REVIEWS IN Aquaculture

REVIEW

Aquaculture in Maritime Spatial Planning Frameworks and Its Contribution to Global Food Security

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ABSTRACT

Increase in aquaculture toward realizing the potential of the ocean as a key food provider requires comprehensive and proactive management approaches to mitigate impacts on coastal areas and to secure space for sustainable aquaculture development in both inshore and offshore areas. Maritime Spatial Planning (MSP) and Marine Functional Zoning (MFZ) are policy instruments employed in the management and regulation of multiple human activities to balance social, economic, and environmental objectives. This work reviews the processes and stages of aquaculture integration into these marine spatial planning frameworks (MSP and MFZ) in major producers, China, the EU, Norway, and Canada. Implementation of aquaculture in the spatial planning frameworks varies widely, partly because the nations reviewed are at different stages of aquaculture development, and partly due to the heterogeneity of institutions, traditions, social acceptance, marine space, and governance. The common challenge of aquaculture impacts and interactions with the environment contribute to the complexity of regulating space for mariculture development. The apparent weak and in some cases receding position of aquaculture in the maritime spatial planning frameworks reviewed here warrants considerable concern with respect to expectations of marine aquaculture as a route for ensuring future seafood provision. There is a need to strengthen the position of aquaculture in marine spatial planning frameworks, particularly when considering its expansion in areas with potential for development. It is recommended that the global scientific, management, and regulatory communities work together with local actors to develop and provide accessible tools that will address sustainability challenges ahead.

1 | Introduction

Maritime domains are subject to increasing demand for resources, competition for space, socio-economic issues, and ecosystem concerns [1]. Maritime[1] Spatial Planning (MSP) and Marine Functional Zoning (MFZ) are policy instruments employed in the management and regulation of multiple human activities to balance social, economic, and environmental objectives (e.g., [2–4]). Examples of major human activities that all need to coexist are capture fisheries, aquaculture, maritime transport, tourism, conservation of nature, and rapidly expanding sectors like offshore renewable energy and deep-sea mining.

From the perspective of increased global demand for food production, expansion of marine aquaculture[2] is regarded as the most promising route for ensuring future provision of seafood [5]. 48% of the total biomass currently obtained from the ocean is cultivated, about 73 million tons, of which 51% are seaweeds, 26% are mollusks, 12% are finfish, and 11% are crustaceans [6]. Costello et al. [5] emphasize that this food provision calls for sustainable development of resources at lower trophic levels than today and a greater focus on extractive[3] species.

Based on a global analysis obtained from a consultation process representing the research community, aquaculture industry, government, conservation groups, education, and fishermen's associations, Galparsoro et al. [7] showed commonality in the main issues hindering expansion in aquaculture (coastal and offshore) with most being attributed to interactions with other maritime activities, conflicts in the use of marine space, and implementation of existing policies and legislation. Critical needs for the expansion included improved planning and management of developments and technological advances, with economic and market needs playing a lesser role. Key procedures recommended to assist expansion were standardization and simplification of regulatory frameworks, better governance, and the adoption of participatory processes in stakeholder engagement. In order to address these issues, the present work reviews the processes and stages of aquaculture integration into the marine spatial planning frameworks, MSP and MFZ, in major producers, China, the EU, Norway and Canada. Aquaculture has ancient traditions in China; today, marine functional zoning (MFZ) is the legal framework regulating use of Chinese marine space at all levels [2], with mariculture playing a very important role as the country accounts for more than 60% of global production, about 42 MMT, half of which are animals and half are seaweeds, including a wide range of species occupying large coastal areas [6]. In the EU, Norway, and Canada, managers apply MSP to varying degrees in regulating aquaculture [8]. In the EU, where some Member States are important shellfish and fish producers, aquaculture shows a decreasing trend, competing for space in many coastal areas [7, 9–10]. In Norway and Canada, salmonids dominate aquaculture. In Norway, the industry has developed into the leading salmon producer globally and gained international recognition in technology and management. Canada is the fourth largest producer of farmed salmon and twelfth in farmed mussels, with production on both the Pacific and Atlantic coasts.

These four distinct situations provide an ideal opportunity to compare and contrast issues, regulations, perspectives, and trends. Historically, in the 1980s, aquaculture regulation was largely independent of other activities in all the countries considered in this review. In the last two decades, legislation has evolved toward more integrated frameworks, but the way in which aquaculture is considered within the context of multisectoral marine management varies widely. In China, aquaculture is both a well-established and significant player in marine systems [11], whereas in the EU, aquaculture is a latecomer to an already crowded environment—marine fish farming in the EU needs to squeeze into a complex scenario of multiple, often competing uses [7]. Norway appears to be in a "sweet spot" along this gradient—having a consolidated and competitive aquaculture industry that coexists to a greater or lesser degree with competing uses of the marine area [12, 13].

Aquaculture strongly depends on the environment, where a range of abiotic and biotic factors and environmental hazards condition productivity and sustainability, thereby demanding space and generating issues related to multi-use conflicts [7, 14]. The *pressures* on the environment vary depending on intensification, species, production method and whether aquaculture is fed or extractive and the interactions with the environment are a function of these pressures and the susceptibility and resilience of the natural environment—the latter aspects, sometimes also termed assimilative capacity, are associated mainly with physical factors such as bathymetry, hydrodynamics (e.g., currents, stratification, significant wave height), and water temperature.

ICES [14] reviewed laws and regulatory standards for monitoring and managing the environmental impacts of aquaculture in member countries and China. Recommendations were made for research on aquaculture-environment interactions required for effective industry regulation with respect to the main risks. A common goal in the development of aquaculture for increasing food security is to achieve environmental sustainability, addressing the UN sustainable development goals and adhering to the principles of the ecosystem approach to aquaculture [15, 16].

Sustainable intensification, or eco-intensification, is a management approach that seeks to ensure adequate food security while guaranteeing environmental preservation. Figure 1 illustrates the relationship between intensification of production, which results in greater food security, and environmental sustainability with respect to the effects of aquaculture on the environment. At low cultivation intensity, the environmental pressure is negligible, but food security is at risk. High intensity is promising in the short-term but risks longer-term environmental sustainability. The ecosystem response is typically non-linear; at a certain tipping point, the environmental state may start to degrade rapidly, and the management response should be swift, and when possible, proactive rather than reactive. As a guiding principle for aquaculture sustainability, it is easier to plan than to retrofit, or alternatively, prevention is cheaper than restoration [17]. The use of predictive modeling and the introduction of new practices such as precision aquaculture may also mitigate the effect of intensification on the environment.

Increase in aquaculture toward realizing the large potential of the ocean as a key food provider will require comprehensive and proactive management approaches to mitigate impacts on coastal areas under pressure and to secure space for sustainable aquaculture development in both inshore and offshore areas. Experiences and lessons learned from the implementation of aquaculture in existing planning frameworks may make a key contribution to the development of the necessary approaches.

In this review, we compiled information from China, the EU, Norway, and Canada, examining the status of and experiences of implementing aquaculture within MSP and MFZ frameworks and related national planning frameworks (e.g., Norwegian aquaculture frameworks), with a focus on environmental objectives.

The implementation processes of the MSP and MFZ frameworks were both assumed to follow analogous stages described through the steps outlined by Ehler & Douvere [18], presented in Figure 2. These stepwise stages are presented as institutional and legal frameworks, baseline of aquaculture and identified

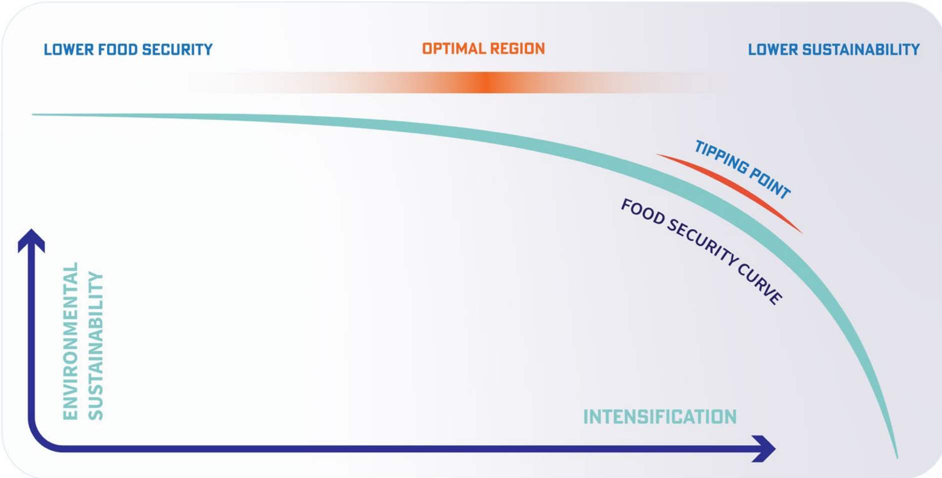

FIGURE 1 | Conceptual diagram of food security, illustrating the relationship between intensification and sustainability.

