Aquatic Foods for Nourishing Nations

Christopher D. Golden[1,2,3*], J. Zachary Koehn[4*], Alon Shepon[1,5,6*], Simone Passarelli[1*], Christopher M. Free[7*], Daniel Viana[1*], Holger Matthey[8], Jacob G. Eurich[9,10], Jessica A. Gephart[11], Etienne Fluet-Chouinard[12], Elizabeth A. Nyboer[13], Abigail J. Lynch[14], Marian Kjellevold[15], Sabri Bromage[1], Pierre Charlebois[16], Manuel Barange[17], Stefania Vannuccini[17], Ling Cao[18], Kristin M. Kleisner[19], Eric B. Rimm[1], Goodarz Danaei[3,20], Camille DeSisto[21], Heather Kelahan[1], Kathryn J. Fiorella[22], David C. Little[23], Edward H. Allison[24], Jessica Fanzo[25], Shakuntala H. Thilsted[24]

[1] Dept. of Nutrition, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA
[2] Dept. of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA
[3] Dept. of Global Health and Population, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA
[4] Center for Ocean Solutions, Stanford University, 473 Via Ortega, Stanford, California 94305
[5] Department of Environmental Studies, The Porter School of the Environment and Earth Sciences, Tel Aviv University, Israel
[6] The Steinhardt Museum of Natural History, Tel Aviv University, Israel
[7] Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA 93106, USA
[8] Markets and Trade Division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
[9] Marine Sciences Institute, University of California, Santa Barbara, Santa Barbara, CA 93106, USA
[10] Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, Santa Barbara, CA 93106, USA
[11] Dept. of Environmental Science, American University, Washington, DC 20016, USA
[12] Department of Earth System Science, Stanford University, Stanford, CA 94305 USA
[13] Department of Biology, 4440K Carleton Technology and Training Centre, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6; b.a.nyboer@gmail.com
[14] U.S. Geological Survey, National Climate Adaptation Science Center, 12201 Sunrise Valley Drive, Reston, VA 20192, USA
[15] Institute of Marine Research, P.O box 1870 Nordnes NO-5817 Bergen, Norway
[16] Economic Consultant, Fisheries Division, Food and Agriculture Organization of the United Nations, Rome, Italy
[17] Fisheries Division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy
[18] School of Oceanography, Shanghai Jiao Tong University, Shanghai, China
[19] Environmental Defense Fund, 257 Park Ave S, New York, NY 10010

[20] Department of Epidemiology, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA
[21] Nicholas School of the Environment, Duke University, 9 Circuit Drive, Durham, NC, 27707, USA
[22] Department of Population Medicine and Diagnostic Sciences and Master of Public Health Program, Cornell University, S2-004 Shurman Hall, Ithaca, NY 14853, kfiorella@cornell.edu
[23] Institute of Aquaculture, University of Stirling, FK94LA, Scotland, UK
[24] WorldFish, Batu Maung, Bayan Lepas, 11960 Penang, Malaysia
[25] Bloomberg School of Public Health and Nitze School of Advanced International Studies, Johns Hopkins University, Washington DC, 20036 USA

* Denotes First Co-Authorship

SUMMARY

Despite contributing to nutritious diets for billions of people, aquatic foods are often undervalued as a nutritional solution because their diversity is often reduced to the protein and caloric value of a single food type (‘seafood’ or ‘fish’). For the first time, we create a cohesive model uniting terrestrial foods with nearly 3,000 taxa of aquatic foods to understand the future impact of aquatic foods on human nutrition. We project two plausible futures to 2030: a baseline scenario with moderate growth in aquatic food production, and a high production scenario with a 15-million-ton increased supply of aquatic foods driven largely by investment and innovation in aquaculture production. By comparing changes in aquatic foods consumption between the scenarios, we then illuminate geographic and demographic vulnerabilities and estimate health impacts from diet-related diseases. Globally, we find that a high production scenario will decrease aquatic food prices by 26% and increase their consumption, thereby reducing the consumption of red and processed meats that can lead to diet-related non-communicable diseases, while also preventing approximately 166 million people from micronutrient deficiencies. This finding provides a broad evidentiary basis for policy makers and development stakeholders to capitalize on the vast potential of aquatic foods to reduce food and nutrition insecurity and tackle malnutrition in all its forms.

Main text

Globally, more than 3.5 billion people suffer from one or more forms of malnutrition (underweight, overweight, and obesity)[1], with at least 50% of all children suffering from micronutrient deficiencies in 2019 (GNR 2020)[2]. By failing to fulfil standards for diversity, nutritional quality, and food safety, dietary inadequacies are the leading reason people suffer from multiple nutrient deficiencies and subsequent morbidity and mortality[3]. Cardiovascular diseases, largely driven by diet-related factors, are the greatest contributor to global mortality, causing 17.8 million deaths in 2017[4], greater than the approximate 2 million deaths caused by COVID-19 in 2020.

