1. Introduction

Increasing per capita demand for seafood (here, covering all aquatic foods produced in freshwater, brackish and marine water systems) is predicted over coming decades despite static fisheries supply. Aquaculture may fill the gap but generally falls below national demand. Lowest production occurs where seafood consumption is negligible or where provision is from fisheries and imports. The Aquaculture Adoption Index considers national production relative to consumption and may be predictive of nations where supply instability may occur, or, where uptake could benefit food security.

Global mean per capita consumption of seafood is at its highest level since records began in the 1960s [1]. In 2019 almost half of global supply (some 90 million tonnes) came from the rapidly expanding aquaculture sector—the remainder from a relatively static wild fishery [2]. Further expansion in per capita consumption will conflate with increasing global affluence to further drive demand to 2050; the required doubling in volume expected to be met by increased aquaculture [3]. Expansion in aquaculture has potential to not only improve nutritional security for millions of people [4] but also offers significant potential as a ‘low stressor’ component of integrated food systems [5]. Here we assess national disparities in seafood consumption (volume, type) and place these in context with relative uptake of aquaculture at national level as a potential means of provisioning future seafood demand.

Seafood from animal sources broadly comprises marine fish, freshwater fish, crustaceans, and molluscs. Cluster analysis of per capita seafood consumption data available for 175 nations [1] proposes five major national consumption sub-types (A–E) based upon the volume and type of seafood consumed by citizens of those nations (figure 1). Sub-type A and B nations display volumetric consumption above the global average (c. 20 kg pp pa$^{-1}$), dominated by marine fish but with access to other diverse seafood types. Sub-type C and D nations consume below average volumes of mainly marine fish with a decreasing propensity for diversity in seafood type consumed. Sub-type E nations consume negligible volumes of seafood (often <2 kg pp pa$^{-1}$), dominated by freshwater fish (supplement 1, tables S1.1 and S1.2 available online at stacks.iop.org/ERL/17/041003/mmedia). Reasons for differences in consumption pattern are complex and multi-factorial [6] but include availability of locations where fisheries and aquaculture can operate [7], wealth and demographic profile of citizens [8], dynamics in the global trading of seafood [9] and religious or cultural practices relating to inclusion of seafood in national diets [10].

While excellent data resources exist for fisheries and aquaculture production at national, regional, and global levels [3, 11], few analyses to date have focused on country-level uptake of aquaculture relative to the seafood consumption habits of those nations [12]. For this, national per capita aquaculture production was normalised against national population size—facilitating a more meaningful trans-national comparison in relative aquaculture uptake than production volume, alone. Per capita aquaculture output as a proportion of total national seafood demand, from 159 nations for which data are available, can be classified as—type 1 (>100% of national demand), type 2 (>50%–100%), type 3 (>25%–50%), type 4 (5%–25%) and type 5 (<5%). When combined with national consumption profiles (Sub-types A–E, above) the resultant Aquaculture Adoption Index (AAI) clusters nations to one of 25 categories according to volume and types of seafood consumed and, the theoretical relative contribution of aquaculture production to overall national seafood demand (figure 2
Figure 1. National seafood consumption sub-types are based upon combined assessment of total mean per capita seafood consumption (ranging from ‘high volume’ to ‘negligible’, where ‘average’ relates to a global average seafood consumption of c.20 kg pp pa at the time of writing) and, consumption of seafood arising from the four major production sub-sectors (marine fish, freshwater fish, crustaceans, and molluscs). Consumption sub-types A–D are dominated by consumption of marine fish, albeit at sequentially declining volumes while consumption profile E is dominated by freshwater fish, albeit at relatively low volumes. Sub-types A–E are further defined by sequentially declining consumption of crustaceans and molluscs with very low to negligible consumption under in sub-types C–E. All data obtained from FAOSTAT Food Supply Livestock and Fish Primary Equivalent database (www.fao.org/faostat/en/#data/CL accessed on 5 March 2020) [1]. Data used to generate figure 1 is provided in supplement 1, table S1.1.

and supplement 2, table S2.1). Due to prolific global trading in seafood the AAI does not presume that national aquaculture production directly provisions seafood demand at the national level. Instead, it offers insight on uptake of aquaculture in national waters relative to the importance of seafood in the diet of that nation—a potentially important measure when assessing future aquatic food security at national level.

Globally, 13 nations support aquaculture sectors which produce more than 100% of their national seafood demand—a further 12 producing over 50%. Conversely, 111 nations support aquaculture sectors producing less than 25% of their current demand, 62 of these with production below 5% (figure 2 and supplement 2, table S2.1). Highest and lowest per capita production from aquaculture relative to national consumption occurs in Chile (579.6%) and Belgium (0.03%), respectively. Norway is the highest per capita producer of seafood from aquaculture (270.1 kg pp⁻¹ pa⁻¹), albeit with a higher relative national consumption
Figure 2. The Aquaculture Adoption Index (AAI) depicts national per capita aquaculture production as a proportion of per capita seafood consumption. The five AAI types reflect the relative uptake of aquaculture at national level as measured against per capita consumption of seafood by citizens of that nation. Further sub-division of AAI types (to sub-types A–E) is based upon the seafood consumption profiles for specific nations (in figure 1). Within each AAI type (e.g. type 1) exist nations in which consumption is both high and diverse (e.g. Norway) and, low and restricted to specific seafood types (e.g. Nepal). Conversely, within each seafood consumption profile sub-type (e.g. A—high volume consumers) are nations producing high volumes of seafood from aquaculture (e.g. Vietnam) and those where aquaculture contribution is negligible (e.g. Portugal). All data obtained from FAO Fisheries Statistical Collections; Global Production Statistics 1950–2017, accessed on 22 July 2021 [11]. Data used to generate figure 2 is provided in supplement 2, table S2.1.
of seafood (52.04 kg pp\(^{-1}\) pa\(^{-1}\)) than in Chile (10.75 kg pp\(^{-1}\) pa\(^{-1}\)).

