

1 Quo Vadimus  
2 **Mind the gap between ICES nations' future seafood consumption and**  
3 **aquaculture production**  
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5 Halley E. Froehlich<sup>1,2</sup>, Jessica Couture<sup>3</sup>, Lynne Falconer<sup>4</sup>, Gesche Krause<sup>5</sup>, James A. Morris<sup>6</sup>, Montse  
6 Perez<sup>7</sup>, Grant D. Stentiford<sup>8,9</sup>, Harri Vehviläinen<sup>10</sup>, Benjamin S. Halpern<sup>3,11</sup>  
7

8 <sup>1</sup> Environmental Studies, University of California, Santa Barbara, Santa Barbara, CA, USA 93106  
9

10 <sup>2</sup> Ecology, Evolution, & Marine Biology, University of California, Santa Barbara, Santa Barbara, CA, USA 93106  
11

12 <sup>3</sup> Bren School of Environmental Science & Management, University of California, Santa Barbara, Santa Barbara,  
13 CA, USA 93106  
14

15 <sup>4</sup> Institute of Aquaculture, University of Stirling, Stirling, FK9 4LA, UK  
16

17 <sup>5</sup> Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Am Handelshafen 12, 27570  
18 Bremerhaven, Germany  
19

20 <sup>6</sup> Marine Spatial Ecology Division, National Centers for Coastal Ocean Science, National Ocean Service,  
21 NOAA 101 Pivers Island Rd., Beaufort, North Carolina USA  
22

23 <sup>7</sup> AQUACOV, Instituto Español de Oceanografía, Centro Oceanográfico de Vigo, 36390 Vigo, Spain  
24

25 <sup>8</sup> International Centre of Excellence for Aquatic Animal Health, Centre for Environment, Fisheries and Aquaculture  
26 Science (Cefas), Weymouth Laboratory, Weymouth, Dorset DT4 8UB, UK  
27

28 <sup>9</sup> Centre for Sustainable Aquaculture Futures, Biosciences, University of Exeter, Stocker Road, Exeter EX4 4PY,  
29 UK  
30

31 <sup>10</sup> Aquatic Production Systems, Natural Resources Institute Finland (Luke), Korkeakoulunkatu 7, FI-33720  
32 Tampere, Finland  
33

34 <sup>11</sup> National Center for Ecological Analysis & Synthesis, University of California, Santa Barbara, Santa Barbara, CA,  
35 USA 93103  
36

37 Corresponding author: H.E. Froehlich (hefroehlich@ucsb.edu)  
38

39 **Abstract**

40

41 As the human population grows and climate change threatens the stability of seafood sources, we face the  
42 key question of how we will meet increasing demand, and do so sustainably. Many of the 20 International  
43 Council for the Exploration of the Sea (ICES) member nations have been global leaders in the protection  
44 and management of wild fisheries, but to date, most of these nations have not developed robust  
45 aquaculture industries. Using existing data and documentation of aquaculture targets from government  
46 and industry, we compiled and analyzed past trends in farmed and wild seafood production and  
47 consumption in ICES nations, as well as the potential and need to increase aquaculture production by  
48 2050. We found that the majority of ICES nations lack long-term strategies for aquaculture growth, with  
49 an increasing gap between future domestic production and consumption—resulting in a potential 7  
50 million tonne domestic seafood deficit by 2050, which would be supplemented by imports from other  
51 countries (e.g., China). We also found recognition of climate change as a concern for aquaculture growth,  
52 but little on what that means for meeting production goals. Our findings highlight the need to prioritize  
53 aquaculture policy to set more ambitious domestic production goals and/or improve sustainable sourcing  
54 of seafood from other parts of the world, with explicit recognition and strategic planning for climate  
55 change affecting such decisions. In short, there is a need for greater concerted effort by ICES member  
56 nations to address aquaculture’s long-term future prospects.