To address these multiple forms of malnutrition, contemporary food policy discourses centre on the role of sustainable and healthy diets in improving human nutrition. The EAT-Lancet Commission report detailed a strategy to transform the global food system into one that could nourish the world without exceeding planetary boundaries[5]. Specifically, their strategy relies on doubling intakes of 'healthy' foods (e.g., fruits, vegetables, legumes, and nuts) and halving consumption of 'less healthy' foods (e.g., red meat and added sugars). The report, however, focused predominantly on terrestrial food production, even as it noted that it would be difficult for many populations to obtain adequate quantities of micronutrients from plant-source foods alone. Yet, treatment of aquatic foods as a homogenous entity ("fish") limited their inclusion and recognition of potential in global diets.

Aquatic food diversity improves food system nutrient diversity

Here, we reframe aquatic foods' role in global food systems as a highly diverse food group, which can supply critical nutrients[6–9] and improve overall health[10]. Aquatic foods are defined as animals, plants, and microorganisms, as well as cell- and plant-based foods of aquatic origin emerging from new technologies[11]. They include finfish, crustaceans (e.g., shrimp, crabs), cephalopods (e.g., squids, octopus), other mollusks (e.g., clams, cockles, sea snails), aquatic plants (e.g., water spinach, *Ipomea aquatica*), algae (e.g., seaweed), and other aquatic animals (e.g., mammals, insects, sea cucumbers). Aquatic foods can be either farmed or wild-caught, and are sourced from inland (e.g., lakes, rivers, wetlands), coastal (e.g., estuaries, mangroves, near-shore) and marine waters, producing a diversity of foods across all seasons and geographic regions.

Relative to the limited variation in terrestrial animal-source foods available to most consumers (e.g., beef, chicken, pork), aquatic animal-source foods present myriad options for supplying nutrients (Fig. 1). To provide evidence of the variability in nutrient composition across this diverse array of aquatic foods, we created the Aquatic Foods Composition Database[12] (AFCD; see Methods), a comprehensive global database comprising macro- and micro-nutrient composition profiles. More than 976 nutrients, inclusive of minerals (e.g., calcium, iron, zinc), vitamins, and fatty acids from 3,528 aquatic foods were synthesized from international and national food composition tables and a comprehensive literature review. To capture non-commercially relevant species, small-scale fisheries and underrepresented aquatic foods were specifically targeted.

Pathways for aquatic foods to benefit human health

Aquatic foods improve human health through three pathways: 1) by reducing micronutrient (e.g., vitamin A, calcium, iron) deficiencies that can lead to subsequent disease; 2) by uniquely providing omega-3 fatty acids, specifically docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), that can reduce the risk of heart disease and promote brain and eye health; and 3) by displacing the consumption of less healthy red and processed meats that can cause adverse health outcomes[10]. Any of these three pathways may overlap in a given individual, or predominantly target consumers of particular geographies or age-sex groups. The third pathway, specifically, is characteristic of the nutrition transition (i.e., the process by which demographic and economic shifts lead to concomitant dietary and epidemiological shifts often accompanying the Westernization of food systems)[13]. To better understand these pathways, we provide evidence of the diversity of aquatic foods and the nutrients they provide as part of overall diets. We also examine how aquatic food policy initiatives and investments in targeted geographies could improve public health. This increased attention on aquatic foods is necessary to elevate and amplify their ability to make important contributions to human nutrition, livelihoods, and well-being.

We explicitly integrated aquatic and terrestrial food systems models to evaluate potential health impacts of increasing global aquatic food production. This integration enables a more realistic portrayal of the trade-offs made within our global terrestrial and aquatic food systems and the diets reliant on them. To understand the potential for increases in aquatic food consumption to alleviate nutrient deficiencies and prevent the nutrition transition, we modelled two plausible scenarios to 2030, using an integrated version of the United Nations Food and Agriculture Organization's (FAO) FISH model[14] and the Aglink-Cosimo model[15], which is jointly maintained by the Organization for Economic Cooperation and Development (OECD) and the FAO. The embedded budgeting framework and price elasticities across foods allowed for additions of aquatic foods and substitutions of aquatic for terrestrial foods within national diets. This affects the supply and demand of a broad range of related food items, and particularly terrestrial animal-source foods such as poultry, pork, beef, lamb, eggs, and dairy products.

We used the integrated model to produce two scenarios: 1) a baseline scenario with projections of moderate growth trends and expert consensus regarding macroeconomic conditions, agriculture and trade policy settings, long-term productivity, international market developments, and average weather conditions; and 2) a high aquatic foods production scenario that assumes higher growth rates in production as a result of increased financial investment and innovation in aquaculture and improved management in capture fisheries[16] (see Methods). The projections are not forecasts about the future, but rather plausible scenarios based on a set of internally-consistent assumptions. Increases in aquaculture and capture fisheries in the high production scenario led to a 26% decrease in the international reference price of aquatic foods, and an increase in aquatic food production by 15 million tons in 2030 as compared to the baseline scenario, an approximate 15% increase in annual global catch.

