to Egypt confirmed that fish were of tremendous importance in the Egyptian diet. The Roman traveler Diodorus Scullus is quoted as saying that "…the Nile contains every variety of fish and in numbers beyond belief: for it supplies the native not only with fish freshly caught but also yields an unfailing multitude for salting." Herodotus, who traveled to Egypt some 2,500 years ago reported that "…all Egyptians in the Nile Delta possess a net with which, during the day, they fish…"

In his account of tilapia in ancient Egypt, Chimits (1957) reproduces a 4,000-year-old bas relief from the tomb of Thebaine showing a nobleman sitting in his garden fishing using a double line with two hooks, his wife seated behind him unhooking fish (**Figure 1**). He appears to be fishing from an artificial, drainable, fish tank (Davis and Gardner, 1954). The relief is remarkable for also showing lotus growing on the top of the tank (for shade, ancient "aquaponics"), and papayas irrigated by pond water in a field being picked by servants (ancient "integrated aquaculture"). Tilapia were transferred from the Nile to not the ponds of nobility but also of commoners (Chimits, 1957) where they certainly would have spawned.

## Canada, USA—3,500 Years+

> "We hypothesize that some kind of shellfish management was indeed widespread in many traditional societies, as reflected in the disparate archaeological and ethnographic information compiled in this paper." (Lepofsky et al., 2015)

In the Pacific Northwest of North America (modern Alaska, USA, British Columbia, Canada and Washington state, USA), vast fisheries with fish traps helped to sustain Indigenous communities for at least 12,000 years (Selkirk, 2021). Morrison (2021) reported a network of 300 or more fish traps installed by the K'omoks that date more than 1,300 years ago. Clam mariculture in engineered rock-walled intertidal terraces and sophisticated shellfish cultivation techniques were practiced (Augustine and Dearden, 2014; Deur et al., 2015; Lepofsky et al., 2015; Moss and Wellman, 2017). Smith et al. (2019) radiocarbon dated nine clam gardens on Northern Quadra Island, British Columbia, Canada and determined some clam gardens in their study area were over 3,500 years old.

First nations peoples along this coast constructed and managed clam gardens of littleneck clams (*Leukoma staminea*) and butter clams (*Saxidomus giganteus*; Williams, 2006; Groesbeck et al., 2014; Lepofsky et al., 2015; Jackley et al., 2016). Indigenous people created and maintained these systems by modifying the marine benthic substrate resulting in some systems that were at least four times more productive and resilient than non-clam gardens (Lepofsky et al., 2015; Holmes et al., 2020). Beyond increased the increased productivity, clam gardens created enhanced systems that promoted biodiversity of other marine species and mammals (Deur et al., 2015). Enhanced Indigenous research in the future could indicate if this overall ecosystem enhancement was the overall goal of these innovations. Recent research on clam gardens in British Columbia also showed that the unique clam garden design provided increased climate resilience by buffering water temperatures and carbonate fluctuations. Traditional practices of returning clam shells to the beach helped buffer against acidic coastal waters from upwellings (Lepofsky et al., 2015).

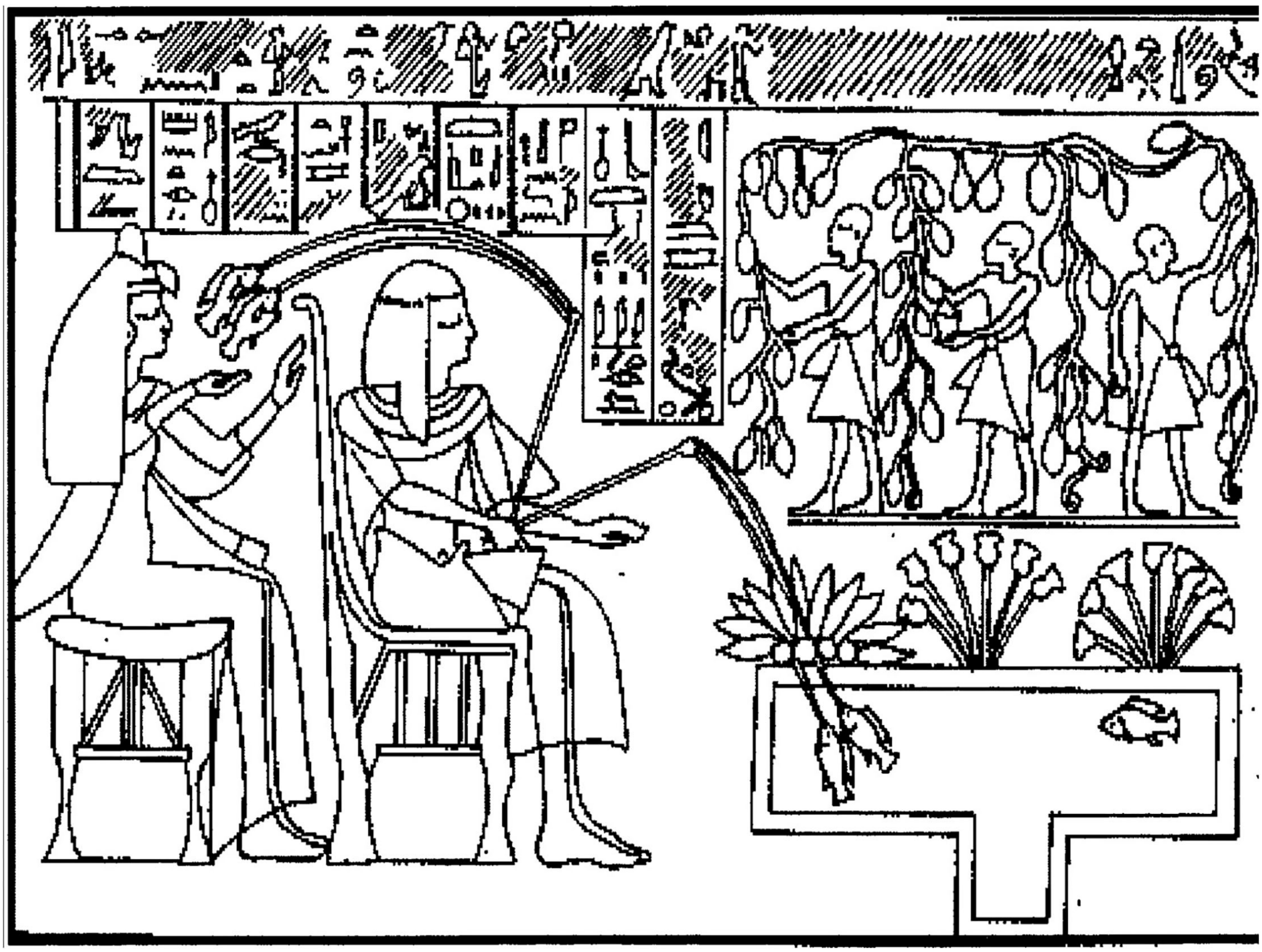

**FIGURE 1 |** Bas relief on the Tomb of Thebaine, Nile Delta, Egypt circa 2000 B.C. Note the central drainage canal, floating lotus plants, and juxtaposition of tank to fruit trees. These components are used in modern aquaculture to harvest fish, provide shade, water quality control by aquaponics plants, and shelter for fish, and direct wastewaters for use by terrestrial agriculture in an integrated aquaculture system. From Chimits (1957) redrawn from author photographs (B.A. Costa-Pierce).

