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Ecological carrying capacity in mariculture: Consideration and application in geographic strategies and policy

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A R T I C L E I N F O

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A B S T R A C T

Governance and management strategies for aquaculture development were examined for a select number of jurisdictions covering a range of marine aquaculture production to better understand the degree to which concepts of "Ecological Carrying Capacity" (ECC) are incorporated into management tools or permitting requirements for aquaculture development. Policies, regulations, and strategic plans were sought through professional knowledge and, at times, using web-based searches. Aquaculture ECC, defined here as, "the magnitude of aquaculture production that can be supported without leading to unacceptable changes in ecological process, species, populations, or communities in the environment," was not strictly applied in any jurisdiction's aquaculture policy documentation. A broadened search to consider the concept of aquaculture carrying capacity (CC) more generally was conducted. Of the ten nations examined, CC concepts could be found in policy documentation of several nations. The inclusion of CC concepts in policy and strategic planning can be used as part of a suite of management tools to promote sustainable aquaculture within FAO's Ecological Approach to Aquaculture.

1. Introduction

Carrying capacity (CC) is a density-dependent concept in applied ecology referencing the maximum population size a species can sustain indefinitely in its environment given its requirements for food, habitat, water and other essential necessities for life [1]. This initial single-species concept of CC has been expanded in other contexts to consider production and ecological community dimensions and scenarios [2]. There are multiple scales at which CC can be interpreted, proposing a hierarchy of population CC (individual species), community CC (multiple interacting species), ecosystem CC (multiple interacting communities), and biosphere CC (multiple interacting ecosystems) [3].

The concept of CC is fundamental to renewable resource management in commercial fisheries, forestry, and agriculture [4], and has been recently applied in models to evaluate the potential limitations of competition, predation and food supply on the success of native species reintroductions [5]. In most cases, applications in these fields have focused on production capacity for a given species, where the intent is to maximize production (biomass) in a given space. This is true, as well, for most applications in aquaculture, where growth rate is typically the key metric reflective of production capacity limitation. Ecological CC (ECC), however, is a broader concept than production capacity alone, and

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considers the species' interactions with the environment in concert with the environment's capacity to support other species' presumed use of the same spatial area for their needs [6,7].

Just as scientists promoted ecosystem-based management in commercial fisheries policy [8], scientists also promote ECC in aquaculture development [9,10]. For this work, the definitions of aquaculture CC are considered as:

i) **Physical Carrying Capacity** — the total area of marine farms that can be accommodated in the available physical space.
ii) **Production Carrying Capacity** — the stocking density at which harvests are maximized, and also referred to as production capacity, as it is in this paper.
iii) **Ecological Carrying Capacity** — the magnitude of aquaculture production that can be supported without leading to unacceptable changes in ecological process, species, populations, or communities in the environment [11]. In some cases, ECC is called environmental CC or ecosystem CC, or is more specifically defined as:
    - **Assimilative Capacity** — the ability of the ecosystem in a water body to absorb anthropogenic inputs of substances without damaging the health of the ecosystem or its ability to provide goods and services [12].
iv) **Social Carrying Capacity** — the level of farming above which society does not support the aquaculture industry [13,14].

This study explores the degree to which ECC concepts have been incorporated into policy, governance or management initiatives throughout a selection of nations with varying degrees of aquaculture development. In this paper, policy is defined as a course of action adopted by the regulatory body or bodies in a given geographic area. Hence, this information gap was explored by taking a top-down review of national and regional aquaculture-related policies, governance, regulations or strategic planning documentation (collectively referred to as "policy documentation") to evaluate whether ECC or assimilation capacity was referenced, and if so, in what context. The authors are members of the International Council for Exploration of the Seas (ICES) Working Group on Ecological Carrying Capacity for Aquaculture (WGECCA) and have intimate knowledge of aquaculture practices and policies in their representative geographies.

2. Methods

The international author team was assembled based on expertise on CC for aquaculture. The ICES - WGECCA author team represents a dozen different regions, mostly in the Atlantic but also including a few regions in the Pacific and Mediterranean.

Relevant documentation on national, state or regional aquaculture policy, regulations and strategic planning, and management were identified through professional knowledge of aquaculture policy and practice in a given location or through authors' professional contacts and a variety of database search methods, depending on the way in which policy and practices were documented in specific jurisdictions. For example, in some cases, author-driven communications to regional managers and regulators posed questions akin to "Is ECC considered with respect to site selection or lease application for aquaculture in your [country/state/region]?" If there was an affirmative response, documentation was requested for review. Where aquaculture zoning was found to be applied in some regions [15,16], the bases of these zoning criteria to consider if and how ECC was factored into the delineation of aquaculture zones were explored. In addition, previously published compendia, such as Food and Agriculture Organization (FAO) of the United Nations (UN) "The State of World Fisheries and Aquaculture (2020)," and regional aquaculture reviews were examined.

This paper focuses particularly on high-level policy, planning, and management documentation of ECC, and not the models or techniques of how ECC is applied. The emphasis of our analyses focuses primarily on the top six producers of aquaculture among the 20 Atlantic ICES member nations [18,19], where production was reported as greater than 150,000 tonnes live weight (t) and value greater than 300 million US dollars (USD)). Production (live weight) and value data of marine aquaculture were queried from the FAO Fisheries and Aquaculture Statistical Query Panel on June 22, 2022 and are presented in each country header [18]. For comparison, four countries in the Pacific are also reviewed and discussed, including the world's leading aquaculture producer, China, and a few smaller Pacific countries that are strategically trying to expand their nation's aquaculture industry. Finally, while this review explores in greater detail the identification of ECC or CC in aquaculture policy of the major aquaculture producing ICES member states, the review process for this paper uncovered relevant information on the subject matter from smaller producing ICES states, as well as neighboring states within the Mediterranean. For completeness, the identification of ECC or CC concepts in aquaculture policy is briefly summarized from a select group of the smaller ICES-member states, and for all of the 16 countries surrounding the Mediterranean Sea.

3. Results

3.1. Major aquaculture producing ICES member states

3.1.1. Norway (1490,280 t; 7.3 billion USD)

Norway is the largest producer of farmed Atlantic salmon (Salmo salar) in the world and also produces bivalves, primarily blue mussel (Mytilus edulis) [18]. Within the Northern European region, Norway has developed an advanced aquaculture licensing and development program. At the national policy level, Norway's strategic plan for aquaculture [20] does not expressly identify ECC as a management or policy goal; however, other vehicles clarify significant environmental review provisions.