In each scenario, we calculated the nutrients supplied to 191 countries from the projected composition of the food system models, by assigning nutrient composition values to the suite of foods being consumed, using the Global Nutrient Database (GND)[17] and the AFCD. The GND uses relatively homogenous nutrient composition values across all aquatic foods, varying only for the twelve categories explicitly modelled in the GND (e.g., demersal fish, pelagic fish, etc.). To expand upon this, we evaluated how overall nutrient supplies changed when considering the full diversity of species consumed at national levels. We disaggregated national consumption to the species level in proportion to species-specific aquaculture and capture production reported by the FAO, and linked these disaggregated species to the AFCD (see Methods).

To assess the role of increased diversity in the aquatic food system, we compared estimated nutrient outputs with and without species diversity fully disaggregated. Instead of twelve GND categories for aquatic foods, we used individual consumption and nutrient composition values for 2,143 taxa. This comparison allowed us to determine whether incorporating species diversity shifted our understanding of the nutrients supplied by aquatic foods, as opposed to relying on the most common commercial species present in the GND (Fig. 2). When using the disaggregated model outputs in the baseline scenario, we found that resulting consumption increased across most measured nutrient intakes, reflecting a significantly higher supply of iron (4% higher; median across countries), zinc (4%), calcium (8%), fatty acids (186%), and vitamin B12 (13%), with a 1% decline in vitamin A. This provides evidence that narrowly focusing on the nutrient contributions of commercially important species groups underestimates the potential benefits of all aquatic foods, especially the diverse foods harvested in small-scale fisheries, for human nutrition.

Aquatic foods can slow the nutrition transition and reduce the global burden of disease

In addition to the key role of aquatic foods in providing essential micronutrients, omega-3 fatty acids, and protein, particularly to people in the Global South, aquatic foods are also critical for preventing diet-related non-communicable diseases such as hypertension, heart disease, stroke, and diabetes. These health benefits are delivered through two mechanisms. First, aquatic foods directly provide omega-3 fatty acids, which have been shown to improve eye health, brain function, and reduce the incidence of heart disease, certain types of cancers, and anxiety and depression[18,19]. Second, aquatic foods displace the consumption of more harmful animal-source foods such as red and processed meats, particularly in the Global North, or can attenuate the increase in consumption in the Global South[20,21], in both cases reducing the risk of diet-related non-communicable disease[22].

In much of the Global North, an increase in aquatic food consumption was associated either with reductions in red meat, poultry, eggs, and dairy consumption, or with no significant impact (i.e., no discernible increases; Fig. 3). In the Global South, an increase in aquatic foods consumption was not associated with declines in the consumption of red meat, poultry, eggs, and dairy.

The combined dietary effect of increasing aquatic foods and reducing red and processed meats can lead to a reduced risk of hypertension, stroke, heart disease, diabetes, colorectal cancer, and breast cancer. Countries that are rapidly undergoing the nutrition transition are most likely to benefit from increases in aquatic foods production, which could avert their citizens' trajectory towards harmful levels of meat consumption. These countries include: China, India, Philippines, Malaysia, Indonesia, Vietnam, South Korea, Mexico, Brazil, Peru, Chile, Nigeria, Russia, USA, and Canada, among others (Fig. 3).

Aquatic foods can reduce micronutrient deficiencies

Deficiencies in key micronutrients, such as iron, zinc, calcium, iodine, folate, vitamins A, B12, and D, has led to 1 million premature deaths annually[23]. Further, an estimated 30% of the global population (≈2.3 billion people) have diets deficient in at least one micronutrient[23]. Nutrient deficiencies can arise from a variety of factors: 1) the formulation, availability, and accessibility of food systems; 2) ecological or environmental conditions—such as soil nutrient loss, drought, or fishery declines—that decrease availability; 3) reduced access to markets and natural resources through tariffs, fisheries governance, or other economic incentives; and/or 4) taste preferences, consumer behaviour, or other individualized factors. Despite these factors, aquatic foods have the capability to reduce or fill this nutrient gap with bioavailable forms of micronutrients. Specifically, for particular geographies where both aquatic foods reliance and nutritional deficiencies are high (e.g., equatorial regions)[7] and in at-risk demographics, such as young children and pregnant and lactating women, who have the greatest nutritional needs.