## Europe–2,000 Years+

Romans in the southern part of the Empire preferred sea fish (Varro 116-27 B.C., 1912). Freshwater ponds were considered inferior and "plebeian" (Balon, 1995). Romans in the south grew oysters on artificial structures (Balon, 1995). Fish storage in brackish waters dates to Medieval times when lagoons and coastal ponds were first established to retain fish swept in by the tides including seabass (*Dicentrarchus labrax*), seabreams (Sparidae), and mullets (Mugillidae; Stead, 2019). The "vallicoltura" coastal aquaculture system was practiced widely on the Adriatic and Tyrrhenian coasts by the Etruscans (Beveridge and Little, 2002). Cicero's chef, Sergius Orata, built saltwater ponds and stored fish, a practice that may have originated in Agrigentum, Sicily (Zeuner, 1963).

The natal region of *Cyprinus carpio carpio* is the Black Sea drainages of the Balkan Peninsula in southeastern Europe including the Danube River below Pannonia, an ancient province of Rome bounded on the north and east by the Danube River (Hoffmann, 1994, 2005; Balon, 1995). Wild carp fisheries were practiced in prehistoric times by the many tribes living in this region (Hoffmann, 2010). Wild populations of common carp were known to the Romans living in riparian settlements along the floodplains of the Danube River which contained the Roman provinces of Camuntum, Peiso Piso, Gerulata, Brigetio, Celamantia where large populations of spawning common carp aggregated every spring (Balon, 1995). Roman population growth, attempts by political authorities to assert power and the evolution of state control, and wars played varying roles in the distribution of carp out of this natal region northwest into Europe.

Common carp (*Cyprinus carpio carpio*) aquaculture was well-developed in Roman lands from at least 100 B.C. to 500 A.D. then evolved after the collapse of the Roman Empire and the establishment of Christianity into carp aquaculture in monastery ponds (Beveridge and Little, 2002). Thereafter aquaculture of common carp in ponds spread

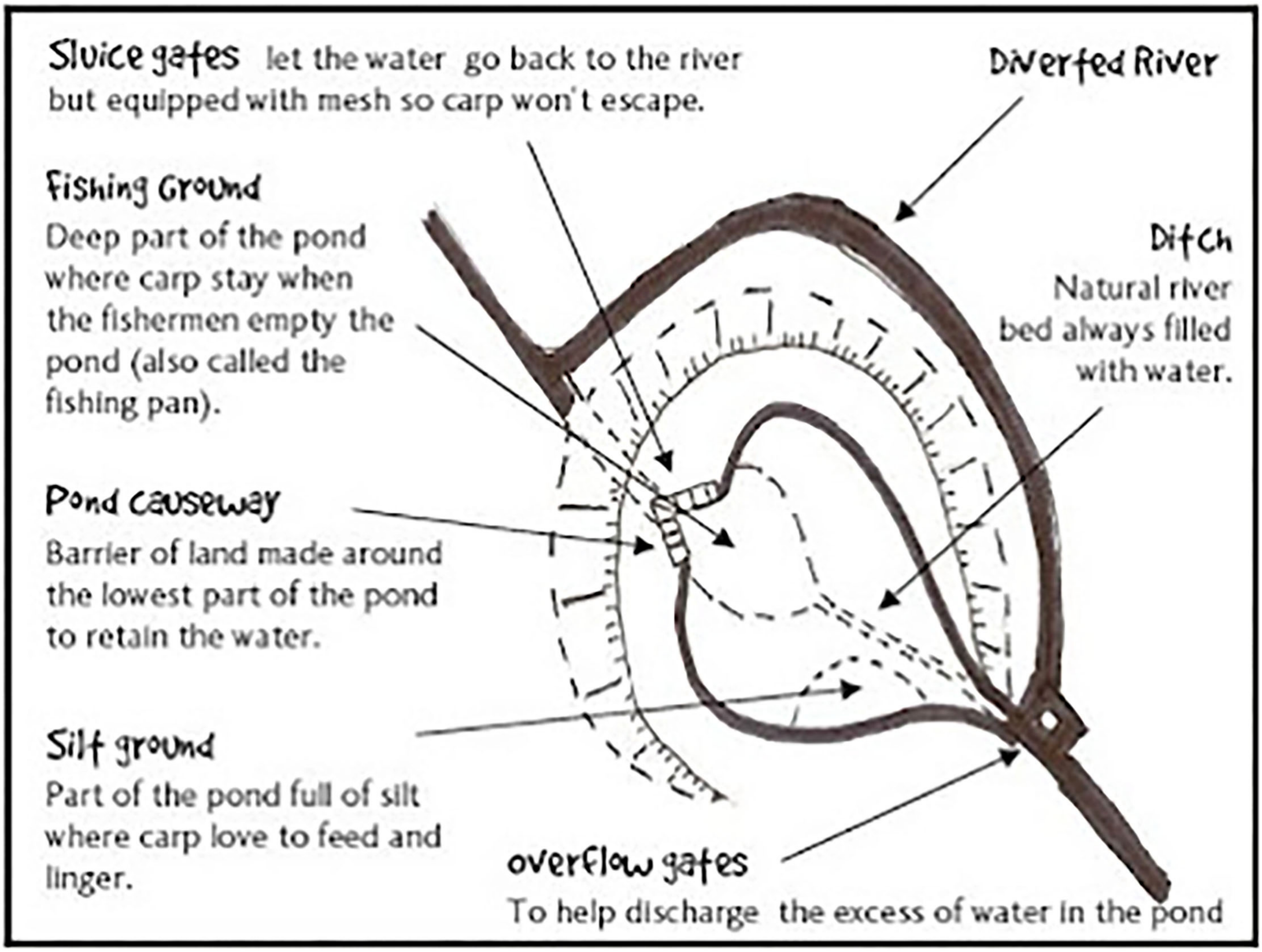


**FIGURE 2 |** Sophisticated aquaculture engineering of a monastery pond in Medieval Europe reconstructed from archeological investigations. Taken from Moisand (2008).

widely into northwestern Europe in late Medieval to Early Modern times.

Balon (1995) attributes the wider distribution of common carp to Roman military advances and a mass migration of people north to the Danube River where they confronted the "formidable forces of Celts and Germans on the opposite shores." Sitwell (1981 in Balon, 1995) state, "In the second century, the comparatively short stretch of river between Vienna and Budapest about 240 km (150 miles) long required no less than four legions to guard it. By contrast all Roman Britain in the second century required only three legions. Roman North Africa possessions managed with a single one." Balon (1995) estimates 20,000 fighters were joined by wives, mistresses, children, slaves, and tradesmen to total 100,000 people along this short stretch of river. Fortresses and Roman towns were established. These people needed food and carp were abundant and easy to obtain protein resource in an area that bordered the largest floodplain (the Piedmont zone) of the Danube River, the westernmost spawning grounds of common carp (Balon, 1995).