Norway's Aquaculture Act [21] regulates the management, control and development of aquaculture in Norway's marine waters. An Ecological Impact Assessment (EIA) is an integral part of the process to determine planning application outcomes in Norway. Just as ECC aims to minimize environmental impact, so does EIA. Following consideration of the EIA, the Aquaculture Act establishes the licensing system to be implemented following provisional approval. The licensing system is administered through the Directorate of Fisheries, which oversees fish health and welfare and conducts surveillance and monitoring of farms for other environmental impacts. The Directorate of Fisheries forwards applications to the applicable authorities to obtain required licensing under other acts, such as the Food Act 2003 or Animal Welfare Act 2010 [22,23]. A license from the Directorate of Fisheries is granted if the operation is "environmentally responsible" based on environmental surveys and documentation of site environmental conditions at the time of establishment, operation and abandonment of the aquaculture facility but no further link to CC is given.

The Directorate of Fisheries defines the technical standards for environmental compliance on fish farms through Norwegian Standards (NS) 9410 and NS 9415 and is responsible for coordinating, administrating and executing environmental surveillance and monitoring. A modular model management system 'Modelling On [growing fish farms] Monitoring' (MOM) is legally required in Norway by the Directorate of Fisheries for site selection of salmon and trout mariculture. Farming operations also require a monitoring program with Environmental Quality Standards. In addition, the creation of spatially bounded production areas was an innovative zoning-like approach that introduced the need for other relevant indicators within production areas, such as salmon lice levels to reflect cumulative impacts at the production area scale rather than farm scale [24]. The amount of sea lice (Lepeophtheirus salmonis) on wild salmon, as determined by modeling of infection rates from nearby cultured stocks, is used as an indicator of ecosystem health through a traffic light approach. Environmental risks from sea lice infection are interpreted as low (green light), moderate (yellow light), or high potential impact (red light). Although sea lice infectivity risk is a relevant environmental indicator from which the sustainable growth of the industry is promoted, the use of a single indicator for ecosystem health does not meet the definition for ECC applied in this paper.

3.1.2. The United Kingdom (211,026 t; 1.35 billion USD)

The United Kingdom of Great Britain and Northern Ireland (UK) is a nation of four countries: Scotland, England, Northern Ireland, and Wales. Aquaculture is devolved within the UK, which means that each UK country has responsibility for policy, regulation, and management of aquaculture in their jurisdiction. Though the Crown Estate owns a considerable amount of the coastal seabed region, a lease is required for all coastal aquaculture in the UK. Scotland is by far the biggest aquaculture producer, with eighty-two percent (82%) of the total UK aquaculture production, and ninety percent (90%) by value; while production is dominated by Atlantic salmon [25], other notable species produced in the UK countries include mussels and oysters. Although aquaculture is devolved, on occasion, high-level documents and policies are prepared at the UK level, for example, policy documents for the EU where the UK was a member state until leaving in 2020. In 2015, to comply with a request by the European Commission, the UK Multi-annual National Plan for the development of sustainable aquaculture was published [26]. ECC is mentioned in this document when describing the Sustainable Mariculture in Lough Ecosystems (SMILE) CC models that are used in Northern Ireland to determine ECC for shellfish in sea loughs (coastal inlets) [27]. SMILE is given as an example of an innovative technique, but this approach is not formally applied elsewhere in the UK.

Since aquaculture is devolved, it is primarily the strategic plans, policies, and regulation within the individual UK countries that influence development of the sector. Scotland's National Marine Plan [28] refers to aquaculture development taking place with "…due regard to the marine environment and CC," (Marine Scotland, 2015 Aquaculture Objective 2), but this does not specifically refer to or mention ECC. The strategic plan for Scottish aquaculture to the year 2030 [29], produced by a consortium of industry representatives, does not mention ECC either. However, though not explicitly mentioned in higher level policy documents, there are other aspects of CC assessment in parts of the planning process for both fish and shellfish. For fish farms in Scottish marine waters, all locations are assessed in terms of how much of the capacity of a water body is used already for aquaculture with models for estimation of capacity for nutrient assimilation based on the exchange of water and amount of waste entering the system, using an environmental index [30]. Furthermore, it is a regulatory requirement for fish farms to have a license to discharge waste, and the assessment is based on the capacity of the environment to assimilate wastes and does not explicitly use the term ECC (SEPA, 2019). For shellfish aquaculture, the "biological" CC for coastal locations is a part of the planning application process based on location of the site and its flow characteristics (tidal water flow is not restricted so that food availability for the shellfish becomes an issue) [31]. Though biological CC in this context could be considered to include ECC, it is a better indicator of potential tonnage growth in an area and therefore more of an indicator of production CC.

A new English Aquaculture Strategy was published in November 2020 [32]. Though there are several mentions of ecological and social implications and ecological impact, there is no expressed mention of ECC. However, one of the core principles indicates, "Aquaculture production should be environmentally, economically and socially sustainable. It should be within the CC of the aquatic environment, have no significant impacts on aquatic biodiversity and habitats, be responsive to climate change and be balanced with the needs of other users." No indication of mechanisms or strategies for implementation are defined.

For Northern Ireland, a national aquaculture strategy or policy does not exist and formal requirements to address ECC in planning permission are not stated in the legislation. The Northern Irish Department of Agriculture and Rural Development (DARD, now DAERA) has given the Agri-Food and Biosciences Institute (AFBI) the responsibility for developing and maintaining models that are used to assess the ECC for shellfish production (e.g., SMILE). Such models are actively used to support planning and management decisions for shellfish in Northern Ireland at the bay scale. Furthermore, cumulative impact assessments for sea loughs are produced that assess the likely impact of aquaculture activities on designated features in and adjacent to designated sties. In these assessments, ECC and threshold chlorophyll-a (chl-a) reduction values are calculated to determine impact of new aquaculture site applications [33].

The Welsh National Marine Plan was published in 2019 and it outlines sector objectives for a range of activities including aquaculture [34]. However, the plan does not specifically mention ECC for aquaculture.

3.1.3. France (150,205 t; 642.6 million USD)

Aquaculture is an important industry in France, mainly due to the production of bivalves, which account for over seventy-five percent (75%) of the country's total production [18]. Integrating the ECC concept in policy as a management tool or permitting requirement for aquaculture development has been under consideration for several years [35]. Since 2015, the authorities have considered modelling tools as relevant to estimate ECC. Further, concepts of CC were included in the National Strategic Aquaculture Plan (Plan stratégique national de développement de l'aquaculture – PSNDA 2018) and in studies to determine the best sites for aquaculture (Meilleurs emplacements aquacoles possibles – MEAP). SISAQUA (Système d'information Spatiale pour l'Aquaculture en Normandie) utilizes AkvaVis, a GIS-based decision support tool, that performs suitability analysis on proposed shellfish farm areas through the utilization of a series of indicators, including production capacity, and can create virtual farm objects to display and interact with models and environmental data [36,37].

