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ECOLOGICAL CARRYING CAPACITY IN MARICULTURE: CONSIDERATION AND APPLICATION IN
GEOGRAPHIC STRATEGIES AND POLICY

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1 **ABSTRACT**

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

16

17 Keywords: aquaculture, carrying capacity, mariculture, policy, management

18

19 **1. INTRODUCTION**

20

21 Carrying capacity (CC) is a density-dependent concept in applied ecology referencing the
22 maximum population size a species can sustain indefinitely in its environment given its

23 requirements for food, habitat, water and other essential necessities for life [1]. This initial
24 single-species concept of CC has been expanded in other contexts to consider production and
25 ecological community dimensions and scenarios [2]. There are multiple scales at which CC can
26 be interpreted, proposing a hierarchy of population CC (individual species), community CC
27 (multiple interacting species), ecosystem CC (multiple interacting communities), and biosphere
28 CC (multiple interacting ecosystems) [3].

29
30 The concept of CC is fundamental to renewable resource management in commercial fisheries,
31 forestry, and agriculture [4], and has been recently applied in models to evaluate the potential
32 limitations of competition, predation and food supply on the success of native species
33 reintroductions [5]. In most cases, applications in these fields have focused on production
34 capacity for a given species, where the intent is to maximize production (biomass) in a given
35 space. This is true, as well, for most applications in aquaculture, where growth rate is typically
36 the key metric reflective of production capacity limitation. Ecological CC (ECC), however, is a
37 broader concept than production capacity alone, and considers the species' interactions with
38 the environment in concert with the environment's capacity to support other species'
39 presumed use of the same spatial area for their needs [6,7].

40
41 Just as scientists promoted ecosystem-based management in commercial fisheries policy [8],
42 scientists also promote ECC in aquaculture development [9,10]. For this work, the definitions of
43 aquaculture CC are considered as:

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

57

58 This study explores the degree to which ECC concepts have been incorporated into policy,
59 governance or management initiatives throughout a selection of nations with varying degrees
60 of aquaculture development. In this paper, policy is defined as a course of action adopted by
61 the regulatory body or bodies in a given geographic area. Hence, this information gap was
62 explored by taking a top-down review of national and regional aquaculture-related policies,
63 governance, regulations or strategic planning documentation (collectively referred to as “policy
64 documentation”) to evaluate whether ECC or assimilation capacity was referenced, and if so, in
65 what context. The authors are members of the International Council for Exploration of the Seas

66 (ICES) Working Group on Ecological Carrying Capacity for Aquaculture (WGECCA) and have
67 intimate knowledge of aquaculture practices and policies in their representative geographies.

68

69 **2. METHODS**

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

73

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

87

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

104

105 **RESULTS**

106

107 **Major Aquaculture Producing ICES Member States**

108

109 *Norway (1,490,280 t; 7.3 billion USD)*

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

116

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

130

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

147

148 *The United Kingdom (211,026 t; 1.35 billion USD)*

149 The United Kingdom of Great Britain and Northern Ireland (UK) is a nation of four countries:
150 Scotland, England, Northern Ireland, and Wales. Aquaculture is devolved within the UK, which
151 means that each UK country has responsibility for policy, regulation, and management of
152 aquaculture in their jurisdiction. Though the Crown Estate owns a considerable amount of the

153 coastal seabed region, a lease is required for all coastal aquaculture in the UK. Scotland is by far
154 the biggest aquaculture producer, with eighty-two percent (82%) of the total UK aquaculture
155 production, and ninety percent (90%) by value; while production is dominated by Atlantic
156 salmon [25], other notable species produced in the UK countries include mussels and oysters.
157 Although aquaculture is devolved, on occasion, high-level documents and policies are prepared
158 at the UK level, for example, policy documents for the EU where the UK was a member state
159 until leaving in 2020. In 2015, to comply with a request by the European Commission, the UK
160 Multiannual National Plan for the development of sustainable aquaculture was published [26].
161 ECC is mentioned in this document when describing the Sustainable Mariculture in Lough
162 Ecosystems (SMILE) CC models that are used in Northern Ireland to determine ECC for shellfish
163 in sea loughs (coastal inlets) [27]. SMILE is given as an example of an innovative technique, but
164 this approach is not formally applied elsewhere in the UK.