Large road networks were constructed by the Romans at this time. As people gained a taste for carp they transported the fish. States Balon (1995), "The earliest record is by the secretary to king Theodorus (475–526 A.D.) of Ravenna, Cassiodorus (490–585 A.D.) who was ordered to transport carp from the Danube to Italy." Live fish transport evolved as common carp can survive wide aquatic environmental conditions that most fish cannot especially adverse temperatures, oxygen, water qualities, and starvation in small containers (Balon, 1974). Zeuner (1963) quotes Pennant in a 1776 article in *British Zoology* who stated the remarkable observation that common carp placed in a "net well-wrapped in wet moss and hung up in a cellar will remain alive, providing the moss is kept wet."

The demand for fish increased dramatically in Europe as Christianity became dominant in the 5th and 6th centuries and taboos on eating terrestrial "flesh" were enforced. The only meats that could be eaten on fasting days were cold-blooded animals such as fish, crustaceans, and shellfish. People were allowed to substitute fish for meat for about 130 days (35%) of the

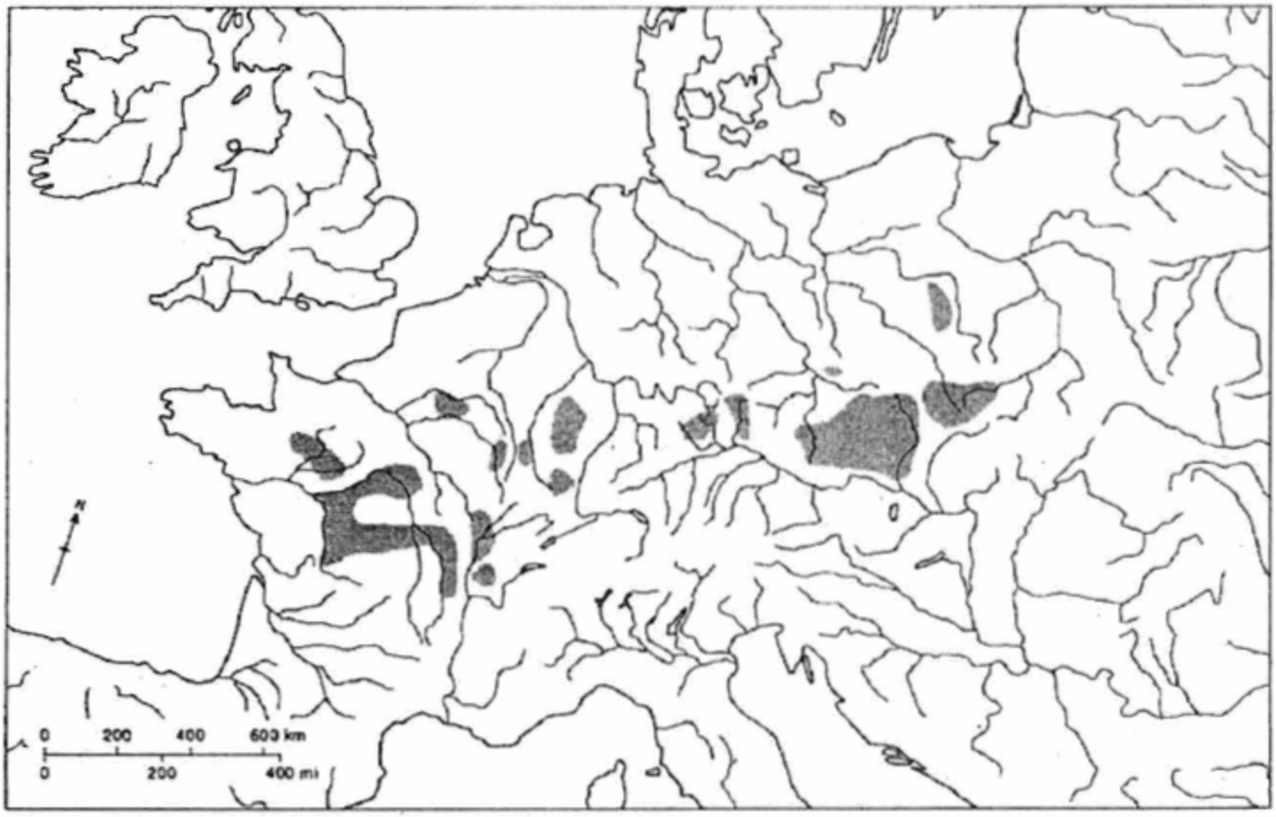


**FIGURE 3 |** Major regions of carp aquaculture by the end of the Medieval. From Hoffmann (2002) and Hoffmann and Winiwarter (2010). Reproduced with permission from the author (R. C. Hoffmann).

year. Medical advice promoted eating freshwater over salted fish (Hoffmann, 2005). Punishment for violations sometimes included the death penalty.

Transport evolved but was not enough to keep settlements and monasteries with adequate supplies of fish as disruptions occurred due to conflicts, weather, etc. which made fishing difficult or impossible. Monks, nuns, and priests who had to follow fasting regulations obediently had difficulty finding fish (Leonhardt, 1906). Storage of fish evolved from these scarcities. Artificial ponds and reservoirs were created called "piscinae" that became popular with Roman elites and monasteries. Charlemagne (768–814 A.D.) the first Holy Roman Emperor was known to store fish and maintain ponds. Some elites spent fortunes on their piscinae. Balon (1995) states that "Consul Lucullus (75 B.C.), whose reputation as a gourmet is well-known, dug through a hill near Naples to bring water to his ponds, which were reputedly more costly than his villa."

The first monasteries were founded in the early 6th century (Monte Cassino monastery in 529 A.D.). Common carp aquaculture grew as monasteries spread northwest and south into Europe from these Roman roots (Dubravius, 1547 in Balon, 1995; Beveridge and Little, 2002). As monasteries gained land and farms during Medieval and Late Medieval times aquaculture pond designs became more sophisticated (Hoffmann and Winiwarter, 2010; **Figure 2**).

Hoffmann (1994, 2005) believe domestication of common carp was obtained in Roman times as spawning was reported to occur in Roman piscinae and also in monastery ponds. Aquaculture flourished in monasteries as the domination of Christianity grew in Europe, and centers of aquaculture expertise became well-known (**Figure 3**). Aquaculture expanded beyond northwestern Europe to the British Isles and Scandinavia (Bonow et al., 2016) (**Figure 4**). European pond aquaculture expanded in early modern times into the English colonies of North America as the rapid depletion of anadromous fish populations occurred there (Robert, 2008).

## South America–2,000 Years+

> "Before it became the New World, the Western Hemisphere was vastly more populous and sophisticated than has been thought—an altogether more salubrious place to live at the time than, say, Europe." Mann (2005).