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58 Keywords: aquatic farming; food security; horizon scanning; adaptive planning

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## 60 Introduction

61  
62 Fisheries have long been the primary source of aquatic food production, with commercial or industrial  
63 fishing dramatically increasing during the early 20<sup>th</sup> century (Worm *et al.*, 2009; Watson and Tidd, 2018).  
64 It was however the lack of effective management during the rise of industrial scale fishing that led to the  
65 overharvest and collapse of many stocks. Yet, policy reform and associated fisheries management, largely  
66 initiated during the mid-1990s, demonstrated effective ways to recover and sustain several of the major  
67 fisheries (Worm *et al.*, 2009; Hilborn and Ovando, 2014; Costello *et al.*, 2016; Hilborn *et al.*, 2020).  
68 Some of the leaders in fisheries research and management are nations of the International Council for the  
69 Exploration of the Sea (ICES)—currently 20 nations, generally aligned with the convention to study and  
70 disseminate research pertaining to the Northern Atlantic Ocean and the resources therein (Went, 1972).  
71 However, these success stories belie an important fact: while the majority of assessed fisheries appear  
72 sustainable, meeting the growing demand and food security need for seafood has not and cannot be met  
73 without other forms of seafood production (freshwater and marine), in particular aquaculture—now  
74 accounting for approximately half of all global aquatic production (FAO, 2018a).

75  
76 During the earlier years of large-scale industrial fishing, the nations of ICES were major global  
77 contributors to both the consumption and production of seafood (Figure 1) and eventually recognized the  
78 need for scientific assessments and management of wild-capture fisheries (Went, 1972), but largely  
79 overlooked aquaculture. However, as the human population has expanded to 7.7 billion people, changes  
80 in the availability and access to seafood have influenced the contribution of ICES nations to global  
81 seafood production and consumption (Figure 1). First, improved fisheries management has recovered  
82 many stocks, but globally catches have stagnated in the absence of global reform adoption, particularly in  
83 coastal developing nations more dependent on seafood for food security (FAO, 2018a). As a result, a  
84 major factor contributing to the change in seafood production came from countries focused on fishing *and*  
85 aquaculture development. China in particular has put tremendous effort towards increasing seafood  
86 production over the last 30 years, now accounting for ca. 60% of all aquaculture production and is the  
87 largest net exporter of seafood globally (Szuwalski *et al.*, 2020). However, such efforts have come with  
88 large, negative environmental consequences (e.g., habitat degradation, invasive species, pollution), which  
89 the country now hopes to address, to some extent, through reduced fishing (catch and effort) and  
90 increased polyculture and offshore aquaculture expansion (Szuwalski *et al.*, 2020)—though  
91 socioecological standards may still be comparatively more lax (Cao *et al.*, 2015). Importantly, the growth  
92 in aquaculture production occurred in parallel with global trade, transporting wild and farmed seafood  
93 products all over the world (Gephart and Pace, 2015). As a result, ICES nations now account for a much

94 smaller proportion of global consumers and producers (Figure 1). Yet, total demand for seafood continues  
95 to increase in ICES countries and around the world, as well as the associated food security issues therein  
96 (FAO, 2018a).

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98 Unanswered is the fundamental question of how ICES nations will continue to develop sustainable  
99 aquaculture industries to help meet their own expected seafood needs and contribute to the global market;  
100 an issue that is likely to become even more relevant with increased uncertainty and security of ocean  
101 resources in the face of climate change. Challenges to sustainable seafood production will continue to be  
102 exacerbated under a changing climate. For fisheries, many wild-stock ranges are expected to shift out of  
103 originally managed extents to track ocean temperature (Pecl *et al.*, 2017; Oremus *et al.*, 2020; Pinsky *et al.*, 2020) and productivity and recruitment declines may lower overall productivity of a system (Britten  
104 *et al.*, 2015; Free *et al.*, 2019). For aquaculture, marine production faces similar temperature and  
105 acidifying pressures as their wild counterparts, while inland production is combating flooding and sea  
106 level rise, while compromising the health and infrastructure of cultured systems (Peterson *et al.*, 2017;  
107 Ahmed *et al.*, 2018; FAO, 2018b; Froehlich *et al.*, 2018). While there is recognition that climate change  
108 threats to aquatic systems will likely grow, the longer-term strategic adaptive planning, especially for  
109 aquaculture, still appears nascent (FAO, 2018b; Hollowed *et al.*, 2019; Reid *et al.*, 2019).

