This is a pre-copyedited, author-produced PDF of an article accepted for publication in *ICES Journal of Marine Science* following peer review. The version of record Halley E Froehlich, Jessica Couture, Lynne Falconer, Gesche Krause, James A Morris, Montse Perez, Grant D Stentiford, Harri Vehviläinen, Benjamin S Halpern, Mind the gap between ICES nations' future seafood consumption and aquaculture production, *ICES Journal of Marine Science*, Volume 78, Issue 1, January-February 2021, Pages 468–477 is available online at: https://doi.org/10.1093/icesjms/fsaa066

Quo Vadimus

Mind the gap between ICES nations' future seafood consumption and aquaculture production

Halley E. Froehlich[1,2], Jessica Couture[3], Lynne Falconer[4], Gesche Krause[5], James A. Morris[6], Montse Perez[7], Grant D. Stentiford[8,9], Harri Vehviläinen[10], Benjamin S. Halpern[3,11]

[1] Environmental Studies, University of California, Santa Barbara, Santa Barbara, CA, USA 93106

[2] Ecology, Evolution, & Marine Biology, University of California, Santa Barbara, Santa Barbara, CA, USA 93106

[3] Bren School of Environmental Science & Management, University of California, Santa Barbara, Santa Barbara, CA, USA 93106

[4] Institute of Aquaculture, University of Stirling, Stirling, FK9 4LA, UK

[5] Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany

[6] Marine Spatial Ecology Division, National Centers for Coastal Ocean Science, National Ocean Service, NOAA 101 Pivers Island Rd., Beaufort, North Carolina USA

[7] AQUACOV, Instituto Español de Oceanografía, Centro Oceanográfico de Vigo, 36390 Vigo, Spain

[8] International Centre of Excellence for Aquatic Animal Health, Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Weymouth, Dorset DT4 8UB, UK

[9] Centre for Sustainable Aquaculture Futures, Biosciences, University of Exeter, Stocker Road, Exeter EX4 4PY, UK

[10] Aquatic Production Systems, Natural Resources Institute Finland (Luke), Korkeakoulunkatu 7, FI-33720 Tampere, Finland

[11] National Center for Ecological Analysis & Synthesis, University of California, Santa Barbara, Santa Barbara, CA, USA 93103

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

Abstract

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

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

Introduction

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

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

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

Given the history and relevance of seafood for ICES countries, we ask what role sustainable aquaculture may play in these countries in the future, which includes consideration of trade and climate change. Drawing on existing quantitative and qualitative data sources, we explored the relative trends and forward-looking strategies for aquaculture among the respective nations who were, and continue to be, leaders in fisheries science and management. First, we assessed the change in aquatic sources of the collective and individual 20 ICES nations by comparing the general trends (tonnage and interannual variation) of wild capture versus aquaculture production over the last five decades, paying particular attention to the top producing countries. Next, to determine how future aquaculture goals of the ICES members matched the prevailing trends, we compiled documents and sources from government and industry on proposed growth targets for each country since 2013. From the references, we extracted set goals, if any, for future aquaculture production (year, tonnage, and type). We then modelled the potential 2050 aquaculture increases (based on the growth targets) to that of the possible total seafood consumption (i.e., demand) over the same time period, noting years of surplus or deficit. Recognizing that seafood from other countries fills domestic deficits, we highlight the top non-ICES seafood-trade partners, aquaculture production in those countries, and the implications for sustainable seafood. Lastly, we sought evidence of a base-level consideration of climate change in relation to future ICES' goals, given the increasing recognition climate change related impacts may challenge aquaculture globally (FAO, 2018b). In that, we looked for mention of 'climate change' within the associated references. Based on the results, we reflect on the future of seafood for the ICES nations and food system accountability in a global market, including adaptive strategies under a changing climate.

