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Aquatic Foods to Nourish Nations

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SUMMARY

Despite contributing to healthy diets for billions of people, aquatic foods are often undervalued as a nutritional solution because their diversity is often reduced to the protein and energy value of a single food type (‘seafood’ or ‘fish’). For the first time, we create a cohesive model that unites 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 over the business-as-usual scenario in 2030, 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 may be 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 group (‘seafood’ or ‘fish’) limited the potential of their inclusion and recognition 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., crabs, shrimp), cephalopods (e.g., octopus, squids), other mollusks (e.g., clams, cockles, sea snails), aquatic plants (e.g., water spinach, *Ipomoea aquatica*), algae (e.g., seaweed), and other aquatic animals (e.g., mammals, insects, sea cucumbers). Aquatic foods can be 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. In this research, we focus on aquatic animal-source foods, which constitute the majority of these sources.

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). Currently, wild fisheries harvest more than 2,300 species and aquaculture growers farm approximately 630 species or species-types[12]. To provide evidence of the variability in nutrient composition across this diverse array of aquatic foods, we created the Aquatic Foods Composition Database[13] (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 3,753 aquatic food taxa 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. Our analysis indicates that the top 6 categories of nutrient-rich animal-source foods are all aquatic foods, including pelagic fish, shellfish, and salmonids (Fig. 1).

Pathways for aquatic foods to benefit human health

Aquatic foods improve human health through at least three pathways: 1) by reducing micronutrient (e.g., vitamin A, calcium, iron) deficiencies that can lead to subsequent disease; 2) by providing the dominant source of the long-chain polyunsaturated fatty acids docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which 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)[14]. 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 and health.

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 mitigate chronic disease risks, we modelled two plausible scenarios to 2030, using an integrated version of the United Nations Food and Agriculture Organization's (FAO) FISH model[15] and the Aglink-Cosimo model[16], 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 in aquatic food production 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 food 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[17] (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 (an approximate 15% increase in annual global production) in 2030 as compared to the baseline scenario. 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 within 22 food commodity categories, using the Global Nutrient Database (GND)[18] and the AFCD. For 21 of the 22 food commodity categories (all terrestrially produced foods), the GND was used as the source of nutrient composition data. For the one commodity category containing aquatic foods, the AFCD nutrient composition values were used. A set of refuse factors is applied to all foods; these refuse factors are highly specific to individual foods and their respective forms of preparation. Within the food group of fish and seafood, these refuse factors vary from 55% for fresh crustaceans to 10% for fresh cephalopods.

To assess the role of diversity in the aquatic food system, we compared estimated nutrient outputs with and without species diversity fully disaggregated at national levels. The GND uses relatively similar 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.).We disaggregated national consumption to the species level in proportion to species-specific aquaculture and capture fisheries production reported by the FAO, and linked these disaggregated species to the AFCD (see Methods). 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 the levels of 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 calcium (8% higher; median across countries), iron (4%), omega-3 long-chain polyunsaturated fatty acids (186%), zinc (4%), and vitamin B_{12} (13%), with a 1% decline in vitamin A. Building off research showcasing that aquatic biodiversity enhances human nutrition[19], this result 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 mitigate chronic disease risks characteristic of the nutrition transition

In addition to the key role of aquatic foods in providing essential micronutrients, long-chain 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 long-chain omega-3 fatty acids, which have been shown to potentially improve eye health, brain function, and reduce the incidence of heart disease and certain types of cancers[20,21]. 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 their increased consumption in the Global South[22,23], in both cases reducing the risk of diet-related non-communicable disease[24].

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 population's 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, B_{12}, and D, have led to 1 million premature deaths annually[25]. Further, an estimated 30% of the global population (≈2.3 billion people) have diets deficient in at least one micronutrient[25]. Inadequate nutrient intakes 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[26,27]. Aquatic foods have the capability to reduce or fill this nutrient gap with bioavailable forms of micronutrients, particularly in geographies where aquatic food reliance and nutritional deficiencies are high (e.g., equatorial regions)[7] and in nutritionally at-risk demographics, such as young children and pregnant and lactating women.