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112 Given the history and relevance of seafood for ICES countries, we ask what role sustainable aquaculture  
113 may play in these countries in the future, which includes consideration of trade and climate change.  
114 Drawing on existing quantitative and qualitative data sources, we explored the relative trends and  
115 forward-looking strategies for aquaculture among the respective nations who were, and continue to be,  
116 leaders in fisheries science and management. First, we assessed the change in aquatic sources of the  
117 collective and individual 20 ICES nations by comparing the general trends (tonnage and interannual  
118 variation) of wild capture versus aquaculture production over the last five decades, paying particular  
119 attention to the top producing countries. Next, to determine how future aquaculture goals of the ICES  
120 members matched the prevailing trends, we compiled documents and sources from government and  
121 industry on proposed growth targets for each country since 2013. From the references, we extracted set  
122 goals, if any, for future aquaculture production (year, tonnage, and type). We then modelled the potential  
123 2050 aquaculture increases (based on the growth targets) to that of the possible total seafood consumption  
124 (i.e., demand) over the same time period, noting years of surplus or deficit. Recognizing that seafood  
125 from other countries fills domestic deficits, we highlight the top non-ICES seafood-trade partners,  
126 aquaculture production in those countries, and the implications for sustainable seafood. Lastly, we sought  
127 evidence of a base-level consideration of climate change in relation to future ICES' goals, given the

128 increasing recognition climate change related impacts may challenge aquaculture globally (FAO, 2018b).  
129 In that, we looked for mention of ‘climate change’ within the associated references. Based on the results,  
130 we reflect on the future of seafood for the ICES nations and food system accountability in a global  
131 market, including adaptive strategies under a changing climate.

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### 133 **Methods**

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135 We used United Nations’ Food and Agriculture Organization (FAO) data (production and food supply) to  
136 compare general trends of production and variation of wild capture and aquaculture (freshwater and  
137 marine; excludes aquatic plants) of the 20 ICES’ nations over the last five decades (FAO, 2013, 2018a).  
138 First, we assessed how the percent of contribution of ICES total (in tonnes) consumption and production  
139 (capture plus aquaculture) has changed over time relative to global trends. Finding declining trends,  
140 which suggests a smaller role in global seafood overall, we next assessed which ICES nations contributed  
141 to the past and more recent production of wild and farmed seafood, and the evenness of that tonnage per  
142 country by comparing the coefficient of variation (CV) of intercountry production. This helped highlight  
143 if aquaculture is more or less skewed than fisheries between the ICES nations, similar to global trends.  
144 Lastly, we compared the yearly percent change in capture and aquaculture production and the probability  
145 [binomial generalized linear model, log link: positive change (0,1) ~ year + type(capture, aquaculture) +  
146 year:type] of seeing more increases instead of declines over time in the respective systems.

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148 For assessing future aquaculture goals, we compiled information (government and industry) on proposed  
149 growth targets for the ICES member nations since 2013. First, we leveraged the ICES members of the  
150 Working Group on Scenario Planning on Aquaculture, from which this project emerged, to provide  
151 known documents or sources about their respective countries and any addition information on the other  
152 nations (i.e., expert knowledge). One review document we heavily leveraged, which provided detailed  
153 reference to aquaculture targets for EU countries (no. countries =12), was O’Hagan *et al.*, 2017. We  
154 paired the expert-elicited collection with Google™ searches for references on any remaining countries of  
155 interest. The search terms included *country name* and *aquaculture, future, horizon, and/or 2050*. We then  
156 read the sources of information (N = 20) and manually extracted future aquaculture production goals  
157 (year, tonnage, and type, such as freshwater, marine, taxa) for the 20 member nations. If we found  
158 multiple goals for a given country for the same time periods, we took the mean of the values. From both  
159 experts and internet searchers, we incorporated industry reported values for nations in which we could not  
160 find explicit government targets (Iceland) or were cited by the government (Scotland). Another important  
161 note, the UK as a whole is the ICES member, but the aquaculture target is the composite of Scotland,

162 England, Wales, and Northern Ireland and a 2030 report (not included) was in progress during the time of  
163 this study. We also noted if the associated references mention ‘climate change,’ which we used as a basic  
164 indicator of recognition and possible consideration for aquaculture growth. All documents and sources  
165 (Supplementary Data Table 1) not in English were either translated by an ICES working group member or  
166 Google™ Translate. While our approach resulted in information on aquaculture growth for every ICES  
167 country, we may have missed other, less accessible documents or sources due to language barriers, policy  
168 relevance, or limits on information sharing. In particular, goals from nations outside of the EU, Norway,  
169 USA, and Canada are likely less certain.