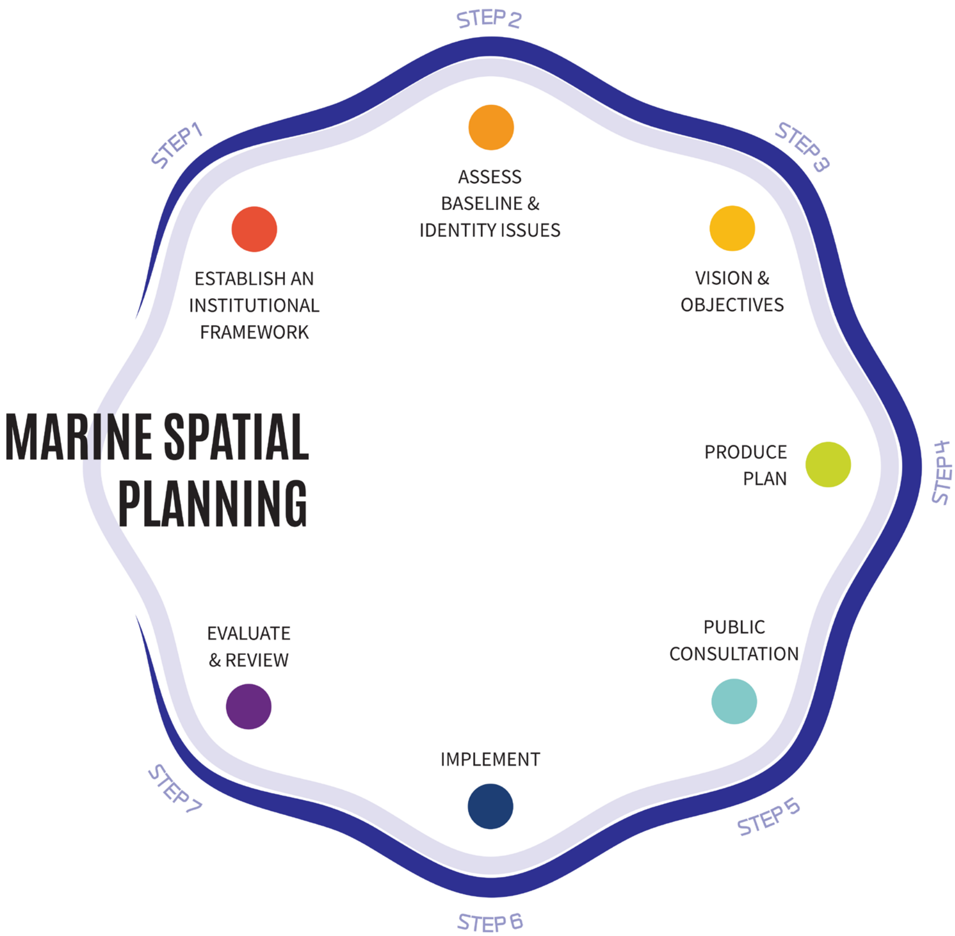

FIGURE 2 | The stepwise process of marine spatial planning (MSP) (adapted from [18]).

issues, visions and objectives for aquaculture development, production of spatial plans including ecosystem management tools, public consultation, implementation of plans, and evaluation and review. This approach allows for some categorized identifications needed to better understand differences and, from there, opportunities for analysis on how governance and management can better support sustainable development of aquaculture. In this review, we compare the steps of relevance for aquaculture across the nations (or blocks) the EU, Norway, China, and Canada, summarized in Table 1.

2 | Institutional Framework

The MSP and MFZ frameworks were instituted in the EU and China, respectively. In the EU, maritime spatial planning (MSP)

TABLE 1 | Comparison of the steps in marine spatial planning (MSP) (adapted from [18]) relevant for aquaculture, across the nations.

The MSP steps	European Union	Norway	China	Canada
Establish Institutional Framework	• Maritime Spatial Planning (MSP) is part of a five-pillar framework of Integrated Marine Policy: (i) Blue growth; (ii) Marine data and knowledge; (iii) MSP; (iv) Integrated maritime surveillance; and (v) Sea basin strategies. • In the EU, MSP directive 2014/89/EU aquaculture is referred only 3 times. • The MSP directive is transposed by Member States, who are obliged to develop a National Maritime Spatial Plan (NMSP) • The Water Framework Directive (WFD—2000/60/EC) for transitional waters, and the Marine Strategy Framework Directive (MSFD—2008/56/EC) direct EU Member States to define ecological/environmental status thresholds based on an ecosystem approach.	• Municipal coastal planning includes aquaculture, is regulated by the Building and Planning Act, which involves a range of sector regulations • Licenses regulated by the Aquaculture Act and issued at county level. • At national level, a regime regulating production of salmonids and the allocation of space (new licenses) are based on environmental impact measures. • The legislations regulating aquaculture planning comply to several EU directives as part of the Agreement on the European Economic Area (EEA) between Norway and the EU.	• Aquaculture is governed by Marine Functional Zoning (MFZ) and based on permits. • The Ocean Development Bureau at municipal or county level, issue aquaculture permits and sea use certificates. • MFZ is updated through decadal amendments and regulatory supplements, so that it will keep up with marine ecological conservation targets, as well as promote sustainable development of aquaculture • According to the Fisheries Law, zoning of aquaculture waters should be carried out in all coastal provinces and municipalities.	• Aquaculture planning is regulated in combination of federal and provincial level, the structure varying by province. • At the federal level, the Department of Fisheries and Oceans manage aquaculture through regulations under the Fisheries Act. • Licenses regulated at provincial level (except in British Columbia where is regulated at the Federal level) • Ocean's Act is the federal framework for integrated coastal and ocean management. • In the federal Canada's Oceans Action Plan, aquaculture is recognized as activity in the marine space.
Assess Baseline and Identify Issues	• Shellfish farming about 55% of aquaculture production. • Finfish is mainly in the Mediterranean and Black Sea. • The issues related to finfish and shellfish aquaculture mainly related to Environmental Impact Assessment (EIA) required by directives	• Salmonids dominate (99.7%) aquaculture production, farmed in open cages distributed along the western coasts. • Growth is currently halted due to regulations based on environmental issues, set by annual risk assessment, salmon lice, welfare and escapes currently being the main. • Environmental issues drive research and industry to develop new technologies and methods for mitigation aiming at increased sustainability.	• Globally the largest aquaculture producer, with highest diversity of species. • Production dominated by seaweed and bivalves, only 15% are fed species of finfish and crustaceans. • Aquaculture waste is a growing concern and the major issue regulating spatial planning. • Issues on improved environmental control and management, by setting a limit for aquaculture space use, re-locations of farming and related business transfer.	• Atlantic salmon contributes 63% of aquaculture production, farmed in cages in both the west and the east coast. • Shellfish production for mussels, oysters and clams is also present across Canada. • Main environmental issues are potential interactions with wild fish species. • Concerns around salmon lice, escapes, and disease have been persistent, although differences exist between provinces.

(Continues)

TABLE 1 | (Continued)

The MSP steps	European Union	Norway	China	Canada
Vision and Objectives	• The European Maritime and Fisheries Fund encourage Member States to draw up National Aquaculture Plans (NAP). • A planned aquaculture production growth has failed.	• A governmental white paper state a vision of growth under the condition of environmental sustainability. • There are prospects of increase in salmonid production and species diversification for farming, including new recourses for feed ingredients.	• Aquatic food consumption has increased at 5% annually over two decades. • Most of the future demand expected to be covered by aquaculture. • State Council issued a strategy stating stabilization of aquaculture production and use of coastal area, while offshore aquaculture area will be controlled. • Objective on returning aquaculture to natural coastal wetlands, balancing aquaculture and conservation.	• Federal government pursue aquaculture development, while considering ecological and socio-economic aspects that ensure the sustainability of the sector. • Federal government renews the vision and objectives on a regular basis to adjust strategies to emerging issues.
Produce Plan	• Very few NAP provide details on spatial planning of locations for aquaculture and is generally unconvincing with respect to species, markets, and other factors. • In general, the NAP appears to provide a direction rather than a target to be met. • The WFD and MSFD directives for marine waters are set for managing surface water quality.	• A specific national Aquaculture act • Mandatory municipal and inter-municipal plans include space for aquaculture. • A national zoning regime regulating production, based on environment impact. • Mandatory environmental impact monitoring (MOM) affecting planning. • Management authorities can regulate activity to mitigate disease outbreak.	• Plans exist at central, regional and local levels. • An aquaculture zoning system and strategic spatial development plan established. • Spatial planning development goal and aquaculture zoning system established, identifying zones as permitted, restricted and prohibited areas. • Planning focus on rational arrangement of aquaculture production and nationally delimit farming areas.	• Plans exist to varying degree in provinces. • Management increases spatial planning activity for aquaculture, by mapping tools to visualize sites and assessing ecosystems for spatial management of shellfish culture. • The development on a specific Aquaculture Act at the federal level has been initiated but it is not completed.