The DSF (Document Stratégique de Façade) specifies the guidelines of the national strategy for the sea and the coastal zones, setting up action plans for the marine environment within the Marine Strategy framework directive (MSFD). Regional Plans for the Development of Marine Aquaculture (Schémas r é gionaux de développement de l'aquaculture marine – SRDAM) have been introduced in the French Law to modernize agriculture and fisheries (July 27, 2010), "The goals of SRDAMs are to make an inventory of existing aquaculture sites and to identify potential sites suitable for aquaculture, and to conciliate the development of marine aquaculture with other coastal activities. They are expected to allow access to new fish farming sites" [38]. SRDAMs have been developed in each region in France and as such represent a spatial zoning strategy for multiple uses. Although SRDAMs included environmental issues when mapping of suitable sites, the concept of CC is not mentioned.

Fish farming is also subject to ICPE standards ("Installations Classified for the Protection of the Environment") established under French environmental law (Environmental Code, Article L511–1) for all activities likely to release pollutants and create risks to the environment or for the security and health of residents [39]. The measures to be set up for "limiting potential environmental impacts, such as losses of biodiversity or degradation of water/bottom quality," are prescribed by the ICPE authorization as a function of the level of production and characteristics of the farming sites. Only farms producing more than 20 t are required to provide an EIA. As an example, to facilitate the procedure, in 2004 the local Corsican authorities asked IFREMER to provide guidelines to facilitate preparation of ICPE requests [40]. These requests mention the importance of evaluating the capacity of receiving ecosystems to assimilate fish farm waste ("assimilative capacity").

One of the key challenges identified in the National Strategic Plan for the Sustainable Development of Aquaculture was to, "better manage and anticipate direct interactions with aquatic environments" [41]. In this light, site selection studies based on DPSIR framework (drivers, pressures, state, impact and response model of intervention) and waste assimilative capacity modelling are encouraged.

3.1.4. Spain (246,653 t; 495.26 million USD)

Spain is the largest producer of bivalves among ICES member states, and produces a considerable amount of finfish, particularly in its Mediterranean waters [18]. Similar to France, bivalve production comprises about seventy-five percent (75%) of Spain's total aquaculture production [18]. Spain is divided politically and administratively into autonomous communities, which have the jurisdiction to regulate aquaculture activities, although these regulations must comply with the regulations those of the Spanish central government. Article 4 of the Spanish Law for the Protection of the Marine Environment states that CC studies are needed when planning the use of marine environments. This requirement is acknowledged in the aquaculture strategic plans developed by the central government; however, it is also recognized that these tools are poorly developed in Spain [42]. Further, the annex of the most recent strategic plan released by the central government (2014–2020) states that CC estimations are complex and theoretical when carried out a priori, recognizing the role of aquaculture practices and local conditions on these estimations [43]. Accordingly, the guidance of the central government is to apply the precautionary principle and environmental monitoring when detailed information is not available for a theoretical estimation of CC [43].

There is no specific guidance by the central government on how to apply the precautionary principle or how to estimate CC. Given the context in Spanish documents, the "E" in ECC is implied though not explicitly stated. Although estimations have been carried out for specific areas in different autonomous communities like the Canary Islands and Catalonia, the methods have not been outlined in the strategic plans of those autonomous communities [44]. The limited work on CC estimations is evident in the lack of citations of CC studies in a review of aquaculture research and development initiatives for the period 1998–2012 [45]. However, CC studies were identified as a research and development priority for the period 2014–2020 [46].

3.1.5. Canada (160,066 t; 730.4 million USD)

Aquaculture is an important industry in Canada, mostly due to the production of Atlantic salmon and other salmonids in sea cages which in 2020 equated to about 92,972 t in British Columbia and 36,552 t in eastern Canada. Bivalves also comprise a large portion of Canada's aquaculture production with 6666 t, primarily oysters, produced in British Columbia and 23,365 t, mostly a mix of mussels and oysters, produced in eastern Canada [47]. Although the concept of ECC can be found in Canadian aquaculture policy, it is not implemented or operationalized in a systematic way either at the provincial or federal level. However, the Department of Fisheries and Oceans (DFO), through the Program for Aquaculture Regulatory Research (PARR) [48] and the Aquaculture-Environments Interaction Program (AIEP) [49], funds considerable research on ECC, illustrating the value of the concept to science-based decision-making in the country.

Aquaculture regulation varies across Canada with the Province of British Columbia issuing leases and DFO issuing licenses and monitoring license conditions, a management board including the province, industry, and DFO issuing leases and associated licenses in Prince Edward Island, and all other provinces and territories issuing leases and licenses. In all cases, DFO is at least partly responsible for regulation of the sector, although Provinces/Territories may also co-regulate environmental aspects.

Although aquaculture operations are currently subject to regulations as outlined in the Fisheries Act and Fishery (General) Regulations, [50, 51] such as prohibition of unlawful "death of fish," "harmful alteration, disruption or destruction of fish habitat," and "deposit of a deleterious substance," with deference to other valid regulations, a forthcoming Aquaculture Act may enhance environmental management [52,53] and "provide a national legislative framework that gives clarity and certainty to the aquaculture industry and other stakeholders across Canada while maintaining environmental protections" [52]. At the National level, the Framework for Aquaculture Risk Management [54] makes explicit reference to the importance of determining the "CC" of sites, although CC is not defined in the framework.

Regulation is largely focused on sediment quality monitoring below and around finfish net cage sites [55]. Most provinces and territories make only passing reference to the notion of ECC in policy. For example, the Province of New Brunswick offers only vague general terms to notions of ECC by stating that aquaculture licenses may be granted that may be subject to "measures to be taken to minimize the risk of environmental degradation" in the New Brunswick Aquaculture Act [56] whereas both the finfish and shellfish development strategies stress the importance of environmental, economic, and social sustainability of aquaculture [57,58]. The Province of Nova Scotia sets out general terms in the Fisheries and Coastal Resources Act to "encourage, promote and implement programs that will sustain and improve the fishery, including aquaculture" and to "support the sustainable growth of the aquaculture industry" [59]. This language was later made more explicit to "ensure that the net environmental impact of an aquaculture operation, from startup to decommissioning, does not exceed the ECC of its location"[59]. This was the only explicit mention of ECC by any level of government in Canada that was found in our review. In British Columbia, the Pacific Aquaculture Regulations state that measures must be taken to "minimize the impact of the aquaculture facility's operations on fish and fish habitat" and "monitor the environmental impact of the aquaculture facility's operations" [60]. This includes providing a habitat map showing the boundaries of the application area and habitat characteristics (glass sponge complexes, coral complexes, shellfish beds, eel grass beds, rockfish habitat, and kelp beds) as well as benthic organic loading estimates for maximum feed rates based on DEPOMOD outputs when applying for new leases [61]. In contrast, the Newfoundland and Labrador Fishery Regulations [62] make no specific reference to aquaculture operations. In short, management of aquaculture activities in Canada does not have an explicit reliance on the calculation of ECC in any laws or regulations, relying moreover on simple (and difficult to quantify) notions of sustainability and through more general guidance expressed as "not having undue impact"-type statements.