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171 To test the feasibility and trajectory of ICES seafood production and consumption, we combined and fit  
172 models to past and future FAO aquaculture data (production and consumption) and the extracted future  
173 values. Comparing linear, exponential, and second order polynomial models using corrected Akaike  
174 Information Criterion (AICc) for model selection (Burnham and Anderson, 2002), we found the  
175 significant exponential model ( $\log(\text{tonnage}) \sim \text{Year}$ ) best described total aquaculture (tonnes) over time  
176 with and without inclusion of the future production values. We then compared future production goals to  
177 the potential total consumption trend – assuming a statistically significant linear increase in total  
178 consumption to 2050 – to calculate the *seafood production deficit* (i.e., total production - total  
179 consumption). We focus on the ‘domestic deficit’ because seafood imported from other countries  
180 (external to ICES) has different environment and policy implications (e.g., displaced socioecological  
181 burden). All data collection, modelling and figures were produced with Microsoft™ Excel and R v3.6.1 (R  
182 Core Team, 2019).

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184 In addition to assessing the ‘domestic deficit,’ we compiled the top import-seafood trade ICES partners  
185 (USD\$) and the production of aquaculture and wild fisheries to qualitatively compare the dependence on  
186 other, potentially less regulated countries for seafood (FAO, 2018a). We gathered the country-specific  
187 trade information from ResourceTrade.Earth, which is supported by the Chatham House Resource Trade  
188 Database (CHRTD) and sourced from the United Nations Commodity Trade Statistics Database (UN  
189 Comtrade) by the United Nations Statistics Division.

## 191 **Results and Discussion**

### 193 *Past trends of catch and production*

194

195 Total aquaculture among the ICES countries is dwarfed by the volume of wild capture fisheries  
196 production (Figure 2a). As of 2015, eight nations (Canada, Denmark, Iceland, Norway, Russia, Spain,  
197 UK, and US) accounted for nearly all (87%) of the total ICES wild capture (total catch = 16.8 million  
198 tonnes), and these same countries contributed the vast majority of aquaculture production (88%) among  
199 the 20 countries (total aquaculture = 3.1 million tonnes; Figure 2b). However, the contribution of tonnage  
200 of wild capture is much more evenly distributed (country CV = 0.83) among the eight countries compared  
201 to aquaculture production (country CV = 1.31). For example, in 2015 the United States landed the most  
202 (by volume) with ca. 5 million tonnes (majority from Alaska pollock *Theragra chalcogramma*), or 26%  
203 of the total ICES catches. In comparison, Norway was the top aquaculture producing country (nearly all  
204 Atlantic salmon *Salmo salar*) with 1.4 million tonnes, or 45% of the total ICES aquatic production  
205 (Figure 2b). Norway is a particularly interesting case, demonstrating both sustained catch and a  
206 comparatively rapid increase in aquaculture production volume, a unique trend among the top ICES  
207 nations.

208  
209 In evaluating past and current temporal trends in production for wild-caught and farmed seafood, we see  
210 capture fisheries production has varied little over time (Figure 3a), and that on average, yearly catches in  
211 a given ICES country have a slightly higher probability of declining from the previous year since the  
212 1990s (Figure 3b). In contrast, aquaculture has seen substantially larger variation in growth, in particular  
213 with large increases in the past when many fish farms were just developing (Figure 3c), with increases in  
214 production from year to year being more probable than declines (Figure 3d); although the yearly trends  
215 were not statistically significant ( $p$ -value = 0.075). In addition, the variation appears to be contracting as  
216 aquaculture grows and matures (Figure 3c). Consistent with global trends, present capture fisheries within  
217 ICES countries appear either relatively stable or declining, while aquaculture has been steadily increasing  
218 (Costello *et al.*, 2016; FAO, 2018a; Hilborn and Costello, 2018).