(Continues)

TABLE 1 | (Continued)

The MSP steps	European Union	Norway	China	Canada
Public Consultation	• Stakeholder consultation varies considerably among EU countries, in degree of involvement and at stages of the planning process. • Consultation periods often too for adequate analysis of often lengthy documents.	• In the municipal coastal planning process public consultations are statutory. • As part of the environmental risk assessment process dialogue meetings are held with science and management. • In the traffic light system implementation process, consultations are with stakeholders from research, management and industry.	• Before zoning plans are implemented, drafts are usually posted on the governments (relevant Ministry) website open for public opinions. • Lack of public participation in the policy making process.	• Regarded fundamental in MSP and required in aquaculture licensing but varies with stages in process and between provinces. • Often, consultation is limited to period near the end of the decision phase. • Limitations in socioeconomic components in planning.
Implement	• Accomplishment of the Maritime Spatial Plan varies considerably among member states. • Often influenced by emerging requirements from other sectors and processes obstacles.	• Accomplishment of coastal plans varies between municipals. • Planning relevant environmental monitoring (MOM) is fully implemented. • The national "traffic light system" regulating production in 13 zones was implanted in 2017 with biennial revisions.	• The Fisheries Law stipulates at all levels the planning and utilization of waters and determine areas for aquaculture. • Aquaculture license and area use permit is issued from the government at or above the county level. • Coastal management agencies delineate three zones; permitted, restricted, or prohibited areas for aquaculture.	• Licensing is a multi-stage process include habitat, fisheries, and environment. • Health management plans at province level are required for fish farming. • Bay management areas based on farmed fish disease risk established in provinces. • Benthic environmental monitoring programs including specific quality thresholds. • Spatial planning for shellfish culture is highly advanced on both coasts planning.
Evaluation and review	• In general terms, the EU is not at the stage where plans are being reviewed using appropriate indicators, especially in the aquaculture sector.	• Municipal plans are evaluated and reviewed by governmental authorities. • Elements in the MOM system has been evaluated and reviewed over the years. • The science basis for the "traffic light system" is evaluated by national and international representatives.	• MFZ undergo regular revisions and amendments to keep up with development targets. • Integration with the new national Territorial Spatial Planning.	• DFO regularly evaluates science applied to regulation in specific processes. • Provincial departments regularly evaluate standards, thresholds, and methodology.

is part of a framework on Integrated Marine Policy where legal directives define the processes with which aquaculture planning must comply [19]. MSP is part of a five-pillar framework of Integrated Marine Policy: (i) blue growth; (ii) marine data and knowledge; (iii) maritime spatial planning; (iv) integrated maritime surveillance; and (v) sea basin strategies. Spatial planning is governed by EU Directive 2014/89/EU. The MSP directive is transposed by Member States, who are obliged to develop a National Maritime Spatial Plan (NMSP).

Aquaculture is widely implemented in Norwegian spatial planning frameworks, where several components comply with EU directives (including Directive 2014/89/EU) as part of the Agreement on the European Economic Area (EEA) regulating relations between the EU and Norway. Planning marine space for aquaculture is regulated by the Building and Planning Act which involves multiple sector regulations and is ultimately decided at the municipal level [13]. Licenses are regulated by the Aquaculture Act and issued by the regional County Council. The legal management framework for aquaculture has in parts been implemented specifically along with the development of the industry, and with the industry as an active stakeholder both at local (municipal) and national level. The most recent management system on aquaculture is a 'traffic light system', established and implemented by the government in 2017 for regulating production, based on salmon lice induced mortality on migrating Atlantic salmon postsmolt in the 13 production zones established along the coast [20].

In China, the Fisheries Law and the Sea Area Use Management Law of the People's Republic of China establish the aquaculture licensing system, define the responsibilities of fisheries administrative departments at all levels, and ensure the orderly utilization of marine spatial resources. The State Oceanic Administration (SOA) affiliated to the Ministry of Natural Resource, oversees marine ecosystem protection and strategic planning, blue economic development, and allocation of sea-use permits. To enable the sustainable use of resources, SOA implements marine functional zoning (MFZ) to optimize industry layout and identify coastal and offshore areas for mariculture [2]. In 2014, the Ministry of Environmental Protection (MEP, now the Ministry of Ecology and Environment) issued the National Ecological Protection Red Line-Technical Guidelines for Delineation of Ecological Function Baselines, which symbolized the launch of the ecological red line system (EPR), another "lifeline" drawn at the national level after the 'red line' of 1.8 billion mu[4] crop-land. As an important supplement to MFZ, the marine ecological red line (MEPR) was fully established in 2016. MEPR designates important marine ecological functional areas, ecologically sensitive areas, and vulnerable areas as control areas, for which the health and safety of marine ecosystems are to be maintained by classified management. Coastal provinces were requested to delineate their respective red line system, with obligatory proportions of marine ecological red line areas ($\geq 30\%$) and retention rates of natural shorelines ($\geq 35\%$). MEPR mainly protects important coastal wetlands, special protected islands, natural landscapes and historical and cultural relics, concentrated distribution areas of rare and endangered species, and important fishery waters. In case of sea use conflicts, aquaculture should give way to MEPR. The Bureau of Fisheries (BOF) at the Ministry of Agriculture and Rural Affairs (MARA) is the highest-level administration, responsible for developing aquaculture strategies, drafting regulations, and supervising their enforcement. MARA issues general legislation at the national level that local authorities should apply in management. Under the guidance of MARA, provinces and municipalities usually adopt similar strategies and policy instruments. The National Marine Environmental Monitoring Center of the Ministry of Ecology and Environment (MEE) is responsible for marine environmental (including aquaculture wastewater) monitoring, following the standards for marine water quality tests (the Fishery Water Quality Standard GB11607-89). Ocean Development Bureaus (ODB) implement monitoring and law enforcement at the local or regional level, including control of discharge from fish farms.

Aquaculture planning in Canada is regulated through a combination of federal and provincial regulations, with the structure planning policies and regulations varying by province. At the federal level, the Department of Fisheries and Oceans (DFO) is responsible for managing aquaculture operations through regulations under the Fisheries Act. Each province in Canada has a different set of planning policies and regulations for aquaculture. The allocation of space (new licenses) is regulated at a provincial level (with the exception of British Columbia and Prince Edward Island, which are managed federally) and largely issued on a case-by-case basis. Canada's Ocean's Act (1996) is the federal framework for integrated coastal and ocean management (ICOM) but does not mention Marine Spatial Planning, while aquaculture is recognized in the federal Canada's Oceans Action Plan as an activity in the marine space.

3 | Aquaculture Production Baseline and Issues

In the EU, focus is on finfish and shellfish farming. In marine aquaculture, shellfish production corresponds to about 55%. Following Brexit (i.e., with the loss of the Scottish salmon component), the EU marine finfish sector consists mainly of bass and bream in the Mediterranean and Black Sea. The issues related to finfish and shellfish aquaculture have some commonality, but there are significant differences: (a) bivalve shellfish are normally cultivated nearshore, taking advantage of more eutrophic conditions and often using intertidal areas; offshore culture exists but is less common; finfish have a substantially higher particulate footprint and therefore tend to be farmed in deeper areas which are typically more oligotrophic and better oxygenated; (b) bivalves are organic extractors so problems with waste feed do not occur; however excessive stocking can lead to carrying capacity issues; (c) filter-feeders are more susceptible, for example, to harmful algal blooms (HAB) and microbiological pathogens; the culinary preparation and the consumption of the whole animal, for example, for oysters, mussels, and clams, introduces additional food safety issues. Environmental Impact Assessment (EIA) is required following Directive 85/377/EEC of 27 June 1985, modified by Directive 97/11/CE of 3 March 1997.

Norwegian aquaculture production consists almost entirely of salmonids (99.7% of the 1.6 MMT produced). Salmonid farming in Norway is one of the country's largest export industries by economic value and is of significant social importance in many regions [21]. A total of 1316 active licenses exist for grow out production distributed along most of the western coast (Norwegian Directorate of Fisheries Official Statistics https://www.fiskeridir.no/english/aquaculture/statistics-for-aquaculture/booklets). The major environmental issues of concern for spatial planning are salmon lice, escapees, and the welfare of farmed fish [22, 23]. Growth has slowed down since 2011 due to increasing problems with the impact of sea lice on wild salmonids; the latter drive research and industry to develop new technologies and production methods for mitigation, aiming to improve the environmental sustainability of the industry. The annual risk assessment on environmental impact of aquaculture ("Risk assessment of Norwegian finfish farming"), published by the Institute of Marine Research since 2010, contributes to promote a risk-based management [24]. The knowledge base and results of the risk assessment were one of the main documents used as a decision basis to select sea lice as the most relevant environmental indicator for the "traffic light system."

China is the largest aquaculture producer in the world, both in volume and number of species [25]; more than 70 mariculture organisms are officially registered, including finfish, shellfish, seaweeds, and sea cucumbers. Production is dominated by low-trophic, unfed species (85%) of primary producers or filter-feeders; the remaining 15% are fed species of finfish and crustaceans. Aquaculture waste discharge is a growing concern and the major environmental issue of concern in spatial planning. Other issues include: (a) conflict of aquaculture with Marine Protected Areas (MPAs), including Aquatic Genetic Resource Conservation Areas; (b) licensing and registration of existing aquaculture farms and areas; (c) relocation of fish farms when they are in conflict with MFZ and MEPR. Conflicts may arise between marine aquaculture and MFZ/MEPR due to the long-standing existence and widespread nature of mariculture. Since mariculture is an important source of employment for many coastal communities, business transfer and relocation of farmers are important issues.