165

166 Since aquaculture is devolved, it is primarily the strategic plans, policies, and regulation within
167 the individual UK countries that influence development of the sector. Scotland's National
168 Marine Plan [28] refers to aquaculture development taking place with "...due regard to the
169 marine environment and CC," (Marine Scotland, 2015 Aquaculture Objective 2), but this does
170 not specifically refer to or mention ECC. The strategic plan for Scottish aquaculture to the year
171 2030 [29], produced by a consortium of industry representatives, does not mention ECC either.
172 However, though not explicitly mentioned in higher level policy documents, there are other
173 aspects of CC assessment in parts of the planning process for both fish and shellfish. For fish
174 farms in Scottish marine waters, all locations are assessed in terms of how much of the capacity

175 of a water body is used already for aquaculture with models for estimation of capacity for
176 nutrient assimilation based on the exchange of water and amount of waste entering the
177 system, using an environmental index [30]. Furthermore, it is a regulatory requirement for fish
178 farms to have a license to discharge waste, and the assessment is based on the capacity of the
179 environment to assimilate wastes and does not explicitly use the term ECC (SEPA, 2019). For
180 shellfish aquaculture, the “biological” CC for coastal locations is a part of the planning
181 application process based on location of the site and its flow characteristics (tidal water flow is
182 not restricted so that food availability for the shellfish becomes an issue) [31] . Though
183 biological CC in this context could be considered to include ECC, it is a better indicator of
184 potential tonnage growth in an area and therefore more of an indicator of production CC.

185

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

193

194 For Northern Ireland, a national aquaculture strategy or policy does not exist and formal
195 requirements to address ECC in planning permission are not stated in the legislation. The
196 Northern Irish Department of Agriculture and Rural Development (DARD, now DAERA) has

197 given the Agri-Food and Biosciences Institute (AFBI) the responsibility for developing and
198 maintaining models that are used to assess the ECC for shellfish production (e.g., SMILE). Such
199 models are actively used to support planning and management decisions for shellfish in
200 Northern Ireland at the bay scale. Furthermore, cumulative impact assessments for sea loughs
201 are produced that assess the likely impact of aquaculture activities on designated features in
202 and adjacent to designated sties. In these assessments, ECC and threshold chlorophyll-a (chl- α)
203 reduction values are calculated to determine impact of new aquaculture site applications [33].

204

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

208

209 *France (150,205 t; 642.6 million USD)*

210 Aquaculture is an important industry in France, mainly due to the production of bivalves, which
211 account for over seventy-five percent (75%) of the country's total production [18]. Integrating
212 the ECC concept in policy as a management tool or permitting requirement for aquaculture
213 development has been under consideration for several years [35]. Since 2015, the authorities
214 have considered modelling tools as relevant to estimate ECC. Further, concepts of CC were
215 included in the National Strategic Aquaculture Plan (Plan stratégique national de
216 développement de l'aquaculture – PSNDA 2018) and in studies to determine the best sites for
217 aquaculture (Meilleurs emplacements aquacoles possibles – MEAP). SISAQUA (Système
218 d'information Spatiale pour l'Aquaculture en Normandie) utilizes AkvaVis, a GIS-based decision

219 support tool, that performs suitability analysis on proposed shellfish farm areas through the
220 utilization of a series of indicators, including production capacity, and can create virtual farm
221 objects to display and interact with models and environmental data [36,37].

222

223 The DSF (Document Stratégique de Façade) specifies the guidelines of the national strategy for
224 the sea and the coastal zones, setting up action plans for the marine environment within the
225 Marine Strategy framework directive (MSFD). Regional Plans for the Development of Marine
226 Aquaculture (Schémas régionaux de développement de l'aquaculture marine – SRDAM) have
227 been introduced in the French Law to modernize agriculture and fisheries (July 27, 2010), “The
228 goals of SRDAMs are to make an inventory of existing aquaculture sites and to identify potential
229 sites suitable for aquaculture, and to conciliate the development of marine aquaculture with
230 other coastal activities. They are expected to allow access to new fish farming sites” [38].

231 SRDAMs have been developed in each region in France and as such represent a spatial zoning
232 strategy for multiple uses. Although SRDAMs included environmental issues when mapping of
233 suitable sites, the concept of CC is not mentioned.

234

235 Fish farming is also subject to ICPE standards (“Installations Classified for the Protection of the
236 Environment”) established under French environmental law (Environmental Code, Article L511-
237 1) for all activities likely to release pollutants and create risks to the environment or for the
238 security and health of residents [39]. The measures to be set up for “limiting potential
239 environmental impacts, such as losses of biodiversity or degradation of water/bottom quality,”
240 are prescribed by the ICPE authorization as a function of the level of production and

241 characteristics of the farming sites. Only farms producing more than 20 t are required to
242 provide an EIA. As an example, to facilitate the procedure, in 2004 the local Corsican authorities
243 asked IFREMER to provide guidelines to facilitate preparation of ICPE requests [40]. These
244 requests mention the importance of evaluating the capacity of receiving ecosystems to
245 assimilate fish farm waste (“assimilative capacity”).