### 220 ***Targets for aquaculture growth***

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222 Since 2013, all ICES countries have government-sponsored and/or industry-lead reports or initiatives that  
223 state potential growth interests or goals for aquaculture (freshwater and marine) within their own  
224 territorial boundaries (Figure 4). That said, we were unable to find explicit targets for only one country,  
225 Estonia (consistent with O'Hagan *et al.*, 2017), but there does seem to be intent for expansion (e.g.,  
226 "...areas for suitable aquaculture will be mapped..."). The vast majority of explicit targets (16 out of 20)  
227 were very short-term, set for the years 2020-2023. In comparison, only three countries (Canada, Spain,  
228 and Norway) outlined more strategic planning out to 2030-2050. Nearly all documented targets were for a

229 doubling of production or less (median goal magnitude = 2), with only four countries setting more  
230 ambitious growth production goals into the future (Portugal: 3.5x by 2020; Belgium: 4.9x by 2023; Spain:  
231 3x by 2030; Norway: 4x by 2050) (Figure 4). Norway's target represents the most substantial proposed  
232 increase in absolute production (3.8 million additional tonnes), while Portugal, Belgium and Spain's  
233 targets represent more modest increases of 25 thousand tonnes, 820 tonnes, and 447 thousand tonnes,  
234 respectively.

235  
236 In addition to general production goals, we also found a tendency of focusing on marine expansion (no.  
237 countries = 14) compared to freshwater (no. countries = 6); this is not necessarily surprising given current  
238 marine production is approximately four-fold that of freshwater aquaculture in ICES countries. Some  
239 countries even specified the species or mode of production they were interested in expanding. For  
240 instance, Norway articulated continued expansion of salmon, but also seaweed species. Similarly,  
241 Germany highlighted Integrated Multi-trophic Aquaculture of mussels and seaweed in the Baltic Sea,  
242 while Latvia emphasized pool and recirculating aquaculture. Of note, nearly all of ICES countries  
243 mentioned *spatial planning* or *zoning* as part of the specific strategy for growth. The association between  
244 spatial planning and aquaculture seems to track with other policies and initiatives globally, including the  
245 reform of the 2013 EU Common Fisheries Policy (CFP) (O'Hagan *et al.*, 2017) and various Regional  
246 Commissions for Fisheries (RECOFI) (Meaden *et al.*, 2015).

247  
248 Sources with mentions of spatial planning tended to co-occur with acknowledgment of preparation for  
249 climate change (84% of sources). However, detailed climate change action plans for aquaculture,  
250 especially long-term, were not apparent in the documents we assessed. This is not to say that ICES  
251 nations are not planning for climate change, as many countries indeed have ongoing research projects  
252 (e.g., EU H2020 CERES and ClimeFish, US NOAA climate science strategy, etc.) and other marine  
253 planning which may include aquaculture, such as the EU Directive 2014/89/EU (O'Hagan *et al.*, 2017).  
254 However, what the specific plans are and how they align with the respective goals for aquaculture growth  
255 were not overtly apparent in the sources assessed. The lack of climate change planning perhaps indicates  
256 a further need within long-term aquaculture strategies.

257  
258 Looking across the ICES members' goals, what emerges is the clear pattern that most countries have  
259 established comparatively conservative targets (median magnitude = 2) for increasing aquaculture  
260 production, though interest in some level of growth appears ubiquitous. Smaller or larger production  
261 targets are not better or worse. That said, such targets do have potential implications for the ability of  
262 countries to meet their own consumption demand and the tradeoffs therein, an issue we explore next.