Methods

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

For assessing future aquaculture goals, we compiled information (government and industry) on proposed growth targets for the ICES member nations since 2013. First, we leveraged the ICES members of the Working Group on Scenario Planning on Aquaculture, from which this project emerged, to provide known documents or sources about their respective countries and any addition information on the other nations (i.e., expert knowledge). One review document we heavily leveraged, which provided detailed reference to aquaculture targets for EU countries (no. countries =12), was O'Hagan *et al.*, 2017. We paired the expert-elicited collection with Google™ searches for references on any remaining countries of interest. The search terms included *country name* and *aquaculture, future, horizon,* and/or *2050*. We then read the sources of information (N = 20) and manually extracted future aquaculture production goals (year, tonnage, and type, such as freshwater, marine, taxa) for the 20 member nations. If we found multiple goals for a given country for the same time periods, we took the mean of the values. From both experts and internet searchers, we incorporated industry reported values for nations in which we could not find explicit government targets (Iceland) or were cited by the government (Scotland). Another important note, the UK as a whole is the ICES member, but the aquaculture target is the composite of Scotland, England, Wales, and Northern Ireland and a 2030 report (not included) was in progress during the time of this study. We also noted if the associated references mention 'climate change,' which we used as a basic indicator of recognition and possible consideration for aquaculture growth. All documents and sources (Supplementary Data Table 1) not in English were either translated by an ICES working group member or Google™ Translate. While our approach resulted in information on aquaculture growth for every ICES country, we may have missed other, less accessible documents or sources due to language barriers, policy relevance, or limits on information sharing. In particular, goals from nations outside of the EU, Norway, USA, and Canada are likely less certain.

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

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

Results and Discussion

Past trends of catch and production

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

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

Targets for aquaculture growth

Since 2013, all ICES countries have government-sponsored and/or industry-lead reports or initiatives that state potential growth interests or goals for aquaculture (freshwater and marine) within their own territorial boundaries (Figure 4). That said, we were unable to find explicit targets for only one country, Estonia (consistent with O'Hagan *et al.*, 2017), but there does seem to be intent for expansion (e.g., "...areas for suitable aquaculture will be mapped..."). The vast majority of explicit targets (16 out of 20) were very short-term, set for the years 2020-2023. In comparison, only three countries (Canada, Spain, and Norway) outlined more strategic planning out to 2030-2050. Nearly all documented targets were for a doubling of production or less (median goal magnitude = 2), with only four countries setting more ambitious growth production goals into the future (Portugal: 3.5x by 2020; Belgium: 4.9x by 2023; Spain: 3x by 2030; Norway: 4x by 2050) (Figure 4). Norway's target represents the most substantial proposed increase in absolute production (3.8 million additional tonnes), while Portugal, Belgium and Spain's targets represent more modest increases of 25 thousand tonnes, 820 tonnes, and 447 thousand tonnes, respectively.

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

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

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

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 ($R^2_{adj} = 0.97$, Fstat = 2308, p-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 ($R^2_{adj} = 0.95$; Fstat = 978; p-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 catch). The most common taxa imported from these countries are shrimp and prawns, which have a record of having significant negative environmental impacts (De Silva, 2012) and human rights violations (Motilal and Prakriti, 2018). While an ICES seafood deficit in production is not a certainty, this analysis demonstrates that it is much more likely under current production and consumption trends, and potentially presents a greater risk of sourcing less sustainable food items.

Conclusions and Recommendations

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

Governance is key to adaptive planning, and targeted policies that support, not just regulate, domestic aquaculture are needed if ICES countries wish to address the skewed production landscape. In a global setting, the restrictive and complex regulatory structures have been identified as important factors stagnating growth of aquaculture in Europe and North America and may have resulted in declining their share of world aquaculture production (Engle and Stone, 2013; Young *et al.*, 2019; Garlock *et al.*, 2020). Aquaculture-specific national legislation which clearly defines requirements and objectives is important, but not always guaranteed (e.g., Canada) (Sanchez-Jerez *et al.*, 2016), particularly for marine aquaculture (Davies *et al.*, 2019). Arguably, clear legislation should apply to state and provincial level governance as well. The Food and Agriculture Organization of the United Nations identified ‘predictability of the rule of law’ as one of four cornerstones of governance principles to support sustainable aquaculture development (Hishamunda *et al.*, 2014). Importantly, legislation likely needs to go beyond robust regulatory standards, which does exist in many of these nations, to include explicit support—which is debatably the case for wild-capture fisheries. For instance, zoned Aquaculture Management Areas – a designated area shared by farmers to minimize risk and impact to the surrounding environment (FAO and World Bank, 2015) – could be a tangible near-term goal for pursuing longer-term aquaculture growth, especially for countries with some form of spatial planning and management already in place. Zoning differs from spatial planning alone in that it specifically prioritizes aquaculture in certain areas over other uses, but rarely at the expense of the environment or other industries (Sanchez-Jerez *et al.*, 2016). Such aquaculture prioritization and support does occur, including in some ICES nations (e.g., Spain, Norway), but is still rare and highly variable (Sanchez-Jerez *et al.*, 2016). In the event of aquaculture zoning, coordinated area-based management beyond a single farm (e.g., ‘beyond farm’ governance, integrated coastal zone management) may also help improve sustainable aquaculture development into the future, as is the case in Norway (Hishamunda *et al.*, 2014; Klinger *et al.*, 2018; Bush *et al.*, 2019). In short, aquaculture would need to become a priority to grow in ICES nations (beyond just Norway), which may not parallel the social or political will of some of the countries being discussed (Froehlich *et al.*, 2017).