246

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

252

253 *Spain (246,653 t; 495.26 million USD)*

254 Spain is the largest producer of bivalves among ICES member states, and produces a
255 considerable amount of finfish, particularly in its Mediterranean waters [18]. Similar to France,
256 bivalve production comprises about seventy-five percent (75%) of Spain’s total aquaculture
257 production [18]. Spain is divided politically and administratively into autonomous communities,
258 which have the jurisdiction to regulate aquaculture activities, although these regulations must
259 comply with the regulations those of the Spanish central government. Article 4 of the Spanish
260 Law for the Protection of the Marine Environment states that CC studies are needed when
261 planning the use of marine environments. This requirement is acknowledged in the aquaculture
262 strategic plans developed by the central government; however, it is also recognized that these

263 tools are poorly developed in Spain [42]. Further, the annex of the most recent strategic plan
264 released by the central government (2014-2020) states that CC estimations are complex and
265 theoretical when carried out *a priori*, recognizing the role of aquaculture practices and local
266 conditions on these estimations [43]. Accordingly, the guidance of the central government is to
267 apply the precautionary principle and environmental monitoring when detailed information is
268 not available for a theoretical estimation of CC [43].

269
270 There is no specific guidance by the central government on how to apply the precautionary
271 principle or how to estimate CC. Given the context in Spanish documents, the “E” in ECC is
272 implied though not explicitly stated. Although estimations have been carried out for specific
273 areas in different autonomous communities like the Canary Islands and Catalonia, the methods
274 have not been outlined in the strategic plans of those autonomous communities [44]. The
275 limited work on CC estimations is evident in the lack of citations of CC studies in a review of
276 aquaculture research and development initiatives for the period 1998-2012 [45]. However, CC
277 studies were identified as a research and development priority for the period 2014-2020 [46].

278

279 *Canada (160,066 t; 730.4 million USD)*

280 Aquaculture is an important industry in Canada, mostly due to the production of Atlantic
281 salmon and other salmonids in sea cages which in 2020 equated to about 92,972 t in British
282 Columbia and 36,552 t in eastern Canada. Bivalves also comprise a large portion of Canada’s
283 aquaculture production with 6,666 t, primarily oysters, produced in British Columbia and
284 23,365 t, mostly a mix of mussels and oysters, produced in eastern Canada [47]. Although the

285 concept of ECC can be found in Canadian aquaculture policy, it is not implemented or
286 operationalized in a systematic way either at the provincial or federal level. However, the
287 Department of Fisheries and Oceans (DFO), through the Program for Aquaculture Regulatory
288 Research (PARR) [48] and the Aquaculture-Environments Interaction Program (AIEP) [49], funds
289 considerable research on ECC, illustrating the value of the concept to science-based decision-
290 making in the country.

291

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

298

299 Although aquaculture operations are currently subject to regulations as outlined in the *Fisheries*
300 *Act* and *Fishery (General) Regulations*, [50,51] such as prohibition of unlawful “death of fish,”
301 “harmful alteration, disruption or destruction of fish habitat,” and “deposit of a deleterious
302 substance,” with deference to other valid regulations, a forthcoming Aquaculture Act may
303 enhance environmental management [52,53] and “provide a national legislative framework
304 that gives clarity and certainty to the aquaculture industry and other stakeholders across
305 Canada while maintaining environmental protections” [52]. At the National level, the

306 Framework for Aquaculture Risk Management [54] makes explicit reference to the importance
307 of determining the “CC” of sites, although CC is not defined in the framework.

308

309 Regulation is largely focused on sediment quality monitoring below and around finfish net cage
310 sites [55]. Most provinces and territories make only passing reference to the notion of ECC in
311 policy. For example, the Province of New Brunswick offers only vague general terms to notions
312 of ECC by stating that aquaculture licenses may be granted that may be subject to “measures to
313 be taken to minimize the risk of environmental degradation” in the New Brunswick *Aquaculture*
314 *Act* [56] whereas both the finfish and shellfish development strategies stress the importance of
315 environmental, economic, and social sustainability of aquaculture [57,58]. The Province of Nova
316 Scotia sets out general terms in the Fisheries and Coastal Resources Act to “encourage,
317 promote and implement programs that will sustain and improve the fishery, including
318 aquaculture” and to “support the sustainable growth of the aquaculture industry” [59]. This
319 language was later made more explicit to “ensure that the net environmental impact of an
320 aquaculture operation, from startup to decommissioning, does not exceed the ECC of its
321 location”[59]. This was the only explicit mention of ECC by any level of government in Canada
322 that was found in our review. In British Columbia, the Pacific Aquaculture Regulations state that
323 measures must be taken to “minimize the impact of the aquaculture facility’s operations on fish
324 and fish habitat” and “monitor the environmental impact of the aquaculture facility’s
325 operations” [60]. This includes providing a habitat map showing the boundaries of the
326 application area and habitat characteristics (glass sponge complexes, coral complexes, shellfish
327 beds, eel grass beds, rockfish habitat, and kelp beds) as well as benthic organic loading

328 estimates for maximum feed rates based on DEPOMOD outputs when applying for new leases
329 [61]. In contrast, the Newfoundland and Labrador Fishery Regulations [62] make no specific
330 reference to aquaculture operations. In short, management of aquaculture activities in Canada
331 does not have an explicit reliance on the calculation of ECC in any laws or regulations, relying
332 moreover on simple (and difficult to quantify) notions of sustainability and through more
333 general guidance expressed as “not having undue impact”-type statements.