By 2030, aquatic foods will contribute a global average of 2.1-2.2% (range represents both scenarios) of calories, 13.0-13.7% of protein, 8.1-8.6% of iron, 7.8-8.2% of zinc, 1.1-1.1% of vitamin A, 26.7-27.8% of vitamin B12, and 100% of EPA and DHA fatty acids. Our food system-wide nutrient calculations assess the level of excess risk each country experiences because of deficiencies in their overall food systems. We calculated summary exposure values (SEVs) of the population to measure this excess risk, comparing the total amount of nutrition derived from apparent consumption against the total amount of nutrition required (see Methods). SEVs range from 0% to 100% and should be viewed as a risk-weighted prevalence, with higher SEVs representing higher risk of micronutrient deficiencies in the diet[24]. The difference in SEVs represents the difference in potential nutritional outcomes between the two aquatic food production scenarios in 2030 (Fig. 4). With overall trends in increasing aquatic food consumption and concomitant reductions in dairy, eggs, poultry, and red and processed meats (Fig. 3), there are large gains in micronutrient and omega-3 fatty acid consumption (Fig. 4). Globally, there will be reductions in micronutrient deficiencies across most assessed nutrients (i.e., 8.1 iron, 5.5 zinc, 36.0 vitamin B12, 49.3 calcium, and 76.8 million DHA+EPA fatty acid deficiencies), while increasing 10.1 million vitamin A deficiencies. Particular geographies will also experience small declines in calcium, iron, vitamin A, and zinc. This phenomenon likely arises from modest reductions in iron- and zinc-rich red meat consumption (as shown in historical trends), and large reductions in calcium- and vitamin A-rich dairy, egg, and poultry consumption. Notably, certain regions characterized by food and nutrition insecurity (e.g., sub-Saharan Africa and Southeast Asia) experience increases in micronutrient nutrition for all measured nutrients. However, some populations will face increasing levels of micronutrient deficiencies if consumption of aquatic foods displaces other foods, as evidenced by increasing calcium deficiency in Turkey, zinc deficiency in Azerbaijan, and vitamin A deficiencies in Norway, Indonesia, and Mexico, among others (Fig. 4).

Recognition of the diversity of aquatic foods and their nutrient composition could be harnessed to direct aquatic food production and consumption across a range of deficient minerals, fatty acids, and vitamins. For instance, if calcium deficiency is an issue in Turkey, then it may be prudent to increase the consumption of pelagic small fish (e.g., herrings, sardines) and focus aquaculture efforts on mussels[25]. Similarly, if vitamin A deficiency is an issue in Brazil, then efforts to promote production of oysters and consumption of sardines may be appropriate[26].

Aquatic foods are vital for certain demographics

Diets are shaped by the structure of food systems. Access to the foods produced by these systems can vary by age, sex, culture, socio-economic status, and geography, as does a given population's reliance on aquatic foods. Consequently, aquatic foods can disproportionately benefit particular segments of society at subnational levels. Aquatic foods are important for both sexes and all ages, but particularly so for young children, pregnant women, and women of childbearing age due to the critical role of micronutrients and essential fatty acids in foetal and child growth and development[27].

Because different age-sex groups have different vulnerabilities to certain health outcomes, there is a disproportionate benefit associated with consuming aquatic foods for particular groups. For instance, the function of reducing micronutrient deficiencies would be more important for children and women of reproductive age, and the function of averting the nutrition transition would be more important for adults. For example, elderly in Tunisia, Algeria, St. Lucia, Iran, and Moldova would experience large benefits in reduced deficiencies of DHA+EPA fatty acids (ΔSEV > -10.0 percentage points) and reduced deficiencies in iron in Kiribati and Congo-Brazzaville (ΔSEV = -3.6 percentage points). In several countries, children would experience large benefits in reduced calcium deficiencies due to increased aquatic foods consumption (ΔSEV percentage points for 5-9 year-olds = -6.0 for girls and -5.5 for boys in Myanmar; -5.9 for girls in Vietnam and Cambodia; -5.1for girls in Morocco; and -4.5 for boys and girls in Gabon; and ΔSEV percentage points for 0-4 year-olds = -4.9 for girls and -4.4 for boys in Maldives and -4.7 for boys and -4.3 for girls in Kiribati). In Panama, Iran, Moldova, Dominica, and Egypt, women of reproductive age (25-49 years) would receive a large health benefit for increased omega-3 fatty acid consumption (ΔSEV= -6.7 - -8.6 percentage points). Across all measured nutrients, when there was a significant difference between the changes accrued in deficiencies in the base vs. high road scenario (n = 71 age-nutrient groups), increased aquatic food production and consumption disproportionately benefitted females (average of 51.4% of countries) over males (average of 18.2% of countries), thus providing a potential pathway for nutritional equity.

Discussion

We illustrate the important role of aquatic foods in improving the future of human health, focusing on supplying critical micronutrients and averting the nutrition transition. Our analyses demonstrate that an increase in production of the rich diversity of aquatic foods, the range of content of multiple nutrients, including micronutrients and omega-3 fatty acids can contribute to many nations being better nourished. We note that our results here highlight the potential benefits that can be derived from a relative increase in aquatic food consumption compared to a baseline in 2030, but do not capture the absolute contribution of these foods to overall diets, which is far larger. Moreover, other health benefits to aquatic food consumption we have not yet been able to quantify include improved birth outcomes, child growth[28], cognition[29], school performance, work performance, as well as nutritional quality of breast milk[30].