3.1.6. United States of America (199,380 t; 369.68 million USD)

Marine aquaculture is a national priority and an increasingly important industry in the United States, with oysters dominating sales value, above that of clams and Atlantic salmon [63,64]. Carrying capacity in the United States is not explicitly included in aquaculture permitting requirements at the national level, though a few examples of ECC approaches have been applied for operations in state waters where most aquaculture activities occur and are locally regulated in addition to being subject to national level regulations. While the terms ECC or CC are not mentioned in the National Oceanic and Atmospheric Administration (NOAA) Marine Aquaculture Strategic Plan (2023–2028) [65], the plan articulates four goals: (1) manage sustainably and efficiently, (2) lead science for sustainability, (3) educate and exchange information, and (4) support economic viability and growth [65].

The high-level goals of NOAA's strategic plan for aquaculture reflect an emphasis on sustainability, a term open to different interpretations when implemented at a regional and local scale, and this variation is also somewhat reflected through the variety of means by which mariculture operations are ultimately permitted within the jurisdictions where mariculture is practiced. To this point, multiple national level agencies are responsible for regulating aquaculture activities in the aquatic environment, including (but not limited to) the Environmental Protection Agency (EPA) through section 404 of the Clean Water Act (CWA). The U.S. Army Corps of Engineers (USACE) impacts aquaculture through its authority in implementing Section 10 of the Rivers and Harbors Act (RHA). Additional agencies consult on the USACE and EPA actions impacting aquaculture regulations, including NOAA's and the U.S Fish and Wildlife Service's (USFWS) authorities in implementing the U.S. Endangered Species Act (ESA) and Fish and Wildlife Coordination Act (FWCA), and NOAA's Essential Fish Habitat provisions under the Magnuson–Stevens Fishery Conservation and Management Act (MSA). Regarding food safety, the U.S. Department of Agriculture's (USDA) federal oversight of states' health inspection services for aquaculture products and the Food and Drug Administration (FDA) Center for Veterinary Medicine regulation of aquaculture treatment medicines and fish and shellfish pathogens.

The National Environmental Policy Act (NEPA) is the umbrella under which all federal permitting Actions must comply in the U.S. NEPA requires examination of individual and cumulative impacts from projects, including aquaculture, and often requires Environmental Assessments (EAs), or for large projects, Environmental Impact Statements (EISs). Because the public scoping of proposed projects under NEPA is conducted at the region or district jurisdictional level by the lead federal 'action agency', issues addressed under NEPA can also vary significantly, and no CC or ECC evaluations are required as a matter of national policy. Though some projects have conducted CC assessments in support of NEPA cumulative effects analyses, no robust policy or guidance toward determining such cumulative effects currently exists specifically for mariculture operations.

Section 10 of the Rivers and Harbors Act of 1899 requires authorization through the USACE for the construction of any structure in or over any navigable water of the United States, including shellfish, macroalgae, and finfish farms. This broad regulatory authority confers upon the USACE the federal action agency status wherein they are required to address NEPA, as well as ensure that other pertinent federal and state laws have been addressed prior to their issuance of an authorization. The most commonly used regulatory mechanism to authorize commercial shellfish aquaculture activities in many production areas in the U.S. is the programmatic Nationwide Permit (NWP) 48 issued by the USACE, which authorizes shellfish mariculture activities deemed to have no more than a minimal individual or cumulative adverse effect on the environment such as the installation of buoys, floats, racks, trays, nets, lines, tubes, containers, and other structures into navigable waters associated with shellfish farming, as well as shellfish seeding, rearing, cultivating, transplanting, and harvesting activities [66]. New NWPs for finfish (NWP 56) and seaweeds (NWP 55) [67] have not been widely used—likely reflecting more of the challenges at the state level in getting these projects implemented than issues with these NWPs per se. The use of these NWP permitting vehicles is up to the discretion of local USACE districts, and they may choose other permitting vehicles such as standard permits if impacts of an activity proposed for authorization using an NWP permitting tool have more than a minimal adverse effect on the environment and to authorize aquaculture activities outside the scope of the NWP program. If the NWP 48 tool is used, for example, regional or project-specific conditions are generally applied by the local USACE district to protect important regional concerns and resources and further ensure that activities eligible under NWP48 "result in no more than minimal individual and cumulative adverse effects on the aquatic environment." [66].

Under the Rivers and Harbors Act (RHA), projects expected to have more than a minimal individual and cumulative adverse effect on the environment or that are outside the scope of the NWP program require the issuance of Standard Permit (SP) by the USACE. The decision whether to issue a SP is based on an evaluation of the probable impacts, including cumulative impacts, of the proposed activity and its intended use on the public interest referred to as the Public Interest Review process. Evaluation of the probable impact which a proposed activity may have on the public interest involves a weighing of all those factors which become relevant in the particular proposal under review. The benefits which reasonably may be expected to accrue from the proposal are balanced against its reasonably foreseeable detriments. The decision whether to authorize a proposal, and if so, the conditions under which it will be allowed to occur, are therefore determined by the outcome of the general balancing process 33 CFR § 320.4.

Ultimately, neither the public interest review process nor regulatory requirements associated with developing programmatic permits explicitly identify ECC in policy statements, regulations, or supporting documents. As the issuance of a USACE Section 10 authorization for mariculture implicitly requires compliance with the numerous federal laws previously referenced as well as state and local laws and statutes, concepts of CC or ECC could be captured through "proxy". In practice, however, our review has not identified where such requirements consistent with our working definition of ECC have been integrated into these other permitting vehicles. For example, in Washington State the EPA-delegated CWA Section 401 certification process is strictly focused on minimizing temporary water quality degradation from turbidity-generating activities in shellfish farm practices and does not consider CC or ECC.

Marine finfish rearing operations in the U.S. and upland mariculture facilities are considered concentrated aquatic animal production facilities that discharge feed and feed wastes into public waters. As a point source of pollutants, these activities require a National Pollution Discharge Elimination System (NPDES) permit under the CWA wherein effluent limitations are set for specific pollutants (e.g., nutrients, pharmaceuticals, antifouling agents, disinfectants) to prevent adverse impacts on existing water and sediment quality [68]. Nutrient limits set in NPDES permits can be considered relational to assimilative capacity approach where nutrients (food) are added into the system, but these permit conditions do not reflect an assessment or application of an ECC approach [69]. NPDES permits for finfish aquaculture require permittees to perform sediment, water quality, and fish escape monitoring and reporting. Again, the focus on these potential impacts is important but markedly different from a holistic consideration of ECC.