334

335 *United States of America (199,380 t; 369.68 million USD)*

336 Marine aquaculture is a national priority and an increasingly important industry in the United
337 States, with oysters dominating sales value, above that of clams and Atlantic salmon [63,64].

338 Carrying capacity in the United States is not explicitly included in aquaculture permitting
339 requirements at the national level, though a few examples of ECC approaches have been
340 applied for operations in state waters where most aquaculture activities occur and are locally
341 regulated in addition to being subject to national level regulations. While the terms ECC or CC
342 are not mentioned in the National Oceanic and Atmospheric Administration (NOAA) Marine
343 Aquaculture Strategic Plan (2023-2028) [65], the plan articulates four goals: (1) manage
344 sustainably and efficiently, (2) lead science for sustainability, (3) educate and exchange
345 information, and (4) support economic viability and growth [65].

346

347 The high-level goals of NOAA’s strategic plan for aquaculture reflect an emphasis on
348 sustainability, a term open to different interpretations when implemented at a regional and
349 local scale, and this variation is also somewhat reflected through the variety of means by which

350 mariculture operations are ultimately permitted within the jurisdictions where mariculture is
351 practiced. To this point, multiple national level agencies are responsible for regulating
352 aquaculture activities in the aquatic environment, including (but not limited to) the
353 Environmental Protection Agency (EPA) through section 404 of the Clean Water Act (CWA). The
354 U.S. Army Corps of Engineers (USACE) impacts aquaculture through its authority in
355 implementing Section 10 of the Rivers and Harbors Act (RHA). Additional agencies consult on
356 the USACE and EPA actions impacting aquaculture regulations, including NOAA's and the U.S
357 Fish and Wildlife Service's (USFWS) authorities in implementing the U.S. Endangered Species
358 Act (ESA) and Fish and Wildlife Coordination Act (FWCA), and NOAA's Essential Fish Habitat
359 provisions under the Magnuson–Stevens Fishery Conservation and Management Act (MSA).
360 Regarding food safety, the U.S. Department of Agriculture's (USDA) federal oversight of states'
361 health inspection services for aquaculture products and the Food and Drug Administration
362 (FDA) Center for Veterinary Medicine regulation of aquaculture treatment medicines and fish
363 and shellfish pathogens.

364

365 The National Environmental Policy Act (NEPA) is the umbrella under which all federal permitting
366 Actions must comply in the U.S. NEPA requires examination of individual and cumulative
367 impacts from projects, including aquaculture, and often requires Environmental Assessments
368 (EAs), or for large projects, Environmental Impact Statements (EISs). Because the public scoping
369 of proposed projects under NEPA is conducted at the region or district jurisdictional level by the
370 lead federal 'action agency', issues addressed under NEPA can also vary significantly, and no CC
371 or ECC evaluations are required as a matter of national policy. Though some projects have

372 conducted CC assessments in support of NEPA cumulative effects analyses, no robust policy or
373 guidance toward determining such cumulative effects currently exists specifically for
374 mariculture operations.

375

376 Section 10 of the Rivers and Harbors Act of 1899 requires authorization through the USACE for
377 the construction of any structure in or over any navigable water of the United States, including
378 shellfish, macroalgae, and finfish farms. This broad regulatory authority confers upon the
379 USACE the federal action agency status wherein they are required to address NEPA, as well as
380 ensure that other pertinent federal and state laws have been addressed prior to their issuance
381 of an authorization. The most commonly used regulatory mechanism to authorize commercial
382 shellfish aquaculture activities in many production areas in the U.S. is the programmatic
383 Nationwide Permit (NWP) 48 issued by the USACE, which authorizes shellfish mariculture
384 activities deemed to have no more than a minimal individual or cumulative adverse effect on
385 the environment such as the installation of buoys, floats, racks, trays, nets, lines, tubes,
386 containers, and other structures into navigable waters associated with shellfish farming, as well
387 as shellfish seeding, rearing, cultivating, transplanting, and harvesting activities [66]. New NWPs
388 for finfish (NWP 56) and seaweeds (NWP 55) [67] have not been widely used—likely reflecting
389 more of the challenges at the state level in getting these projects implemented than issues with
390 these NWPs per se. The use of these NWP permitting vehicles is up to the discretion of local
391 USACE districts, and they may choose other permitting vehicles such as standard permits if
392 impacts of an activity proposed for authorization using an NWP permitting tool have more than
393 a minimal adverse effect on the environment and to authorize aquaculture activities outside

394 the scope of the NWP program. If the NWP 48 tool is used, for example, regional or project-
395 specific conditions are generally applied by the local USACE district to protect important
396 regional concerns and resources and further ensure that activities eligible under NWP48 “result
397 in no more than minimal individual and cumulative adverse effects on the aquatic
398 environment.” [66].