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***Mind the domestic production gap***

Applying each country’s aquaculture growth trajectories out to the year 2050 and modelling the potential growth over time, we uncovered that ICES nations’ goals appear feasible given past aquaculture production trends (Figure 5a). We specifically found that an exponential model performed best (according to AICc model selection) in describing past (since 1950) and potential future production among three models tested ( $R^2_{adj} = 0.97$ ,  $F_{stat} = 2308$ ,  $p\text{-value} < 0.001$ ). Notably, the reported projection from the FAO is a little lower than the ICES national goals (Figure 5a). However, while the trajectories may seem achievable based on previous growth of the sector, there are potential constraints and bottlenecks to aquaculture development, such as a lack of available sites (Sanchez-Jerez *et al.*, 2016), lost production from disease (Stentiford *et al.*, 2017), highly restrictive regulations (Sea Grant, 2019), and poor public perception and social license (Froehlich *et al.*, 2017), among other factors. As the industry grows, these problems can increase, and may slow or limit production for any given country. Nonetheless, assuming these challenges are addressed and aquaculture production goals of each country are met, ICES countries’ goals could reflect production potential in the future, with Norway driving 2050 growth (Figure 5b). Norwegian aquaculture is already the largest producer in ICES, but it is unclear if (Atlantic salmon) production will continue to be increasingly challenged by sea lice (Young *et al.*, 2019) or aided by offshore expansion (e.g., SalMar ASA). Interestingly, Norway meeting the proposed four-fold increase would result in their total aquaculture production surpassing their capture fisheries prior to 2050.

We also found that ICES nations have a mounting domestic seafood production deficit from consuming more seafood than they produce (Figure 5c), meaning a growing reliance on imports that may be less sustainable. If we assume a linear relationship of total seafood consumption (tonnage) over time ( $R^2_{adj} = 0.95$ ;  $F_{stat} = 978$ ;  $p\text{-value} < 0.001$ ), we would expect to see an average 57% increase in the total amount consumed by 2050 (since 2013; Figure 5a), trends that align with the projected average of the regions of interest (World Bank, 2013). Compared to the time since the greatest ICES seafood surplus (1988), small domestic deficits appeared to have occurred in 2008 and 2016 (Figure 5c). Accounting for a continued rise in ICES consumption and the production goals of the associated nations, we project a seafood deficit of about 7 million tonnes by 2050 (Figure 5c). Unless aquaculture growth targets are set significantly higher for the other nations excluding Norway, ICES countries will likely become even more reliant on other large seafood producers, such as China (Figure 5a). In fact, the top three, non-ICES seafood trading partners (India, China, and Indonesia), by import value (total USD in 2017 = \$23.7 billion), all have aquaculture production which is equal or exceeds their capture fisheries (in total, 2.2 times great than

297 catch). The most common taxa imported from these countries are shrimp and prawns, which have a record  
298 of having significant negative environmental impacts (De Silva, 2012) and human rights violations  
299 (Motilal and Prakriti, 2018). While an ICES seafood deficit in production is not a certainty, this analysis  
300 demonstrates that it is much more likely under current production and consumption trends, and potentially  
301 presents a greater risk of sourcing less sustainable food items.

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### 304 ***Conclusions and Recommendations***

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306 There is historical precedent for ICES nations to be at the forefront of sustainable seafood production,  
307 whether through domestic and/or better trade dimensions. Over the decades, the exploration and  
308 implementation of new tools and strategies to better manage wild fisheries have been recognized and  
309 adopted to various extents among these nations. While great strides were made to support best fisheries  
310 practices – including governance, funding, and research support – to recover many wild stocks, much less  
311 effort has been given in most of the ICES nations to usher in aquaculture practices in a similar, but more  
312 anticipatory manner. Interestingly, we found that even with the apparent recognition by all current ICES  
313 countries that aquaculture will play an increasingly important role in future seafood production, most  
314 planning appears very short term and conservative. Development of long-term aquaculture strategies is  
315 not just about absolute production, but must also include measures to advance improved husbandry,  
316 technology, and participation in the changing seafood market, ideally with sustainability leading these  
317 components. While the goals moving forward to 2050 by the ICES nations may be feasible as the  
318 growing challenges are addressed, growth predominantly depends on one country, Norway. Even if the  
319 goals are met, it does not reconcile the deficits in seafood production, requiring increases in imports of  
320 seafood, often from places with considerably fewer rules and regulations for sustainable harvest or  
321 production. In addition, lack of aquaculture consideration creates a major gap in adaptively planning for  
322 the impact of climate change on the seafood sectors domestically and from exporting countries (FAO,  
323 2018b; Froehlich *et al.*, 2018; Thiault *et al.*, 2019).