Clean Water Act (CWA) Sections 402 and 403 require that a NPDES permit for a discharge into the territorial seas (coast to 12 nautical miles, or farther offshore in the contiguous zone or the ocean), be issued in compliance with EPA's regulations for preventing unreasonable degradation of the receiving waters. Before issuing a NPDES permit, discharges must be evaluated against EPA's published Ocean Discharge Criteria (ODC) for a determination of unreasonable degradation. The NPDES implementing regulations at 40 CFR § 125.121(e) defines unreasonable degradation of the marine environment as the following: 1. Significant adverse changes in ecosystem diversity, productivity, and stability of the biological community within the area of discharge and surrounding biological communities; 2. Threat to human health through direct exposure to pollutants or through consumption of exposed aquatic organisms; or, 3. Loss of aesthetic, recreational, scientific or economic values, which is unreasonable in relation to the benefit derived from the discharge. The ODC evaluates unreasonable degradation as required by 40 CFR § 125.122. It also assesses whether the information exists to make a "no unreasonable degradation" determination, including any recommended permit conditions that may be necessary to reach that conclusion.

Since the majority of finfish aquaculture is conducted in state waters, it is subject to state and local level management decisions in addition to federal requirements. For example, in Washington State commercial finfish net pen aquaculture on state-owned aquatic lands was recently prohibited through an executive order of the state lands commissioner unrelated to any analysis of CC or ECC [70]. In contrast to the exclusion of opportunities for future finfish aquaculture in the Puget Sound, an approach is under consideration in San Diego Bay to identify aquaculture opportunities. Discretely zoned Areas of Interest (AOI) within and outside of the Bay are being evaluated for their interaction with Essential Fish Habitat (EFH), protected species, and other ocean uses by the National Centers for Coastal Ocean Science (NCCOS), Port of San Diego and NOAA-Fisheries. Selective application of culture methods and gear types are being considered for each AOI based on avoiding adverse effects to EFH supported in each of the AOI's.

The spatial planning approach being explored in San Diego Bay's state waters is somewhat similar to aquaculture development direction in southern California's federal waters offshore (i.e., greater than 3 miles from state lands), where Aquaculture Opportunities Areas (AOAs) are being evaluated through marine spatial planning techniques under the premise of an "ecosystem approach to aquaculture"[71]. To date, two regions of the U.S. West and Gulf Coasts have been identified and spatial analysis has been conducted to evaluate their ability to support sustainable aquaculture development, but the effort does not specifically reference CC or ECC as a focus [72,73].

On the U.S. East and Gulf Coasts, CC policy has not been applied at a regional scale. In most states, there is limited pre-planning for lease sites. For example, in some northern east coast states proponents must undergo a lengthy stakeholder review process to obtain leases or licenses and permits to conduct aquaculture. Rhode Island has a planning rule for coastal salt ponds based on CC principles stating that up to five percent (5%) of the surface area of a water body can be designated for aquaculture [74]. This rule came from negotiation between a diverse group of stakeholders with intent to preserve areas for wild clam harvesting and other recreational activities, while allowing the sustainable aquaculture industry to grow. After a decade of this rule in place, Rhode Island is rapidly approaching their five percent (5%) capacity limit [75]. In Virginia, ECC isn't used on a regular basis, but has been applied in particular permitting situations. In these cases, the Virginia Marine Resources Commission (VMRC) requests an advisory opinion from the Virginia Institute of Marine Science (VIMS) which is then considered in decision-making. In South Carolina and Florida, CC calculations are not mandated, but specifically mentioned in the best management practices documents. In Georgia, there is no mention of CC in state guidelines, although there is mandatory ecological monitoring and relocation might be necessary if "danger is posed to the local ecosystem". Likewise, in Mississippi, state guidelines mandate that activities "must be performed in a manner that would not cause substantial negative impacts to tidal marsh or coastal or marine habitats". In Massachusetts aquaculture licenses can only be issues if it determined that they "will cause no substantial adverse effect on the shellfish or other natural resources of the city or town" where they are proposed [76]. In conclusion, the U.S. has several programs across governmental levels aimed at protecting the environment under which aquaculture is regulated. Though CC concepts are implied or supported in some of these regulations, there is no strict enforcement or programmatic encouragement of an ECC or CC approach, and a CC approach is only occasionally implemented at a local level.

3.2. Small-scale ICES and mediterranean producers

Concepts of ECC or CC in policy among some of the smaller ICES aquaculture producers were also identified during our review and are briefly addressed here. As with larger producing ICES member states, references to CC concepts as conditions of environmental review or underpinning national aquaculture strategy were also highly variable. The Strategic Plan for Portuguese Aquaculture (2014–2020), a country that produced only 0.4% of aquaculture product among ICES states in 2018 [17], targets an increase of production to 25,000 t by 2023 without reference to ECC or CC concepts. This omission is notable, given the extensive research applications of ECC and other CC concepts in the country [77,78]. The Republic of Ireland's National Strategic Plan for Sustainable Aquaculture Development [79] references CC as a factor in the scaling and phasing of individual shellfish farms to build regulatory confidence, "A key factor in determining the scale of potential developments using ecosystem-based management is the concept of CC", which considers environmental limits aimed at avoiding "unacceptable change to the natural ecosystems [79]." However, no regulations require ECC or CC evaluations expressly. Finfish production in the Republic of Ireland is evaluated on a site-specific basis and "environmental CC" is referenced as a plan goal [79]. In practice, Ireland's capacity assessments are focused on limiting potential sea lice infestation through "single bay management plans [79]," similar to the practice in Norway—a single metric environmental indicator approach, not an ECC assessment per se. Denmark, the largest producer of bivalves among the northern Europe and Baltic ICES-member states, does not require any systematic evaluation of ECC or other CC concepts through their Fisheries Act of 2004, as an objective of their national aquaculture policy [80], or through the issuance of licenses by the Danish Directorate of Fisheries. New mariculture finfish farms have been banned in the country since 2019 and tools to assess environmental impacts of existing finfish farms up for permit renewal are fluid, with a focus on advection and dispersion water quality models that do not reflect ECC.

Among the 16 countries surrounding the Mediterranean Sea, aquaculture production is highly variable, as are the state of national aquaculture strategies. Most countries mandate the preparation of an EIA prior to permitting an aquaculture lease, but do not require ECC modeling in that process (except for Italy, Morocco, Israel) (Table 1). Even though most Mediterranean countries do not reference either CC or ECC in their national aquaculture strategy, several of these countries do consider CC in a research context.