The diversity of aquatic foods highlighted here evidences the limitations of treating them as a homogenous group in assessments of global food systems and diets. The EAT-Lancet Commission Report[5] undervalues the importance of aquatic foods; key food policy dialogues (e.g., the UN Sustainable Development Goal 2: Zero Hunger) ignore aquatic foods completely; and funding for the aquatic foods sector from the World Bank and Regional Development Banks lack targeted support[31]. Two main issues seem pervasive in misunderstanding the importance of aquatic foods. First, a very narrow view of the diversity of 'fish' and 'seafood' is often taken, with a focus on a set of commercially grown or wild-harvested finfish and bivalves, ignoring the vast diversity of other species, and other forms of culture production systems[32], and wild harvest made primarily by subsistence and artisanal small-scale fisheries[33]. Second, nutritional contribution of aquatic foods has traditionally focused on its low contribution to global energy (i.e., calories) and protein intake, yet has failed to consider the contribution of aquatic foods to nutrition via highly bioavailable essential micronutrients and omega-3 fatty acids. The Aquatic Foods Composition Database presented here enables future studies to move beyond this limited view of nutrition from aquatic foods.

It is critical to consider where and how aquatic foods are produced, as environmental, social, and economic impacts can vary widely across both the wild capture and aquaculture sectors (see Supplementary Methods for more on food cultures). Wild fish caught with destructive fishing methods, vessels that produce higher levels of greenhouse gas emissions, or unregulated or poorly regulated fisheries can have negative consequences that offset the benefits of increasing production. Similarly, aquaculture is often touted as a sustainable alternative to wild capture fisheries—a way to reduce or avoid increased pressure on overexploited stocks while providing affordable and necessary protein for human consumption. Despite the variability in environmental impacts across animal-source food production sectors, aquaculture (as wild capture fisheries) nearly always produces fewer greenhouse gas emissions and uses less land than red meats[34]. Yet, there are potential trade-offs to aquaculture intensification that extend beyond reduced greenhouse gas emissions and land use. Insufficiently regulated aquaculture can have negative impacts, including space competition with other sectors, including capture fisheries[35], potentially negative interactions with wild fishery populations[36], and lower nutrient content of farmed species not fed adequately[32]. Increasing dominance of a few species also threatens the sector's resilience[37].

A number of exciting innovations have occurred throughout the aquatic foods sector that capitalize on the unrecognised nutritional value of aquatic foods by-products and aim to deliver nutrients to those most in need. Processed fish products that are micronutrient-dense have been developed both as supplements within conventional meal preparation and in ready-to-eat formats (e.g., fish powders for infant feeding, wafers for out-of-home adolescent consumption, fish chutney for pregnant and lactating women)[38,39]. Innovation is required not only in the products themselves but also in their accessibility. Approaches that overcome social constraints to vulnerable individuals being able to consume enough aquatic foods to meet their nutritional needs, even in contexts where aggregate consumption may be high, are especially important. Simple techniques like smoking and drying can increase the safety and longevity of aquatic food products and support nutritionally vulnerable populations.

Synthesis

Our findings suggest strategic policy opportunities: 1) national-level nutritional assessments of countries most likely to experience micronutrient benefits could prompt policies and investments to direct products to those in need by improving fisheries management; enhancing sustainable aquaculture; or building more equitable regional trade networks; 2) diversity of aquatic foods nutrient portfolios should be harnessed in planning for nutrition-oriented sustainable aquaculture production, in designing national dietary guideline recommendations, and for public health interventions targeting particular nutrient deficiencies among vulnerable populations living in particular geographies; 3) the role of aquatic foods in slowing the nutrition transition could be leveraged to focus investments in countries experiencing rapid westernization of diets, and 4) age-sex profile vulnerabilities could lead to policies and investments for including aquatic foods in safety net programs that benefit the diets of those most vulnerable (e.g., pregnant and lactating women, young children, elderly). The policy imperative is therefore to include aquatic foods in food and nutrition policy and to ensure that the governance of and development investment in aquatic food systems aims to preserve, support and innovate with the diversity of species, production and harvest methods, product forms and distribution channels that allow aquatic foods to play an important part in global nutrition. This could include orienting markets for aquatic foods to take into account equitable access of essential nutrients, especially for those who are malnourished, the poor and vulnerable. The results presented on the nutritional and health benefits of aquatic foods can be used to better formulate national dietary guidelines and public health interventions, including safety net and school feeding programs, by improving diet quality with aquatic foods. Targeting specific population groups, for example, women and children in the first 1000 days of life, school children, and the elderly will aid nations to be better nourished. Research on the additional benefits of aquatic foods 'on the plate' to improve the nutritional quality of meals by enhancing the bioavailability of micronutrients of plant-source foods can further expand the potential of diverse aquatic foods in nourishing nations. All of these potential interventions could ensure that aquatic foods nourish nations.