The agricultural technology called "chinampas" was well-known throughout ancient Latin and Northern South America in

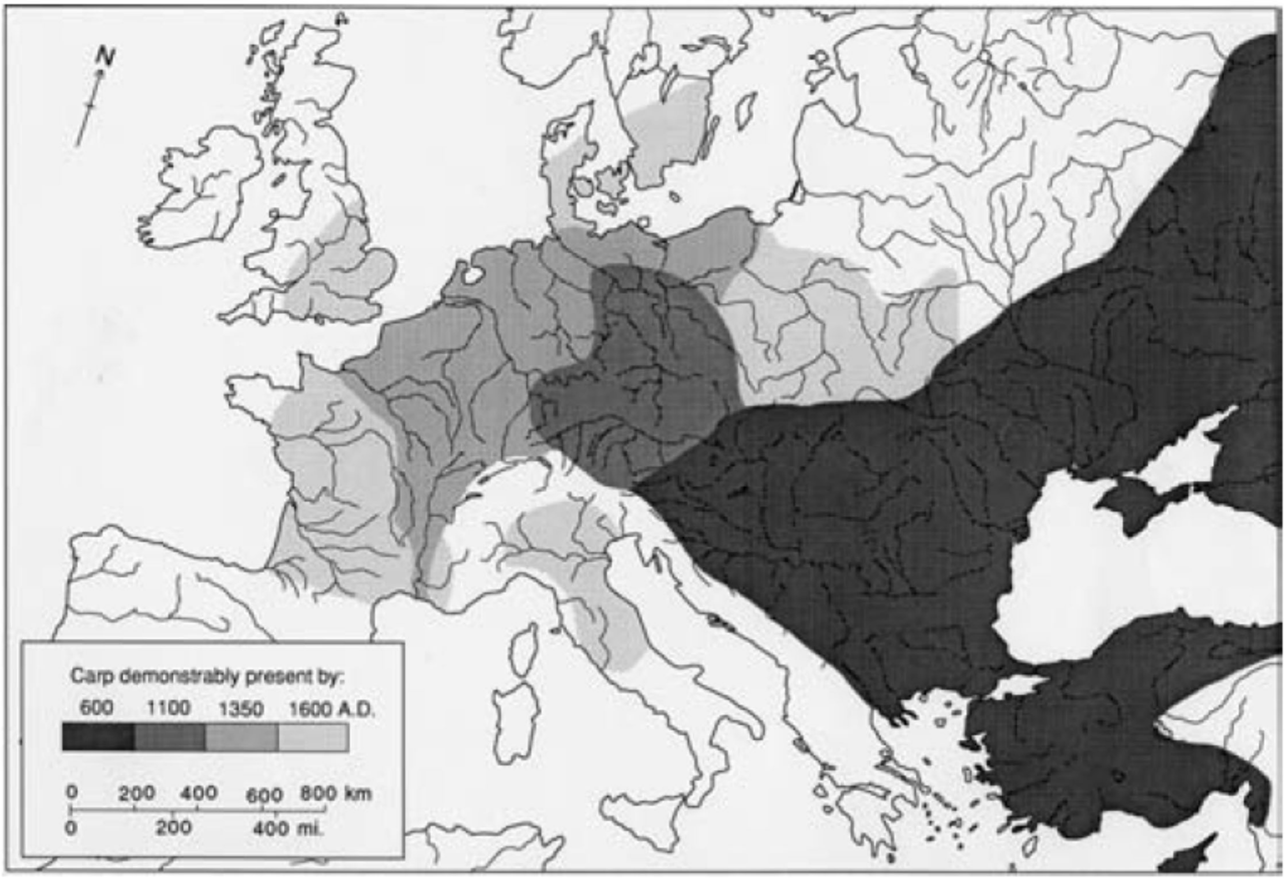


**FIGURE 4 |** Expansion of carp aquaculture over 1,000 years from natal river regions of southeastern Europe northwest to reach the British Isles and Scandinavia. From Hoffmann (2005). Reproduced with permission from the author (R. C. Hoffmann).

antiquity (**Figure 5**). "Chinampa" is a Nahuatl word spoken since ancient times by the Aztecs and translates roughly to "net of branches". Chinampas have been thought to have developed in the Valley of Mexico in and around the Texcoco and Xochimilco lakes (Coe, 1964). Chinampas were built by cutting trees and piling up tree branches and debris in mounds, then heaping nutrient rich sediments dug from canals, causeways, lakes and wetlands onto the tree debris to make raised agricultural beds about 100–200 m long and 5–20 m wide. Chinampas were designed to be surrounded by excavated canals. Water containing nutrients would be drawn up into the agriculture beds by a dense network of crop roots (manioc, beans, squash, and sweet potatoes) and agroforestry species (palm, nut, and fruit trees). Nutrient rich organic muds would be taken regularly from canals and ponds and piled on top to maintain structural integrity and fertility (Aghajanian, 2007). Large compost pits of dark earth have been found indicating intensive crop production on the raised beds (Carneiro, 1984; Glaser and Woods, 2004).

Erickson (2000, 2001) and Heckenberger et al. (2008) reported that 2,000 years B.P. extensive settlements were present in the western Amazon region of Bolivia (Pando, Beni) and Brazil (Acre, Rondônia) and that these cultures were sustained by a vast network of chinampas. The western Amazon region is a vast area of low-lying savannahs that for most of the year are dry and water scarce. During the rainy season however, floodwaters cover much of the low-lying lands turning the ecosystem into shallow wetlands and ponds. Erickson (2000, 2001) studied the Baure in Bolivia where Indigenous nations developed and managed sophisticated wetland/pond/canal aquaculture systems that covered at least 525 km$^2$ (**Figure 6**). These integrated agriculture-aquaculture ecosystems likely extended into what is today tropical forests of the western Amazon all the way to the Llanos regions of modern Columbia and Venezuela. Roosevelt et al. (1996) found such systems throughout the "várzea" as the Amazonian floodplain is known.

Mann (2008) stated that "sizable, regionally organized populations" extended across this vast region of South America. Research by Heckenberger et al. (2008) showed a distribution of population centers across about 20,000 km$^2$ having an estimated a pre-colonial population of 50,000. Debates about population sizes have fueled decades of anthropological debates that have called the "Amazon archaeology wars" (Erickson, 1994, 2000). Research has questioned if the dense Amazonian forests, vast savannahs and wetlands of the western Amazon are primordial or are secondary growth ecosystems modified extensively by anthropogenic agriculture-fishing and aquaculture