399

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

412

413 Ultimately, neither the public interest review process nor regulatory requirements associated
414 with developing programmatic permits explicitly identify ECC in policy statements, regulations,
415 or supporting documents. As the issuance of a USACE Section 10 authorization for mariculture

416 implicitly requires compliance with the numerous federal laws previously referenced as well as
417 state and local laws and statutes, concepts of CC or ECC could be captured through “proxy”. In
418 practice, however, our review has not identified where such requirements consistent with our
419 working definition of ECC have been integrated into these other permitting vehicles. For
420 example, in Washington State the EPA-delegated CWA Section 401 certification process is
421 strictly focused on minimizing temporary water quality degradation from turbidity-generating
422 activities in shellfish farm practices and does not consider CC or ECC.

423

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

436

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

452

453 Since the majority of finfish aquaculture is conducted in state waters, it is subject to state and
454 local level management decisions in addition to federal requirements. For example, in
455 Washington State commercial finfish net pen aquaculture on state-owned aquatic lands was
456 recently prohibited through an executive order of the state lands commissioner unrelated to
457 any analysis of CC or ECC [70]. In contrast to the exclusion of opportunities for future finfish
458 aquaculture in the Puget Sound, an approach is under consideration in San Diego Bay to identify

459 aquaculture opportunities. Discretely zoned Areas of Interest (AOI) within and outside of the
460 Bay are being evaluated for their interaction with Essential Fish Habitat (EFH), protected
461 species, and other ocean uses by the National Centers for Coastal Ocean Science (NCCOS), Port
462 of San Diego and NOAA-Fisheries. Selective application of culture methods and gear types are
463 being considered for each AOI based on avoiding adverse effects to EFH supported in each of
464 the AOI's.

465

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

474

475 On the U.S. East and Gulf Coasts, CC policy has not been applied at a regional scale. In most
476 states, there is limited pre-planning for lease sites. For example, in some northern east coast
477 states proponents must undergo a lengthy stakeholder review process to obtain leases or
478 licenses and permits to conduct aquaculture. Rhode Island has a planning rule for coastal salt
479 ponds based on CC principles stating that up to five percent (5%) of the surface area of a water
480 body can be designated for aquaculture [74]. This rule came from negotiation between a

481 diverse group of stakeholders with intent to preserve areas for wild clam harvesting and other
482 recreational activities, while allowing the sustainable aquaculture industry to grow. After a
483 decade of this rule in place, Rhode Island is rapidly approaching their five percent (5%) capacity
484 limit [75]. In Virginia, ECC isn't used on a regular basis, but has been applied in particular
485 permitting situations. In these cases, the Virginia Marine Resources Commission (VMRC)
486 requests an advisory opinion from the Virginia Institute of Marine Science (VIMS) which is then
487 considered in decision-making. In South Carolina and Florida, CC calculations are not mandated,
488 but specifically mentioned in the best management practices documents. In Georgia, there is
489 no mention of CC in state guidelines, although there is mandatory ecological monitoring and
490 relocation might be necessary if "danger is posed to the local ecosystem". Likewise, in
491 Mississippi, state guidelines mandate that activities "must be performed in a manner that
492 would not cause substantial negative impacts to tidal marsh or coastal or marine habitats". In
493 Massachusetts aquaculture licenses can only be issued if it determined that they "will cause no
494 substantial adverse effect on the shellfish or other natural resources of the city or town" where
495 they are proposed [76]. In conclusion, the U.S. has several programs across governmental levels
496 aimed at protecting the environment under which aquaculture is regulated. Though CC
497 concepts are implied or supported in some of these regulations, there is no strict enforcement
498 or programmatic encouragement of an ECC or CC approach, and a CC approach is only
499 occasionally implemented at a local level.