Trade is intertwined with domestic seafood governance, especially if ICES nations intend to address the displacement of social and ecological burdens bound to imported seafood. We found the potential for a domestic seafood production deficit more likely now and increasingly so in the future, which increases the chance of imports of less expensive seafood from less regulated countries in the absence of interregional laws. This ‘whole system’ perspective (i.e., beyond local or domestic impacts) applies to nearly every commodity in this globalized age (Kissinger *et al.*, 2011), but seafood in particular is one of the most traded commodities on the planet and production is so heavily skewed globally (ca. 90% of production in SE Asia) (Gephart and Pace, 2015). Accountability of the impacts of our food beyond local 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 Monitoring Program (81 FR 88975) are helping address some issues around trade and traceability of seafood (Gephart *et al.*, 2019). However, with mislabelling and fraud (Stawitz *et al.*, 2016; Luque and Donlan, 2019), worker’s rights and slavery (Diana *et al.*, 2013) and climate change (Brown *et al.*, 2017), the scale and complexity of the international seafood issues are overwhelming in the absence of larger political initiatives at the national and global scale.

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

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

Figure Legends

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

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

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

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

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

Acknowledgments

This research was part of the ICES Working Group on Scenario Planning on Aquaculture (WGSPA). Authors HEF and BSH acknowledge funding from the Zegar Family Foundation through the 'Anticipating Climate Change Impacts on Ocean Aquaculture' and 'Environmental Impact and Sustainability of Global Food Systems' projects, as well as travel support from the National Oceanic and Atmospheric Administration (NOAA). HEF also recognizes support from the University of California, Santa Barbara. MP acknowledges the travel support from the Xunta de Galicia-GAIN through the "Group with growth Potential" project (IN607B 2018/14). GK acknowledges funding from the Earth System Knowledge platform (ESKP) of the Helmholtz Association. LF acknowledges funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 678396 (TAPAS: Tools for Assessment and Planning of Aquaculture Sustainability). HV acknowledges support from European Maritime and Fisheries Fund Operational Programme for Finland 2014-2020. Many thanks to Erik Williams and Dr. Nikolai Klibansky (NOAA Fisheries), as well as Meghan Balling (CSS contractor, NOAA National Ocean Service) for their review of this manuscript. Additional thanks to the anonymous reviewers for their thoughtful comments, which greatly improved the manuscript.

References

Ahmed, N., Thompson, S., and Glaser, M. 2018. Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability. Environmental Management.

Britten, G. L., Dowd, M., and Worm, B. 2015. Changing recruitment capacity in global fish stocks. Proceedings of the National Academy of Sciences: 201504709.

Brown, M. E., Carr, E. R., Grace, K. L., Wiebe, K., Funk, C. C., Attavanich, W., Backlund, P., *et al.* 2017. Do markets and trade help or hurt the global food system adapt to climate change? Food Policy, 68: 154–159.

Burnham, K. P., and Anderson, D. R. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer Science & Business Media.

Bush, S. R., Oosterveer, P., Bottema, M., Meuwissen, M., de Mey, Y., Chamsai, S., Lien, H. H., *et al.* 2019. Inclusive environmental performance through 'beyond-farm' aquaculture governance. Current Opinion in Environmental Sustainability, 41: 49–55.

Cao, L., Naylor, R., Henriksson, P., Leadbitter, D., Metian, M., Troell, M., and Zhang, W. 2015. China's aquaculture and the world's wild fisheries. Science, 347: 133–135.

Costello, C., Ovando, D., Clavelle, T., Strauss, C. K., Hilborn, R., Melnychuk, M. C., Branch, T. A., *et al.* 2016. Global fishery prospects under contrasting management regimes. Proceedings of the National Academy of Sciences: 201520420.

Davies, I. P., Carranza, V., Froehlich, H. E., Gentry, R. R., Kareiva, P., and Halpern, B. S. 2019. Governance of marine aquaculture: Pitfalls, potential, and pathways forward. Marine Policy, 104: 29–36.

De Silva, S. S. 2012. Aquaculture: a newly emergent food production sector—and perspectives of its impacts on biodiversity and conservation. Biodiversity and Conservation, 21: 3187–3220.