3.3. Non-ICES nations

3.3.1. China (37,554,327 t; 40.62 billion USD)

China is the world leader in aquaculture production, an order of magnitude above that of the next leader in production (8220,782 t live weight Indonesia) and value (8.42 billion USD Chile). The Ministry of Agriculture and Rural Affairs of China released a plan for aquaculture development in 2016 [81]. Although the plan has been released at the national level, operations are approved, and licenses issued and implemented, by regional government fishery administrations at or above the county level. The Ministry's guiding outline of the plan identifies the topic "Analysis of Carrying Capacity." Although a definition of CC is not provided, based on the aspects deemed relevant in that section of the plan, as well as the tone of the guiding ideology and basic principles, it suggests a strong focus on ECC, "All Bureaus of Fisheries Management at all administrative levels should evaluate the local CC of tidal flats and aquaculture waters, and the needs of the aquaculture industry to construct the general idea for the development, utilization and protection of aquaculture waters on the tidal flats [81]." Although the implementation of the plan must rely on a scientific assessment of CC, the lack of a clear definition of CC in the plan has resulted in heterogenous methodologies. For example, Ecopath has been used to inform the aquaculture planning in Qingdao [82], and primary production was used to inform aquaculture development in Weihai [83].

3.3.2. Chile (1503,030 t; 8.42 billion USD)

Chile, the third largest producer in the world and responsible for nearly 60,000 employees, produces primarily salmon, rainbow trout, and mussels, followed by oysters, scallops, marine algae, and smaller quantities of other species [18]. The main areas of aquaculture in Chile lie in the southern half of the country, especially in the Patagonian fjord ecosystem, with lesser production along the central and northern coasts. Chile currently has no policy or guidance concerning ECC; however, several strategies have been adopted aimed at sustainable production and harvest of aquaculture crops and reducing and avoiding impacts to aquatic ecosystems [84]. According to current Chilean regulations, the production CC of a site is mainly reflected by the oxygen condition of the sediments beneath it. These regulations focus on several variables contained in an EIA (RAMA; Environmental Regulation for Aquaculture; Supreme Decree 320/2001). The EIA of aquaculture projects in Chile is the main administrative tool for decision-making, and in allowing identification of preventive measures to mitigate negative impacts. However, water body capacities are estimated individually (site by site) and not at broader scales, so no sound CC estimates at a fjord/channel scale are available. Therefore, an important knowledge gap is the

Table 1
Identification of Carrying Capacity Concepts in National and Regional Aquaculture Policy or Strategy. AZA = Allowable Zone for Aquaculture.

Country	National Aquaculture Strategy or Policy)	ECC or CC referenced in national policy or strategy?	ECC or CC Implemented in Research or as Regional or Local Requirement	State of ECC or CC implementation
Major Aquaculture Producing ICES Member States				
Norway	Yes	No	Yes	No express application of ECC models required, but significant environmental monitoring leveraged for finfish farming reflective of CC considerations.
(UK) Northern Ireland	No	No	Yes	EcoWin with ShellSim modeling applied at local licensing level for shellfish, per SMILE program.
(UK) Scotland	Yes	Yes	Yes	Aquaculture carrying capacity is mentioned in National Marine Plan, but plan is not expressly focused on aquaculture strategy.
(UK) England	Yes	Yes	Yes	Research applications, but no specific regional requirements, despite recognition in national policy.
(UK) Wales	Yes	No	No	Welsh National Marine Plan outlines objectives for aquaculture.
France	Yes	Yes	Yes	Not implemented as a matter of marine policy but referenced in freshwater aquaculture considerations. Research applications in the marine.
Spain	Yes	Yes	Yes	Studied but not implemented by any state yet as a requirement.
Canada	No	No	Yes	Identified in provincial requirements of Nova Scotia only.
United States	Yes	No	Yes	Only applied in research applications. No express state or local requirements.
Small-scale ICES and Mediterranean producers				
Albania	Yes	No	No	No guidelines for aquaculture site selection and no use of ECC in current (2014) policy.
Algeria	No	No	Yes	Studied but not used in policy.
Croatia	Yes	Unknown	Unknown	Not applied locally.
Cyprus	Yes	Yes	Unknown	EIA is part of licensing by law, but ECC or CC analysis not required.
Denmark	Yes	No	No	ECC or CC analysis not required or applied currently.
Egypt	Yes	Yes	No	Not applied locally or regionally.
Greece	Yes	No	Yes	As opposed to EIA, ECC is not a formal part of Greek legislation, but is used to some extent to assess farm impact.
Ireland	Yes	Yes	Yes	Identified as policy objective but methods and requirements at local level not defined, except on applicable transboundary operations where outputs of EcoWin and ShellSim modeling under Northern Ireland's SMILE program are spatially relevant.
Israel	Yes	Yes	Yes	ECC models (NPD and Ecospace) used to support spatial planning for aquaculture.
Italy	Yes	No	Yes	ECC is estimated rather than measured to support EIA.
Malta	No	Yes	No	ECC is not required as part of EIA as opposed other criteria.
Montenegro	No	No	No	FAO AZA principals followed for zoning, but ECC is not required.
Morocco	No	Unknown	Yes	

(continued on next page)

Table 1 (*continued*)

Country	National Aquaculture Strategy or Policy)	ECC or CC referenced in national policy or strategy?	ECC or CC Implemented in Research or as Regional or Local Requirement	State of ECC or CC implementation
Slovenia	Yes	Unknown	Unknown	ECC used for planning AZA. Not applied locally.
Sweden	Yes	No	No	Regional and local aquaculture zoning under development.
Tunisia	Yes	Unknown	No	Use of ECC explored by gov. with FAO, current implementation unreported.
Turkey	Yes	No	No	ECC is not part of the criteria for planning AZA.
Non-ICES nations				
China	Yes	Yes	Yes	Local implementation of methods applied variable.
Chile	No	No	Yes	Early research evaluating production capacity elements, but no regional or local requirements.
New Zealand	Yes	No	No	Regional coastal plans specify zoning for aquaculture.
Australia	Yes	No	Yes	Not required in national policy; identified in regional state policy with varying requirements.

application of tools addressing CC for relevant water bodies (fjords, channels etc.). This information could lead to policy in Chile focused on ECC that ensures more sustainable aquatic farming and minimizes risks [84].