500

501 **Small-scale ICES and Mediterranean producers**

502

503 Concepts of ECC or CC in policy among some of the smaller ICES aquaculture producers were
504 also identified during our review and are briefly addressed here. As with larger producing ICES
505 member states, references to CC concepts as conditions of environmental review or
506 underpinning national aquaculture strategy were also highly variable. The Strategic Plan for
507 Portuguese Aquaculture (2014-2020), a country that produced only 0.4 percent (0.4 %) of
508 aquaculture product among ICES states in 2018 [17], targets an increase of production to
509 25,000 t by 2023 without reference to ECC or CC concepts. This omission is notable, given the
510 extensive research applications of ECC and other CC concepts in the country [77,78]. The
511 Republic of Ireland’s National Strategic Plan for Sustainable Aquaculture Development [79]
512 references CC as a factor in the scaling and phasing of individual shellfish farms to build
513 regulatory confidence, “A key factor in determining the scale of potential developments using
514 ecosystem-based management is the concept of CC”, which considers environmental limits
515 aimed at avoiding “unacceptable change to the natural ecosystems [79].” However, no
516 regulations require ECC or CC evaluations expressly. Finfish production in the Republic of
517 Ireland is evaluated on a site-specific basis and “environmental CC” is referenced as a plan goal
518 [79]. In practice, Ireland’s capacity assessments are focused on limiting potential sea lice
519 infestation through “single bay management plans [79],” similar to the practice in Norway—a
520 single metric environmental indicator approach, not an ECC assessment *per se*. Denmark, the
521 largest producer of bivalves among the northern Europe and Baltic ICES-member states, does
522 not require any systematic evaluation of ECC or other CC concepts through their Fisheries Act of
523 2004, as an objective of their national aquaculture policy [80], or through the issuance of

524 licenses by the Danish Directorate of Fisheries. New mariculture finfish farms have been
525 banned in the country since 2019 and tools to assess environmental impacts of existing finfish
526 farms up for permit renewal are fluid, with a focus on advection and dispersion water quality
527 models that do not reflect ECC.

528

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

535

536 **Non-ICES nations**

537

538 *China (37,554,327 t; 40.62 billion USD)*

539 China is the world leader in aquaculture production, an order of magnitude above that of the
540 next leader in production (8,220,782 t live weight Indonesia) and value (*8.42 billion USD* Chile).

541 The Ministry of Agriculture and Rural Affairs of China released a plan for aquaculture
542 development in 2016 [81]. Although the plan has been released at the national level,
543 operations are approved, and licenses issued and implemented, by regional government fishery
544 administrations at or above the county level. The Ministry's guiding outline of the plan
545 identifies the topic "Analysis of Carrying Capacity." Although a definition of CC is not provided,

546 based on the aspects deemed relevant in that section of the plan, as well as the tone of the
547 guiding ideology and basic principles, it suggests a strong focus on ECC, “All Bureaus of Fisheries
548 Management at all administrative levels should evaluate the local CC of tidal flats and
549 aquaculture waters, and the needs of the aquaculture industry to construct the general idea for
550 the development, utilization and protection of aquaculture waters on the tidal flats [81].”
551 Although the implementation of the plan must rely on a scientific assessment of CC, the lack of
552 a clear definition of CC in the plan has resulted in heterogenous methodologies. For example,
553 Ecopath has been used to inform the aquaculture planning in Qingdao [82], and primary
554 production was used to inform aquaculture development in Weihai [83].

555

556 *Chile (1,503,030 t; 8.42 billion USD)*

557 Chile, the third largest producer in the world and responsible for nearly 60,000 employees,
558 produces primarily salmon, rainbow trout, and mussels, followed by oysters, scallops, marine
559 algae, and smaller quantities of other species [18]. The main areas of aquaculture in Chile lie in
560 the southern half of the country, especially in the Patagonian fjord ecosystem, with lesser
561 production along the central and northern coasts. Chile currently has no policy or guidance
562 concerning ECC; however, several strategies have been adopted aimed at sustainable
563 production and harvest of aquaculture crops and reducing and avoiding impacts to aquatic
564 ecosystems [84]. According to current Chilean regulations, the production CC of a site is mainly
565 reflected by the oxygen condition of the sediments beneath it. These regulations focus on
566 several variables contained in an EIA (RAMA; Environmental Regulation for Aquaculture;
567 Supreme Decree 320/2001). The EIA of aquaculture projects in Chile is the main administrative

568 tool for decision-making, and in allowing identification of preventive measures to mitigate
569 negative impacts. However, water body capacities are estimated individually (site by site) and
570 not at broader scales, so no sound CC estimates at a fjord/channel scale are available.
571 Therefore, an important knowledge gap is the application of tools addressing CC for relevant
572 water bodies (fjords, channels etc.). This information could lead to policy in Chile focused on
573 ECC that ensures more sustainable aquatic farming and minimizes risks [84].

574

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

590

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

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

603

604 The primary resource management legislation in New Zealand with relevance to aquaculture
605 and CC is the Resource Management Act (RMA) which regulates resource development
606 activities on land and in the marine environment (with the exception of sea fisheries) up to 12
607 nautical miles offshore at the boundary of the Coastal Management Area and the Exclusive
608 Economic Zone [93]. The purpose of the RMA is to promote the sustainable management of
609 natural and physical resources and its' definition of "sustainable management" includes a
610 requirement for the safeguarding of "the life-supporting capacity of air, water, soil and
611 ecosystems". The NZ government is undertaking comprehensive reform of the RMA and will be

612 replaced with new legislation. The RMA provides for a hierarchy of national, regional and local
613 policy statements and planning instruments that, among other things, can set specific
614 management objectives, environmental bottom lines and decision-making criteria relevant to
615 consenting and marine spatial planning. The decision-making system under the RMA requires
616 that the effects of an activity are understood and monitored at the farm scale, and that the
617 effects are “acceptable”. The process for determining acceptability often considers the
618 assimilative capacity of the environment, however the methods employed are not consistently
619 applied across farms or regions. Though CC is not explicitly included into governance policy,
620 production CC and assimilative capacity are considered in management approaches.