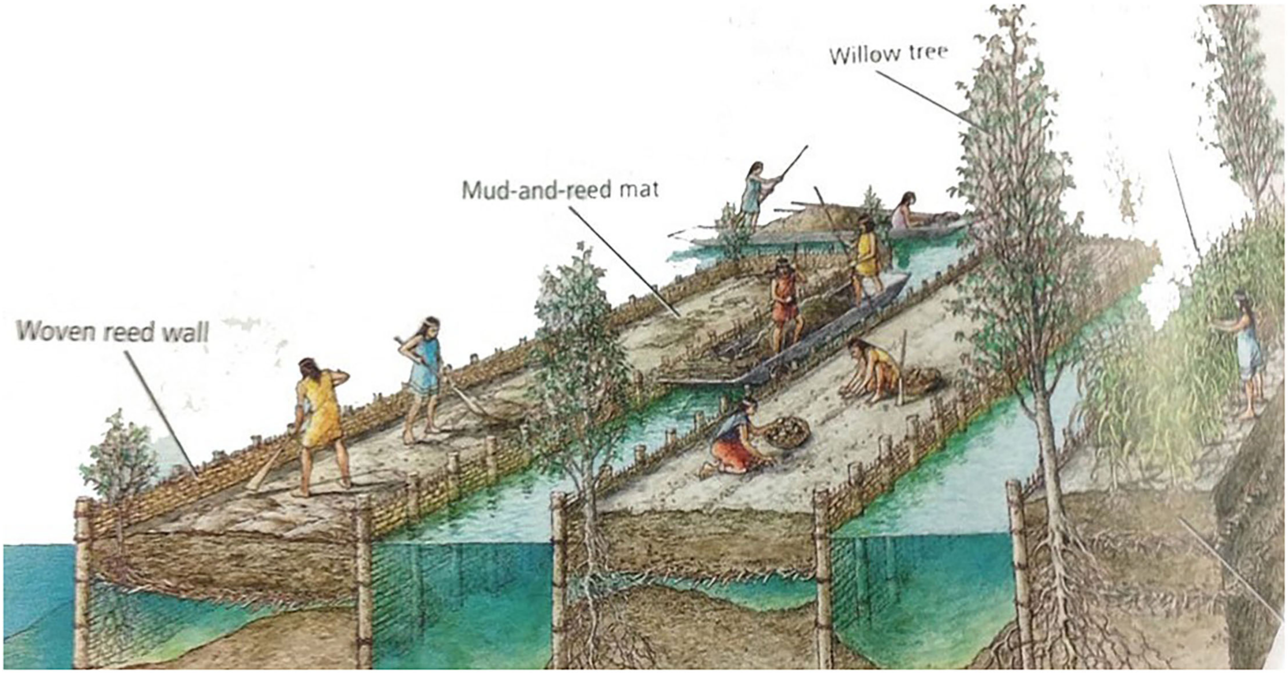


**FIGURE 5 |** An artist's conceptual illustration of chinampas, a wetland agriculture-aquaculture system that was common from the valley of Mexico City to the western Amazon regions of South America. Development of the systems stretch back as far as 6,000 years B.P. From Aghajanian (2007).

before European colonialism. Are the modern landscapes, ecological forms and functions of this area much more recent and exist now as secondary growth that occurred only after the massive depopulation of these regions 400–500 years B.P. due to European colonialism and diseases?

Western Amazonian settlements were not cities in the modern context but were "highly self-organized anthropogenic landscape(s) of late prehistoric towns, villages, and hamlets, with well-planned road networks" (Heckenberger et al., 2008). Permanent plazas were political ritual centers. Heckenberger et al. (2008) theorized that ancient civilizations "in broadly forested regions, such as temperate Europe, eastern North America, and the Amazon basin, are generally more dispersed and less centralized than classical (oasis) civilizations in Egypt, Mesopotamia, and Indus River areas or, in the South American case, coastal desert or arid highland river valleys." Erickson (cited in Mann, 2008) stated these cultures were radically different than the Aztecs, Incas, and Mayas as they transformed permanently regional ecosystems, creating "a richly patterned and humanized landscape" that is "one of the most remarkable human achievements on the continent."

Fish traps and weirs were present throughout the ancient world. Aquaculture likely arose from capture and holding wild fish and other aquatic species. There is extensive archeological and anthropological evidence that the interactive land-water farming systems of the western Amazon were more than a floodplain trap fishery. They were capture-based aquaculture systems that produced tremendous amounts of aquatic proteins for thousands of people (Erickson, 2000, 2001; Erickson and Brinkmeier, 2007; Blatrix et al., 2018). Blatrix et al. (2018) studied the earthwork systems in Bolivia and compared them to floodplain fisheries in Africa. In contrast to Africa, Blatrix et al. (2018) found large, designed ponds and canal diversions that served not only as traps but engineered aquaculture systems that could store fish alive for long periods of time. They stated that while both "weir-fishing and pond-fishing are both practiced in African floodplains today…in combining the two, this pre-Columbian system appears unique in the world." Erickson (2000) estimates that 100,000–400,000 fish/ha in the canals and yields of 1 metric ton/ha/year for shallow ponds in these seasonal systems. He also points out that large middens of edible snails (*Pomacea gigas*) have been found which likely were managed/cultured in the canals and ponds. These snails are prolific, growing rapidly at high densities and could have produced hundreds of tons of additional aquatic foods. Erickson (2000) cite Swing et al. (1987) who found *Pomacea gigas* at a density of about 24/m$^3$ in Bolivian wetlands. Snail middens have been found throughout the Beni and nearby regions of Bolivia and Brazil. Erickson (2000, 2001) calls the wetland complex of Baures in Bolivia "a form of intensive aquaculture" as chinampas, settlement mounds, raised causeways and extensive wetland management, with canals, dams, ponds, and fish weirs and traps were found throughout the landscape. It is unknown if domestication of aquatic species occurred. Erickson states, "Rather than domesticate the species that they exploited, the people of Baure domesticated the landscape."

**FIGURE 6 |** An aerial LIDAR image of a portion of the Beni region of Bolivia that reveals the extent of the chinampas (raised agricultural fields) and the vast irrigation canals that today is hidden by a dense forest canopy. The Beni is about 78,000 km$^2$ of raised agricultural fields (chinampas) integrated with fishponds/canals (Erickson, 2001; Mann, 2005, 2008; Heckenberger et al., 2008). Photograph by Clark Erickson, University of Pennsylvania. Reproduced with permission from the author (Clark Erickson).

## Hawaii—700 Years+

> "The whole distance to the village of Whyeete is taken up with innumerable artificial fishponds extending a mile inland from shore, in these the fish taken by nets in the sea are put, and though most of the ponds are fresh water, yet the fish seem to thrive and fatten... The ponds are several 100 in number and are the resort of ducks and other water fowl." T. Bloxam, British naturalist on H. M. S. Blonde, describing Waikiki in 1825 (Handy and Handy, 1972).

The ancient aquaculture systems of Hawai'i are unique in that they connect an isolated island society with sophisticated ocean harvesting and integrated marine aquaculture to an entire watershed management/food production system (the *ahupua'a*; Costa-Pierce, 1987; Gon and Winter, 2019; Winter et al., 2020; **Figure 7**). Hawaiian marine aquaculture systems are remarkable in terms of their diversity, distinctive management, and extent of development, especially given the small size of Hawai'i. Although the Hawaiian systems are relatively recent (about 1,500–2,000 years old) in comparison to others reviewed here, the evolution of ocean fishing to trapping/storage and onwards to aquaculture farming systems parallels the evolution of aquaculture in Indigenous societies worldwide.

There is evidence that Hawaiian fisheries had sustaining yields of more than 12 MT/km$^2$ (120 kg/ha) prior to the arrival of Europeans (McClenachan and Kittinger, 2012). Fisheries were characterized by adaptive management whose design had a unique royal control and enforcement of marine common properties. Hawaiians had strict regulations on marine fisheries as the documented high population density in antiquity added pressure on marine fishery ecosystems (Summers, 1964; Kamakau, 1976). Kaiser and Roumasset (2014) discussed the tumultuous social-ecological transitions from the ancient Hawaiian *konohiki* management/regulatory system of the *ahupua'a* ecosystems that occurred when taken over into the United States.