Figure Legends

Fig. 1: Nutrient diversity of all aquatic foods in relation to terrestrial animal-source foods
Aquatic (blue) and terrestrial (green) food richness assessed as a ratio of the concentration of each nutrient per 100 grams to the daily recommended nutrient intake (RNI). See Table S5 for the RNI values and their citations. Food groups ordered by nutrient richness, or the mean across the ratio of each individual nutrient concentration per 100g of food to the RNI. Higher values indicate meeting a higher percentage of the daily recommended intake. Foods organized according to average nutrient richness across the selected nutrients.

Fig. 2 Difference in daily per capita intake of various nutrients from increasing aquatic food production and fully accounting for species diversity. The maps show the difference in mean nutrient intakes in 2030 under the high and baseline production scenarios when fully accounting for species diversity. Values greater than zero indicate higher nutrient intake under the high production scenario. Values less than zero indicate lower nutrient intake under the high production scenario. The boxplots show the difference in mean nutrient intakes in 2030 under both production scenarios, with and without fully accounting for species diversity. In the boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers. Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded).

Fig. 3. Fish and red meat consumption shifts resulting from an increase of aquatic foods. The percent difference in mean **(A)** aquatic food, **(B)** red meat (i.e., bovine, ovine, and pork) **(C)** poultry, **(D)** egg, and **(E)** dairy consumption in 2030 under the high and baseline production scenarios. Country typologies are featured in **(F)**. All countries increased their aquatic food consumption, which led to 1). increased consumption of non-aquatic animal-source foods (red); 2) stable consumption of non-aquatic animal-source foods (green); and 3) reduced consumption

of non-aquatic animal-source foods (blue). In **(A)-(E)**, values greater than zero indicate higher consumption under the high production scenario. Values less than zero indicate lower consumption under the high production scenario. Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded).

Fig. 4 Shifts in micronutrient deficiencies resulting from an increase of aquatic foods. The maps show the difference in Summary Exposure Values (SEVs) in 2030 under the high and baseline production scenarios by country. Values less than zero indicate reduced risk (lower SEVs) under the high production scenarios. Values greater than zero indicate elevated risk (higher SEVs) under the high production scenario. The bottom panel shows the difference in the number of people with micronutrient deficiencies, by age-sex group. Values less than zero indicate fewer micronutrient deficiencies under the high production scenario and values greater than zero indicate more micronutrient deficiencies under the high production scenario. Countries smaller than 25,000 km^2 are illustrated as points (small European countries excluded).

METHODS

Food System Modelling Approach

The Aglink-Cosimo and FAO FISH models are recursive-dynamic, partial equilibrium models used to simulate developments of annual market balances and prices for the main agricultural commodities produced, consumed, and traded worldwide. Aglink-Cosimo is managed by the Secretariats of the OECD and FAO, and used to generate the annual OECD-FAO Agricultural Outlook and policy scenario analyses. The FAO FISH model was integrated into Aglink-Cosimo to represent the aquatic foods component of the overall global food and agriculture system. Once integrated, the fish, fishmeal, and fish oil of the FISH model become just three other commodities among all the commodities covered in the merged model and they are fully simultaneous with the rest of the commodities. Two alternative outlook projections, a baseline and high production scenario, were used to represent food production, consumption, and trade through to 2030 for 19 food groups. The high production scenario reflects an imposed change to aquatic food production, attributed to increased financial investment in aquaculture and improved management in fisheries production. Although the high production scenario is optimistic, it is within the realm of possible futures, and is used to explicitly highlight the potential nutritional and health gains that could arise from targeted interventions. Species composition of broad commodity categories and feed composition (which could affect nutrient composition of products) were left unchanged between the present and 2030. We estimated country-level aquatic food consumption for both marine and freshwater capture and aquaculture projections to 2030 based on the Aglink-Cosimo baseline and high production outputs. A full description of the high production scenario parameters and assumptions can be found in the Supplementary Methods.

Global Nutrient Database (GND)

The GND matched over 400 food and agricultural commodities from the FAO's Supply and Utilization Accounts to food items in the United States Department of Agriculture Food Composition Database and obtained data on nutrient composition of the Supply and Utilization Accounts food items[17]. After adjusting for the inedible portion of each food item, the GND can estimate the national availability of macronutrients and micronutrients in a given year. Based on this, the 22 food group model outputs from the Aglink-Cosimo model were cross-walked to the GND, and nutrient supply was estimated for each scenario (Table S1).

Post-Model Species Disaggregations

Aquatic foods in the GND database are based on FAO FishStat production data and currently include the following categories: i) demersal fish; ii) pelagic fish; iii) fish oils; iv) crustaceans; v) cephalopods; vi) other marine fish; vii) freshwater fish; viii) other molluscs; ix) aquatic mammals; x) other aquatic animals; and xi) aquatic plants. To derive more resolved consumption estimates, we first assigned fish consumption estimates to freshwater and marine species based on historical shares. Within these broad categories, consumption was then assigned to capture and aquaculture sources to allow for future projections to reflect increased share (for some key species) in aquaculture production. Next, we used FAO FishStat production data to predict which species are actually being consumed in each country, adjusting for trade flows. We assumed that future diets preserved the current taxonomic make-up within each of these categories.