621

622 The New Zealand Coastal Policy Statement (NZCPS), established under section 56 of the RMA,
623 sets up a framework for the management of New Zealand’s coastline within which regional
624 government must prepare regional coastal plans [94]. Whereas the RMA provides guiding
625 principles for the sustainable management of activities such as aquaculture, regional coastal
626 plans under the NZCPS set environmental bottom lines for decision makers considering any
627 aquaculture consent application or zoning proposal (Supreme Court Decision: Environmental
628 Defense Society v New Zealand King Salmon, 2012) [95]. In this hierarchical structure, any
629 consented marine farms or established aquaculture management zones must be compliant
630 with conditions set under their consents which, in turn, must reflect the policies and rules of
631 the regional coastal plans and NZCPS. Other than a few regions where aquaculture
632 management areas were established prior to 2011, the regional councils consider the effects of
633 each application on its local environment on a case-by-case basis. Two regional coastal plans

634 that were reviewed make reference to CC with one adopting the term as a descriptor for the
635 maintenance of the essential characteristics of an area (Environment Southland, 2013) and the
636 other making reference to monitoring in the Wilson Bay Marine Farming Zone (WBMFZ: 25
637 km²) in the Firth of Thames (1,100 km²), Waikato [96]. While ECC played a small role in forming
638 the basis of the WBMFZ management framework, with chlorophyll *a* depletion and benthic
639 indicators monitored as reflections of ECC [97,98], it was considered for scientific merit only
640 and not due to policy requirements.

641

642 *Australia (94,458 t; 877.03 million USD)*

643 Like New Zealand, Australia's aquaculture production value is between that of the United
644 Kingdom and Canada and has a strategic plan for aquaculture development, making it a good
645 reference for comparison to Atlantic ICES nations. Salmonids dominate aquaculture production
646 in Australia comprising more than half of national production and value [99]. Crustacean and
647 mollusc culture each comprise less than ten percent (10%) of production and value in Australia
648 and are dominated by prawns and oysters respectively [99]. Australia published its National
649 Aquaculture Strategy in 2017, as a follow-on from their National Aquaculture Statement
650 [100,101]. The documents outline an initiative and strategy for increasing production of
651 Australian aquaculture products to 2 billion AUD per year by 2027, in concert with a focus on
652 streamlining regulation, and investing in research, development and extension [101]. Neither
653 document refers to CC as a factor in consideration for the development of the aquaculture
654 industry, but the strategy recognizes that environmental performance is regulated and
655 implemented at the state level, "Responsibility for environmental regulation, including the

656 approval of new aquaculture developments and ongoing monitoring and compliance, is
657 generally a matter for state and Northern Territory governments” [99–101]. In this light, the
658 regulation and consideration of aquaculture CC in the state of South Australia represents a
659 unique example.

660

661 Aquaculture policy in the state of South Australia is defined and implemented through the
662 Minister of Agriculture Food and Fisheries and underpinned by the Aquaculture Act of 2001
663 [102]. This act established zoning as a spatial tool in which areas suitable for aquaculture
664 enterprises could be developed. Within the state of South Australia there are 12 aquaculture
665 zoning policies [102]. For example, the aquaculture zoning policy of the Eastern Spencer Gulf
666 Region of South Australia defines the maximum area allowable to be leased for aquaculture
667 within 9 “prescribed areas” and the class of species that can be cultured within them. The
668 maximum hectares allowable for aquaculture activities is based on, “a conservative measure of
669 the impact the prescribed species may have on the surrounding marine environment” [15].
670 Though the term CC is not explicitly used in this policy, production CC is effectively described in
671 the policy as a limit of nine percent (9%) of the prescribed areas can be used for aquaculture.
672 However, with the further incorporation of exclusion zones, only about two percent (2%) of the
673 zoned areas are allowed to support aquaculture operations. Five of the zones do not allow
674 supplemental feeding (shellfish only), one (Wallaroo East) defines a maximum biomass of 2,000
675 t, and in the remaining three areas loading is subject to license conditions [15,102].