## Other Ancient Centers of Aquaculture

There are other notable centers of aquaculture in antiquity that deserve mention and further research. Integrated agriculture/aquaculture systems were present in Cambodia

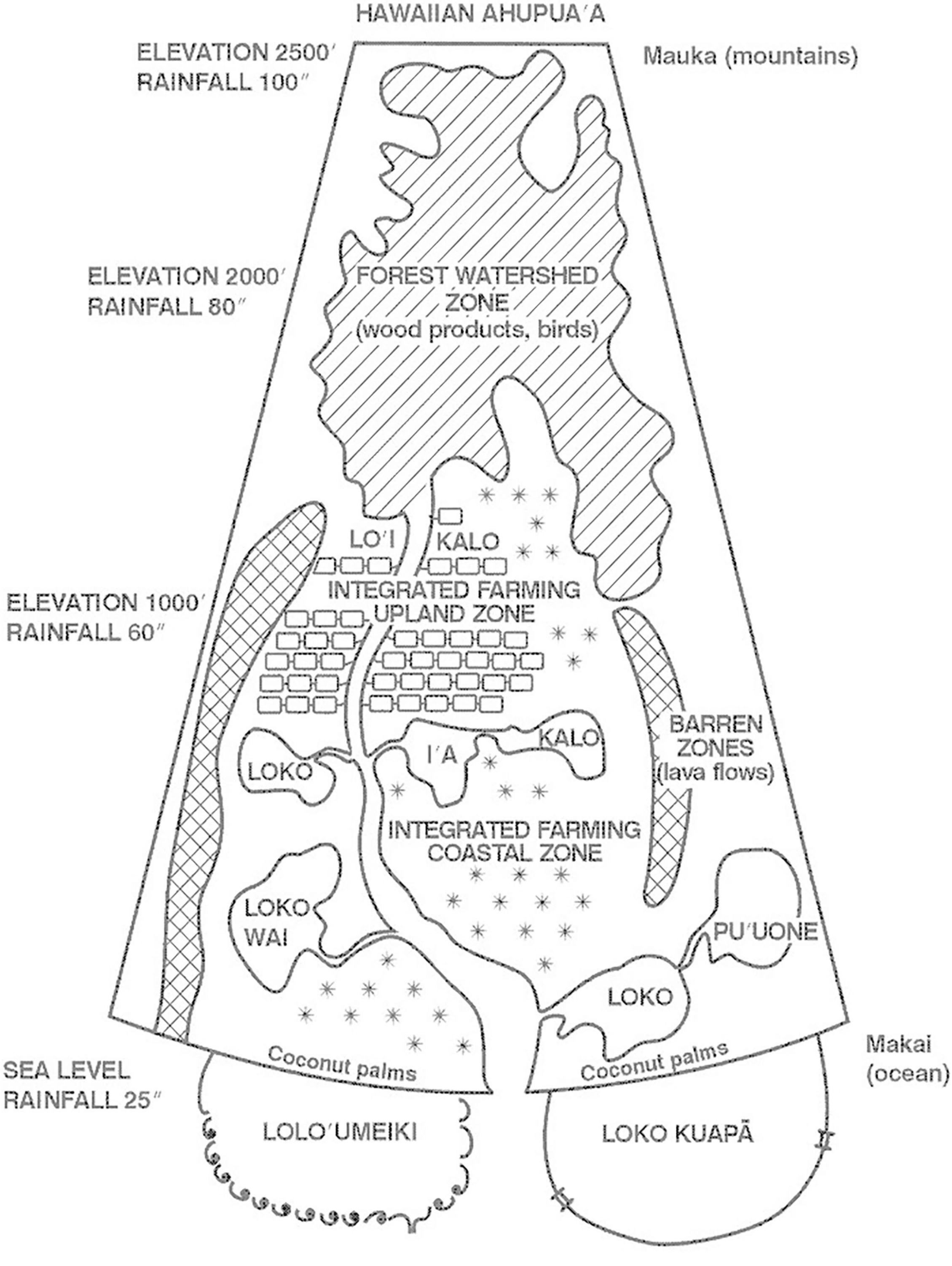


**FIGURE 7 |** The *ahupua'a* aquaculture ecosystems stretched from inland highland integrated taro-fishponds, to lakes, reservoirs and ponds in the wetland lowlands to sophisticated marine aquaculture systems built out into nearshore oceans. They sustained a high population density of Hawaiians until European contact (Kikuchi, 1973, 1976; Costa-Pierce, 1987; Gon and Winter, 2019; Winter et al., 2020). Reproduced with permission from the author (B.A. Costa-Pierce).

1,000 years B.P. Cage culture of fish may have developed first in Cambodia then spread to Indonesia (Beveridge, 1996). Freshwater integrated aquaculture in Cambodia was likely influenced to a large extent by connections to China (Edwards et al., 1997). Milkfish aquaculture in coastal "tambaks" in Indonesia dates from 1,200 to 1,400 AD (Schuster, 1952).

## INDIGENOUS NATIONS MOVING FORWARD

There is a new and growing recognition of the historical and cultural significance of Indigenous aquaculture worldwide by international and non-governmental organizations, scientists, and most importantly, by Indigenous nations themselves. For Indigenous peoples their ancient advances, as exemplified by their past successes, can be a source of pride and help ameliorate the cultural damage of colonialization. The wisdom and spiritual connections to their aquaculture ancestors and their network connections throughout the world to other Indigenous aquaculture communities is being incorporated into education programs and lessons for future generations.

Recovery of the traditional knowledge and wisdom of Indigenous people who designed and managed aquaculture ecosystems is important not only culturally and spiritually to them but also for the world as they demonstrate alternative, community-based models of applied, ecological aquaculture leadership, knowledge, and science. Indeed, these communities are ancestors of all global aquaculture practitioners alive today and into the future. The Indigenous knowledge systems of aquaculture are part of not only their birthrights but of all humanity (Ogar et al., 2020).

Recovery of the past wisdom of aquaculture through partnerships globally between Indigenous communities and anthropologists/archeologists needs to be prioritized (e.g., the "applied archaeology" of Erickson, 1994). McNiven (2003) emphasized that investigations of the spiritual complexity of Indigenous "saltwater people" in Australia assisted in explaining enigmatic marine stone arrangements found in Queensland. There is recent recognition that the Indigenous aquaculture wisdom of the past needs not only to be preserved and celebrated but also can lead development of an alternative future for aquaculture globally.

FAO (2019) designated the mulberry-silkworm-fishpond and rice-fish aquaculture ecosystems as Globally Important Agricultural Heritage Systems (GIAHS; **Figure 8**). In Victoria, southwest Australia, the short-finned eel aquaculture ecosystem of the Gunditjmara people was one of the first places included on Australia's National Heritage List in 2004. The site was then designated as a UNESCO World Heritage Site, The Budj Bim National Heritage Landscape (Builth, 2014; McNiven, 2017). In 2005 another site, the Brewarrina homeland of the Barkindji people, was designated as the Brewarrina Aboriginal Fish Traps National Heritage Place (Australian Government, 2021). At this site fish traps, ponds and weirs stretch some 0.5 km along the Darling (Baaka, Barka) river in New South Wales. These Australian sites are much more than museums of the past but continue as examples of ecological aquaculture and the FAO ecosystem approach to aquaculture as the Gunditjmara continue their ancestral aquatic management to today (McNiven and Bell, 2010). The Gunditj Mirring Traditional Owners Aboriginal Corporation was "established to continue our connection to Gunditjmara country and to progress our rights and interests in our cultural identity, social justice, native title, cultural heritage and land justice for our Gunditjmara country" (Gunditjmirrig Traditional Owners Aboriginal Corporation, 2015).