324

325 Governance is key to adaptive planning, and targeted policies that support, not just regulate, domestic  
326 aquaculture are needed if ICES countries wish to address the skewed production landscape. In a global  
327 setting, the restrictive and complex regulatory structures have been identified as important factors  
328 stagnating growth of aquaculture in Europe and North America and may have resulted in declining their  
329 share of world aquaculture production (Engle and Stone, 2013; Young *et al.*, 2019; Garlock *et al.*, 2020).  
330 Aquaculture-specific national legislation which clearly defines requirements and objectives is important,

331 but not always guaranteed (e.g., Canada) (Sanchez-Jerez *et al.*, 2016), particularly for marine aquaculture  
332 (Davies *et al.*, 2019). Arguably, clear legislation should apply to state and provincial level governance as  
333 well. The Food and Agriculture Organization of the United Nations identified ‘predictability of the rule of  
334 law’ as one of four cornerstones of governance principles to support sustainable aquaculture development  
335 (Hishamunda *et al.*, 2014). Importantly, legislation likely needs to go beyond robust regulatory standards,  
336 which does exist in many of these nations, to include explicit support—which is debatably the case for  
337 wild-capture fisheries. For instance, zoned Aquaculture Management Areas – a designated area shared by  
338 farmers to minimize risk and impact to the surrounding environment (FAO and World Bank, 2015) –  
339 could be a tangible near-term goal for pursuing longer-term aquaculture growth, especially for countries  
340 with some form of spatial planning and management already in place. Zoning differs from spatial  
341 planning alone in that it specifically prioritizes aquaculture in certain areas over other uses, but rarely at  
342 the expense of the environment or other industries (Sanchez-Jerez *et al.*, 2016). Such aquaculture  
343 prioritization and support does occur, including in some ICES nations (e.g., Spain, Norway), but is still  
344 rare and highly variable (Sanchez-Jerez *et al.*, 2016). In the event of aquaculture zoning, coordinated  
345 area-based management beyond a single farm (e.g., ‘beyond farm’ governance, integrated coastal zone  
346 management) may also help improve sustainable aquaculture development into the future, as is the case in  
347 Norway (Hishamunda *et al.*, 2014; Klinger *et al.*, 2018; Bush *et al.*, 2019). In short, aquaculture would  
348 need to become a priority to grow in ICES nations (beyond just Norway), which may not parallel the  
349 social or political will of some of the countries being discussed (Froehlich *et al.*, 2017).

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351 Trade is intertwined with domestic seafood governance, especially if ICES nations intend to address the  
352 displacement of social and ecological burdens bound to imported seafood. We found the potential for a  
353 domestic seafood production deficit more likely now and increasingly so in the future, which increases  
354 the chance of imports of less expensive seafood from less regulated countries in the absence of  
355 interregional laws. This ‘whole system’ perspective (i.e., beyond local or domestic impacts) applies to  
356 nearly every commodity in this globalized age (Kissinger *et al.*, 2011), but seafood in particular is one of  
357 the most traded commodities on the planet and production is so heavily skewed globally (ca. 90% of  
358 production in SE Asia) (Gephart and Pace, 2015). Accountability of the impacts of our food beyond local  
359 and national borders is legally difficult, but morally deserves attention (Kissinger *et al.*, 2011; Halpern *et al.*, 2019). Certification, blockchain, and improved monitoring, such as the USA’s new Seafood Import  
361 Monitoring Program (81 FR 88975) are helping address some issues around trade and traceability of  
362 seafood (Gephart *et al.*, 2019). However, with mislabelling and fraud (Stawitz *et al.*, 2016; Luque and  
363 Donlan, 2019), worker’s rights and slavery (Diana *et al.*, 2013) and climate change (Brown *et al.*, 2017),

364 the scale and complexity of the international seafood issues are overwhelming in the absence of larger  
365 political initiatives at the national and global scale.