In Canada, Atlantic salmon contributes around 63% of aquaculture tonnage and 74% of value (in 2019); production takes place in sea cages off the Atlantic provinces of New Brunswick, Nova Scotia, and Newfoundland, and off the Pacific coast of British Columbia (BC). Shellfish production for mussels, oysters, and clams is also present on both coasts of Canada. Management issues in Canadian aquaculture focus on the interaction of farmed and wild salmon populations [26], as well as particulate waste deposition and its implications for benthic species, particularly lobster [27]. Migration of spawners and juveniles to and from rivers is a major issue regarding interaction with salmon farms and potential disease/sea lice transmission, especially in BC where there are five species of wild salmonids and a valuable commercial fishery [28]. Concerns around salmon lice, escapees, and disease have been persistent, although differences exist between the Atlantic and Pacific coasts. Social acceptability is a major hurdle for the aquaculture industry, particularly for the finfish sector [29], although social opposition has recently emerged against bivalve farming [30].

4 | Vision and Objectives

The European Maritime and Fisheries Fund (EMFF) encouraged Member States to draw up National Aquaculture Plans (NAP). Lopes et al. [10] provide a critical overview of the plans. Their analysis suggests a planned growth rate of 28% between 2013 and 2023 (APR of 2.4%). However, Eurostat data from the period 2008 to 2018 (http://longline.co.uk/meta) show an APR of −2%.

In Norway, the governmental white paper "Predictable and Environmental Sustainable Growth of the Aquaculture Industry" states a vision of growth under the condition of environmental sustainability, over economic and social sustainability.[5] There are prospects of increasing production of salmonids and diversification of the industry with additional finfish species, lobsters, and non-fed species including macroalgae, bivalves, and tunicates, some also candidates as future feed ingredients [31, 32].

China's aquatic food consumption has been growing steadily at approximately 5% annually over two decades. By 2030, China's population is expected to reach 1.5 billion, and the total demand for aquatic products is expected at 70 million tons. Most of these products will come from aquaculture. In 2013, the State Council issued the "Several Opinions on Promoting the Sustainable and Healthy Development of Marine Fisheries," stating that "by 2015, the output of marine products will be stabilized at about 30 million tons, and marine aquaculture area will be stabilized at about 2.2 million ha, of which the offshore marine aquaculture area will be controlled within 1.15 million ha." The Chinese process is relevant to the Blue Growth policy [33], advocating for sustainable development of aquaculture, improved environmental control and management, by setting a limit for aquaculture space use. A recent trend of "Return aquaculture to natural coastal flat and wetlands" also aims for balancing aquaculture growth and ecosystem conservation. However, due to the lagging behind of legislation, the commercialization of emerging aquaculture types such as offshore aquaculture inevitably brings about a range of ecological, economic, and social risks [34].

The Canadian federal government has pursued aquaculture development and frames it as a sector that can benefit Canadians while upholding the ecological and socio-economic values associated with Canada's ocean and inland waters.[6] Management is conducted on a case-by-case basis, which has led to the current transition from open net-pen to close containment systems in British Columbia, with the ultimate goal of protecting Pacific salmon.[7] The most recent strategy released by DFO in 2019, *A new way forward for aquaculture*,[8] has identified four major priorities to promote a more sustainable and economically successful aquaculture sector: (i) more scientific research, (ii) more engagement with Indigenous Peoples, (iii) clearer regulations for operators, (iv) better monitoring and enforcement.

5 | Production of Plans

5.1 | European Union

The National Aquaculture Plans (NAP) that the EU encourages member states to develop do not provide details on spatial planning of locations for aquaculture, but some National MSPs (e.g., Portugal) do. However, it is not a very convincing plan with respect to species, markets, and other factors. In general, the NAPs appear to provide a direction rather than a target, since it is not very clear how the proposed targets will be met—none of the plans provide credible information on critical bottlenecks such as licensing delays and social acceptance of local aquaculture developments [10].

The Water Framework Directive (WFD—2000/60/EC) for transitional waters, and the Marine Strategy Framework Directive (MSFD—2008/56/EC) for marine waters are the fundamental instruments for managing surface water quality. Both the WFD and MSFD are based on a definition of spatial areas or regions, for which a particular quality status is required. In the WFD, surface waters are classified into different types, for which type-specific ecological quality status classes are defined for a number of biological quality elements. This method is applied to derive a final classification, where the key threshold is the boundary between good and moderate ecological status. In the latter case, management measures are required to move water bodies into good status.

The MSFD uses a different approach, whereby European seas are classified as marine regions, which in turn may be further divided into sub-regions. The environmental quality status of these is evaluated on the basis of 11 functional descriptors, some of which clearly bear a (non-exclusive) relationship to aquaculture. The MSFD simplifies the classification system, considering only whether a water body is at good status or not.

The division of EU estuaries and coastal areas into spatial zones, each of which must satisfy a set of quality criteria in order to meet good status, clearly overlaps with the spatial planning process, although neither directive contains any reference to this. Furthermore, the interaction between aquaculture and water quality is hardly considered—no reference to it exists in the WFD, and one mention is made in the MSFD in the context of "nutrient and organic matter enrichment," that is, as a pressure. This omission is inconsistent with the EU vision for food security and highlights the need for harmonization of the "quality," "food production," and "spatial planning" directives.

5.2 | Norway

In Norway, the Building and Planning Act requires municipalities to plan their marine areas including aquaculture [13], which is primarily based on criteria for farming salmonids. Currently, space planned for aquaculture is used for new and relocated sites under existing licenses, regulated by the Aquaculture Act and issued by the regional County Councils. Merging of inter-municipal/regional planning is promoted.

The governmental white paper "Predictable and Environmentally Sustainable Growth of the Aquaculture Industry" launched an aquaculture zoning framework that regulates salmonid production ("traffic light system"), based on scientific principles and with strong stakeholder involvement.[5] This planning framework regulates production and the allocation of space (new licenses) on a zonal scale based on environmental impact measures [14]. The "traffic light system" is based on a yearly impact assessment of salmon lice on wild salmonids [35]. However, only sea lice induced mortality on migrating Atlantic salmon postsmolt is currently included in the assessment. The coast has 13 production zones, where the level of mortality decides whether production can grow (green, $< 10\%$ mortality), remain as it is (yellow, 10%–30% mortality) or needs to reduce (red, $> 30\%$ mortality) (Figure 3).[9] Management authorities can at any time implement measures such as culling and fish/boat transfer at sites or within affected areas based on disease outbreak [36] and regulate production at sites in accordance with the results from monitoring of benthic impact (MOM) [37].

5.3 | China

Initiated in 1989 and continuously revised thereafter, the marine functional zoning (MFZ) is a marine spatial management plan in China that allocates specific functions to marine space, based on the geographical location, natural resource status, environmental conditions, and socio-economic needs. MFZ is the overarching policy framework for all kinds of sea use in China, and MEPR is conservation-focused marine spatial planning under the framework of MFZ; therefore, any aquaculture activities should comply with MFZ and MEPR.

Government authorities at all levels are responsible for strengthening the general planning and comprehensive utilization of local or regional water bodies and determining which areas can be used for aquaculture. If aquaculture enterprises and individual farmers need to use waters and tidal flats for setting up or expanding a fish farm, they should apply to the government authorities at or above the county level for an aquaculture license and a sea use permit. An aquaculture zoning system was first announced by the Fisheries Law in 2013. In 2016, the Ministry of Agriculture issued the "Work Specifications for the Planning of Aquaculture Waters and Tidal Flats" and the "Outline for the Preparation of Aquaculture Water and Tidal Flats Plan," highlighting the importance of aquaculture spatial planning, and requiring rational arrangement of aquaculture production and planning in the whole country. In 2017, the "Thirteenth Five-Year Plan for the Development of National Fisheries" put forward the development goal of "improving quality and increasing efficiency, reducing volume and increasing income," and proposed "improving the planning for aquaculture waters and tidal flats, and scientifically zoning aquaculture areas". However, not until the launch of the Strategic Plan for Quality Development of Agriculture in 2018–2022 (2019), zoning of aquaculture, that is, "determination of aquaculture carrying capacity, and rationally define areas permitted, restricted and prohibited for aquaculture" has been carried out in China.