Diana, J. S., Egna, H. S., Chopin, T., Peterson, M. S., Cao, L., Pomeroy, R., Verdegem, M., *et al.* 2013. Responsible Aquaculture in 2050: Valuing Local Conditions and Human Innovations Will Be Key to Success. BioScience, 63: 255–262.
Engle, C. R., and Stone, N. M. 2013. Competitiveness of U.S. Aquaculture Within the Current U.S. Regulatory Framework. Aquaculture Economics & Management, 17: 251–280.
EU ClimeFish. 2020, EU Horizon. ClimeFish. https://climefish.eu/.
Falconer, L., Hjøllo, S. S., Telfer, T. C., McAdam, B. J., Hermansen, Ø., and Ytteborg, E. 2019. The importance of calibrating climate change projections to local conditions at aquaculture sites. Aquaculture: 734487.
FAO. 2013. FAOSTAT database collections. Food and Agriculture Organization of the United Nations, Rome, Italy. http://faostat.fao.org.
FAO, and World Bank. 2015. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture. Policy Brief.
FAO. 2018a. The State of World Fisheries and Aquaculture: Meeting the sustainable development goals. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAO. 2018b. Impacts of climate change on fisheries and aquaculture: Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper, 627. Rome, Italy.
Free, C. M., Thorson, J. T., Pinsky, M. L., Oken, K. L., Wiedenmann, J., and Jensen, O. P. 2019. Impacts of historical warming on marine fisheries production. Science, 363: 979–983.
Froehlich, H. E., Gentry, R. R., Rust, M. B., Grimm, D., and Halpern, B. S. 2017. Public Perceptions of Aquaculture: Evaluating Spatiotemporal Patterns of Sentiment around the World. PLOS ONE, 12: e0169281.
Froehlich, H. E., Gentry, R. R., and Halpern, B. S. 2018. Global change in marine aquaculture production potential under climate change. Nature Ecology & Evolution, 2: 1745.
Garlock, T., Asche, F., Anderson, J., Bjørndal, T., Kumar, G., Lorenzen, K., Ropicki, A., *et al.* 2020. A Global Blue Revolution: Aquaculture Growth Across Regions, Species, and Countries. Reviews in Fisheries Science & Aquaculture, 28: 107–116.
Gephart, J. A., and Pace, M. L. 2015. Structure and evolution of the global seafood trade network. Environmental Research Letters, 10: 125014.
Gephart, J. A., Froehlich, H. E., and Branch, T. A. 2019. Opinion: To create sustainable seafood industries, the United States needs a better accounting of imports and exports. Proceedings of the National Academy of Sciences, 116: 9142–9146.
Halpern, B. S., Cottrell, R. S., Blanchard, J. L., Bouwman, L., Froehlich, H. E., Gephart, J. A., Jacobsen, N. S., *et al.* 2019. Opinion: Putting all foods on the same table: Achieving sustainable food systems requires full accounting. Proceedings of the National Academy of Sciences, 116: 18152–18156.
Handisyde, N., Telfer, T. C., and Ross, L. G. 2017. Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. Fish and Fisheries, 18: 466–488.
Hilborn, R., and Ovando, D. 2014. Reflections on the success of traditional fisheries management. ICES Journal of Marine Science, 71: 1040–1046.
Hilborn, R., and Costello, C. 2018. The potential for blue growth in marine fish yield, profit and abundance of fish in the ocean. Marine Policy, 87: 350–355.
Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., Moor, C. L. de, *et al.* 2020. Effective fisheries management instrumental in improving fish stock status. Proceedings of the National Academy of Sciences.
Hishamunda, N., Ridler, N., and Martone, E. 2014. Policy and governance in aquaculture: lessons learned and way forward. FAO Fisheries and aquaculture technical paper: I.
Hollowed, A. B., Barange, M., Garçon, V., Ito, S., Link, J. S., Aricò, S., Batchelder, H., *et al.* 2019. Recent advances in understanding the effects of climate change on the world's oceans. ICES Journal of Marine Science.

Kissinger, M., Rees, W. E., and Timmer, V. 2011. Interregional sustainability: governance and policy in an ecologically interdependent world. Environmental Science & Policy, 14: 965–976.

Klinger, D. H., Maria Eikeset, A., Davíðsdóttir, B., Winter, A.-M., and Watson, J. R. 2018. The mechanics of blue growth: Management of oceanic natural resource use with multiple, interacting sectors. Marine Policy, 87: 356–362.

Luque, G. M., and Donlan, C. J. 2019. The characterization of seafood mislabeling: A global meta-analysis. Biological Conservation, 236: 556–570.

Meaden, G. J., Aguilar-Manjarrez, J., Corner, R. A., O'Hagan, A. M., and Cardia, F. 2015. Marine spatial planning for enhanced fisheries and aquaculture sustainability – its application in the Near East. FAO Fisheries and Aquaculture Technical Paper, 604. Rome, Italy.