There are larger opportunities. Community-based, hyper-local aquaculture ecosystems serve to demonstrate new aquatic food production systems rooted in the ancient past but that continue to evolve today. These systems can ameliorate climate change and help preserve the Earth's remaining biodiversity. An estimated 80% of the world's remaining biodiversity is located in the Indigenous nations worldwide (Sobrevila, 2008). Indigenous communities can not only reclaim their past wisdom but also advance an alternative path to intensive, industrial aquaculture plus lead locally and globally the ecosystem approach to aquaculture advanced by the FAO (2010). A transformation of food production systems is needed to meet the challenges of simultaneously adhering to the planetary dimensions, food security and advancing human health and wellness (Bengoa, 2001; Gordon et al., 2017; Chang et al., 2018; Willett et al., 2019; Kuempel et al., 2021).

Indigenous cultures of Bolivian Amazon were once densely populated in well-organized settlements. They designed, developed and managed a savannah ecosystem experiencing seasonal floods and seasonal droughts. The land had poor soils and lacked drainage. Using ecological knowledge they nurtured an integrated, interactive land-water farming ecosystem combining chinampas agriculture, fisheries and aquaculture to support their societies. States Erickson (1994), "The ancient inhabitants of the area created an agricultural landscape to solve these problems and make the area highly productive." Realizing the productive potential this integrated farming ecosystem and its applicability to many areas with similar conditions throughout the lowland tropics as an alternative to cutting down the rainforest, participatory research and community-based programs over the last 20 years have been developed. Erickson (1994) called these "applied archaeology" and joined with partners from international to Indigenous (Inter-American Foundation, the Parroquia of San Ignacio, the Bolivian Institute of Archaeology, Biological Station of the Department of the Beni, and the University of Pennsylvania Museum of Anthropology and Archaeology) to reconstruct the ecosystem designs for the ancient chinampas/integrated aquaculture systems of their ancestors.

Erickson and Brinkmeier (2007) describes work with the Community of Bermeo, Department of the Beni, Bolivia with Indigenous families. Design and reconstruction works were based on traditional knowledge and participatory research informed by archaeological excavations and mapping. The reconstructed modern systems have produced impressive harvests and success spread to the communities of Bermeo and Villa Esperanza who donated lands, with the Inter-American Foundation providing funds to pay community members a daily


**FIGURE 8 |** The Zhejiang Huzhou Mulberry-Silkworm-Fish Pond Aquaculture Ecosystem in China is estimated to be more than 2,500 years old existing to today. It has been designated by the FAO (2019) as a "Globally Important Agricultural Heritage System." Photo taken from: http://www.xinhuanet.com.

wage to build and maintain the systems. Community members recorded data to document if production can be sustainable. Results to date are that over a long period of continuous cropping high yields can be maintained and that the systems are labor-efficient with little maintenance necessary to keep them at high production (Erickson and Brinkmeier, 2007).

The Hawaiian fishpond/*ahupua'a* ecosystem restoration movement involves many segments of society to recover and advance Indigenous knowledge in aquaculture. Alternative models for local sustainability are being led by Kua'aina Ulu 'Auamo, the Edith Kanakaole Foundation, Kamehameha Schools, among others. In Washington and Alaska, USA, the Swinomish nation is recovering its ancient Indigenous aquaculture knowledge to implement its first modern-day clam garden as part of their comprehensive plan to strengthen solutions through Indigenous knowledge for food, climate, cultural, and environmental benefits (Morrison, 2020). Members of the Eyak Athabaskan Alaska Indigenous community are developing seaweed aquaculture as an alternative/supplement to the herring fishery in the Copper River Delta. In Australia, the North Australian Indigenous Land and Sea Management Alliance Ltd. has been created. In New Zealand, nearly 21,000 ha have been set aside for aquaculture by the Māori community.

Internationally, at the 2020 IUCN World Conservation Congress in Marseille, France, the Global Indigenous Network for Aquaculture (GINA) was established (Global Indigenous Network for Aquaculture, 2020). In 2019, the Pacific Indigenous Aquaculture Collaborative Hub created by Alaska, Hawai'i and Washington NOAA Sea Grant programs gathered over 150 participants from throughout the Pacific basin for an Indigenous aquaculture meeting in Hawai'i. One outcome was formation of the Pacific Sea Garden Collective (2022) which has developed a spectacular, interactive website of Indigenous fisheries and aquaculture innovations throughout the Pacific basin as "a collective of Indigenous knowledge holders, community practitioners, university researchers, and artists working together to foster learning about sea gardens drawing from traditional and scientific knowledge with the vision of supporting their resurgence as adaptive strategies today."

Restoration aquaculture has been defined recently by The Nature Conservancy (2021) as occurring "when commercial

**TABLE 2 |** Evaluation of evidence of six historical case studies.

| Cases | Seafood eating cultures experiencing aquatic food shortages? | Documented pressures on fishery resources? | Evidence of ancient aquaculture development? | Summaries of key anthropological evidence |
|---|---|---|---|---|
| China | Yes | Yes | Yes | China experienced famine in some province nearly every year for over a 1,000 years (Mallory et al., 1927). In ~2,000 B.C. Yu Wang issued a conservation edict prohibiting fishing during the spawning seasons (Wu, 1985). The sophistication of aquaculture in ancient China is well-documented [Fan Li (1988)] |
| Egypt | Yes | Yes | Yes | Egyptians in the Nile delta consumed seafoods in large quantities but there was seasonal food shortages (Davis and Gardner, 1954). Both marine and freshwater proto-aquaculture was present in antiquity (Chimits, 1957; Sisma-Ventura, 2018) |
| Europe | Yes | Yes | Yes | Unprecedented population increases; conflicts; environmental pollution and fisheries collapses and shortages (Hoffmann, 1995a,b, 1996, 2010). Walford (1878) chronicled 350 famines in Europe/Middle East dating to Rome in 436 B.C. (Ehrlich and Ehrlich, 1972). The rise of Christianity and religious prohibitions led to pond aquaculture which spread throughout Europe and Scandinavia (Balon, 1995; Hoffmann, 1995a,b, 1996; Beveridge and Little, 2002; Boissoneault, 2019) |
| Australia | Yes, seasonally | Yes, seasonally | Yes | Fish traps, ponds and weirs in Gunditjmara and Brewarrina and were governed with laws to ensure their spiritual, political, social, and trade uses between indigenous groups (McNiven and Bell, 2010; McNiven et al., 2012; McNiven, 2015; Australian Government, 2021) |
| Northwestern North America (Alaska, B.C., Washington) | Yes | Yes | Yes | Large marine fish and shellfish consuming cultures (Williams, 2006); increased populations and pressures on wild fisheries and regulations; Morrison (2021); reported discoveries of hundreds of fish traps; sophisticated marine aquaculture development of clams (Groesbeck et al., 2014; Holmes et al., 2020) |
| Hawai'i | Yes | Yes | Yes | High population densities increased pressures on marine fisheries; strong royal regulations (Kamakau, 1976; McClenachan and Kittinger, 2012); development of entire watersheds for integrated freshwater and marine aquaculture systems (Costa-Pierce, 1987; Gon and Winter, 2019; Winter et al., 2020) |
| Beni, Bolivia; Brazil | Yes, seasonally | Yes, seasonally | Yes | Seasonal droughts led to fish shortages and fish storage; and stringent regulations on fish harvests. Sophisticated raised bed/integrated aquaculture systems developed (Erickson, 2000; Heckenberger et al., 2008) |