676

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

689

690 The state’s policy recognizes that overstocking an area with shellfish is likely to be first
691 recognized by existing growers in the growth rate of their bivalves. As articulated, this policy
692 suggests an interpretation of capacity based more on bivalve production metrics, as opposed to
693 a more holistic ECC context--with the primary impetus towards ensuring any new production
694 does not occur at the detriment of existing operations. Operational conditions are ultimately
695 defined at the level of individual leases and licenses, and monitoring conditions are specified to
696 ensure capacity metrics are followed. For example, models developed by the South Australian
697 Research and Development Institute (SARDI) were used to predict the outputs of a 3,000 t of
698 Yellowtail Kingfish operation and understand the CC of the Spencer Gulf marine system and of

699 the Wallaroo East subtidal aquaculture zone [15]. They found that for all model scenarios, none
700 exceeded the Australian National Water Quality Management Strategy (ANWQMS) water
701 quality guidelines for dissolved inorganic nitrogen. These results were corroborated by benthic
702 video surveillance. These types of monitoring provisions, coupled to reference site evaluations,
703 have demonstrated that finfish culture has not caused a significant environmental impact to
704 date in areas where practiced in South Australia [15].

705

706 **DISCUSSION**

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

717

718 Requirements for CC analysis were found primarily at the regional or local levels, with decision
719 making implemented at these levels. National aquaculture policy where CC concepts are at
720 least referenced, such as in Australia, China, France and the United Kingdom, typically defer to

721 regional authorities for decision-making and interpretation of how CC should be evaluated. At
722 the regional and local levels, results indicate that both consideration of CC and interpretation of
723 CC terminology as a strategic concept in aquaculture policy and management is inconsistent.
724 These inconsistencies likely arise due to national policy, where present, deferring to regional
725 management for implementation.

726

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

739

740 In some jurisdictions where CC terminology was absent from policy, evidence of ECC as a
741 priority was still apparent through research projects on ECC supported by local, national and/or
742 EU funding. This disconnection between research applications and policy direction

743 demonstrates a clear science-policy gap at present. For example, the French Ministry (through
744 the Convention cadre Ifremer-DPMA) has funded the project MOCAA (Modeling ecosystem
745 assimilation capacity for a sustainable aquaculture) wherein the main objective is to develop a
746 suite of modeling tools to assess the environmental impact of marine inland and open-water
747 fish farms, based on the evaluation of the biological waste assimilation capacity of the receiving
748 ecosystem in consideration of the characteristics of the receiving environment (e.g.,
749 bathymetry, hydrodynamics, sensitivity of benthic ecosystems, etc.) [103]. The development of
750 tools to evaluate “assimilative carrying capacity” is listed as an action plan in the new Strategic
751 Plan for Sustainable Aquaculture 2021-2027. Other French studies developed a modeling tool
752 to evaluate the effect of nitrogen and phosphorus inputs into the Thau Lagoon on oyster
753 stocking densities and oyster performances, and the impact of stocking density on
754 phytoplankton depletion and the ecological status of the lagoon based on metrics of dissolved
755 inorganic nitrogen and phosphorous, and total nitrogen and phosphorous [104,105]. Despite
756 the funding of ECC projects, French policy does not explicitly include ECC.

757

758 Other examples that consider interactions of cultured species with the ecosystem [27,106–
759 108] and social CC [109–111] reflect how the consideration of ECC and other CC concepts at the
760 research application scale are anything but ‘new’. Furthermore, in Canada there is a distinct
761 disconnect between science and policy with respect to ECC. Our review reflects stronger
762 recognition and value in conducting research that aligns with CC concepts for aquaculture
763 management in some jurisdictions, even though CC is rarely included explicitly in national
764 policies.

765

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

775

776 From our review, it is clear a one-size-fits-all approach to considering how ECC should be
777 considered for aquaculture development in all global regions of production is not likely tenable.
778 As this analysis revealed, a holistic ECC approach to permitting is likely not immediately
779 practical within the legal and regulatory context in most of these nations. If the goal is to
780 incorporate ECC in aquaculture permitting, a more legally compatible definition or vision for
781 ECC may be necessary. Furthermore, when attempting to calculate ECC, many of the elements
782 of ECC are not directly comparable within a multi-factor mass balance equation.
783 Notwithstanding this, an opportunity exists to harmonize working definitions for CC that
784 underlie aquaculture policies to facilitate broader incorporation of the concept as a component
785 of national and regional aquaculture policy, and facilitate transboundary cooperation,
786 particularly when water resources influencing aquaculture production are shared. In the

787 absence of comprehensive environmental data needed to thoroughly assess ECC, evaluating
788 specific metrics that are indicative of specific societal values could serve as a more immediate
789 approach to sustainable development and management of aquaculture. Ultimately, the
790 inclusion of ECC in policy and strategic planning can be used as part of a suite of management
791 tools to promote sustainable aquaculture within FAO's Ecological Approach to Aquaculture.

792

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800

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1173 Table 1. Identification of Carrying Capacity Concepts in National and Regional Aquaculture

1174 Policy or Strategy. AZA = Allowable Zone for Aquaculture.

1175

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	ECC used for planning AZA.
Slovenia	Yes	Unknown	Unknown	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.