Regional patterns in aquaculture adoption also exist. Of 41 African nations for which data are available, 37 produce less than 25% of their national seafood demand from aquaculture—27 of these below 5% and, in many cases, coinciding with low to negligible seafood consumption (sub-types C, D and E; figures 1 and 2). Conversely, Asia has the highest number of countries producing at least 50% of national seafood demand from aquaculture—including several of the largest global producers by volume (e.g. China, India, Indonesia, Vietnam, Thailand, Bangladesh). Despite this, 20 of the 41 Asian nations for which data are available produce less than 25% of their national seafood demand from aquaculture—half of these below 5%. Europe is dominated by nations producing less than 50% of their national seafood demand from aquaculture—27 of the 37 nations producing below 25%. A similar pattern exists in the Americas, albeit with five nations in Latin America (e.g. Ecuador) where per capita aquaculture production exceeds national seafood demand. Island states in the Caribbean (e.g. Barbados) are generally depicted by high national seafood consumption and very low (<5%) aquaculture production. Within Oceania, 6 of the 7 nations for which data are available produce less than 25% of their national seafood demand from aquaculture, only New Zealand reaching near parity between seafood demand and aquaculture output (figure 2 and supplement 2, table S2.1).

Country-level seafood consumption data does not discriminate between that sourced from capture fisheries versus aquaculture, nor the net contribution of imports [1]. However, modelling of international seafood trade flows has estimated equal contributions of fisheries and aquaculture (c. 41%, 2011 data) to direct human consumption, a further 17% contribution from fishery products processed to fishmeal for use in aquaculture feeds and, significant dependence of the EU, USA, and Japanese markets on imports for consumption [13]. Guillen et al. proposed that accountability for sustainability of national seafood supply should thus be defined by the ‘seafood consumption footprint’ of that nation, rather than by its production alone [13]. The AAI extends this proposition by considering the specific provisioning of seafood from aquaculture relative to current national seafood demand. Subsequently, it may be appropriate for application in national-level aquatic food strategies where the aim is to: (a) develop aquaculture production in a proportional and representative manner relative to national seafood consumption needs (e.g. species choice, scale, product type) [14], (b) directly account for the footprint of seafood consumption of that nation (i.e. by reducing the ‘off-shoring’ of production impact to exporting nations) [13], (c) Protect against imported seafood supply chain failure or other disruptions or disputes with potential to impact trade [15, 16], (d) position the national aquaculture sector within the wider aquatic and terrestrial food system of the nation [17] and, (e) harness wider benefits of sustainable aquaculture development at national level (e.g. quality employment, wealth generation, food security, protection of biodiversity, climate resilience) [18].

The global aquaculture sector has matured over the past two decades as a major food sector but still faces significant challenges as a provider of sustainable protein [11, 19]. As aquaculture looks set to dominate the provision of global seafood supply by 2050, understanding relative adoption of aquaculture to seafood demand at national level will become an important measure in assessing sustainability of supply at country-, regional- and global-levels.

2. Conclusions

- Per capita consumption of seafood varies considerably by country, both in volume and diversity of types consumed.
- Cluster analysis revealed five major per capita consumption sub-types, ranging from high volume consumers of mainly marine fish (sub-type A) to negligible volume consumers of mainly freshwater fish (sub-type E).
- Aquaculture uptake (measured in terms of per capita production at national level) was compared to per capita seafood consumption to create the AAI.
- Five AAI Types were described—ranging from those nations whose aquaculture sector produced >100% of national per capita seafood consumption to those nations where less than 5% of current demand is represented by the existing national industry.
- Although we do not presume that national aquaculture production provisions national consumer demand directly, the AAI provides an insight into the national appetite to deploy aquaculture relative to national dietary reliance on seafood.

3. Methods

Consumption profiles (figure 1) were created using data from FAOSTAT [1] (data provided in supplement 1, table S1.1). Consumption values (kg pp\(^{-1}\) pa\(^{-1}\)) were transformed to a log (10) scale where 0 values are given a pseudo value of 0.001 and grouped according to hierarchical clustering [20]. Countries were assigned to one of five types (A–E) based on dendrogram clusters, visualised with modular leaf ordering [21]. Accompanying bar charts display actual consumption values (kg pp\(^{-1}\) pa\(^{-1}\)) followed by proportional contribution of seafood sector consumption (by % of total). Maldives, Kiribati, and Iceland were removed from the analysis based on relatively high values of marine
fish consumption compared to other nations. Grenada, Solomon Islands and Mongolia were removed as almost sole consumers of marine fish. The world map was plotted with the ‘sf’ and ‘rnaturalearth’ packages in R [22]. For generation of AAI types (1–5), national per capita seafood consumption data (from [1]) and national per capita aquaculture production data (derived from [19]) were used to calculate the differential—AAI types defined according to the proportion of current per capita seafood consumption represented by current per capita production (data are provided in supplement 2, table S2.1).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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