In the last 20 years, diseases and harmful algal blooms (HABs) have had major impacts on marine aquaculture in Chile, threatening the sustainable exploitation of bivalves in northern and southern Chile, and central and southern Peru [85,86]. Infectious Salmon Anemia (ISA) is a leading hazard within the Atlantic salmon industry in Chile, as also seen in Norway and other locations farming Atlantic salmon. Changing climate and oceanic environments are also having substantial impacts in Chile, as evidenced by ocean acidification, increasing ocean water temperatures and altered freshwater runoff and their combined or synergistic effects on the growth and survival of cultured species [84]. However, environmental monitoring is expanding rapidly with real-time in-situ and satellite data now available from several sources (http://www.eula.cl/musels). Field observations are currently being augmented in Chile with modeling software (for example, MOM modeling for fish farms [84]) to determine the optimal aquaculture farming volume and to better understand the distribution and concentration of HABs in local waters (https://www.ifop.cl) [87]. These are not formal requirements, however, as applied in Norway, and are reflective more of production capacity applications rather than a broader ECC evaluation.

3.3.3. *New Zealand (116,814 t; 909.4 million USD)*

The value of aquaculture in New Zealand is between that of the United Kingdom and Canada with a strategic plan for aquaculture development, and therefore a good reference for comparison to Atlantic ICES nations. New Zealand's aquaculture industry is based primarily on Greenshell mussels, Chinook salmon and Pacific oysters [88]. Ecological CC assessment is not required as an aquaculture management tool at the national or regional policy level in New Zealand, although it has been recognized as a potentially useful tool for managing areas specifically zoned for aquaculture [89–92]. Any studies that investigated ECC in New Zealand were not commissioned in response to official policy or plans that specifically required ECC to be developed as a management tool. Instead, these studies were commissioned due to an informal recognition of the potential of ECC inform adaptive management frameworks [89–91] used by regional authorities in their management of areas specifically zoned for aquaculture.

The primary resource management legislation in New Zealand with relevance to aquaculture and CC is the Resource Management Act (RMA) which regulates resource development activities on land and in the marine environment (with the exception of sea fisheries) up to 12 nautical miles offshore at the boundary of the Coastal Management Area and the Exclusive Economic Zone [93]. The purpose of the RMA is to promote the sustainable management of natural and physical resources and its' definition of "sustainable management" includes a requirement for the safeguarding of "the life-supporting capacity of air, water, soil and ecosystems". The NZ government is undertaking comprehensive reform of the RMA and will be replaced with new legislation. The RMA provides for a hierarchy of national, regional and local policy statements and planning instruments that, among other things, can set specific management objectives, environmental bottom lines and decision-making criteria relevant to consenting and marine spatial planning. The decision-making system under the RMA requires that the effects of an activity are understood and monitored at the farm scale, and that the effects are "acceptable". The process for determining acceptability often considers the assimilative capacity of the environment, however the methods employed are not consistently applied across farms or regions. Though CC is not explicitly included into governance policy, production CC and assimilative capacity are considered in management approaches.

The New Zealand Coastal Policy Statement (NZCPS), established under section 56 of the RMA, sets up a framework for the management of New Zealand's coastline within which regional government must prepare regional coastal plans [94]. Whereas the RMA provides guiding principles for the sustainable management of activities such as aquaculture, regional coastal plans under the NZCPS set environmental bottom lines for decision makers considering any aquaculture consent application or zoning proposal (Supreme Court Decision: Environmental Defense Society v New Zealand King Salmon, 2012) [95]. In this hierarchical structure, any consented marine farms or established aquaculture management zones must be compliant with conditions set under their consents which, in turn, must reflect the policies and rules of the regional coastal plans and NZCPS. Other than a few regions where aquaculture management areas were established prior to 2011, the regional councils consider the effects of each application on its local environment on a case-by-case basis. Two regional coastal plans that were reviewed make reference to CC with one adopting the term as a descriptor for the maintenance of the essential characteristics of an area (Environment Southland, 2013) and the other making reference to monitoring in the Wilson Bay Marine Farming Zone (WBMFZ: 25 km2) in the Firth of Thames (1100 km2), Waikato [96]. While ECC played a small role in forming the basis of the WBMFZ management framework, with chlorophyll a depletion and benthic indicators monitored as reflections of ECC [97,98], it was considered for scientific merit only and not due to policy requirements.

3.3.4. Australia (94,458 t; 877.03 million USD)

Like New Zealand, Australia's aquaculture production value is between that of the United Kingdom and Canada and has a strategic plan for aquaculture development, making it a good reference for comparison to Atlantic ICES nations. Salmonids dominate aquaculture production in Australia comprising more than half of national production and value [99]. Crustacean and mollusc culture each comprise less than ten percent (10%) of production and value in Australia and are comminated by prawns and oysters respectively [99]. Australia published its National Aquaculture Strategy in 2017, as a follow-on from their National Aquaculture Statement [100,101]. The documents outline an initiative and strategy for increasing production of Australian aquaculture products to 2 billion AUD per year by 2027, in concert with a focus on streamlining regulation, and investing in research, development and extension [101]. Neither document refers to CC as a factor in consideration for the development of the aquaculture industry, but the strategy recognizes that environmental performance is regulated and implemented at the state level, "Responsibility for environmental regulation, including the approval of new aquaculture developments and ongoing monitoring and compliance, is generally a matter for state and Northern Territory governments" [99–101]. In this light, the regulation and consideration of aquaculture CC in the state of South Australia represents a unique example.

Aquaculture policy in the state of South Australia is defined and implemented through the Minister of Agriculture Food and Fisheries and underpinned by the Aquaculture Act of 2001 [102]. This act established zoning as a spatial tool in which areas suitable for aquaculture enterprises could be developed. Within the state of South Australia there are 12 aquaculture zoning policies [102]. For example, the aquaculture zoning policy of the Eastern Spencer Gulf Region of South Australia defines the maximum area allowable to be leased for aquaculture within 9 "prescribed areas" and the class of species that can be cultured within them. The maximum hectares allowable for aquaculture activities is based on, "a conservative measure of the impact the prescribed species may have on the surrounding marine environment" [15]. Though the term CC is not explicitly used in this policy, production CC is effectively described in the policy as a limit of nine percent (9%) of the prescribed areas can be used for aquaculture. However, with the further incorporation of exclusion zones, only about two percent (2%) of the zoned areas are allowed to support aquaculture operations. Five of the zones do not allow supplemental feeding (shellfish only), one (Wallaroo East) defines a maximum biomass of 2000 t, and in the remaining three areas loading is subject to license conditions [15,102].

The Eastern Spencer Gulf policy is notable in that ECC is fundamentally considered in the determination of loading in license conditions. "The biological requirements of the Prescribed Class of species are used to determine the CC for farming of that species within an aquaculture zone (emphasis added) and a conservative maximum hectare limit is set based on this and the underlying benthic environment's assimilative capacity to absorb the resulting nutrients from supplementary fed species. Similarly, the potential for nutrient removal resulting from bivalve bivalves is considered in calculating CC, and limitations on biomass can be conservatively set." As such, this policy represents one of few where CC estimations are expressed as a defined metric. The further differentiation of assimilative capacity considerations of the environment to consider nutrients released from finfish culture, in comparison to nutrient removal as a metric for shellfish CC, reflects a level of policy sophistication around the concept, but the application does not directly conform to the ECC definition adopted in this paper.