For marine species disaggregation, we used country-specific FAO FishStat historic catch and production data from 2014 to proportionally assign consumption projections to the Aglink-Cosimo outputs. Freshwater species, with the exception of salmon which were calculated separately using FAO trade data, and any fish destined to fishmeal, fish oil, or discards were removed. National apparent consumption of marine seafood by species from all producing sectors and sources (aquaculture, capture, and import) was calculated by subtracting exports from production, using FAO food balance sheets (according to the proportion of species within each seafood commodity category), and adding imports (assuming a species mix within trade codes proportional to trade partner production). Negative apparent consumption was assumed to be zero. Finally, we scale total harvest by the edible portion of each species.

Consumption of freshwater taxa was generated by matching FAO FishStat production and trade labels nested in the same commodity group (see Supplementary Methods). All commodities were converted to live weights using freshwater conversion factors[40]. The proportion of freshwater species consumed was further disaggregated with household survey data[40], and recreational fishery consumption (see Supplementary Methods). Household surveys were used to adjust the volume of capture fishery relative to aquaculture in 31 countries, as well as used to disaggregate unidentified commodity groups for five countries[40]. Recreational fisheries data from ancillary sources were included for 11 countries that have high but potentially under-reported recreational participation. Finally, we estimated consumable harvest by scaling total harvest by edible proportion (see Supplementary Methods).

Aquatic Foods Composition Database

The Aquatic Foods Composition Database (AFCD) synthesizes information from international and national food composition tables and peer-reviewed literature. Food composition tables were assumed to be correct and directly integrated. Data were sourced from international food composition databases from the USDA, FAO INFOODS and the EU SMILING project in SE Asia, as well as individual food composition tables from Australia, New Zealand, Pacific Islands, South Korea, India, Bangladesh, West Africa, Canada, Norway, and Hawaii, and previous reviews of peer-reviewed literature[9].

The search strategy focused on studies between 1990 and 2020, and prioritized specific journals known to include food composition data (e.g., Food Chemistry, Journal of Food Composition and Analysis). A broader search was also conducted using Web of Science including 20 aquatic and 15 nutritional search terms, with elimination hedges to avoid irrelevant studies (see Supplementary Methods for full terms). Peer-reviewed data were collected from 830 individual studies. In total, AFCD contains 29,603 lines of data representing 3,666 unique taxa.

We estimated the likely mix of species consumed as described above and then matched these individual species identities with the AFCD. To link disaggregated species to the AFCD, we used a hierarchical approach to fill the nutritional value for all 7 nutrients to all species consumed globally (Supplemental Fig. S16). When multiple entries were present for a single species, we took the mean of all entries. We built this hierarchy according to the following order: 1) scientific name, 2) average of species genus, 3) average of species family, 3) common name, 4) average of species order, and 5) average of GND category. In the disaggregation effort, we found 2,143 different aquatic species being consumed globally. We matched the following nutrients: iron, zinc, protein, vitamin A, vitamin B12, omega-3 fatty acids and calcium. After this matching process, we updated the estimates of nutrient intake at national levels.

National and Subnational Distributions of Intake

To evaluate the health impacts of aquatic foods consumption, we first modelled the distribution of habitual dietary intake across age-sex groups and geographies. Using SPADE (Statistical Program to Assess Habitual Dietary Exposure), an R-base package that uses 24-hour recall data to remove within-person variability and estimate habitual intake distributions[41], we estimated usual intakes of iron, zinc, vitamin A, vitamin B12, calcium, omega-3 fatty acids (DHA+EPA), and red meat. These distributions relied on the availability of individual dietary intake data with variable days of 24-hour recalls, which were available in 13 datasets to which we had access, including: United States, Zambia, Mexico, China, Lao, Philippines, Uganda, Burkina Faso, Bulgaria, Romania, Italy, Bangladesh, and Bolivia. A summary of the datasets used to estimate the subnational intake distributions is available in Supplemental Table S4.

We fit gamma and log-normal distributions to the habitual intake distributions for all available age-sex groups (Figures S6-S12) using the *fitdistrplus* package[42]. We selected the distribution with the best Kolmogorov-Smirnov (KS) goodness-of-fit statistic (0.002-0.373) as the final distribution for each group. The parameters of this best fitting distribution describe the shape of habitual intake distribution for each age-sex group and can be shifted along the x-axis in response to changing diets.

Assigning Various Countries to a Typology of Subnational Intake

We disaggregated country-level intakes into subnational distributions of intake in three steps. First, we disaggregated the European Union, which is modelled as a single entity in the integrated model, into its 27 constituent countries (Table S2). Second, we disaggregated country-level mean intakes into age-sex-level mean intakes using the Global Expanded Nutrient Supply (GENuS) database[43] for all nutrients except omega-3 fatty acids and vitamin B12, which are not included in the GENuS database. We used the SPADE habitual intake output to derive age-sex-level mean intakes for these two nutrients. Finally, we used the SPADE habitual intake output to describe the shape of intake distribution for each age-sex group.