or subsistence aquaculture provides direct ecological benefits to the environment, with the potential to generate net positive environmental outcomes." There is growing evidence that Indigenous peoples practiced restoration aquaculture in ancient times. For example, the shellfish mariculture practices of the Kwakwaka'wakw people on the Northwest Coast of North America enhanced rocky reef habitats that increased the biodiversity of numerous species, including octopus, sea cucumber, whelks, chiton, and red turban snails, improving marine ecosystem biodiversity (Deur et al., 2015; Smith et al., 2019). Restoration aquaculture has the opportunity to recognize and embrace further the wisdom and technological advances of Indigenous peoples and support knowledge production to develop modern restorative practices that advance the environment together with equality, justice, social and cultural benefits, including greater community health and wellness.

## CONCLUSION AND RECOMMENDATIONS

Seven case studies of the cultural/environmental history of aquaculture were reviewed. Case studies covered an extensive part of human history in diverse parts of the world (China, Australia, Egypt, Europe, Latin/South America, Canada/USA, Hawai'i). Evidence was found that: (1) in all cultures aquatic foods were among the most important, traditional protein foods, (2) regular, long term and/or seasonal resource scarcities of wild aquatic or marine resources existed with documented resource regulations resulting and demands increasing, and (3) aquaculture development evolved from fishery knowledge, scarcities and demands to storage/banking of wild catches (**Table 2**). Evolution of sophisticated aquaculture farming systems may be a natural evolutionary part of societies whose population densities and increased resource demands exceeded the carrying capacities of wild aquatic ecosystems to support them. This review supports a structural theory of aquaculture anthropology that when the demands of aquatic/seafood-eating peoples exceeded available supplies from wild fisheries to provide for them, they developed aquaculture.

Two shortcomings of this review were: (1) is its singular authorship and (2) selected case studies reviewed here limited to those available in English. Singular authorship resulted in the unintended exclusion of ancient wisdom in traditional knowledge systems that exists in the oral traditions of Indigenous Nations worldwide not only in written documents as reviewed herein (Gewin, 2021). Reid et al. (2020) has pointed to more inclusive methods of "two-eyed seeing" that engage Indigenous peoples in a pro-active, participatory manner to lead transformations of the fisheries profession. As a review paper there will be rightful criticisms of both the content and also of this lack of inclusion. It is my sincere wish that this paper will lead to more active attention to the need for Indigenous aquaculture to be examined not only as part of our shared historical legacies but also globally on its own merits as a viable, alternative path for the future of aquaculture.

The anthropology and archeology of aquaculture in Indigenous societies worldwide is little developed outside of the case studies reviewed here in English. There are a very small number of scientists working together with Indigenous aquaculture societies. McNiven (2017) called for an "Indigenous archaeology" which he "described variously as a sea change, a quiet revolution, and paradigm shift." This relates directly to another limitation of this study since only the available literature in English was used. Balon (1995) also pointed to this problem of bias when analyzing eastern European, Balkan, and Russian literature on aquaculture in antiquity. Such bias extends to other known ancient centers of Indigenous aquaculture and languages with a special note here of Mexico and Central America, Japan, Korea, Cambodia, Indonesia, Melanesia, and Micronesia. In addition, most of this review concerned "fish." There was no extensive study of the ancient Indigenous aquaculture developments in molluscs and other invertebrates, seaweeds, or marine and aquatic plants which are known to be important parts of the culture of aquaculture throughout human history. Macroalgae serve as traditional foods in China, Japan, Korea, and Indonesia as well as other Asian countries and coastal communities in Europe, Canada, and the USA (Delaney et al., 2016). In Japan, scallop systems date to the Jumon period 14,000 years B.P. (Kosaka, 2016). It is apparent from these limitations that Western, colonial and Indigenous communities can use new ways of thinking to rediscover, reengage, and reclaim the sites, traditions, and forgotten dimensions of their aquaculture heritages.

Perino et al. (2019) give a feasible pathway for the restoration of complex ecosystems through a "rewilding" pathway that is feasible financially. Modern aquaculture concepts in "restoration aquaculture" (The Nature Conservancy, 2021) point a way for new communities of practice for community-based aquaculture informed by Indigenous anthropology and archaeology to heal and advance both colonially-impacted (Euro-American, Australian) and intact Indigenous Nations worldwide. More aquaculture alternatives to export-driven, large-scale upscaling are waiting to be found using livelihood approaches (St. Gelais et al., 2022) and making financial instruments available to Indigenous aquaculture communities for restoration, nutrient credits and trading, and community-conserved biodiversity hotspots (such as aquaculture in MPAs, Le Gouvello et al., 2022). These would allow aquaculture developers worldwide to support aquaculture development by traditional knowledge keepers in Indigenous Nations, help ameliorate climate and biodiversity crises, and reorient economies to more su stainable approaches. Tangible actions with Indigenous Nations such as participatory governance for "radical transformation" of aquaculture (Costa-Pierce, 2021) are required where respect and adherence to treaty rights and making long-term investments to build trusted relationships must go hand-in-hand with conservation and non-Indigenous entities working in aquaculture.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

BC-P designed the study and wrote the manuscript.

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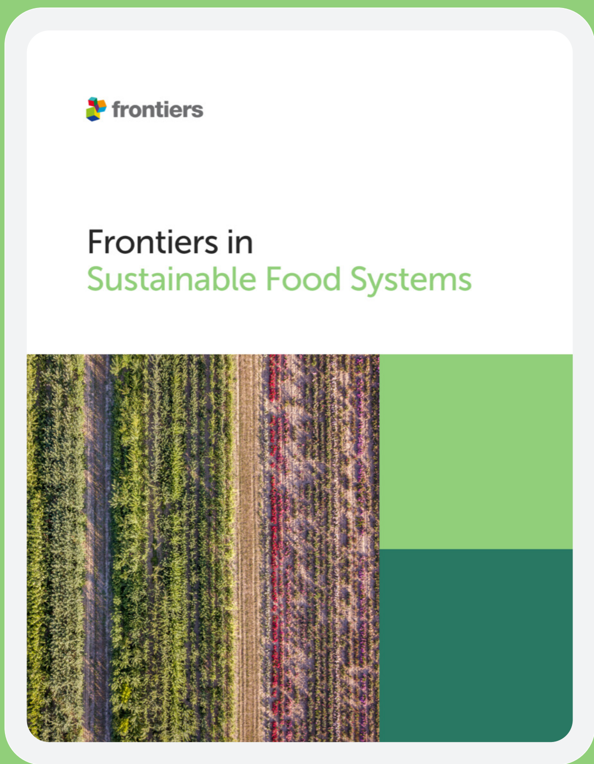


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