5.4 | Canada

Marine Spatial Planning is central to advancing Canada's ocean agenda. Conceived as an integrated process balancing sustainable ocean management, MSP in Canada seeks to balance sustainable ocean management, biodiversity conservation, and the

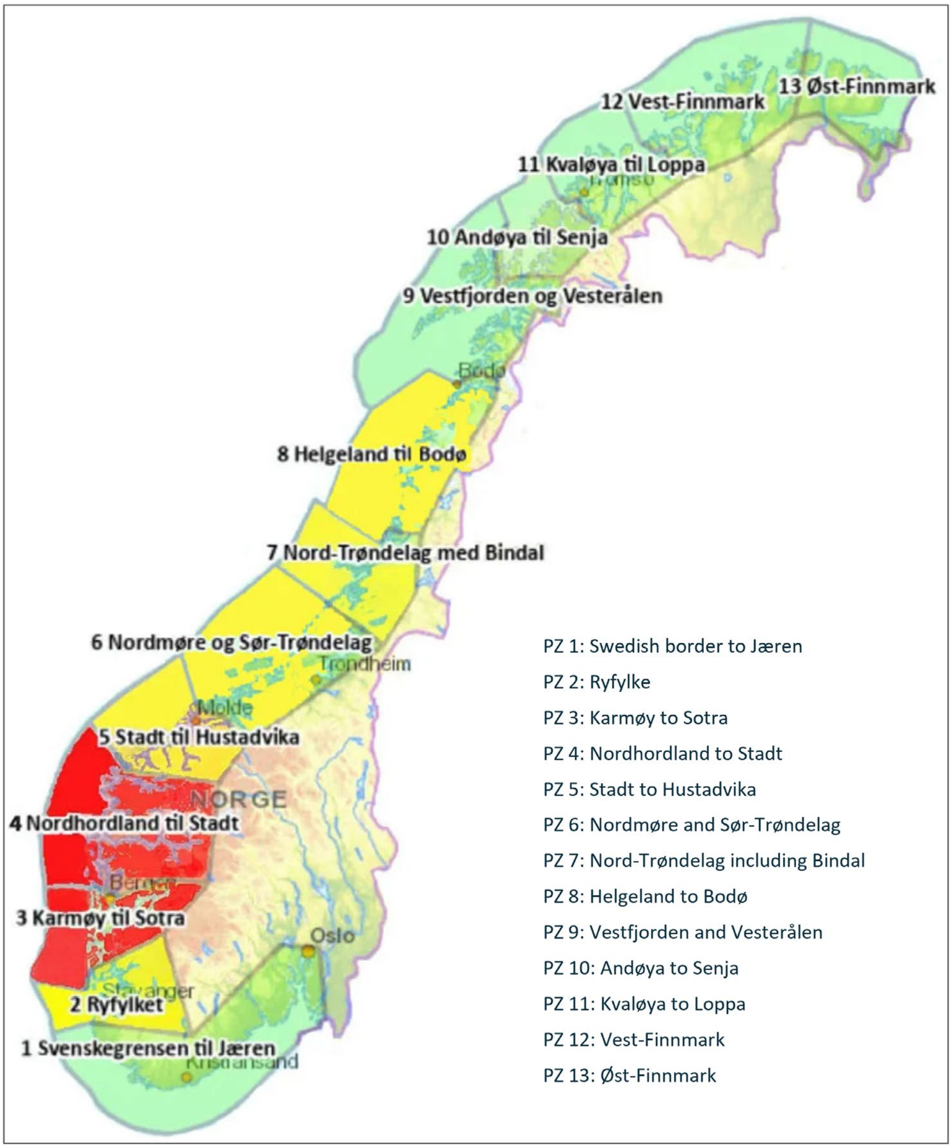

FIGURE 3 | The current "traffic light" map of the 13 aquaculture production zones (PZ) along the Norwegian coastline. In zones with green color production of salmonids can grow with 6%, yellow color gives no growth in production and in zones with red color the production of salmonids must be reduced by 6%.

blue economy.[10] While the current plans cover large geographic areas at a high level, they also provide guidance for sector-specific developments, including aquaculture. For example, the recently released plan for the Scotian Shelf and Bay of Fundy highlights the establishment of an Aquaculture Development Area (ADA) in the Municipality of Argyle (Nova Scotia) as a process consistent with MSP principles, where partnerships, consultation, interdisciplinary data, and regulatory processes were combined in a GIS-based decision-support tool to identify suitable sites for shellfish and marine plant aquaculture [38]. Although MSP is not necessarily mentioned in provincial regulations, its principles, such as community engagement and conflict recognition with other users, are embedded in practice (e.g., Nova Scotia recognizes other users of the public waters surrounding the proposed aquaculture operations as a key component for making a final decision[11]). Spatial approaches to aquaculture are increasingly integrated into Canadian decision-making, including the use of spatially explicit models to inform sustainability and expansion [39, 40] and the development of tools to assess site suitability.[12] As mentioned above, aquaculture is regulated under the Fisheries Act[13]; however, in 2018 the federal government committed to developing a stand-alone Aquaculture Act. A discussion paper was released in 2020 as a starting point, but no further progress has been made. It is important to note that this discussion paper made no explicit reference to MSP.

6 | Spatial Planning and Ecosystem Management Tools

The processes and various stages in planning and implementation of MFZ and MSP, including site selection and carrying capacity assessment can be supported by a range of measures and tools, such as instruction guidelines, information, consultations, science-based assessments, geographic information systems (GIS), decision support systems, internet of things (IoT), and so forth. Tailored support and tools for aquaculture are relatively scarce, while GIS-based decision support systems developed by nations in this review are examples that have potential for better supporting aquaculture implementation in MSP and MFZ.

The Norwegian information system BarentsWatch (https://www.barentswatch.no/en) is open web-based including specific portals presenting continuously updated data of relevance for aquaculture planning. It is partnered by 10 ministries, 29 directorates and research institutions, and exemplifies a national level tool with ministerial commitment and financial support, applicability in the aquaculture industry, management, and for public use.

The Aquaculture Spatial Planning Decision Support System (APDSS) described for China is derived from the Akvavis concept adapted for use also in Norway, the United Kingdom, and France, but with very different issues and scales of aquaculture [41, 42]. The Aquarisk and AquaScape tools are tailored for generic use.

APDSS was developed for Sanggou Bay, Shandong province, China. It uses a GIS system, integrating biological, chemical, and physical oceanographic survey data, ecosystem models, and map services, to provide decision support for aquaculture spatial planning and production management. It allows browsing of environmental data, policy and environmental suitability evaluation, organism growth prediction and carrying capacity evaluation. Based on national and local MFZ and MEPR plans, APDSS divides offshore waters into permitted, restricted, or prohibited areas for aquaculture (Figure 4). In parallel, according to the main factors affecting the growth of cultured organisms such as kelp, for example, light intensity, temperature, current speed, inorganic nitrogen, salinity and depth of water, an evaluation is made on whether those environmental conditions meet the growth requirements of the organisms. The evaluation index divides the sea areas into four levels of suitability for aquaculture, adding biological considerations to aquaculture zoning. APDSS has both desktop and internet applications, with similar data and graphical display functions.

AquaRisk is a cloud-based platform that shifts the paradigm of aquaculture risk management for farming, insurance, and finance. The app uses state-of-the-art scoring algorithms to assess multi-factorial risk for animal health, environment, engineering, governance, and husbandry. AquaRisk is engineered to detect risks that cause financial and insurance losses for aquaculture farms and benchmark risk across farming sites, ranking risk indicators into five categories to provide actionable intelligence. This is deployed as an action center that supplies a farm assessment for remediating issues, quantitative and qualitative analytics, and assessment related to financial impact.

AquaScape is a cloud-based scalable platform that responds to the need of sustainable aquaculture governance, enabling regulators, farmers, the supply chain, and others to obtain visibility into aquaculture metrics and analytics (Figure 5). AquaScape is engineered to maximize aquaculture sustainability outcomes over the next decade through: (i) adoption of technology for aquaculture licensing and regulatory policy; (ii) models of production and environmental footprint to support sustainability of coastal systems; (iii) analytics on disease incidence and severity; (iv) provision of analytics to the supply chain to improve sourcing transparency.

7 | Public Consultation

While stakeholder engagement is often incorporated throughout all stages of MSP processes (Figure 2), stakeholder engagement can involve different levels of interaction and participation [43] from more one-way communication of information to direct

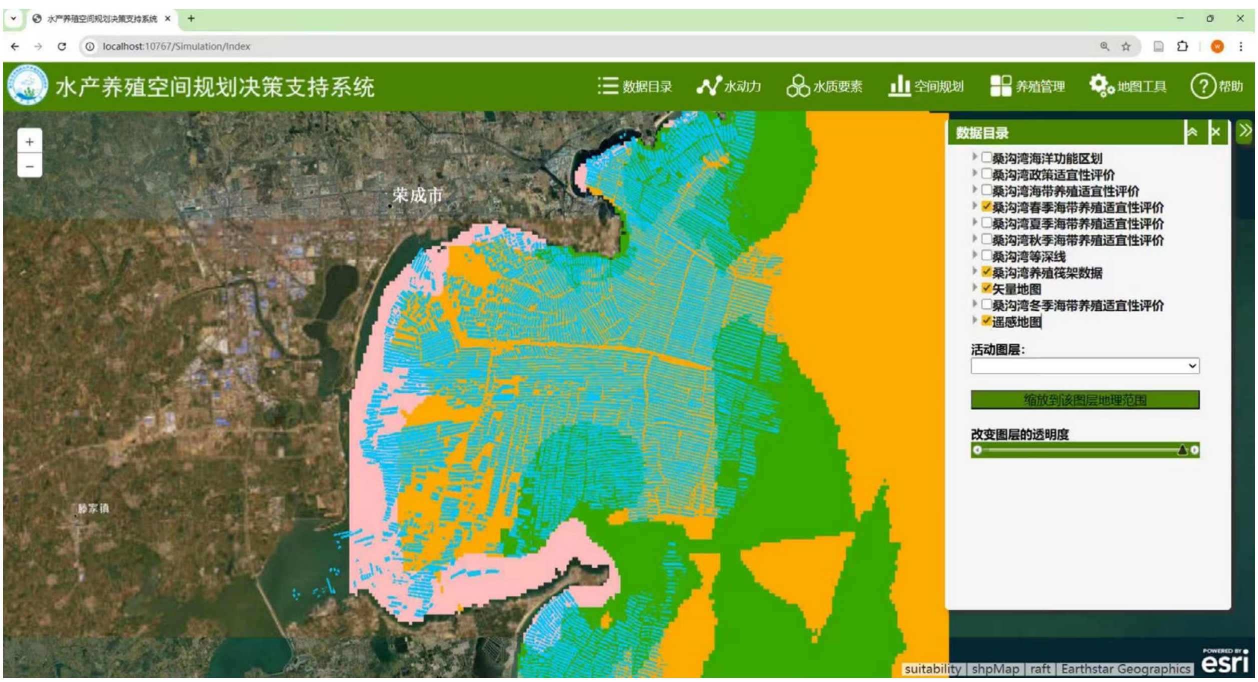

FIGURE 4 | The Aquaculture Spatial Planning Decision Support System (APDSS) tool implemented for Sanggou Bay, China. Space covered by longline farms are indicated in light blue. Green-, yellow-, and pink-colored polygons are permitted aquaculture zone, restricted aquaculture zone, prohibited aquaculture zone, respectively.