The GENuS database uses historical national dietary trend data to estimate the availability of 23 individual nutrients across 225 food categories for 34 age-sex groups in nearly all countries in 2011[43]. We used these estimates to calculate scalars for relating country-level availability to age-group-level availability as:

$$\text{scalar}_{c,n,a,s} = \text{availability}_{c,n,a,s} / \text{mean}(\text{availability}_{c,n})$$

Where the scalar for country *c*, nutrient *n*, age group *a*, and sex *s* is calculated by dividing the nutrient availability for each age-sex group by the mean nutrient availability for all age-sex groups. We assume these ratios of nutrient availability are proportional to ratios of nutrient intake and scale the country-level mean nutrient intakes as follows:

$$\text{Intake}_{c,n,a,s} = \text{Intake}_{c,n} * \text{Scalar}_{c,n,a,s}$$

We used the same process to disaggregate intakes for omega-3 fatty acids and vitamin B12 but used the country-level and age-sex-level means derived from SPADE habitual intakes described above. See Tables S1-S3 for details on crosswalking the COSIMO-Aglink and GENUS outputs.

We then used the SPADE habitual intake outputs to characterize the distribution of nutrient intakes within each age-sex group. The habitual intake data and associated statistical probability distributions are incomplete across all country-nutrient-age-sex combinations (Figure S5) so we filled gaps by imputing data from the nearest neighbour (37% of age-sex groups). First, we filled within-country gaps by borrowing intake distributions, in order of preference, from the: (i) nearest age group within a sex and country; (ii) the opposite sex from within a country; and (iii) the nearest country geographically and/or socioeconomically (Figure S13). We then mapped these to the rest of the world, based on UN sub-regions, with a few expert-identified modifications (Figure S14).

Health Impact Modelling Approach

Summary exposure values (SEV) integrate relative risks of sub-optimal diets with actual intake distributions (Murray Lancet 2020). They estimate the population level risk related to diets and compare it to a population where everyone is at a maximal risk level, giving values ranging from 0% (no risk) to full population-level risk (100%). For low aquatic food consumption and high red meat consumption, we use relative risk derived from the Global Burden of Disease[24]. For micronutrient deficiency risk assessment, we derived continuous relative risk curves for iron, zinc, vitamin A, and calcium, based on the probability approach for calculating micronutrient deficiencies[44]. To evaluate the risk of micronutrient deficiencies, intake distributions are compared against requirements. The latter is defined as a continuous risk curve that has a value of 1 at low intakes, 0.5 at the relevant EAR (estimated average requirement) and zero at large intakes. These absolute risk curves are based on the cumulative normal distribution function of requirements[45] with a mean at the EAR and a coefficient of variation of 10%. The latter value is used when more information on exact nutrient requirement is unavailable[44,46]. The prevalence of risk at the population level is derived by computing the *expected* micronutrient deficiency across the entire population[45], by applying an integral of the intake distribution per age-sex-location-nutrient multiplied by its specific relative risk. The values derived range from 0 and 1, and evaluates - as SEV - the risk of micronutrient deficiency on a population level from no risk (0) to maximal (1; everyone is at risk). Estimated average requirements were derived from several sources (WHO 2004, Dary and Hurrell 2006, Otten et al. 2006). Because zinc and iron requirements depend on other dietary factors (e.g., inhibitors such as phytate), we used three levels for each nutrient, based on overall diets, which crudely divide between diets based on their cereals and animal-source foods intakes[47,48]. We then assigned each country to either of the zinc and iron value, based on its SDI. For vitamin B_{12}, we use the values used by the Institute of Medicine[49] but acknowledge that uncertainties regarding recommended intakes exist, and use a coefficient of variation of 25% instead of the default 10% in constructing our risk curves[50].

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Regarding aquatic food products, any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Author Contributions

CDG and SHT conceptualized the research idea, with significant methodological and design input from JZK, AS, CMF, DV, and HM. Data acquisition and compilation was conducted by subgroups for the Aquatic Foods Composition Database (CDG, JZK, CD, HK, KJF, MK, DV), Global Nutrient Database (HM), Aglink-Cosimo model (HM), FAO Fish model (PC, SV, MB), species disaggregation models (EFC, EAN, JAG, AJL, DV, JGE, CDG), subnational distribution model (SP, CDG, LC, SB), and health impact models (AS, CDG, GD, ER). The food systems modelling was led by HM and PC; subnational distributions modelling was led by SP and SB; and the health impact modelling was led by AS, CF, and GD. CDG drafted the original manuscript, and all co-authors edited and revised the writing.

Additional Information:

Supplementary Information is available for this paper.

Correspondence and requests for materials should be addressed to Christopher Golden at golden@hsph.harvard.edu

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