In the high production scenario by 2030, aquatic foods may contribute a global average of 2.2% of energy, 13.7% of protein, 8.6% of iron, 8.2% of zinc, 16.8% of calcium, 1.1% of vitamin A, 27.8% of vitamin B_{12}, and 98-100% of EPA and DHA fatty acids, an approximate 0-10% increase for each nutrient above 2020 reference values. 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 age- and sex-specific nutrient demands (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[28]. The difference in SEVs estimates the change in potential risk of nutritional deficiencies between the two aquatic food production scenarios in 2030 (Fig. 4). With overall trends in increasing aquatic food consumption and concomitant reductions in poultry, eggs, dairy, and red and processed meats (Fig. 3), there are large gains in micronutrient and omega-3 fatty acid consumption (Fig. 4). Globally, the high production scenario will lead to reductions in micronutrient deficiencies across most assessed nutrients (i.e., 8.1 million iron, 5.5 million zinc, 49.3 million calcium, 36.0 million vitamin B_{12}, 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 supply. 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, one prudent option may be to increase the consumption of pelagic small fish (e.g., herrings, sardines)[29]. Similarly, if vitamin A deficiency is an issue in Brazil, then efforts to promote the production of oysters or the consumption of sardines may be appropriate[30]. These types of food system solutions will require sub-national targeting of vulnerable populations and will rely on efforts to increase both production and consumption.

Aquatic foods can support certain vulnerable 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 sub-national 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[30].

Because different age-sex groups have different vulnerabilities to certain health outcomes, a disproportionate benefit is 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 attenuating chronic disease morbidity and mortality 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 the Republic of Congo (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, a segment of reproductive-aged women (25-49 years) would receive a large health benefit for increased DHA+EPA consumption (ΔSEV= -6.7 - -8.6 percentage points). Across all measured nutrients, there were significant differences in deficiencies between the base vs. high road scenario (n = 71 age-nutrient groups), where 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 attenuating chronic disease morbidity and mortality that is characteristic of 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 aquatic food omega-3 fatty acids, can improve the diets of many nations. 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.

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. This classification ignores the vast diversity of other species, and other forms of culture production systems[32], and wild harvest 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, failing to consider the contribution of aquatic foods to nutrition via highly bioavailable essential micronutrients and long-chain 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. 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 and many aquatic foods outperform poultry[34]. Yet, potential trade-offs to aquaculture intensification extend beyond reduced greenhouse gas emissions and land use. Insufficiently regulated aquaculture can have negative impacts, including space competition with other sectors, including, for example, capture fisheries[35], potentially negative interactions with wild fishery populations resulting from nutrient discharge, escapements, and disease[34]. Increasing dominance of a few species also threatens the sector's resilience[36]. Sustainably and equitably achieving the human health benefits of expanded aquaculture production will require policies and technologies that mitigate impacts on adjacent ecosystems, industries, and communities[17].

Several 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)[37,38]. 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 at national levels 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. Measures to ensure that these products are safe and do not exceed recommended intake of preservatives like salt, for example, are needed.

Synthesis

Our findings suggest strategic research and policy opportunities:

1) in countries where there are high burdens of micronutrient deficiencies, supply chains and availability of aquatic foods may be strengthened by improving fisheries management;

enhancing sustainable aquaculture; and building more equitable national and regional trade networks;

2) promoting a diversity of nutrient-rich aquatic foods in sustainable aquaculture systems, in designing national food-based dietary guidelines, and for public health interventions targeting particular nutritional deficiencies among vulnerable populations living in particular geographies;

3) incentivizing access and affordability of aquatic foods in countries experiencing a rapid nutrition transition;

4) prioritizing aquatic foods in social protection programs including food assistance, school meal programs, and safety nets for the most nutritionally vulnerable, including pregnant and lactating women, young children in the first 1000 days, and the elderly.

In line with the Committee on World Food Security's Voluntary Guidelines on Food Systems and Nutrition[39], calling for greater attention to diverse nutritious foods for transformation of food systems, national food and nutrition policy may include and prioritize aquatic foods where culturally and socially appropriate. Also, policy may ensure that the governance of and investment in aquatic food systems aim to preserve, support and innovate with: a diversity of aquatic species; improved production and harvest methods and practices; and increasing efficient and safe distribution channels. These measures should enable aquatic foods to play an important role in nourishing nations and improving global nutrition and health.