366

367 Not only do ICES countries need to plan domestically and internationally for aquaculture, these efforts  
368 should be done in the context of changing environmental conditions. Climate change is already impacting  
369 fisheries and aquaculture, including ICES members (e.g., USGCRP, 2018), and conditions are predicted  
370 to get more challenging in the coming decades, especially in the absence of active mitigation and  
371 adaptation measures (Sumaila *et al.*, 2016; Handisyde *et al.*, 2017; FAO, 2018b; Free *et al.*, 2019;  
372 Hollowed *et al.*, 2019; Thiault *et al.*, 2019; Oremus *et al.*, 2020). Of note, and reminiscent of a  
373 historically narrow focus in fisheries, plans for wild-capture management under climate change are slowly  
374 forming as impacts and conflicts emerge and better methods to predict impacts on productivity and  
375 behavior develop (FAO, 2018b; Free *et al.*, 2019; Hollowed *et al.*, 2019; Sumaila *et al.*, 2019; Thiault *et*  
376 *al.*, 2019). Yet, we lack even a map of current aquaculture production locations (freshwater and marine)  
377 around the world, making the real versus potential impact on aquaculture highly uncertain, and  
378 precautionary planning much more important and challenging (Froehlich *et al.*, 2018). Some regional  
379 assessments are emerging (e.g., Falconer *et al.*, 2019; EU ClimeFish, 2020), but more research and  
380 support around climate change impacts, mitigation, and adaption for aquaculture are sorely needed.

381

382 In general, ICES' governments need more deliberate and strategic plans about the extent to which they  
383 wish to increase aquaculture production in their own waters versus importing farmed and capture species  
384 from other countries' waters, and how these decisions may fair under a changing climate. While the  
385 solution of 'producing more' domestically may sound simple, it is in fact a grand challenge that emerges  
386 from highly complex socio-economic and cultural values around seafood, alongside population and  
387 demand growing for seafood, and climate change threatening both fishing and aquaculture sectors, as well  
388 as the people who depend on them. Our results highlight that this challenge should not be left to reactive  
389 future decisions. Instead, nations must proactively prepare for the complex issues ahead.

390

391 **Figure Legends**

392

393 **Figure 1.** Trends in the percent of total global consumption and production of seafood (wild capture and  
394 aquaculture) from ICES nations. The sudden peak corresponds with the socio-political changes in  
395 Russia/Soviet Union. The declining trend in percent of global contribution is largely due to increasing  
396 human population and greater demand in other parts of the world. Data source: FAO, 2018a.

397

398 **Figure 2.** ICES nations (a) highlighted in *maroon*, with total combined production (million tonnes) over  
399 time (*inset panel*) and (b) corresponding individual national aquaculture (*orange*) and fisheries catch  
400 (*blue*) freshwater and marine (excludes seaweeds) tonnage time series (1960-2015) (FAO, 2013, 2018a).

401

402 **Figure 3.** Interannual variability of capture (*blue*) and aquaculture (*orange*) tonnage for each ICES nation  
403 over time as shown by percent (%) change in production between subsequent years (a & c) and the  
404 probability the change is positive in a given year across all ICES countries (b & d).

405

406 **Figure 4.** Magnitude of proposed aquaculture growth targets relative to 2013 FAO production estimates  
407 as calculated from the country-specific documentation.

408

409 **Figure 5.** (a) Past and future trends of ICES aquaculture (*black*) and wild (*gray*) capture. ICES goals are shown in  
410 *red* and FAO estimates in *orange*, with the exponential-model fit with 95% confidence intervals. Current (2013) and  
411 future (2050) total consumption levels are depicted as *blue* horizontal *solid* and *dashed* lines, respectively. Chinese  
412 aquaculture is shown as the *small, dotted pink* line for reference of production scale. (b) Total ICES capture (*light*  
413 *blue*), ICES aquaculture excluding Norway (*green*), and Norwegian aquaculture (*aqua*). (c) Domestic seafood  
414 deficit in millions of tonnes over time (non-consecutive years) as calculated by consumption minus combined  
415 (fisheries and aquaculture) production based on the reported targets; *light blue* positive values show no deficit (i.e.,  
416 surplus) and *orange* negative values indicate deficits by 2050.

417

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419

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434

435

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