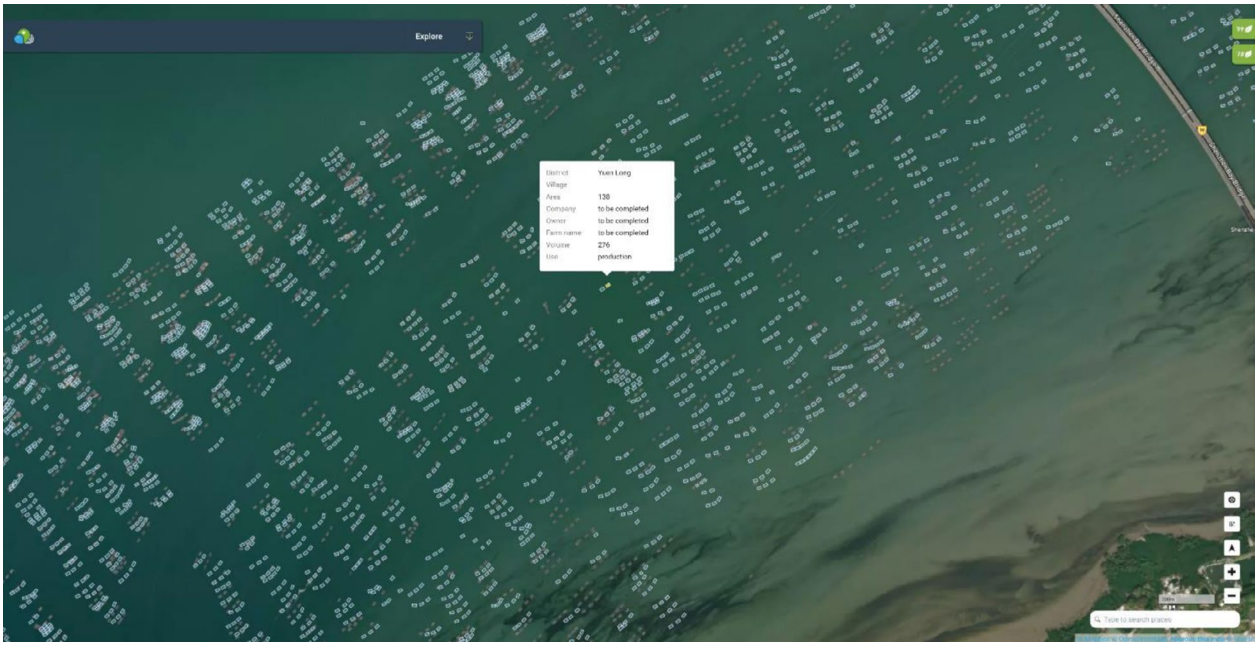

FIGURE 5 | AquaScape for management of Hong Kong oyster aquaculture in Deep Bay (Hong Kong/PRC).

partnership and sharing of decision-making [44]. The extent to which stakeholder consultation is taken into account varies considerably among EU countries. In some cases, the planning process involves the relevant actors at an early stage, and in others a more top-down approach is used, with the public being provided with an opportunity to respond after a draft plan has been prepared. In the latter case, it is often difficult to make significant changes, either due to governance or communication challenges and non-participation by stakeholders [45]. Consultation periods are often too short to allow an adequate analysis of what are often lengthy documents. Furthermore, some stakeholders may be difficult to reach, and others may respond poorly to invitations [44].

In Norway, coastal area planning at municipal level involves a consultation process for stakeholders (residents, business interests, etc.). Impact assessments and public consultations are statutory. During the subsequent licensing process of site allocation, the public also has appeal rights. As part of the implementation of the "traffic light system," hearings and consultation processes involved relevant research institutions, regulatory agencies, industry, and other stakeholders. Public consultation engagements and stakeholder interactions and oppositions are seen at all levels from industry, management, governance and policy [46, 47].

Public consultation processes in China are conducted with hearings, expert reviews and consultation processes, when MFZ, MEPR, or Aquaculture Zoning Plans are enacted and implemented. Expert review meetings are usually held, which may involve industry, academic and research representatives. The reviewed draft policies, as well as major sea use plans, are usually posted on the government's (relevant Ministry) website for about 2 weeks and are open for public opinions. However, this may not raise enough public notice due to the lack of public participation.

In Canada, public consultation and engagement, especially among coastal residents and First Nations, is a cornerstone of MSP and is required for new aquaculture applications in every province. Each province has some form of public and stakeholder consultation during the administrative process of license and lease applications. As application procedures are often largely industry-initiated, stakeholders and the public may be involved at different stages in the application process; however, these processes are often limited to a public comment period near the end of the decision phase. There is an overall perceived concern over limited consultation and legitimacy on aquaculture management [48] and potential conflicts of interest arising from the dual role of the government as promoter and regulator of aquaculture [49]. In Nova Scotia, these concerns led to the creation of the independent Aquaculture Review Board (ARB).[14] The ARB holds adjudicative hearings for new finfish applications or expansions of existing sites, where proponents and opponents present evidence, cross-examine, and are represented by legal counsel. This process was originally applied to all types of aquaculture; however, it was determined that the cost of the process was a barrier for the proponent of a low-trophic aquaculture site and deemed unnecessary due to the lower risk of these types of activities. At the Federal level, the Canadian Science Advisory Secretariat (CSAS), led by DFO, includes stakeholders and rights-holders in discussions to address scientific questions relevant to aquaculture management, such as assessing embayment carrying capacity for shellfish [39, 40] or evaluating the environmental interactions of proposed sites [50]. These processes reflect the Canadian emphasis on environmental aspects over social and community considerations, which are often not discussed at this level during the establishment of leases or during the monitoring of farm performance.

8 | Implementation

In the EU, the MSP directive is transposed by Member States, who were obliged to develop a National Maritime Spatial Plan

(NMSP) by 31 March 2021. The implementation of aquaculture within NMSP varies considerably among Member States. Partly, this is because several other requirements emerge which condition licensing. In some countries, a two-stage process exists: the first component is the deployment within a particular area, and the second is the regulation of the activity itself. The latter component is often that which presents more obstacles—in general, the spatial allocation is a necessary part of the process but is by no means sufficient [51].

In Norway, the level of implementation and stages of revision of municipal plans including aquaculture vary. Accomplishment of the plans and their revisions are overseen by the county governor. Implementation of the plans and the revision processes do not always keep up with the strong dynamism in the industry regarding technology, criteria for site selection, and interactions with the environment and society. A series of legal requirements from different sectors that are implemented as part of the management framework is linked to planning of space for aquaculture and the licensing process. More specifically, the monitoring of benthic environments at fish farming sites (the MOM system) is fully implemented in aquaculture management of licensing and operation. On a national level, the "traffic light system" was implemented in 2017. An expert committee passes on science data and an assessment of sea lice induced mortality in migrating Atlantic salmon postsmolt on a yearly basis to an advisory committee that biannually proposes a ministerial decision on production regulation in each of the 13 aquaculture production zones [52, 53].

In China, the people's government at or above the county level implements MFZ, as well as the planning of waters used for mariculture, and issues sea use licenses and aquaculture permits to enterprises and individual farmers. From 2018 to 2020, coastal provinces and municipalities across the country have carried out the delineation of the "three zones" (permitted, restricted, or prohibited areas) for aquaculture, and compiled regional aquaculture water and tidal flat plans (2018–2030).