Figure Captions

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). Each shaded box represents the median value of each nutrient in a muscle tissue (e.g., fillet) sample across all species comprised within each taxonomic group. Food groups were ordered vertically by their mean 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. See Table S5 for the RNI values and their citations.

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). All European Union (EU) member countries have the same value because they are modelled as a single economic unit in the Aglink-Cosimo model.

Fig. 3. Fish and red meat consumption shifts resulting from an increase of aquatic foods. 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, **(E)** dairy, and **(F)** all non-aquatic animal-source food consumption in 2030 under the high and baseline production scenarios. 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 km2 are illustrated as points (small European countries excluded). All European Union (EU) member countries have the same value because they are modelled as a single economic unit in the Aglink-Cosimo model.

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 to 2030 for 22 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[18]. 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).

Species Disaggregation

Aquatic foods in the GND 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 historical 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 scaled 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 and disaggregated 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 1,063 individual studies. In total, AFCD contains 29,912 lines of data representing 3,753 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 assign the nutritional value for all 7 nutrients to all species consumed globally (Supplemental Fig. S7). 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: protein, iron, zinc, calcium, vitamin A, vitamin B_{12}, and omega-3 long-chain polyunsaturated fatty acids. After this matching process, we updated the estimates of nutrient intake at national levels.

National and Sub-national 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, calcium, vitamin A, vitamin B_{12}, 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 PDR, Philippines, Uganda, Burkina Faso, Bulgaria, Romania, Italy, Bangladesh, and Bolivia. A summary of the datasets used to estimate the sub-national intake distributions is available in Supplemental Table S7.

We fit gamma and log-normal distributions to the habitual intake distributions for all available age-sex groups (Figures S9-S15) 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 Sub-national Intake

We disaggregated country-level intakes into sub-national 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 S5). 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 B_{12}, 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 B_{12} but used the country-level and age-sex-level means derived from SPADE habitual intakes described above. See Table S6 for details on crosswalking the Aglink-Cosimo 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 S8) 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 S16). We then mapped these to the rest of the world, based on UN sub-regions, with a few expert-identified modifications (Figure S17).

Health Impact Modelling Approach

Summary exposure values (SEV) integrate relative risks of sub-optimal diets with actual intake distributions[28]. 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 long-chain omega-3 fatty acids (EPA+DHA), we used the updated IHME relative risk curves for omega-3 EPA+DHA that are only associated with ischemic heart disease and have different values for adolescent and adult subpopulations (with no risk for children). These relative risk curves capture mild risk associated with consumption of long-chain omega-3 fatty acids under 0.4 g/d[28]. For micronutrient deficiency risk assessment, we derived continuous relative risk curves for iron, zinc, calcium, and vitamin A, 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 to 1, and evaluates the risk of micronutrient deficiency, as SEV, on a population level from no risk (0) to maximal (1; everyone is at risk). Estimated average requirements were derived from several sources[47–49]. 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[50,51]. We then assigned each country to their proxy zinc and iron values, based on its SDI. For vitamin B_{12}, we use the values used by the Institute of Medicine[52] 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[53].

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Data Availability Statement

Code

The code associated with the diversity disaggregation is available in this Github repository: https://github.com/cg0lden/Fisheries-Nutrition-Modeling

The code associated with the SPADE analysis is available in this Github repository: https://github.com/cg0lden/subnational_distributions/tree/master/scripts/BFA%20paper%20scripts

The code associated with the health impacts analysis is available in this Github repository: https://github.com/alonshepon/Health-Benefit-Calculation-BFA

Data

All processed outputs and non-proprietary raw inputs are available on Github.

The data associated with the diversity disaggregation is available in this Github repository: https://github.com/cg0lden/Fisheries-Nutrition-Modeling

The data associated with the SPADE analysis is available in this Github repository: https://github.com/cg0lden/subnational_distributions/tree/master/data/raw/BFA%20paper%20data

The data associated with the health impacts analysis is available in this Github repository: https://github.com/alonshepon/Health-Benefit-Calculation-BFA

Proprietary input datasets protected by data-sharing agreements (i.e., the GND) are not posted in these repositories

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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), sub-national distribution model (SP, CDG, LC, SB), and health impact models (AS, CDG, GD, ER). The food systems modelling was led by HM and PC; sub-national 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.
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