Motilal, S., and Prakriti, P. 2018. Routledge Handbook of Development Ethics. Routledge. 461 pp.

O'Hagan, A. M., Corner, R. A., Aguilar-Manjarrez, J., Gault, J., Ferreira, J., Ferreira, J. G., O'Higgins, T., *et al.* 2017. Deliverables 2.1 and 2.2 Regional review of Policy-Management Issues in Marine and Freshwater Aquaculture. AquaSpace, Ecosystem Approach to making Space for Aquaculture, EU Horizon 2020 Project Grant No. 633476. UCC-MaREI.

Oremus, K. L., Bone, J., Costello, C., García Molinos, J., Lee, A., Mangin, T., and Salzman, J. 2020. Governance challenges for tropical nations losing fish species due to climate change. Nature Sustainability: 1–4.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., *et al.* 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science, 355: eaai9214.

Peterson, J., Griffis, R., Zador, S. G., Sigler, M. F., Joyce, J. E., Hunsicker, M., Bograd, S., *et al.* 2017. Climate Change Impacts on Fisheries and Aquaculture of the United States. *In* Climate Change Impacts on Fisheries and Aquaculture, pp. 159–218. Wiley-Blackwell.

Pinsky, M. L., Selden, R. L., and Kitchel, Z. J. 2020. Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities. Annual Review of Marine Science, 12: 153–179.

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. URL https://www.R-project.org/.

Reid, G. K., Gurney-Smith, H. J., Flaherty, M., Garber, A. F., Forster, I., Brewer-Dalton, K., Knowler, D., *et al.* 2019. Climate change and aquaculture: considering adaptation potential. Aquaculture Environment Interactions, 11: 603–624.

Sanchez-Jerez, P., Karakassis, I., Massa, F., Fezzardi, D., Aguilar-Manjarrez, J., Soto, D., Chapela, R., *et al.* 2016. Aquaculture's struggle for space: the need for coastal spatial planning and the potential benefits of Allocated Zones for Aquaculture (AZAs) to avoid conflict and promote sustainability. Aquaculture Environment Interactions, 8: 41–54.

Sea Grant. 2019. Overcoming Impediments to Shellfish Aquaculture through Legal Research and Outreach: Case Studies. Sea Grant Law.

Stawitz, C. C., Siple, M. C., Munsch, S. H., Lee, Q., and Derby, S. R. 2016. Financial and Ecological Implications of Global Seafood Mislabeling. Conservation Letters, 10: 681–689.

Stentiford, G. D., Sritunyalucksana, K., Flegel, T. W., Williams, B. A., Withyachumnarnkul, B., Itsathitphaisarn, O., and Bass, D. 2017. New paradigms to help solve the global aquaculture disease crisis. PLoS pathogens, 13: e1006160.

Sumaila, U. R., Bellmann, C., and Tipping, A. 2016. Fishing for the future: An overview of challenges and opportunities. Marine Policy.

Sumaila, U. R., Tai, T. C., Lam, V. W. Y., Cheung, W. W. L., Bailey, M., Cisneros-Montemayor, A. M., Chen, O. L., *et al.* 2019. Benefits of the Paris Agreement to ocean life, economies, and people. Science Advances, 5: eaau3855.

Szuwalski, C., Jin, X., Shan, X., and Clavelle, T. 2020. Marine seafood production via intense exploitation and cultivation in China: Costs, benefits, and risks. PLOS ONE, 15: e0227106.

Thiault, L., Mora, C., Cinner, J. E., Cheung, W. W. L., Graham, N. A. J., Januchowski-Hartley, F. A., Mouillot, D., *et al.* 2019. Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries. Science Advances, 5: eaaw9976.

USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA.

Watson, R. A., and Tidd, A. 2018. Mapping nearly a century and a half of global marine fishing: 1869–2015. Marine Policy, 93: 171–177.

Went, A. E. J. 1972. The History of the International Council for the Exploration of the Sea. Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences, 73: 351–360.

World Bank. 2013. FISH TO 2030: Prospects for Fisheries and Aquaculture. Agriculture and Environmental Services Discussion Paper 03, 83177-GLB. The World Bank, Washington DC.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding Global Fisheries. Science, 325: 578–585.

Young, N., Brattland, C., Digiovanni, C., Hersoug, B., Johnsen, J. P., Karlsen, K. M., Kvalvik, I., *et al.* 2019. Limitations to growth: Social-ecological challenges to aquaculture development in five wealthy nations. Marine Policy, 104: 216–224.