In Canada, although Marine Protected Areas (MPAs) have been the most visible federal initiative regarding MSP, the current MSP approach recognizes the need to integrate conservation with relevant economic sectors such as fisheries, aquaculture, and shipping. In BC, the Marine Plan Partnership for the North Pacific Coast (MaPP) is an explicit MSP collaboration between 18 First Nations and the provincial government, involving a variety of marine uses, including shellfish aquaculture. MSP principles have been at the core of the implementation stage of aquaculture, not only for licensing purposes but also for key processes such as health management plans, determining the areas of effect, as well as carrying capacity. Health management plans are required for fish farming via provincial governments, and at the federal level via DFO and the Canadian Food Inspection Agency (CFIA), which interacts with farmed fish health in relation to disease control. Management occurs via epidemiological modeling and risk assessment, which also assists in fish health from a husbandry perspective. The creation of bay management areas for the control of farmed salmon diseases was implemented in New Brunswick via tidal connectivity and is one of the early examples of applied MSP [54]. Spatial modeling has been used in BC for the same health management purposes with the added consideration of disease risk to wild migrating salmon [55]. Bay Management Areas (BMA) remain as a planning tool in farmed fish health management, but they play no part in planning processes beyond aquaculture. There are formal benthic monitoring and deposition modeling programs administered by DFO and the provinces, some embedded in the Aquaculture Activities Regulations. Further, spatial approaches such as Predicted Exposure Zones (PEZs), which estimate the distance that dissolved or particulate material could travel from a farm, are used to evaluate site suitability [50]. Spatial planning for shellfish culture is highly advanced on both coasts, using food limitation and models of carrying capacity. DFO and the provinces have used these models in management decisions, which affirms the extent to which spatial modeling has been incorporated into MSP [39, 40].

9 | Evaluation and Review

In the EU, monitoring is required for purposes of impact assessment and water quality regulations (see discussion above on the WFD and MSFD). However, in many cases, particularly for larger farms or those that first occupy an ocean area, the authorities (usually regional) often shift the requirements for monitoring on the farms themselves and extend this to approve expansion plans. In general terms, the EU is not at the stage where plans are being reviewed using appropriate indicators, especially in the aquaculture sector, partly due to the obstacles to growth discussed earlier. The NMSP developed by member states in the EU should be reviewed every 10 years.

In Norway the implementation of municipal spatial plans is evaluated and reviewed by governmental authorities (county governor) that initially assess the state of the system and subsequently review it on a regular basis. Municipal authorities are often constrained by capacity and competence in planning the marine areas. Elements in the MOM system have been evaluated and reviewed over the years, based on changes in industry. The high flexibility of the system allows for adaptations, accommodating different environmental effects. The scientific basis for the "traffic light system" has been evaluated by the Royal Norwegian Research Council, assisted by an international committee [56]. The regulatory regime on the production zones is disputed by part of the industry. There are management, business interests and public concerns on whether the spatial planning regimes can secure sustainable development. In 2025, the Ministry of Trade, Industry and Fisheries published a white paper suggesting replacing the "traffic light system" with a more holistic system that includes the actual impact of aquaculture on environment, fish health and fish welfare [57]. This new system is yet to be developed and implemented.

In China, since its inception in 2002, MFZ has undergone revisions, amendments and regulatory supplements [58], to keep up with China's marine ecological conservation targets. Though inadequate for a systematic ecological evaluation of MFZ, regular monitoring of exemplary fisheries waters (e.g., water quality and planktons) and marine ecosystems is conducted by the MEE, results published annually in the *Bulletin on the Status of China's Marine Ecological Environment*.[15] In 2017, China started to integrate spatial planning such as the main functional zoning, land use planning, urban–rural planning and MFZ into a unified national spatial planning, to coordinate the multiple regulations and strengthen law enforcement. Now, as an integral part of the new Territorial Spatial Planning,[16] MFZ will keep an emphasis on MEPR control of Marine Protected Areas (MPA) and sensitive habitats.

In Canada, aquaculture development is overseen at the federal level by the Department of Fisheries and Oceans (DFO). Canada has revised its regulatory system for monitoring in the form of Aquaculture Activities Regulations (AAR)[17] oriented toward environmental performance, usually in shared governance with the provinces. Monitoring is required as part of regulations under the federal Fisheries Act and AAR, focusing heavily on benthic monitoring. Most provinces also have environmental monitoring requirements and plans for benthic impact and fish health, including reporting on mortalities, escapes, and sea lice incidents. DFO regularly evaluates science applied to regulation through the Canadian Science Advisory Secretariat, for example, assessing methodologies [59] or determining the aquaculture pathways of effects [60], which are currently being reassessed through new CSAS processes. Provincial departments usually participate in these CSAS processes and can implement their outcomes into their regulations.

10 | Perspectives on Contributions to Global Food Security

China, the EU (as applicable), Norway, and Canada are major players within marine aquaculture, with an aggregate production in 2022–23 of about 16.8 MMT [6, 61]; in addition, these actors are highly relevant in both technology and management, and all have governmental visions and objectives to develop their mariculture industries. Their institutional frameworks are largely customized for spatial planning in aquaculture, although applications of the frameworks in the EU seem to be underexploited. The implementation of aquaculture in the spatial planning frameworks varies widely, partly because the nations reviewed are at different stages of aquaculture development, and partly due to the heterogeneity of institutions, traditions, social acceptance, marine space, and governance. The nations show substantial differences in stage of aquaculture development, factors impacting the management and direction of the industry; China intends to stabilize production and delineate areas for mariculture, with this activity facing new and increasing competition from other users of the coastal area [62, 63]. In the EU, mariculture is at present decreasing, despite measures taken to promote growth. In Norway, the growth in salmon production is leveling off, regulated by national sustainability measures, and in Canada a policy process was put in place to transition Atlantic salmon culture from open net-pen to closed containment systems on the West Coast waters [64]. The common challenges of aquaculture impacts and interactions with the environment contribute to the complexity of challenges regulating access to space for mariculture development. The aquaculture implementation to MSP and MFZ frameworks varies also within the nations (blocks) (i.e., the EU, China and Canada), at national and provincial levels, which potentially can provide information from experience and developments that is not shown in this review.

A general concern and condition in spatial planning for aquaculture is carrying capacity, defined through the four pillars: physical, production, ecological and social, understood as the maximum production that does not lead to unacceptable changes to the ecosystem and society [65, 66]. The first step in the calculation of carrying capacity is MSP or MFZ, that is, determining where aquaculture can take place; this includes the effect of environment on aquaculture, evaluated through a set of suitability metrics, and also a range of multi-use aspects—for instance, is aquaculture allowed within a marine protected area, or how are buffer zones set with respect to designated fishing grounds or other uses such as recreation.

The definition of zones where aquaculture can physically take place [67, 68] is by no means a recommendation that such zones should be entirely occupied by aquaculture, nor does it indicate what stocking densities and areal coverage should be licensed for a particular zone. It should, however, be applicable to one species or set of species since environmental thresholds are species-specific (see http://meta.longline.co.uk). In the case of coastal planning in Norway, the municipalities designate areas for aquaculture based on suitability for salmonid farming and assessment of conflicts with other sectors. The municipal autonomy in the decision process is often seen as a limitation to the competence needed for assessing the criteria on suitability, requiring external expert support. Overstocking of a zone designated as suitable through MSP or MFZ, either due to unacceptable spatial coverage and/or excessive density, will result in aquaculture that far exceeds carrying capacity. It is therefore key to combine MSP/MFZ with other carrying capacity pillars [65] that account for the effect of aquaculture on the environment.

An example fully implemented in aquaculture management is the Norwegian Modelling-Ongrowing fish farms-Monitoring (MOM) system, assessing background conditions of new sites and impact monitoring on existing farm locations [37]. The development and operational components largely comply with the MSP steps (Figure 2). The system includes a risk-based monitoring program and threshold values for allowable impacts (Environmental Quality Standards; EQS) linking the environmental measures to the social [37]. The system is flexible and allows for substitution of the model parameters and the monitoring program including the EQS, accommodating different environmental effects, changes, and type of industry [69–71].

MSP or MFZ is always the starting point, but two further aspects of zoning should be qualified since the domain of interest is the marine environment—these issues are often overlooked because maps are two-dimensional representations with static boundaries. The first is the three-dimensional nature of marine systems and how this is exploited in aquaculture, which is far better understood in China than in the other nations included in this review. A textbook example is Sanggou Bay in NE China, where Integrated Multi-Trophic Aquaculture (IMTA) takes place at various vertical levels in the water column—seaweeds at the surface, finfish in the upper layer, oysters, scallops and abalone on vertical dropper ropes, and abalone and sea cucumbers at the bottom [70–72].

Open-water IMTA is incipient in the West, currently not a commercially viable option and unlikely to undergo major development due to market considerations, licensing issues, the conventional farming technology and production costs [73–75]. A direction of IMTA extracting particulate waste from fish farming in Canada and Norway is that any mitigation would be best achieved by placing the extractive species, such as deposit feeders, beneath the cages rather than horizontally to the farms [74, 76]. The 3D nature of marine water bodies—the same applies to a lesser extent in lakes—has important consequences for planning; this was of no concern in spatial planning originally developed for land, and the GIS tools used for MSP are not tailored to the extra vertical dimension.

The second aspect is the hydrodynamics of the water masses for which MSP and MFZ are produced. Some of the water movement is accounted for by means of buffer zones, but these generally fail to capture the large advective water movements driven by tidal currents, prevailing winds, and freshwater runoff. In a conventional approach where an area designated as suitable contains finfish cages or shellfish rafts, the emphasis with respect to environmental effects is on bottom coupling, where particle deposition is assessed using sediment indicators such as sulfide or organic enrichment.