The state's policy recognizes that overstocking an area with shellfish is likely to be first recognized by existing growers in the growth rate of their bivalves. As articulated, this policy suggests an interpretation of capacity based more on bivalve production metrics, as opposed to a more holistic ECC context–with the primary impetus towards ensuring any new production does not occur at the detriment of existing operations. Operational conditions are ultimately defined at the level of individual leases and licenses, and monitoring conditions are specified to ensure capacity metrics are followed. For example, models developed by the South Australian Research and Development Institute (SARDI) were used to predict the outputs of a 3000 t of Yellowtail Kingfish operation and understand the CC of the Spencer Gulf marine system and of the Wallaroo East subtidal aquaculture zone [15]. They found that for all model scenarios, none exceeded the Australian National Water Quality Management Strategy (ANWQMS) water quality guidelines for dissolved inorganic nitrogen. These results were corroborated by benthic video surveillance. These types of monitoring provisions, coupled to reference site evaluations, have demonstrated that finfish culture has not caused a significant environmental impact to date in areas where practiced in South Australia [15].

4. Discussion

Though the inclusion of CC concepts in aquaculture development policy is growing, consideration in policy is immature and varied in interpretation. Few policy statements reviewed explicitly mention ECC or CC as an objective, goal, or guiding concept. Where the term is found in policy, national statutes that required CC analysis for aquaculture are rare. An exception is China where "all Bureaus of Fisheries Management at all administrative levels should evaluate the local CC of tidal flats and aquaculture waters" [81]. England and the Republic of Ireland mention CC in their documentations but do not necessarily require CC analysis [32,33]. The US and Canada do not explicitly require ECC, but do have national level policies towards the sustainable development of aquaculture which align with ECC concepts and goals.

Requirements for CC analysis were found primarily at the regional or local levels, with decision making implemented at these levels. National aquaculture policy where CC concepts are at least referenced, such as in Australia, China, France and the United Kingdom, typically defer to regional authorities for decision-making and interpretation of how CC should be evaluated. At the regional and local levels, results indicate that both consideration of CC and interpretation of CC terminology as a strategic concept in aquaculture policy and management is inconsistent. These inconsistencies likely arise due to national policy, where present, deferring to regional management for implementation.

Holistic analyses of ECC, as considered by the ECC definition proposed in this paper, were not expressly defined as an objective in regional or local areas where some form of CC assessment was required or recommended. National plans more often referenced the concept of sustainability of the industry in balance with the environment and community, with regional and/or local plans, spatial planning initiatives, or requirements defining environmental monitoring metrics and thresholds (if defined) as a proxy for ECC. When monitoring metrics were implemented in a region, they included only one or two factors only (e.g., sea lice incidence rate in Norway, chla) and not a comprehensive suite of environmental metrics that are clearly related to ECC. Moreover, these limited monitoring criteria, were not an attempt to avoid unacceptable changes in ecological processes for the full array of desired ecosystem characteristics and services that may be sought by the people in that geography, but rather, designed for a singular target.

In some jurisdictions where CC terminology was absent from policy, evidence of ECC as a priority was still apparent through research projects on ECC supported by local, national and/or EU funding. This disconnection between research applications and policy direction demonstrates a clear science-policy gap at present. For example, the French Ministry (through the Convention cadre Ifremer-DPMA) has funded the project MOCAA (Modeling ecosystem assimilation capacity for a sustainable aquaculture) wherein the main objective is to develop a suite of modeling tools to assess the environmental impact of marine inland and open-water fish farms, based on the evaluation of the biological waste assimilation capacity of the receiving ecosystem in consideration of the characteristics of the receiving environment (e.g., bathymetry, hydrodynamics, sensitivity of benthic ecosystems, etc.) [103]. The development of tools to evaluate "assimilative carrying capacity" is listed as an action plan in the new Strategic Plan for Sustainable Aquaculture 2021–2027. Other French studies developed a modeling tool to evaluate the effect of nitrogen and phosphorus inputs into the Thau Lagoon on oyster stocking densities and oyster performances, and the impact of stocking density on phytoplankton depletion and the ecological status of the lagoon based on metrics of dissolved inorganic nitrogen and phosphorous, and total nitrogen and phosphorous [104,105]. Despite the funding of ECC projects, French policy does not explicitly include ECC.

Other examples that consider interactions of cultured species with the ecosystem [27,106–108] and social CC [109–111] reflect how the consideration of ECC and other CC concepts at the research application scale are anything but 'new'. Furthermore, in Canada there is a distinct disconnect between science and policy with respect to ECC. Our review reflects stronger recognition and value in conducting research that aligns with CC concepts for aquaculture management in some jurisdictions, even though CC is rarely included explicitly in national policies.

When CC terminology in policy is present, explicit use of ECC remains largely absent and there is evidence of inconsistent interpretation of how to evaluate CC. For example, in the East Spencer Gulf region of Australia, analyses typically focused on measuring assimilative capacity or production capacity within regional zones where aquaculture was already considered an allowable use of the areas' waters. These zones were typically addressed through marine spatial planning exercises involving local communities and authorities. Marine spatial planning is a different approach than the modeling tools used by France and Mediterranean aquaculture producers. Similarly, China requires CC but the interpretation and implementation relies on local level and inconsistent methods are applied.

From our review, it is clear a one-size-fits-all approach to considering how ECC should be considered for aquaculture development in all global regions of production is not likely tenable. As this analysis revealed, a holistic ECC approach to permitting is likely not immediately practical within the legal and regulatory context in most of these nations. If the goal is to incorporate ECC in aquaculture permitting, a more legally compatible definition or vision for ECC may be necessary. Furthermore, when attempting to calculate ECC, many of the elements of ECC are not directly comparable within a multi-factor mass balance equation. Notwithstanding this, an opportunity exists to harmonize working definitions for CC that underlie aquaculture policies to facilitate broader incorporation of the concept as a component of national and regional aquaculture policy, and facilitate transboundary cooperation, particularly when water resources influencing aquaculture production are shared. In the absence of comprehensive environmental data needed to thoroughly assess ECC, evaluating specific metrics that are indicative of specific societal values could serve as a more immediate approach to sustainable development and management of aquaculture. Ultimately, the inclusion of ECC in policy and strategic planning can be used as part of a suite of management tools to promote sustainable aquaculture within FAO's Ecological Approach to Aquaculture.

Author statement

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