If a zone is considered suitable in MSP/MFZ, a license application may require farm-scale modelling, for example, with respect to local benthic effects. Models such as FARM [77], ORGANIX [73], DEPOMOD [78] or MOM [37] are used for this purpose, but these models only address environmental effects at the local scale and have very limited potential for assessment of interactions among farms within a zone [79]. To reduce the

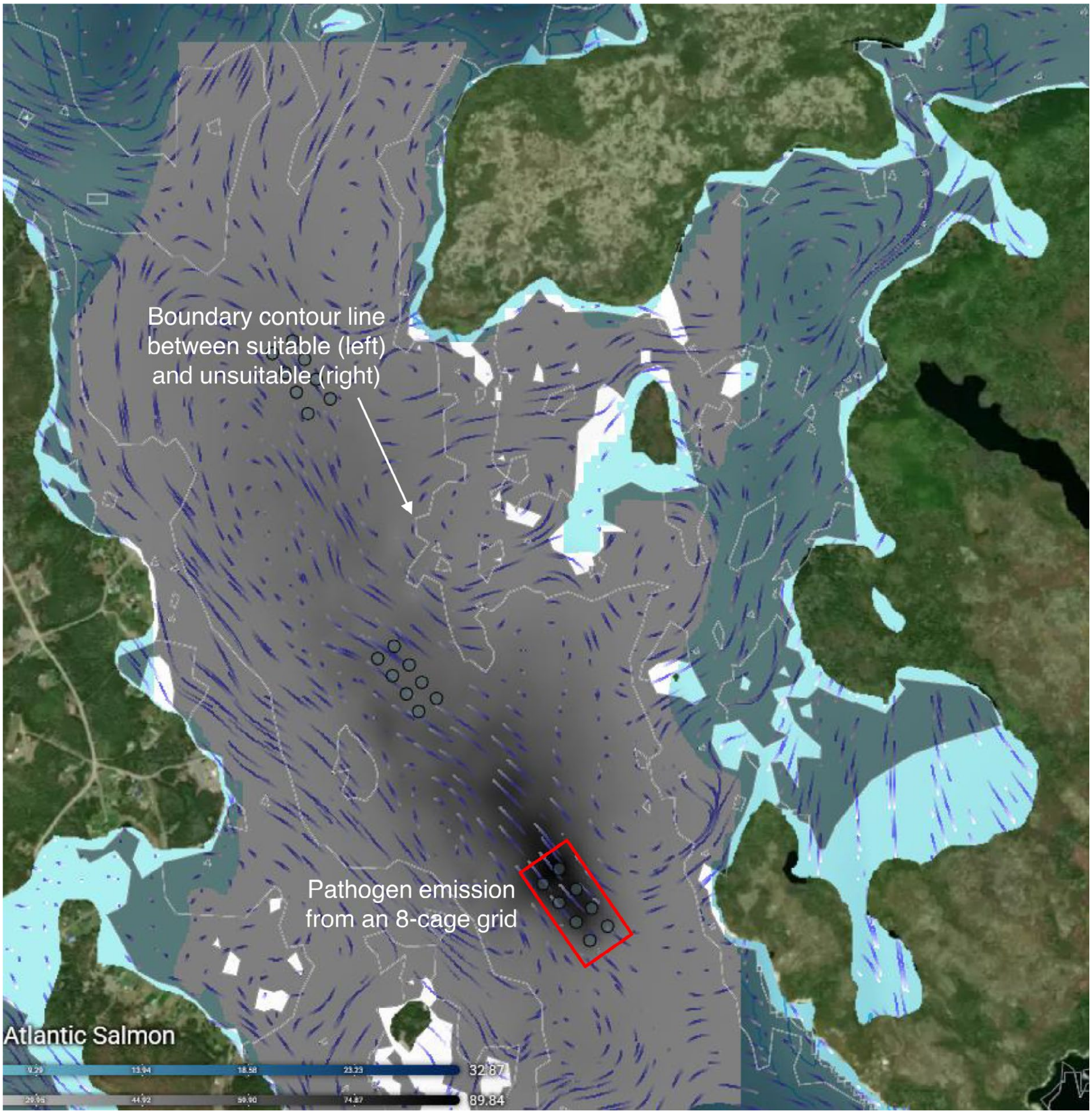

FIGURE 6 | Conceptual map for Whitehead Harbour, Nova Scotia, Canada, produced using the FINS software. The gray surface is the pathogen plume from an 8-cage salmon grid in the southern part of the bay. The residual current flows northwest. The middle grid is clearly affected by the pathogen, but the area to the east of the contour line marked on the map, which is classified by MSP as unsuitable for aquaculture, is also partly affected by the pathogen plume.

risk of disease transfer and other interactions between farms, a precautionary minimum distance of 5 km is recommended, while a shorter distance may apply based on assessments of local conditions.[18] On a regional and national scale, the "traffic light system" regulating Norwegian salmonid production is currently based on the effects of the parasite salmon lice on wild salmonids, exemplifying how water movement is accounted for in zoning. The decision on where to set the borders for the 13 zones (Figure 3) was based on connectivity analysis (3D particle dispersion modelling) determining the areas with least connectivity between existing sites aiming to reduce the risk of salmon lice advection between the zones. Moreover, if aquaculture is licensed in a suitable spatial zone, advective transport of dissolved nutrients or pathogens may lead to environmental issues in other areas classified as unsuitable for aquaculture. This is illustrated with the Farming In Natural Systems (FINS) platform (Figure 6), used here to simulate how a pathogen plume is transported by advection and dispersion into an area classified as unsuitable for aquaculture. The three 8-cage conceptual grids shown in the image are in an area designated as suitable, but the consequences of the activity extend into an unsuitable area.

The legal instruments for marine planning in the EU (e.g., 2014/89/EU) do not reference further steps related to carrying capacity—the EU directive above refers only (Article 8) to the potential identification of "aquaculture areas"—the term "carrying capacity" is never used. The Norwegian legal regulations on planning for aquaculture at the municipal level and the operational requirement for production follow the strategic principle "The degree of utilization of the location in relation to its carrying capacity must be within defined, measurable limits" [80], for example, the MOM system assessing benthic impact indices within acceptable levels [37] and the "traffic light system" level of salmon lice causing mortality in wild salmonids.[19] In Canada, carrying capacity is not mentioned in the most recent marine spatial plan for the Scotian Shelf and Bay of Fundy [38], an area with substantial aquaculture development. Although carrying capacity is not explicitly referenced in aquaculture regulations, models based on the concept of carrying capacity have been used to inform sustainability and expansion in Canada [39, 40]. There is a body of literature dealing with site selection (e.g., [81–84]) that has been applied separately from carrying capacity analysis dealing with the production, ecology, or social pillars.

Conversely, a number of ecosystem-scale carrying capacity modelling studies (e.g., [32, 85–89]) have not explicitly considered MSP or MFZ as a first step in their analysis—this is also a limitation, but less of a concern because such studies typically include physiological modelling of the species of interest, which in itself contributes to site selection. There are notable exceptions where the two approaches have been used in conjunction (e.g., [65, 90–92]).

MSP and MFZ may thus be considered powerful tools for ensuring that mariculture is permitted according to well-defined suitability criteria—spatial planning per se is necessary but not sufficient for a holistic approach to site selection. There are substantial benefits in integrating spatial planning and dynamic modelling of the natural and social environments in order to obtain a holistic assessment of carrying capacity.

Over the next decades, a rapidly growing world population, much of it in the Global South, creates planetary challenges to food security; in parallel, most of the world's aquaculture production, and an important part of its mariculture, takes place in areas with limited data, infrastructure, training, and management tools—the West is arguably overregulated and mariculture, already at a low base, will grow slowly. For the steps of production of spatial plans, public consultation, implementation, and evaluation and review, there are substantial differences between the nations in the inclusion of aquaculture. The apparent weak and in some cases receding position of aquaculture in several of these steps reviewed here warrants considerable concern with respect to the expectations of marine aquaculture as a route for ensuring future seafood provision [5]. As reference to major players in marine aquaculture, this review shows that there is a need for strengthening the position of aquaculture in the marine spatial planning frameworks, particularly when considering its expansion in areas with potential for development [65, 93].

The global scientific, management, and regulatory communities must therefore work together with local actors to develop and provide accessible tools that will help address the sustainability challenges that lie ahead; this requires a combination of zoning, harmonization of multiple uses, environmental risk assessments, and precautionary assessment of carrying capacity to enable sustainable growth of mariculture for the future of mankind.

Author Contributions

Øivind Strand: conceptualization, writing – original draft, writing – review and editing, project administration. **Hui Liu:** writing – original draft, conceptualization, writing – review and editing. **Joao G. Ferreira:** conceptualization, visualization, writing – original draft, writing – review and editing. **Ramon Filgueira:** writing – review and editing. **Ellen Sofie Grefsrud:** conceptualization, visualization, writing – review and editing. **Pia Kupka Hansen:** conceptualization, writing – review and editing. **Qianwen Sun:** writing – review and editing. **Jenny Weitzman:** conceptualization, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Endnotes

[1] Also termed Marine Spatial Planning. In this review, the terms are used interchangeably.

[2] *Marine aquaculture*, *mariculture*, and *aquaculture* are used interchangeably in this review since it deals only with the marine environment.

[3] Organic, such as filter-feeding bivalves, or inorganic, that is, seaweeds.

[4] The mu is a Chinese unit of area, equivalent to 1/15 of a hectare.

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